Measurements in the development and Testing of Electrical drivers and Power Electronics

Francesco Raimondi – Teledyne LeCroy
Zsolt Kapitany - Elsinco

TELEDYNE LECROY
Everywhereyoulook™

Veszprém, Oct 29 2019

Video, Application and Posters at : https://teledynelecroy.com/static-dynamic-complete/

Teledyne LeCroy Overview

- LeCroy was founded in 1964 by Walter LeCroy
    - Original products were high-speed digitizers for particle physics research
- Corporate headquarters is in Chestnut Ridge, NY
- Long history of innovation in digital oscilloscopes
    - First digital storage oscilloscope
    - Highest bandwidth real-time oscilloscope (100 GHz)
- LeCroy became the world leader in protocol analysis with the purchase of CATC and Catalyst
    - Frontline Test Equipment and Quantum Data were also recently acquired (2016)
- In 2012, LeCroy was acquired by Teledyne Technologies and renamed Teledyne LeCroy

Agenda

- New Product announcement
- Before the main topic some basic capabilities we need to handle for a good measurements and the information needed
- Power in the various forms…

- Demos, Labs, Questions

Teledyne LeCroy Pioneered 8-Channel Oscilloscopes and MDAs
Still the Leading 8-Channel High Definition Oscilloscope

HDO8000 launched in 2014

- 8 channel, 12 bits, 1 GHz
  - Yokogawa had 8 channel, 8 bits, 500 MHz oscilloscope
  - Tektronix 5 Series launched in 2017
    - There are many tradeoffs which will be described later

Motor **D**rive **A**nalyzer (MDA) models launched in 2015

- Built on HDO8000 platform
- Includes 3-phase electrical and mechanical power software
  - Static, dynamic, complete

The HDO8000 Has Been Extremely Successful But…

Customers have asked for a few enhancements

- Display Size
- More Bandwidth
- Longer Memory
- Smaller Footprint

Capture Every Detail with the WaveRunner 8000HD
The Only 8-channel, 12-bit, 2 GHz High Definition Oscilloscope

- The most resolution
  - HD4096 delivers 12 bits all the time
  - 16x closer to perfect

- The most channels and flexibility
  - 8 analog and 16 digital channels
  - Up to 16 analog channels with OscilloSYNC™ technology
  - No analog/digital channel tradeoffs

- The longest memory
  - 5 Gpts records with simple navigation and no compromises

Capture Every Detail with the WaveRunner 8000HD
The Only 8-channel, 12-bit, 2 GHz Oscilloscope

- The most resolution
  - HD4096 delivers 12 bits all the time
  - 16x closer to perfect

Tagline

- The most channels and flexibility
  - 8 analog and 16 digital channels
  - Up to 16 analog channels with OscilloSYNC™ technology
  - No analog/digital channel tradeoffs
- The longest memory
  - 5 Gpts records with simple navigation and no compromises

Capture Every Detail with the WaveRunner 8000HD
The Only 8-channel, 12-bit, 2 GHz High Definition Oscilloscope

1 ▪ The most resolution

- HD4096 delivers 12 bits all the time
- 16x closer to perfect

3 Key Messages

2 ▪ The most channels and flexibility

- 8 analog and 16 digital channels
- Up to 16 analog channels with OscilloSYNC™ technology
- No analog/digital channel tradeoffs

3 ▪ The longest memory

- 5 Gpts records with simple navigation and no compromises

Capture Every Detail with the WaveRunner 8000HD
The Only 8-channel, 12-bit, 2 GHz High Definition Oscilloscope

1 ▪ The most resolution
  - HD4096 delivers 12 bits all the time
  - 16x closer to perfect

2 ▪ The most channels and flexibility
  - 8 analog and 16 digital channels
  - Up to 16 analog channels with OscilloSYNC™ technology
  - No analog/digital channel tradeoffs

3 ▪ The longest memory
  - 5 Gpts records with simple navigation and no compromises

Supporting Evidence

Capture Every Detail with the WaveRunner 8000HD The Only 8-channel, 12-bit, 2 GHz High Definition Oscilloscope

- The most resolution
  - HD4096 delivers 12 bits all the time
  - 16x closer to perfect
- The most channels and flexibility
  - 8 analog and 16 digital channels
  - Up to 16 analog channels with OscilloSYNC™ technology
  - No analog/digital channel tradeoffs
- The longest memory
  - 5 Gpts records with simple navigation and no compromises

The WaveRunner 8000HD Addresses Each Customer Request

Customers have asked for a few enhancements

- ✓ Display Size
  - 15.6” HD Display (1920 x 1080)
- ✓ More Bandwidth
  - Up to 2 GHz
- ✓ Longer Memory
  - Up to 5 Gpts
- ✓ Smaller Footprint
  - New industrial design

Introducing the WaveRunner 9000

- 15.4” widescreen capacitive touch screen
- 40 GS/s sample rate
- 500 MHz - 4 GHz bandwidths
- “M” Models at 2.5 GHz & 4 GHz
- 128 Mpts memory
- MAUI with OneTouch
- 16 digital channels with 1.25 GS/s
- Modern high performance CPU/processor

Teledyne Test: LeCroy Arbitrary Waveform Generator

New

High Definition (HD) Dual Channel Arbitrary Waveform Generator

a. Vertical Resolution 16 bit (accurately generates waveform details)

b. Wide output voltage window ±12 V (50Ω into 50Ω) and ±24V (50Ω into High Impedance) without the need of an external amplifier

c. 3 instruments in one: Function Generator and Arbitrary Waveform Generator plus the capability to add the Digital Pattern Generator, 8 Ch.

d. Arbitrary Waveform Memory 128Mpts./Ch Std (up to 1 Gpts/Ch optional) - Generates complex pseudo-random waveforms for long play testing

T3AWG3252 and T3AWG3352
250 MHz and 350 MHz, sinewave AFG mode

High Definition (HD) Stimulus-Response

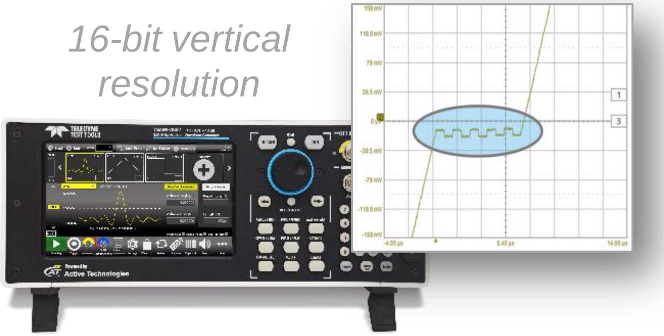
Clean signal

Real-world signal

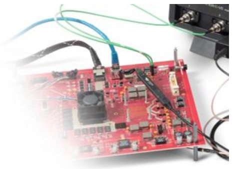
Stress test

Noise and interference immunity

16-bit vertical resolution



HD AWG (stimulus)



Device Under Test (DUT)

12-bit vertical resolution

HD scope (response)

What are the T3SP15D and T3SP10D ?

- **TDR (Time Domain Reflectometers)**

✓ **Innovative**

  - Not a fault locator but a **Signal Integrity Analyzer** detecting degradations and discontinuities for the todays single-ended and differential transmission lines and cables used in the modern serial data standards

✓ **Highly Accurate**

  - Adopting the most **accurate calibration method (OSL)** using state-of-the-art calibration kit as used for the most expensive VNA.

✓ **Ultra-Portable**

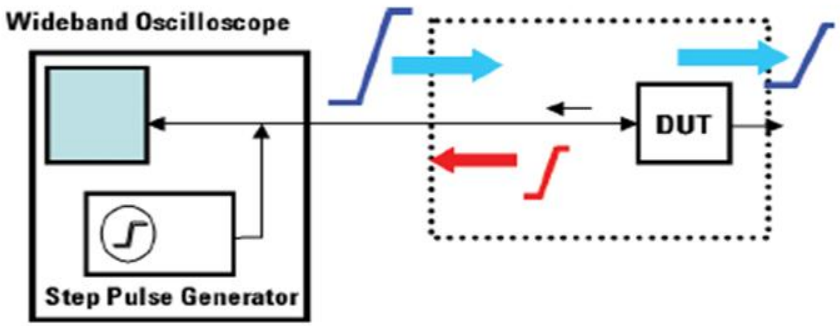
  - Go anywhere in test lab or in the field, battery operated (option)

✓ 8 models available:

  - T3SP10D (50ps) and T3SP15D (35ps) including precision phase match cables (50 ± 1 Ω, <1ps skew)
  - BUNDLE-version adding the (OSL) Calibration Kit
  - B-version adding the internal battery

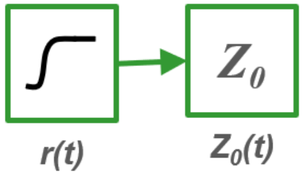
TDR - Time Domain Reflectometry

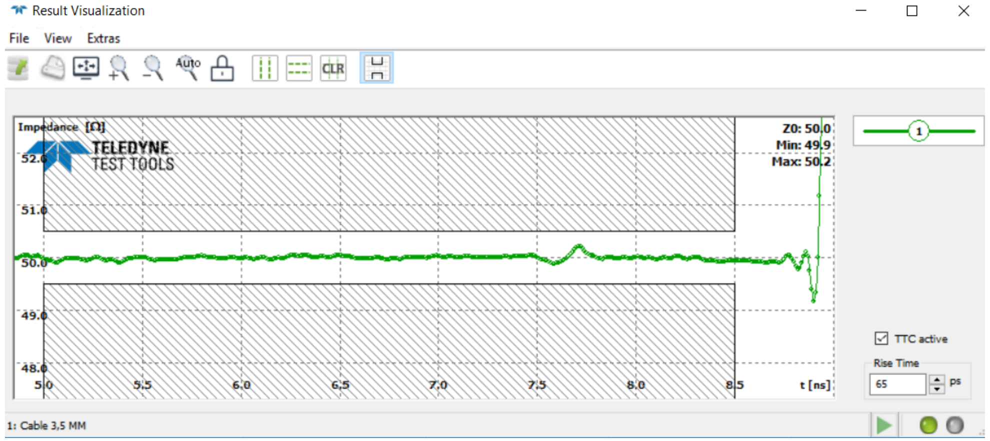
- TDR measures impedance mismatch and discontinuities that cause reflections (types and distances) in the transmission lines thought which the signal travel.
- Reflections decrease signal quality affecting signal rise time, pulse width, jitter ….
- Step Response and Impedance profile are fundamental to ensure Signal Integrity.



TDR Block Diagram

Step Response





Z0: 50.0
Min: 49.9
Max: 50.2

☑ TTC active

Rise Time 65 ps

1: Cable 3,5 MM

Impedance Profile

Transmission Line Characteristic Impedance Profile (Zo vs. distance)

Repeatable, easy and very quick measurements with T3SP TDR

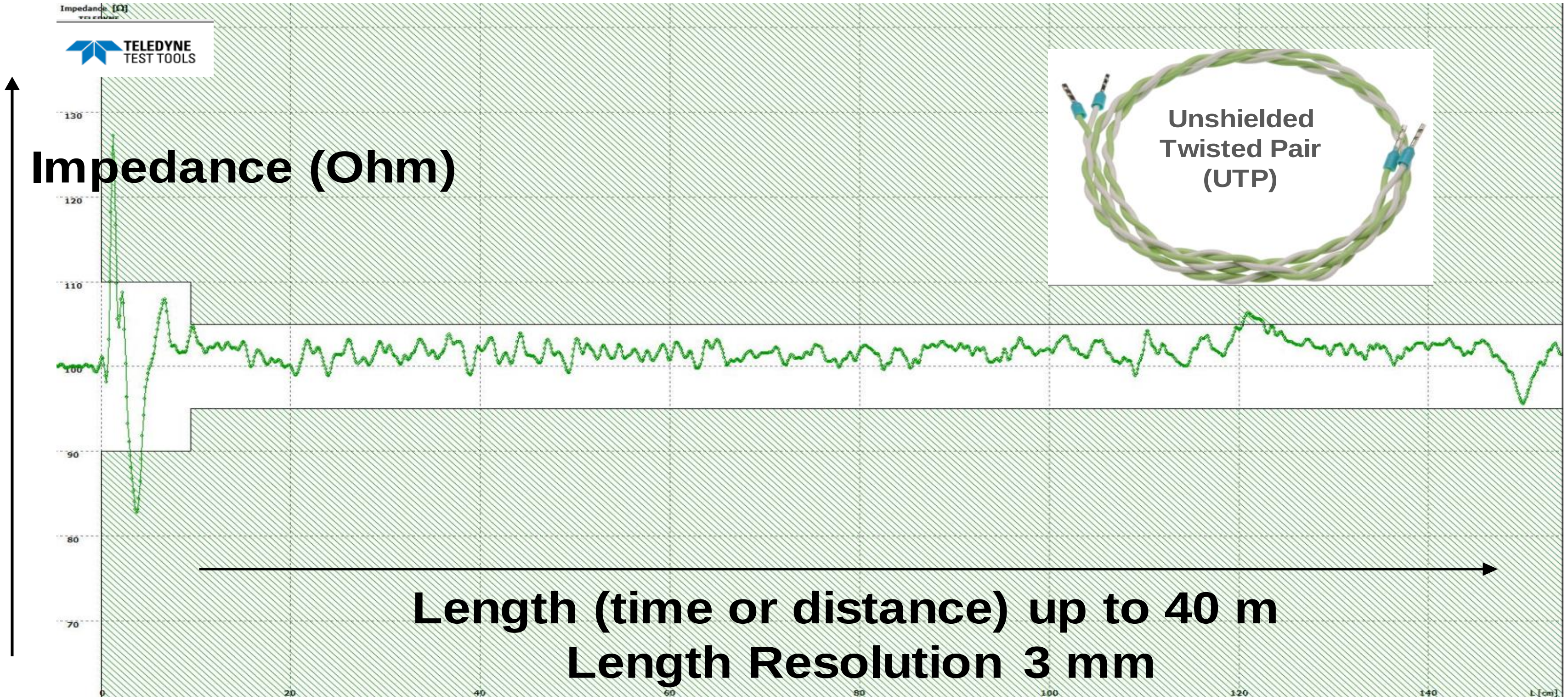
- ✓ Very accurate impedance measurements
- ✓ Spatial resolution < 3 mm (T3SP15D)

TDR - Time Domain Reflectometry

- TDRs (Time Domain Reflectometers) are the ideal measurement tool to accurately characterize and diagnose **impedance variations along the length transmission line.**

- TDR locates faults, degradation and discontinuities in metallic cables, connectors, PCB , transmission lines or any other electrical path.

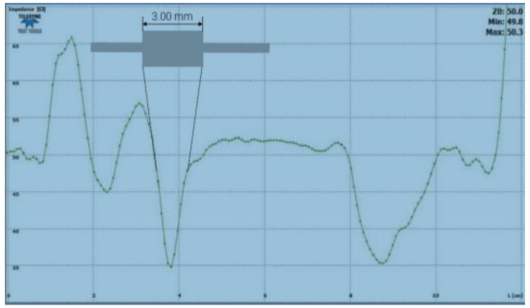
- Key Specifications are Rise Time , Spatial Resolution and Distance Length Range



Length (time or distance) up to 40 m
Length Resolution 3 mm

T3SP15D and T3SP10D are highly accurate TDRs

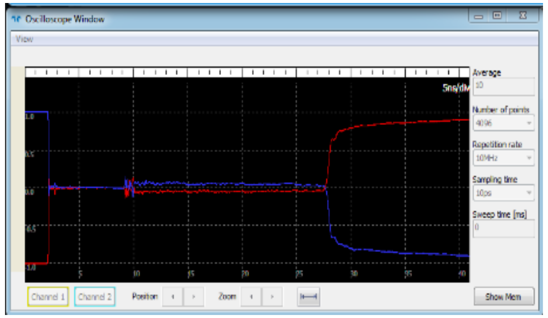
- **High Resolution Calibrated True Differential TDR (Time Domain Reflectometer)**



High Resolution	Spatial Fault Resolution < 3 mm (FR4)	Precisely locate and identify signal integrity artifacts along the transmission path through which the signal travel
Calibrated	OSL (Open-Short-Load) Calibration Method	Highest accuracy on impedance profile (Ohm) vs. length (or time) and on return loss (dB) vs. frequency (│S11│)
True Differential	Two pulses with inverse polarity used as a stimulus	Ideal for twisted pair and differential design No ground connection required

And more :

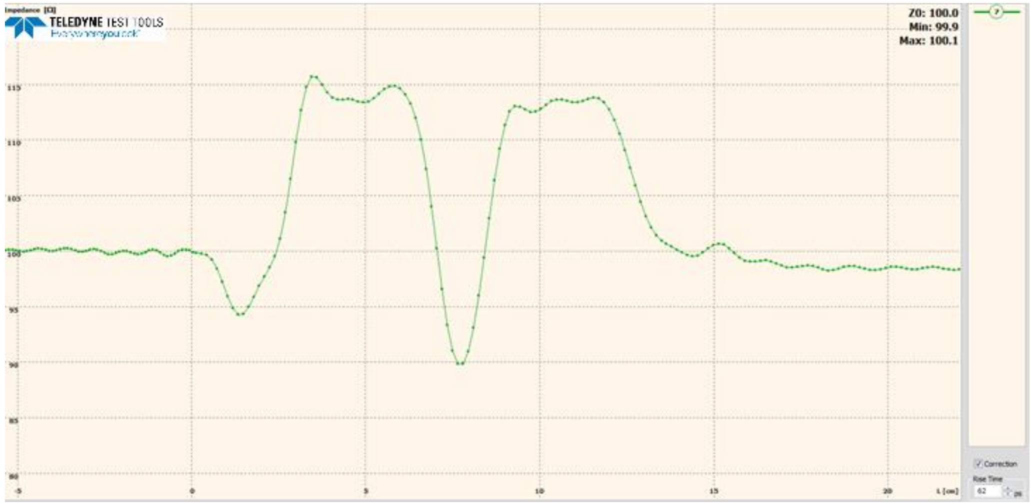
- Ultra-Portable and Battery operated (measure everywhere)
- ESD-Protected (operate safely)



What is different between T3SP10D and T3SP15D?

- **T3SP10D**
- S-paramter (S11) up to **10GHz**
- Rise time after calibration: **50ps**
- Connector: **SMA**
- Cable Callibration kit: **SMA**
- Resolution (FR4): < **4.2mm**

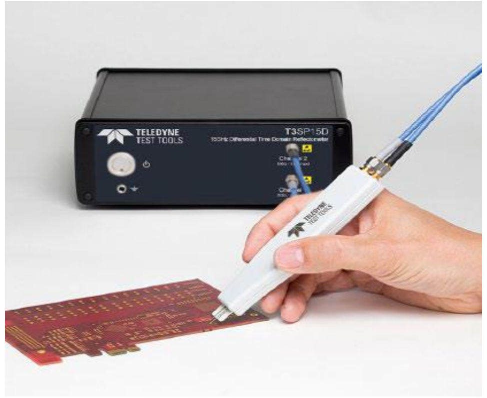
- **T3SP15D**
- S-paramter (S11) up to **15GHz**
- Rise time after calibration: **35ps**
- Connector: **2.92mm**
- Cable & Callibration kit: **3.5mm**
- Resolution (FR4): **<3 mm**



TDR Differential Probes

T3SP-DPROBE

(variable pitch)



T3SP-DPROBE-F

(fixed pitch)

Parameter	Value / Unit	Comments
Impedance	100 Ω	VSWR < 1.05
Electrical Length	690ps	
Probe Tips	Fixed Blades	Copper beryllium (3 pairs of replacement tips included)
Pitch	0.1 – 5 mm	adjustable
Pin Configuration	Signal - Signal	
Connectors	SMA female	compatible with 2.92mm and 3.5mm connectors
Frequency Range	DC – 18GHz	valid for probe without tips
Dimensions	130 × 34 × 14 mm	casing only
	157.5 × 34 × 14 mm	with connectors and tips
Material	Aluminum	
Specials		direct in-circuit TDR testing

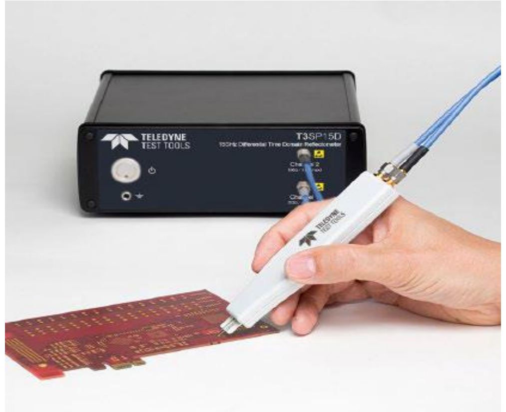
Parameter	Value / Unit	Comments
Impedance	100 Ω	VSWR < 1.05
Electrical Length	830ps	
Probe Tips	Spring-loaded pin	
Pitch	2.54 mm	fixed
Pin Configuration	Signal - Signal	
Connectors	SMA female	compatible with 2.92mm and 3.5mm connectors
Frequency Range	DC – 5GHz	valid for probe without tips
Dimensions	131 × 32 × 13.2 mm	casing only
	131 × 32 × 15.6 mmm	with connectors and tips
Material	Polystyrene	

Exceptional measurements repeatability

What‘s next: TDR Single-ended Probes

T3SP-SEP

(variable pitch)



T3SP-SEPROBE-F

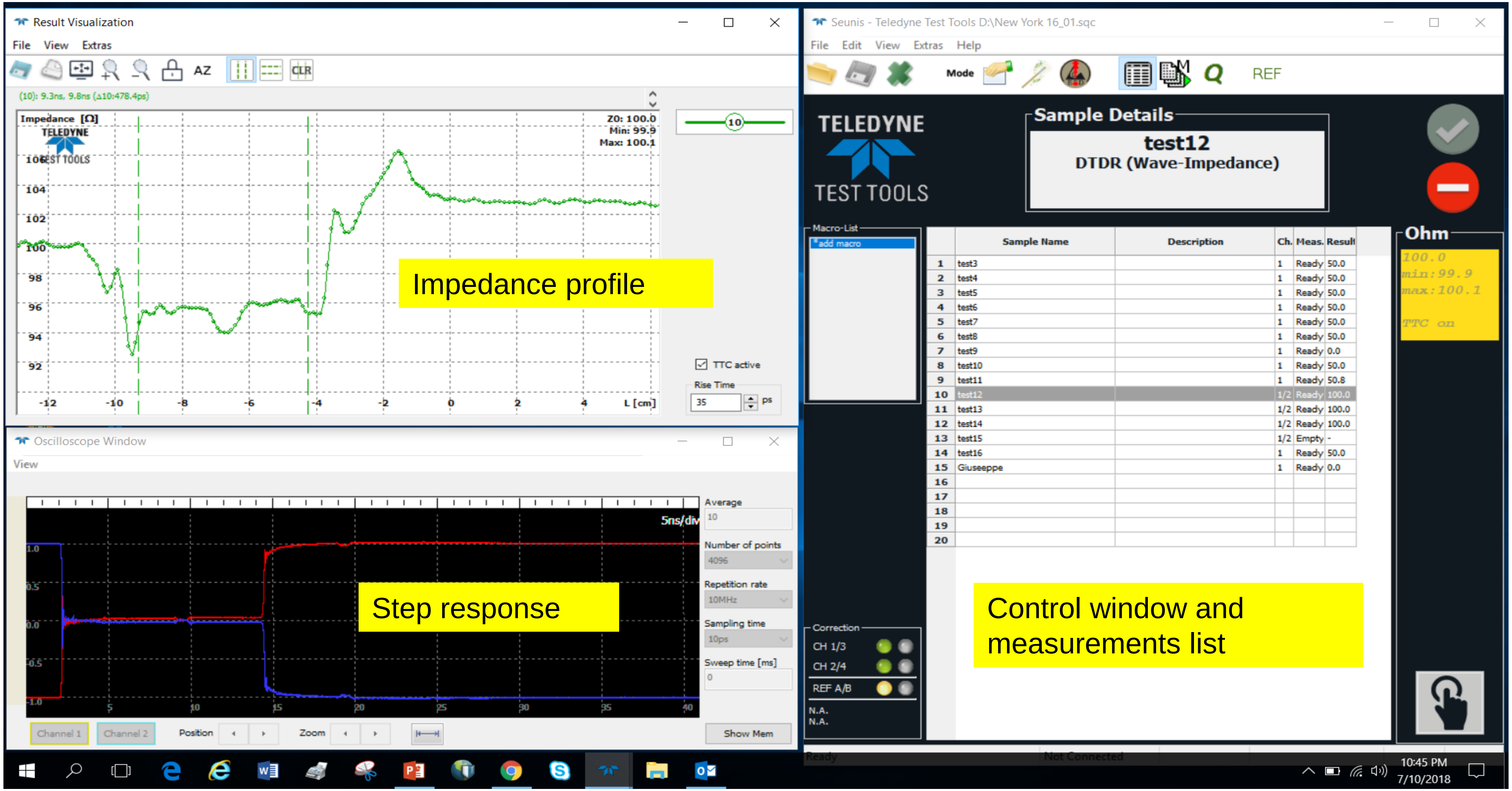
(fixed pitch)

Parameter	Value / Unit	Comments
Impedance	50 Ω ±1 Ω	
Electrical Length	100 ps	
Probe Tips	spring loaded	
Pitch	1.0, 1.27, 1.65, 2.0 & 2.5 mm	variable
Pin Configuration	S-G	
Connectors	2.92 mm female	compatible with SMA and 3.5 mm connectors
Frequency Range	DC – 10 GHz	
Dimensions	29.8 x 9.0 mm	(length x diameter)
Material	Brass	
Specials		direct in-circuit TDR testing

Parameter	Value / Unit	Comments
Impedance	50 Ω ±1 Ω	
Electrical Length	850 ps	
Probe Tips	spring-loaded	
Pitch	2.54 mm	fixed
Pin Configuration	S-G	
Connectors	SMA female	compatible with 2.92 mm and 3.5 mm connectors
Frequency Range	DC – 5 GHz	valid for probe with tips
Dimensions	131 x 32 x 13.2 mm	casing only
	131 x 32 x 15.6 mm	with connectors and tips
Material	Polystyrene	

Exceptional measurements repeatability

Simple and intuitive user interface



Z0: 100.0
Min: 99.9
Max: 100.1

☑ TTC active

Rise Time 35 ps

Impedance profile

Average 10

Number of points 4096

Repetition rate 10MHz

Sampling time 10ps

Sweep time [ms] 0

Step response

Sample Details

test12
DTDR (Wave-Impedance)

	Sample Name	Description	Ch.	Meas.	Result
1	test3		1	Ready	50.0
2	test4		1	Ready	50.0
3	test5		1	Ready	50.0
4	test6		1	Ready	50.0
5	test7		1	Ready	50.0
6	test8		1	Ready	50.0
7	test9		1	Ready	0.0
8	test10		1	Ready	50.0
9	test11		1	Ready	50.8
10	test12		1/2	Ready	100.0
11	test13		1/2	Ready	100.0
12	test14		1/2	Ready	100.0
13	test15		1/2	Empty	-
14	test16		1	Ready	50.0
15	Giuseeppe		1	Ready	0.0
16					
17					
18					
19					
20					

Ohm

100.0
min:99.9
max:100.1

TTC on

Control window and measurements list

WavePro HD – No compromise!!!
Brief Product Introduction

TELEDYNE LECROY
Everywhereyoulook™

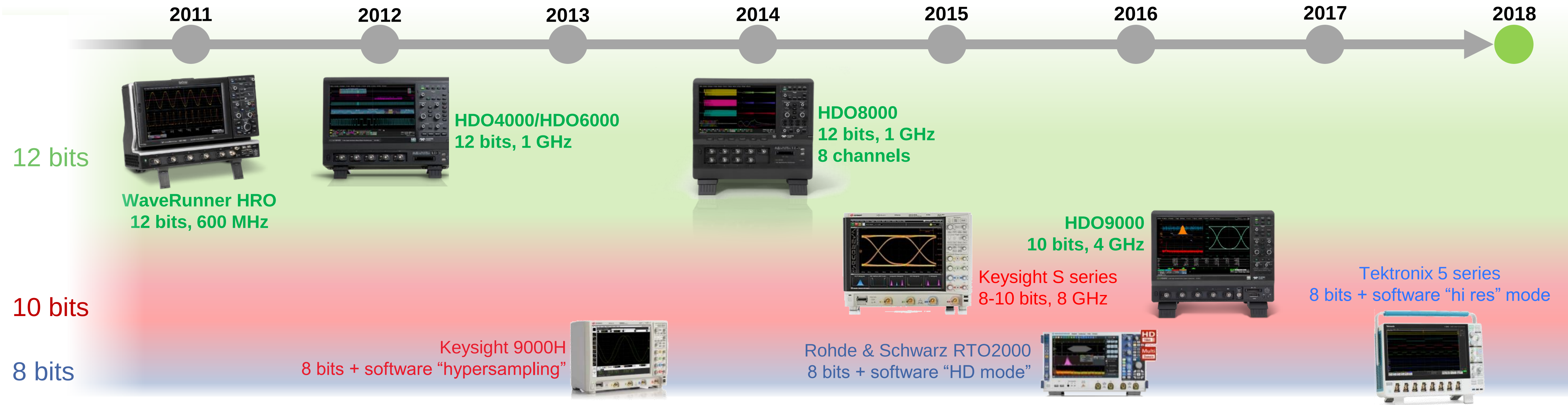
Teledyne LeCroy High Definition Leadership

Teledyne LeCroy has led

- 2011: First 12-bit resolution, high bandwidth oscilloscope
- 2012: 12-bit bandwidth extended to 1 GHz
- 2014: 12-bit, 1 GHz extended to 8 channels

Competitors have lagged

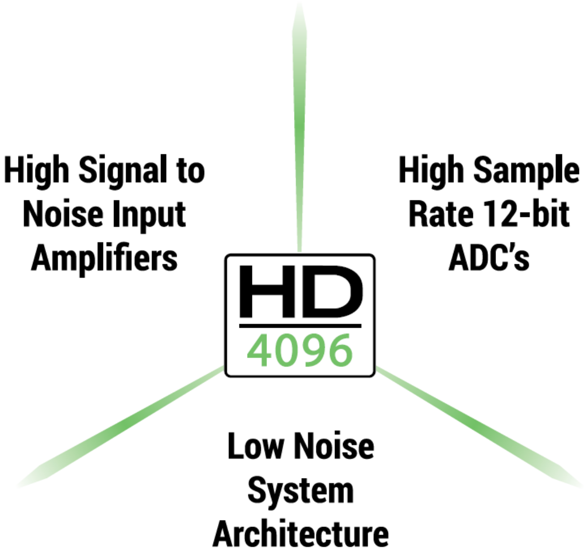
- Lower-resolution offerings
- Software-based solutions with serious performance compromises

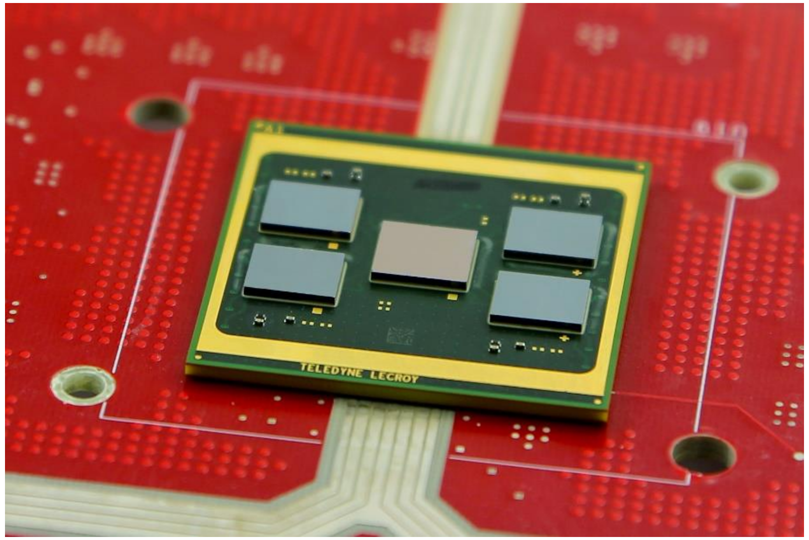


Next-generation HD4096 High Definition Technology

- Teledyne LeCroy HD4096 technology provides superior measurement performance:
  - 12-bit high sample rate ADCs
  - High signal-to-noise amplifiers
  - Low noise system architecture

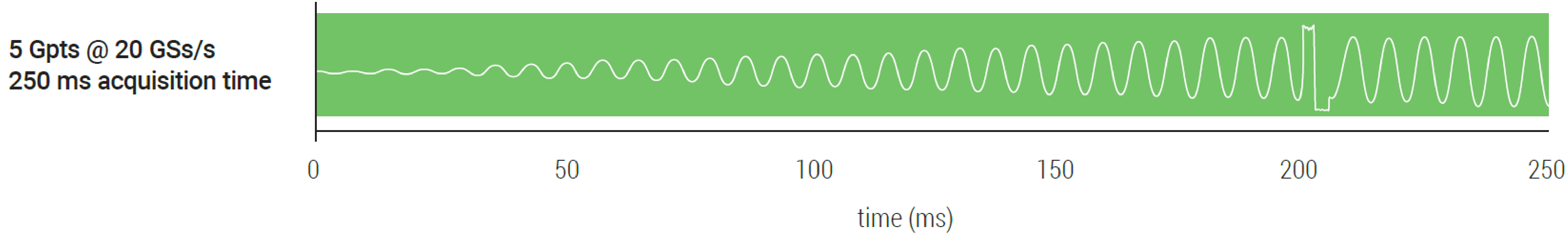
- A new chipset extends HD4096 to 8 GHz
  - 12-bit, 20 GS/s ADCs
  - High signal-to-noise 8 GHz front-end amplifiers





Next-generation memory management system

- Up to 5 Gpt acquisition memory
- 250ms records at full 20 GS/s sample rate
- Enables capture of infrequent events



WavePro HD: Capture Every Detail

Two industry-first acquisition capabilities:

- 8 GHz with 12-bit resolution
  - Full resolution at all sample rates
- 5 Gpoint acquisition memory
  - Extremely responsive operation
  - Intuitive waveform navigation
    - Use timebase scale and position knobs or zoom traces

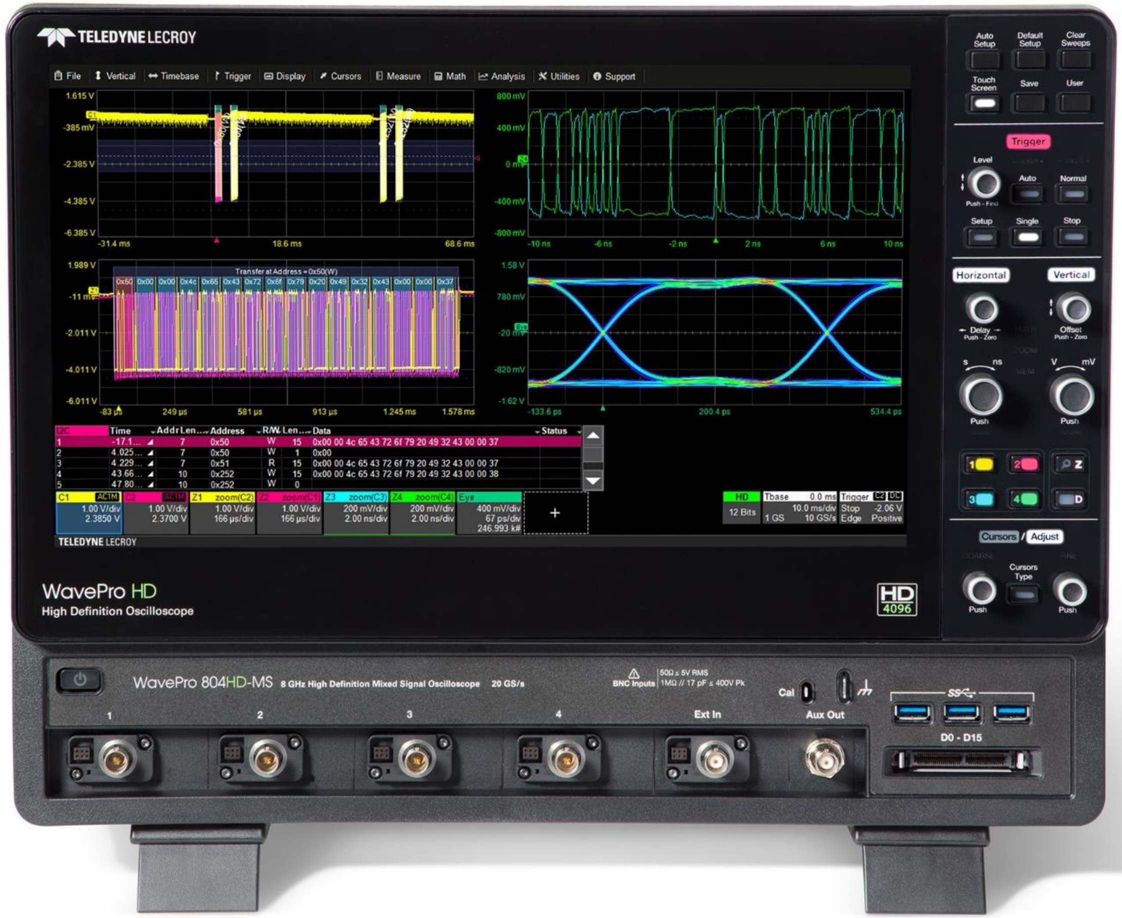
Launching **Tuesday May 8**

WavePro HD at a glance

- 8, 6, 4, and 2.5 GHz models
    - 6 and 8 GHz on 2 channels
- 12-bit resolution
- 20 GS/s sample rate on 2 channels
    - 10 GS/s on 4 channels
- 5 Gpt max acquisition memory

- 15.6” full HD capacitive touchscreen
- 8 GHz ProBus2 probe interface
- 16 digital channels (-MS models)
- Windows 10

- Starting at $31,000



New ProBus2 probe interface

- WavePro HD features the new ProBus2 interface, supporting up to 8 GHz bandwidth on a BNC-compatible connector

- New ProBus2 probes:
  - **D830-PB2**
    8 GHz differential probe
  - **D610-A-PB2** and **D620-A-PB2**
    6 GHz differential probes

- ProBus 2 probes and inputs are cross-compatible with legacy Teledyne LeCroy ProBus probes and inputs

WavePro HD

Models, Banner Specifications and Pricing

	WavePro 254HD WavePro 254HD-MS	WavePro 404HD WavePro 404HD-MS	WavePro 604HD WavePro 604HD-MS	WavePro 804HD WavePro 804HD-MS
Bandwidth (2 Ch)	2.5 GHz	4 GHz	6 GHz	8 GHz
Bandwidth (4 Ch)	2.5 GHz	4 GHz		
Channels	4			
Resolution	12-bit			
User Interface	MAUI with OneTouch			
Sample Rate (2 Ch / 4 Ch)	20 GS/s / 10 GS/s			
Standard Mem (2 Ch / 4 Ch)	100 Mpt / 50 Mpt			
Max Mem (2 Ch / 4 Ch)	5 Gpt / 2.5 Gpt			
Display	15.6” Full HD (1920 x 1080)			
Digital Channels	16			
MSO Max Input Freq	250 MHz			
MSO Sample Rate	1.25 GS/s			

WavePro HD

HD4096 12-bit technology

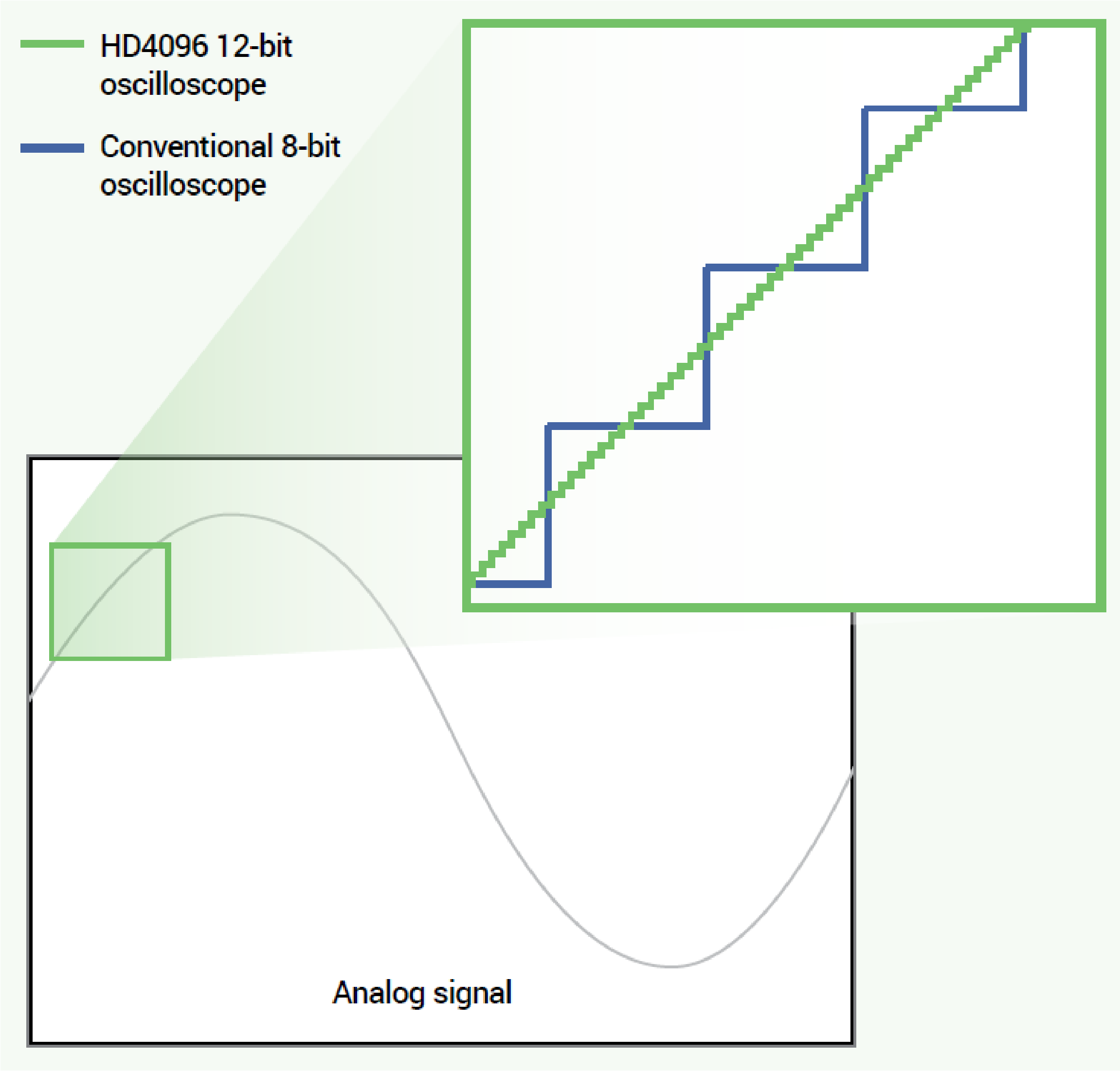
TELEDYNE LECROY
Everywhereyoulook™

HD4096 High Definition Technology

16x Closer to Perfect

- HD4096 delivers signals that are 16x closer to perfect when compared to an 8-bit oscilloscope

- Clean, Crisp Waveforms
  - Thin traces show the actual waveform with minimal noise interference
- More Signal Details
  - Small waveform details can be clearly seen
- Unmatched Measurement Precision
  - Measurements are more precise and far less affected by quantization noise
  - 0.5% gain accuracy ensures maximum measurement confidence

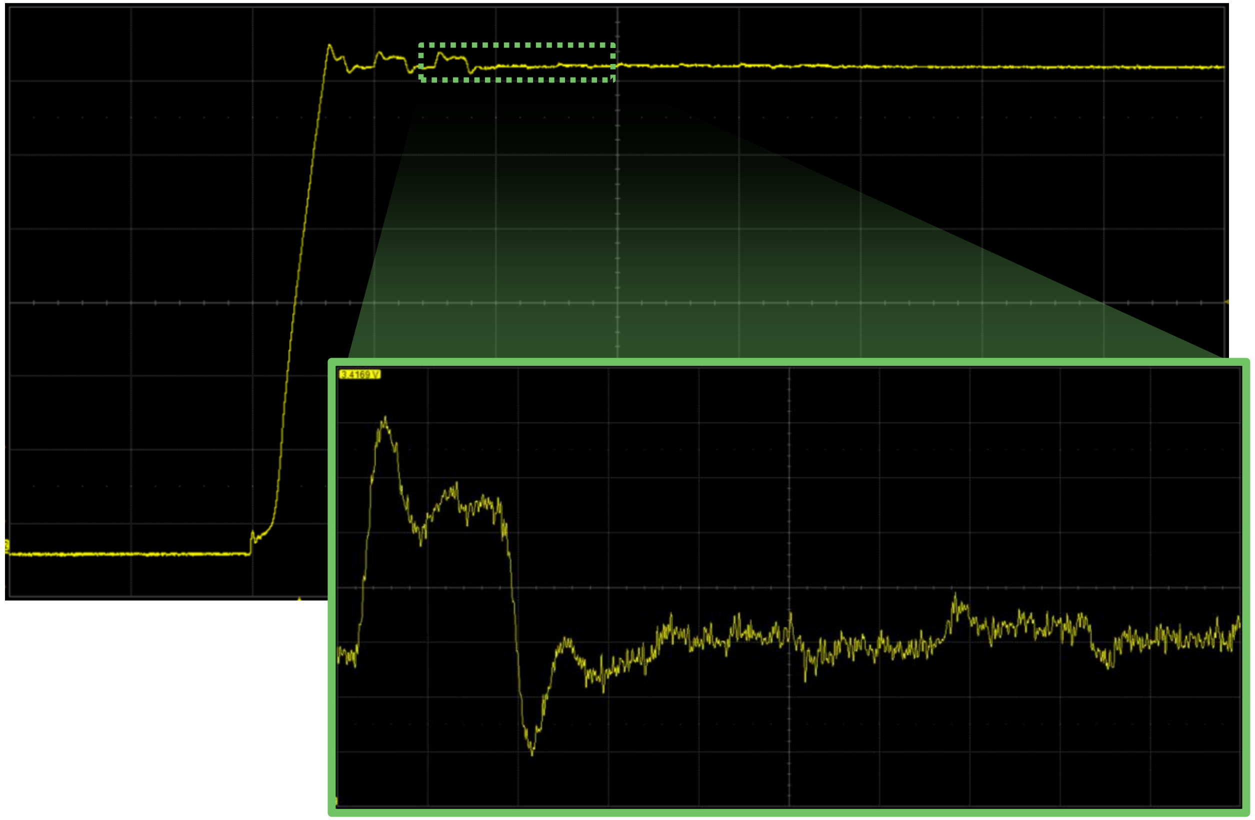


HD4096: 16x closer to perfect

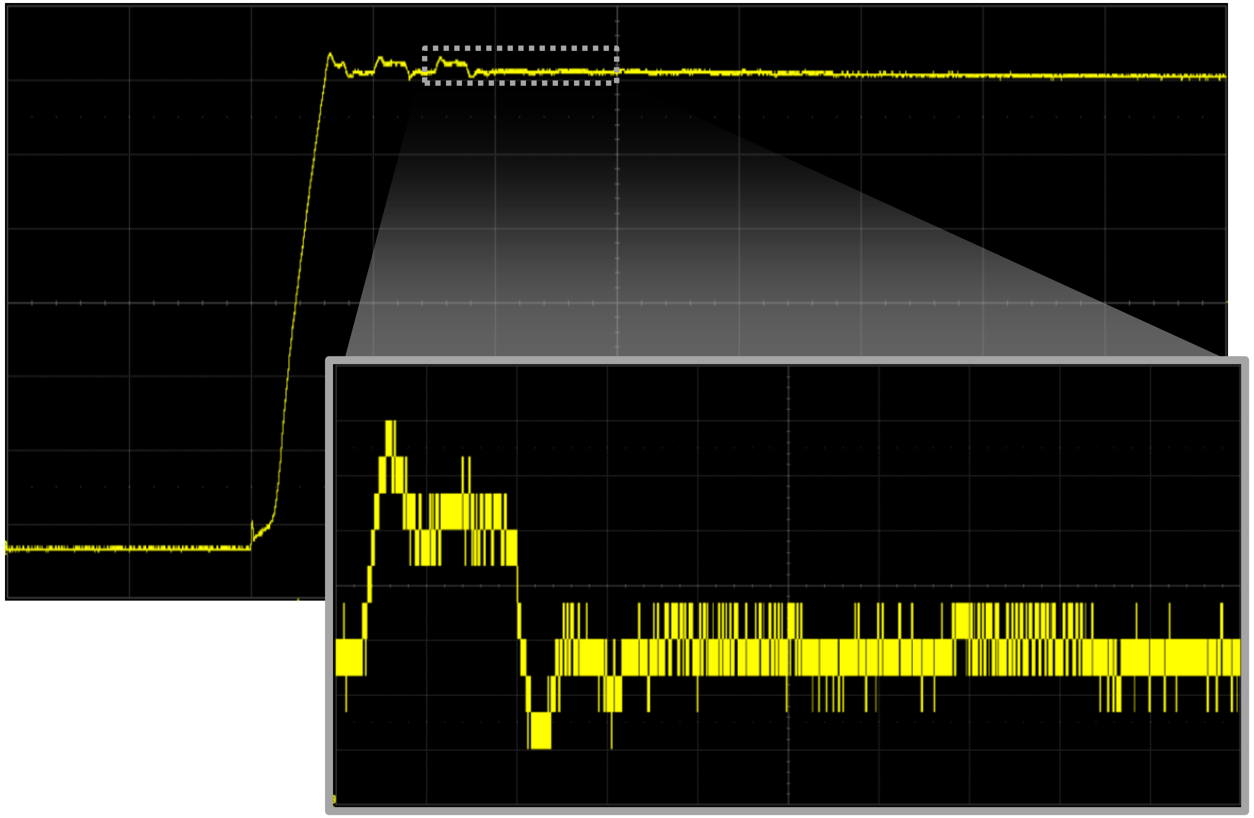
16x lower quantization noise – see more signal detail

WavePro HD’s 12-bit resolution means quantization steps are 16x smaller. The difference is clear when compared to an 8-bit oscilloscope – much finer details are easily resolved.

HD4096 12-bit WavePro HD oscilloscope



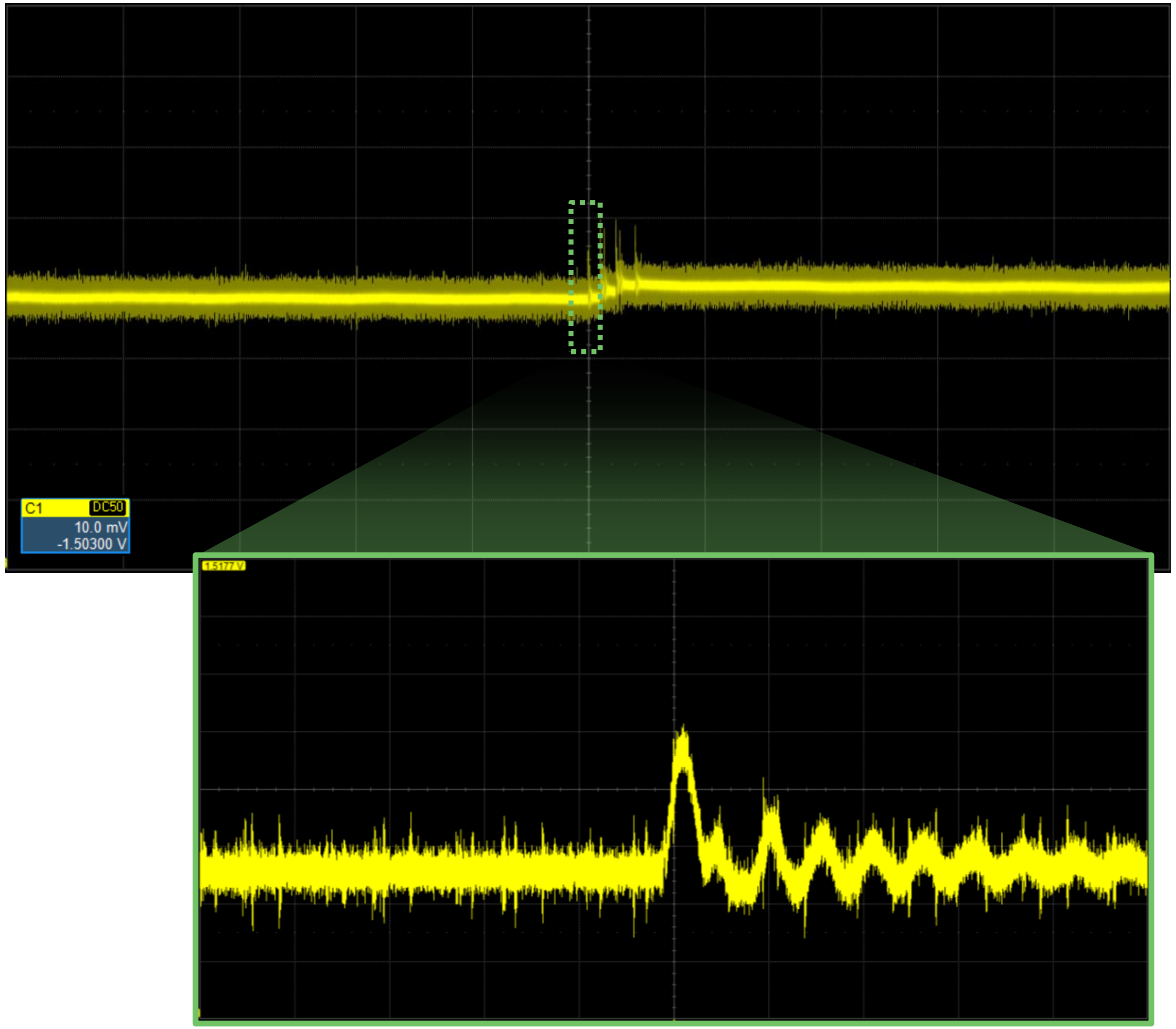
Conventional 8-bit oscilloscope



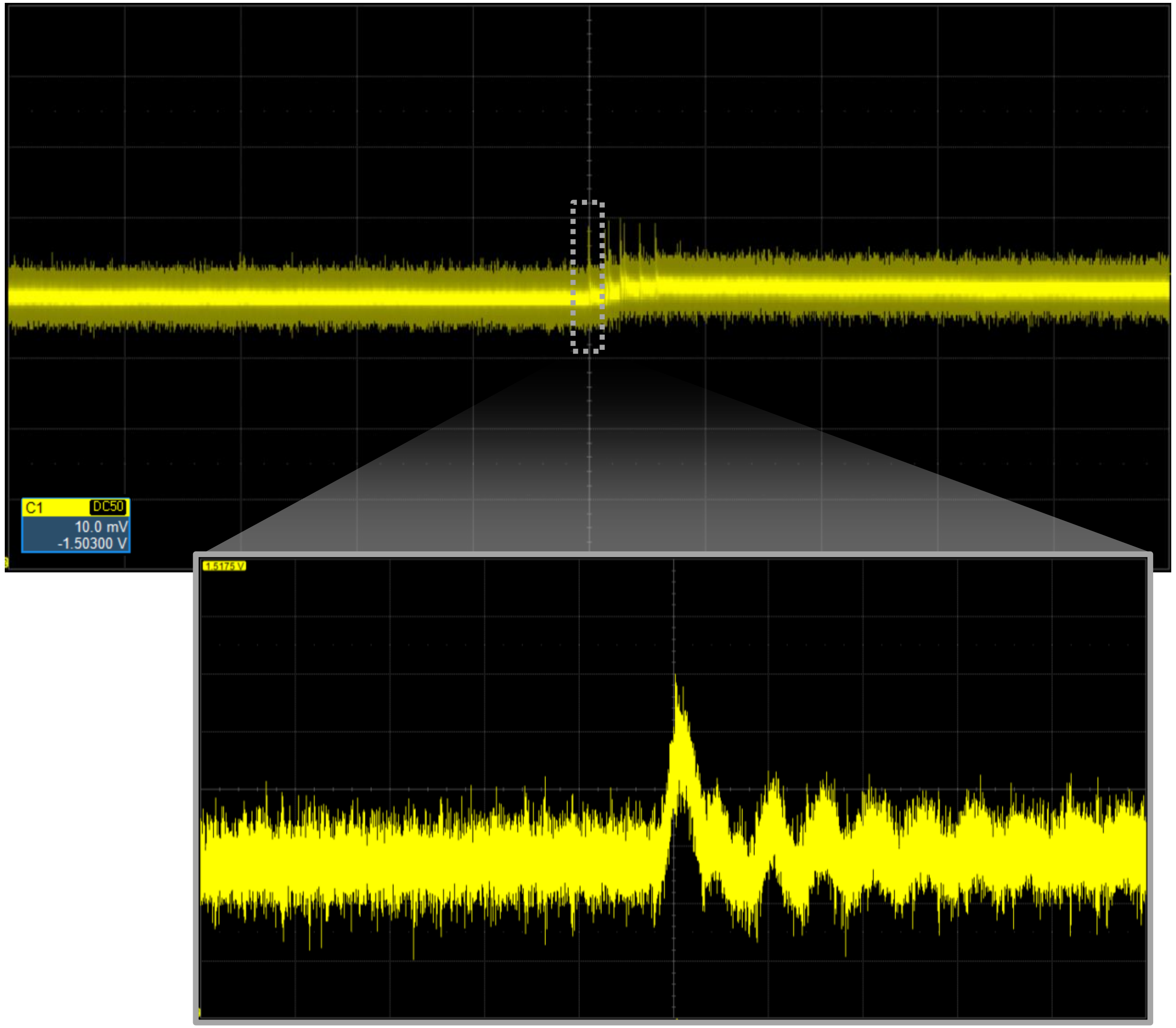
HD4096: 16x closer to perfect

4 GHz RP4030 Power Rail Probe acquiring a 1.5V power rail signal

HD4096 12-bit WavePro HD oscilloscope



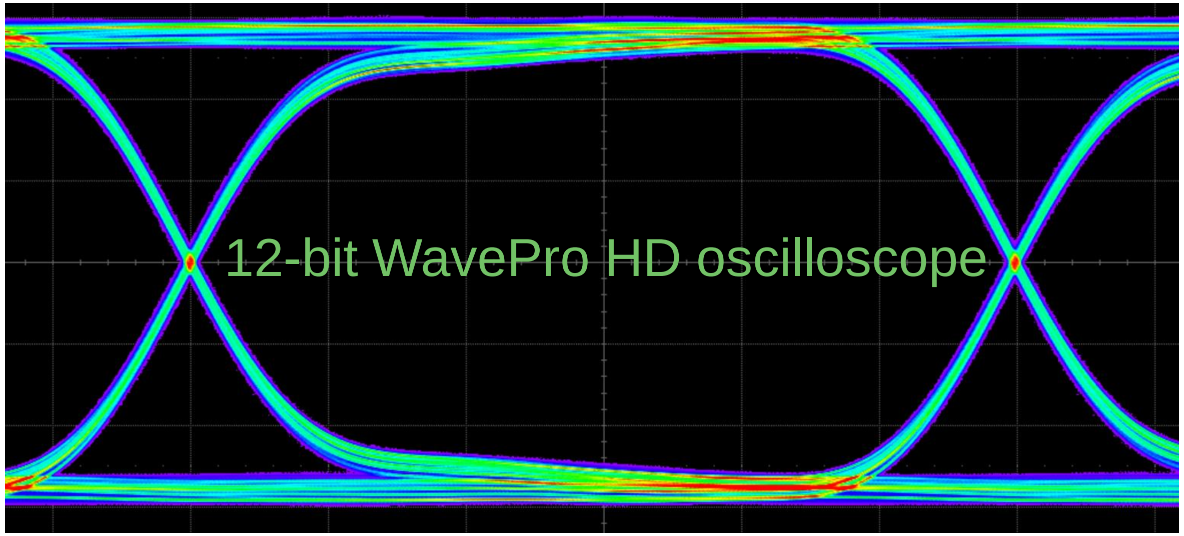
Conventional 8-bit oscilloscope



HD4096: 16x closer to perfect

12-bit resolution at 8 GHz for improved serial data analysis

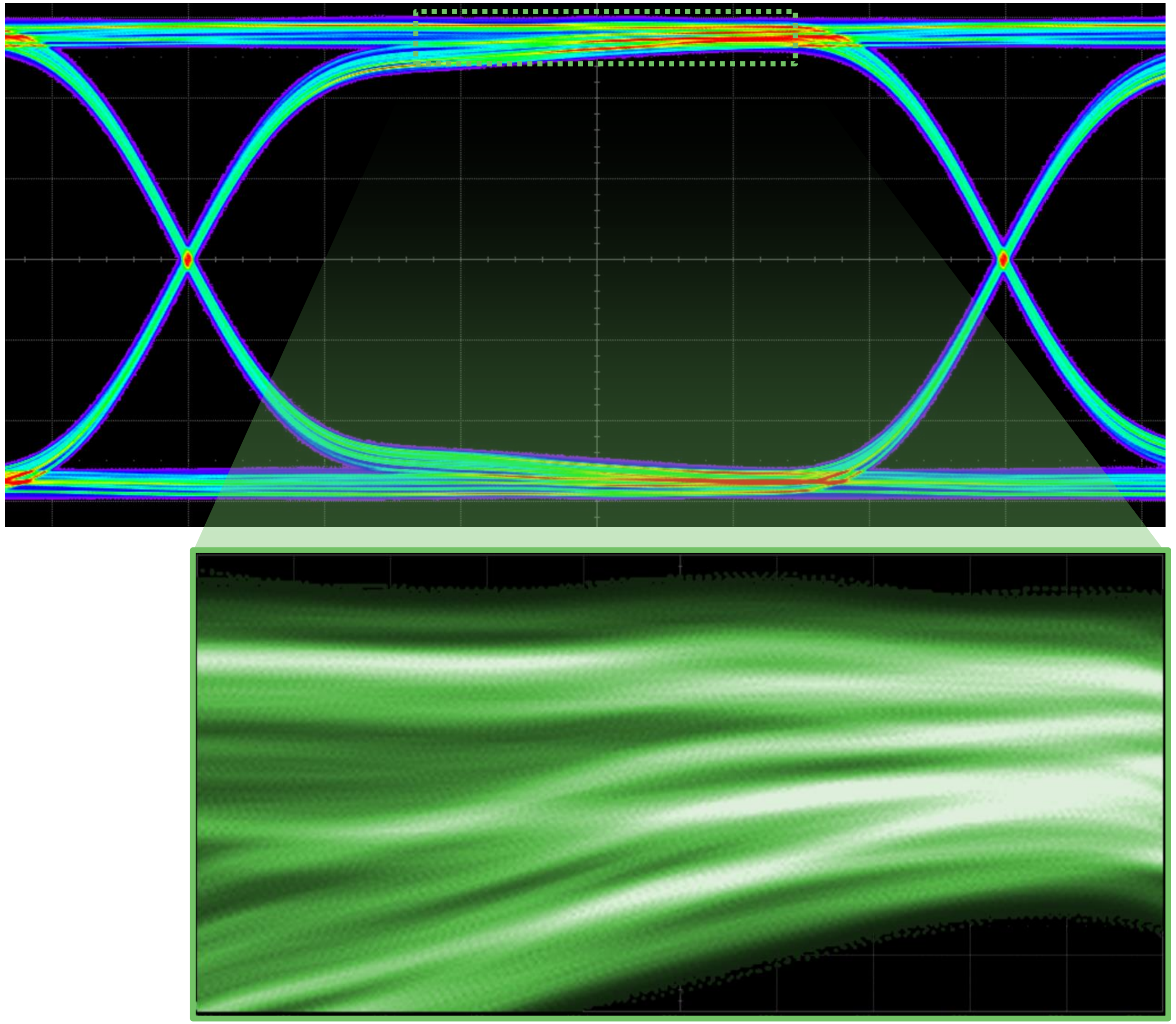
- 2.5 Gb/s signal acquired with:
  - 8 GHz WavePro 804HD
  - 8 GHz conventional 8-bit oscilloscope (SDA 808Zi-B)
- WavePro HD shows:
  - More visible details
  - Lower noise
  - Lower jitter values



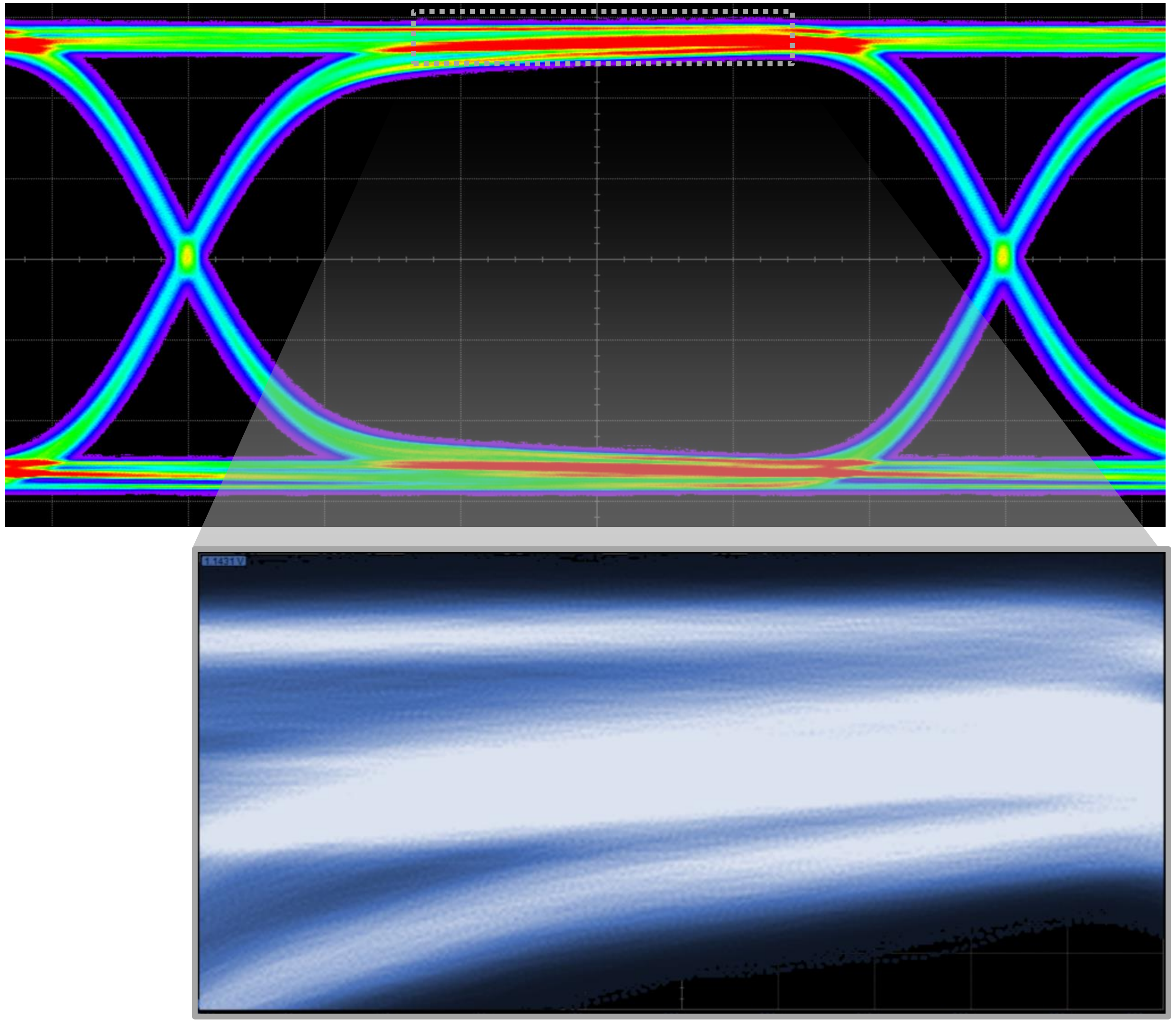
HD4096: 16x closer to perfect

Lower noise for better visibility

HD4096 12-bit WavePro HD oscilloscope



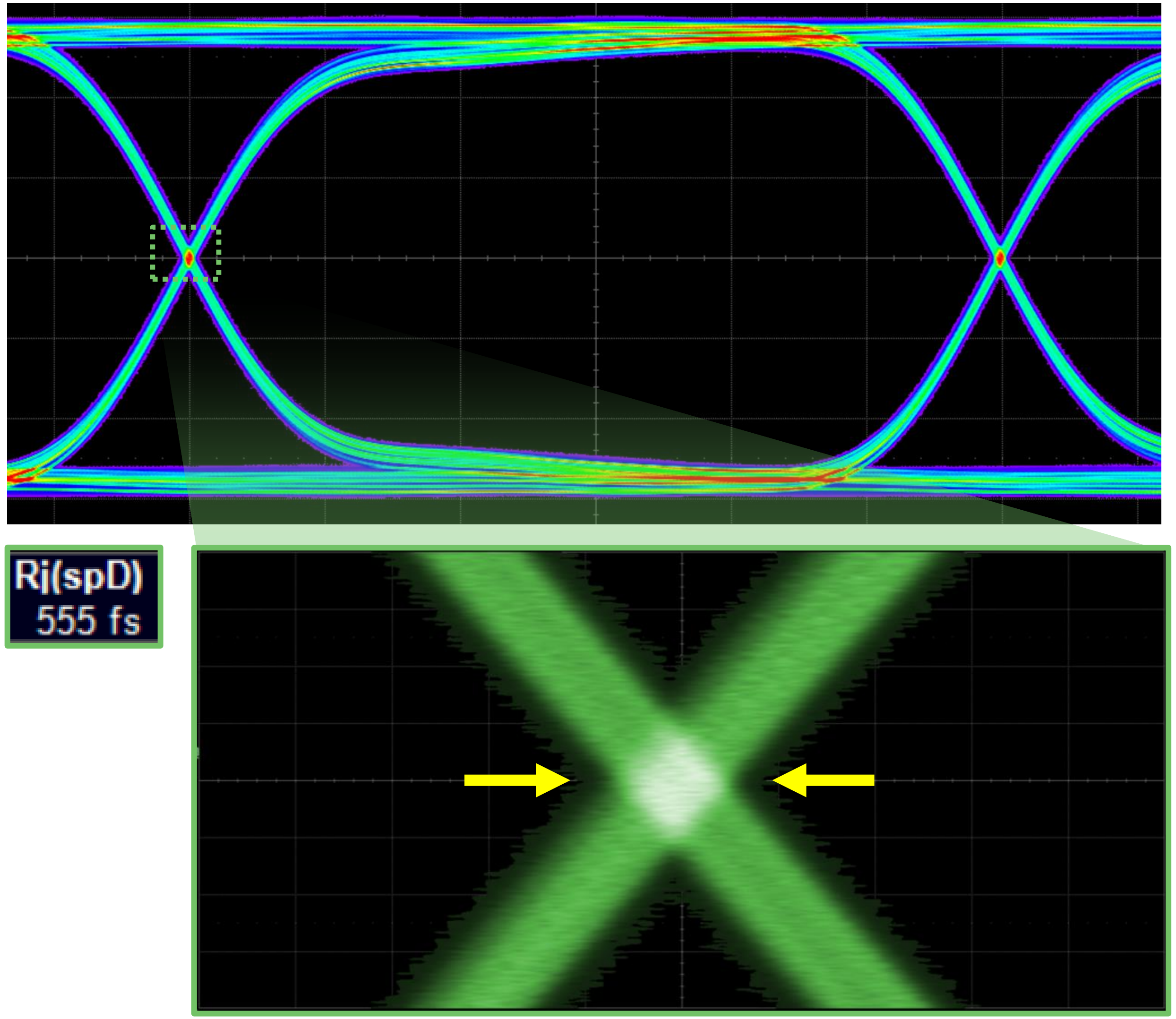
Conventional 8-bit oscilloscope



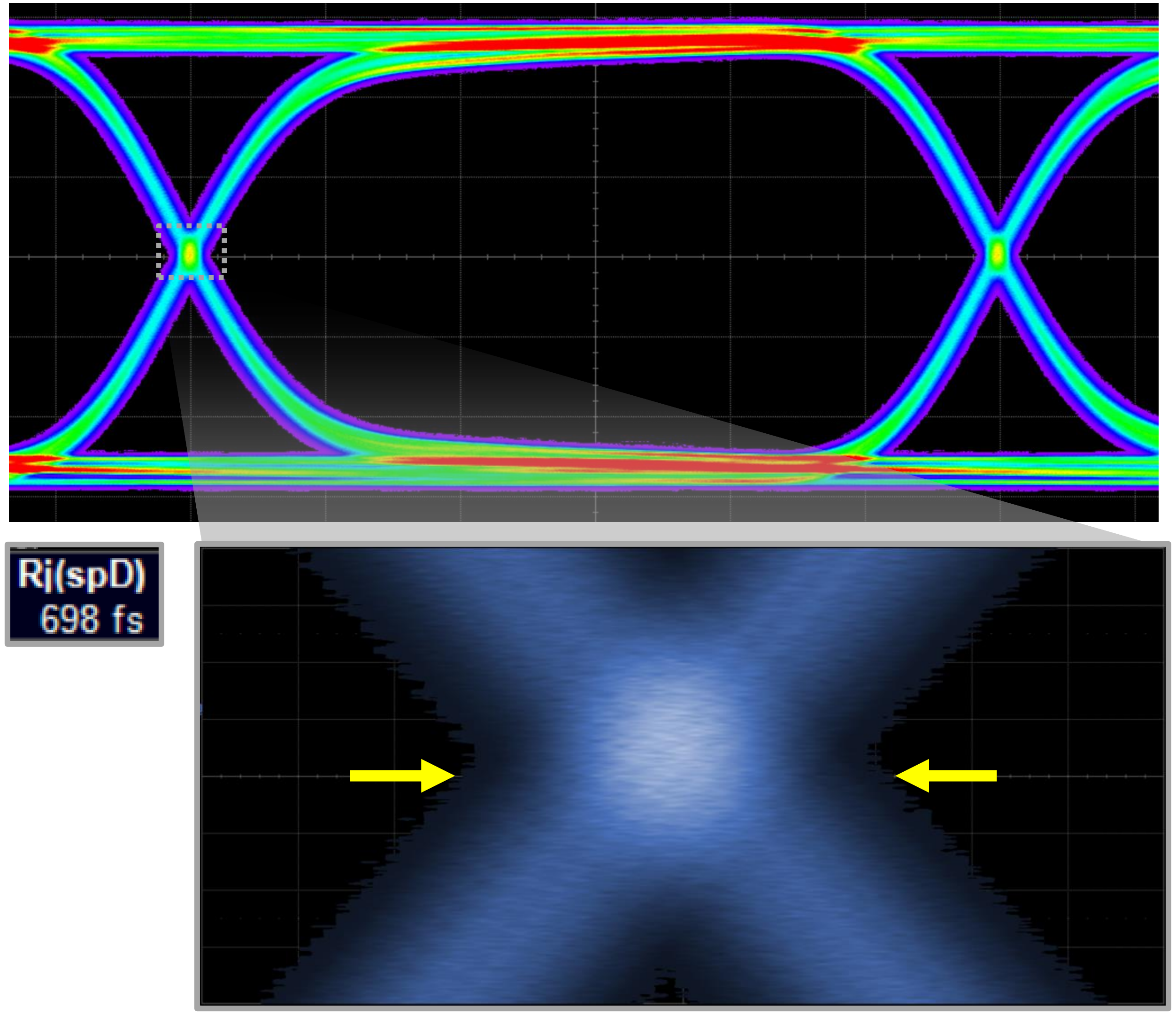
HD4096: 16x closer to perfect

Unmatched measurement precision

HD4096 12-bit WavePro HD oscilloscope



Conventional 8-bit oscilloscope

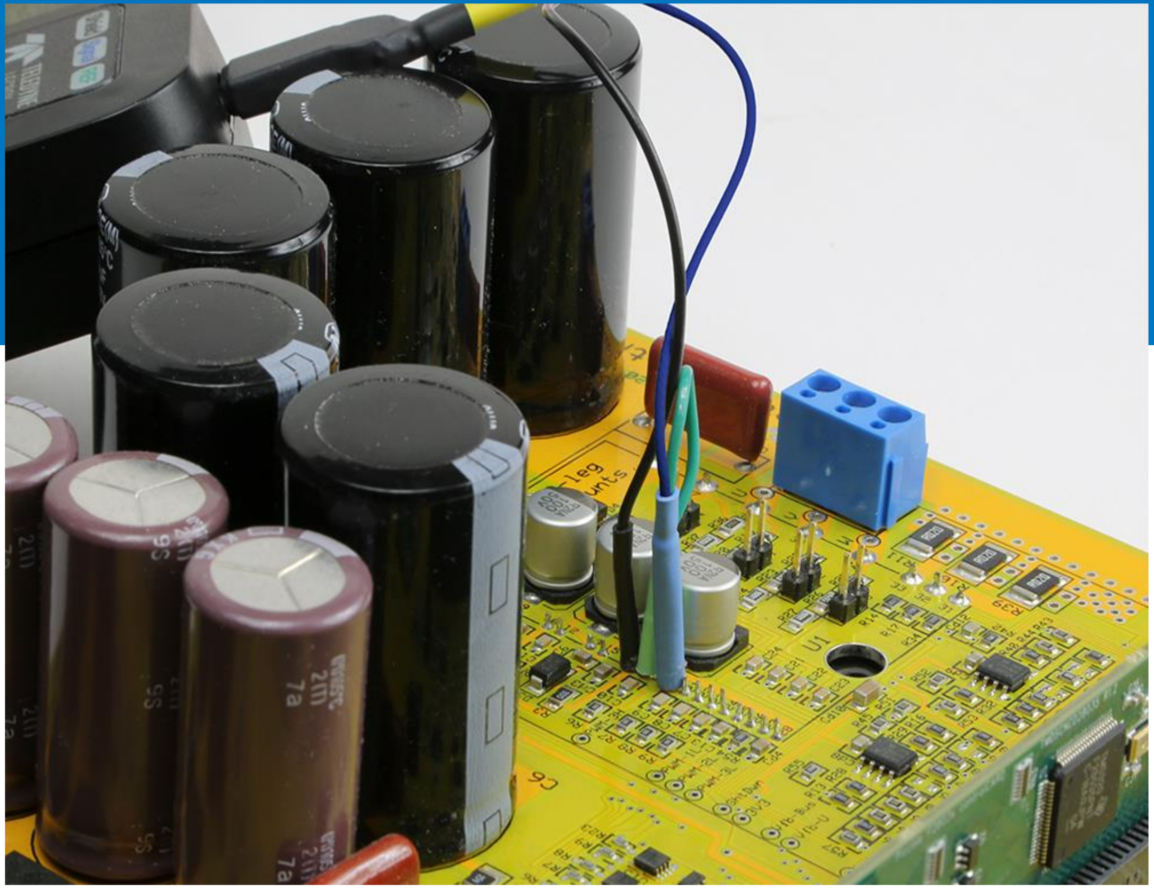


Agenda

- Common Circuit in Power Electronics
- Probing
- Device Characterization (MOSFET, IGBT, Transistor,..)
- System Measurements
  - Inverters, Motors, Power Supply

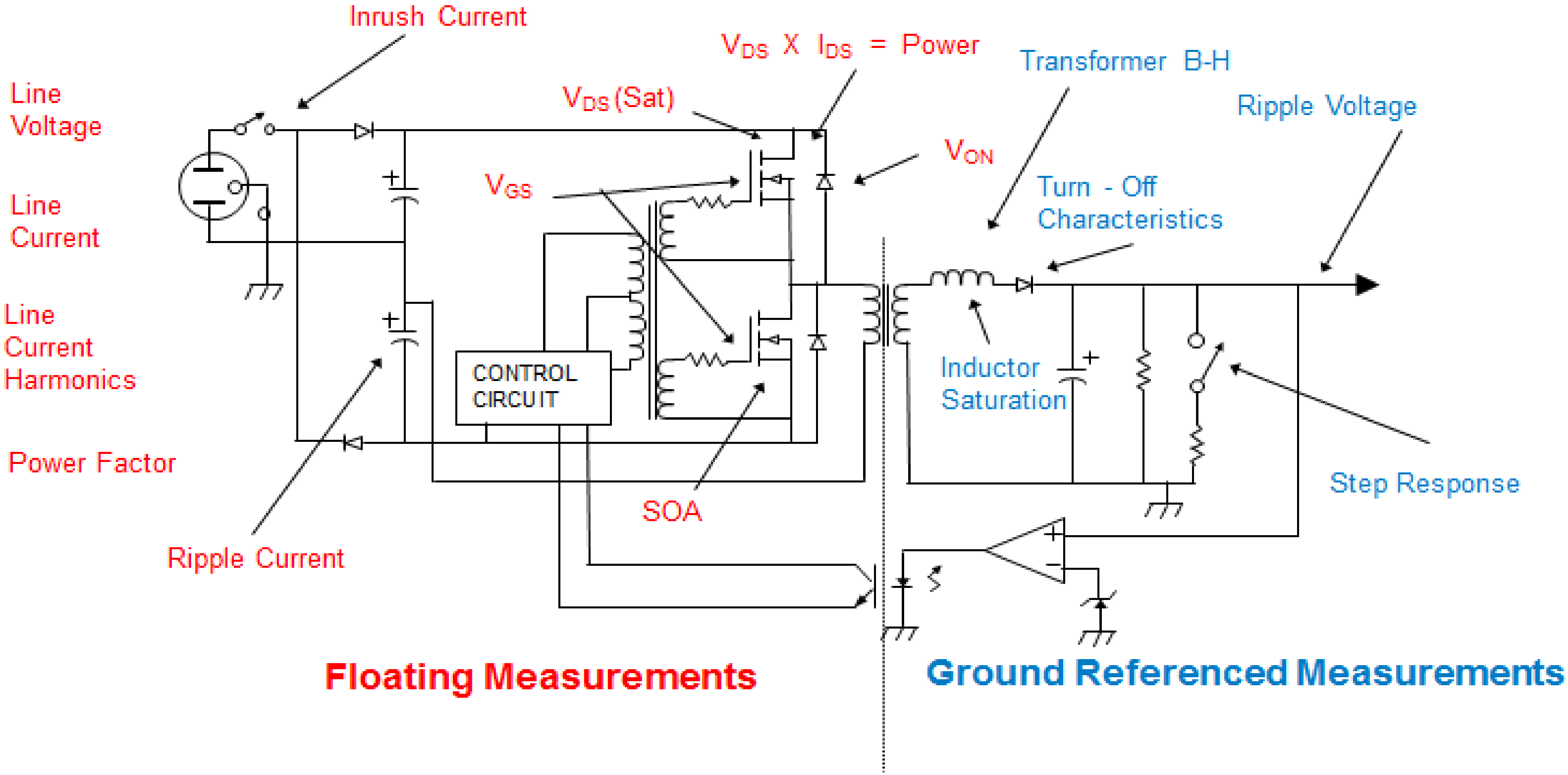
- Conclusions
- Questions

Power Electronics Probing – What to Use and Why



TELEDYNE LECROY
Everywhereyoulook™

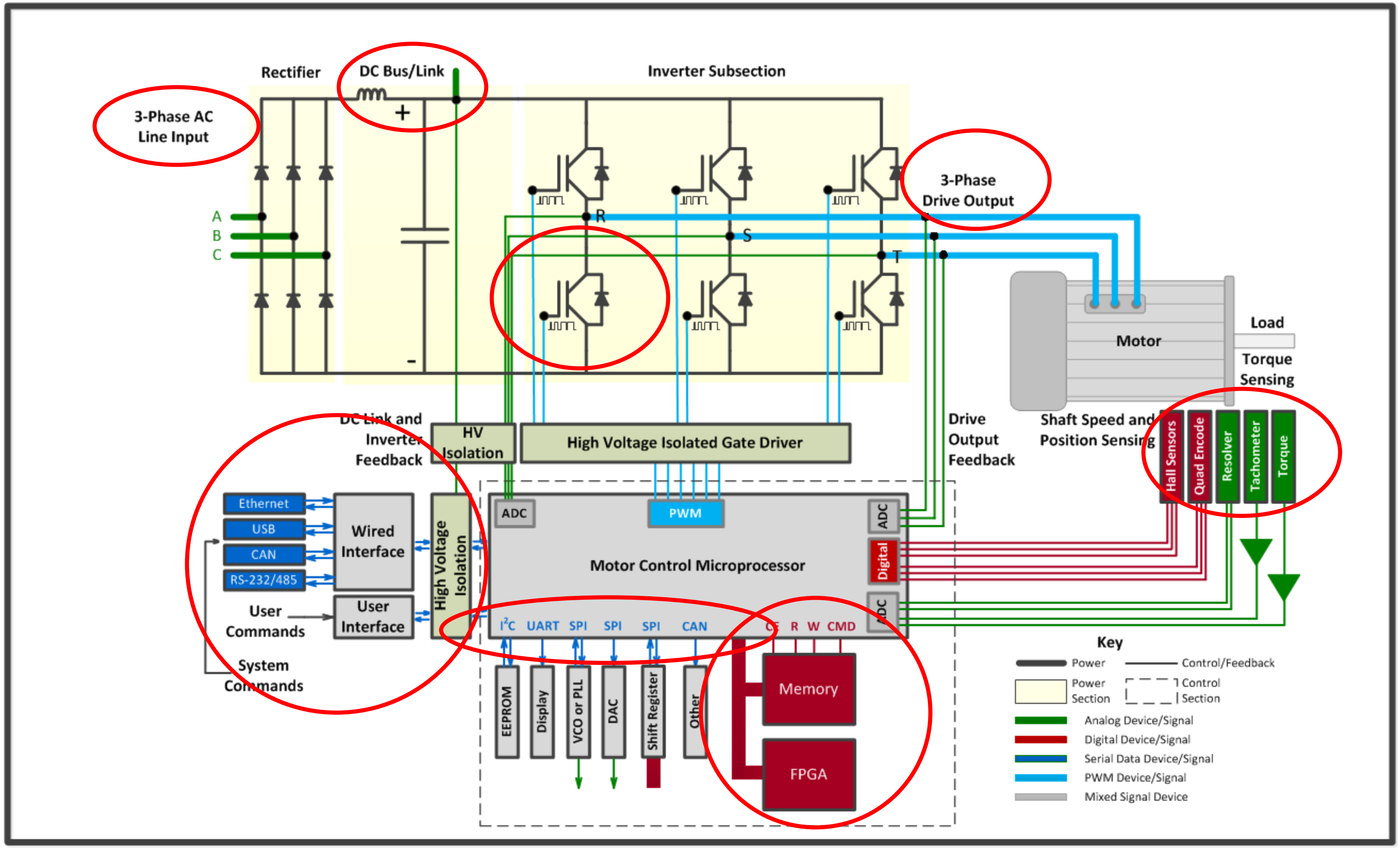
Which measurements and which probe



Examples of Power Measurements

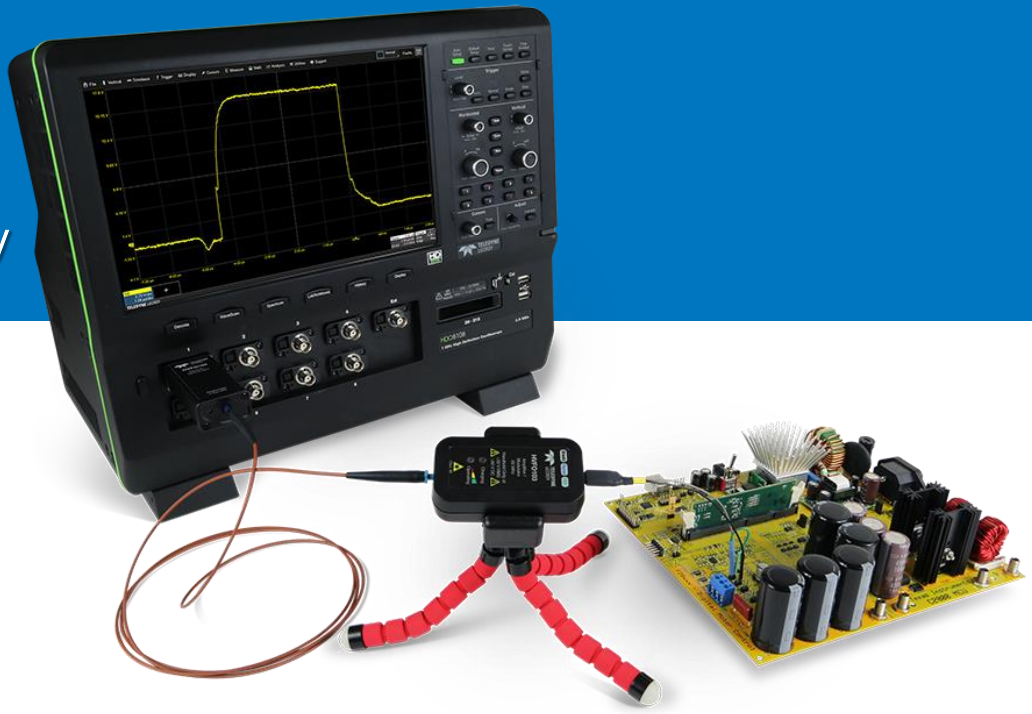
Complex Three Phase System

- Power Section Measurements
  - Line input
  - PWM output
  - Efficiencies
- Motor Integration
  - Torque
  - Speed
  - Position
  - Power
- Embedded Control Debug
  - Analog
  - Digital
  - Serial Data
  - Control Loop
  - PWM



Probing in Power Electronics – What to Use and Why

Choosing the right voltage probe is important for safety of the operator, equipment, and DUT. Choosing the wrong probe won't necessarily cause harm, but it may give you the wrong result. The difference between the "right" probe and the "wrong" probe is usually not black and white, but more of a shade of gray.



TELEDYNE LECROY
Everywhereyoulook™

Important Probe Specifications

Understanding what each probe specification means is the first step in choosing the right probe for your application.

TELEDYNE LECROY
Everywhereyoulook™

Important probe specifications

- Bandwidth
- Voltage Dynamic Range
- Voltage Offset Capability
- High Voltage Isolation
- Input Impedance
- Attenuation
- Common Mode Rejection Ratio (CMRR)

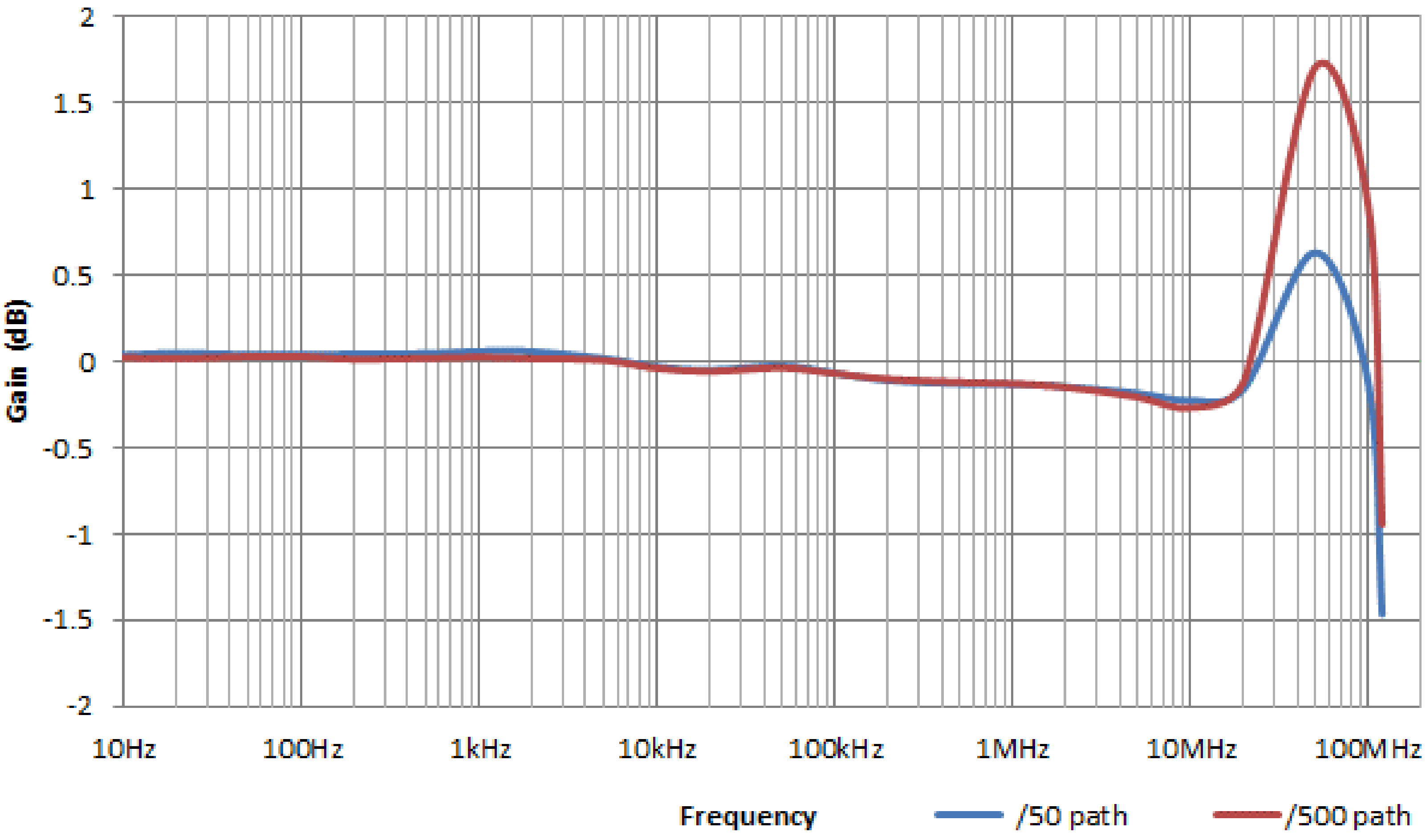
Bandwidth

- The frequency at which the magnitude drops 3 dB lower than the nominal (DC) response
  - Note: 3 dB = 30% magnitude
  - A Teledyne LeCroy oscilloscope is typically calibrated for bandwidth at 2 dB point.
- Bandwidth * $T_{RISE_{10\text{-}90}}$ = 0.35 to 0.45
  - Rough approximation based on 4th order Bessel rolloff (0.35) to brick wall rolloff (0.45)
  - Can be used to calculate bandwidth of signal content
  - Signal with rise time of 1 ns has ~ 350 to 450 MHz of bandwidth (using formula, above)
- Typically, it is desired for the measurement system to have 2-3x the bandwidth of the signals to be measured
  - Assures that measurement system does not materially impact the signal content
- Oscilloscope bandwidth desired to be > probe bandwidth
  - If they are the same, then 3 dB rolloff of each will equate to 6 dB rolloff total.
  - However, a Teledyne LeCroy probe bandwidth rating is almost always a probe+oscilloscope bandwidth rating (this is not true of all oscilloscope vendors)

Bandwidth

Example Frequency Response of HVD3106

- Very flat low frequency response (DC to 5 kHz)
- Slow rolloff to 10 MHz (0.25 dB)
- 0.5 to 1.5 dB peaking at 60 MHz
    - Which seems extreme, but this has less peaking than other probes in this class

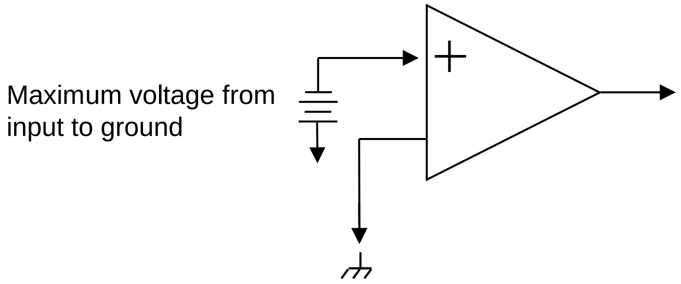


Voltage Dynamic Ranges

The following is true for a probe or a stand-alone amplifier

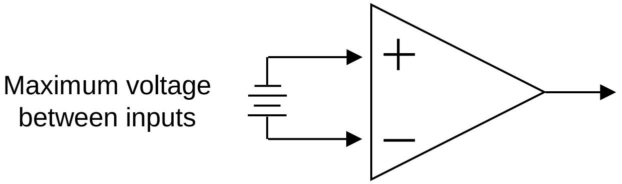
- Single-ended Range
  - Maximum voltage between input and ground
  - Ground is directly tied to oscilloscope ground. **Therefore, this ground connection cannot be a floating voltage!**
- Differential Mode Range (DMR)
  - Maximum voltage difference that can be applied between the + and - inputs.
  - No ground / board reference connection is required.
  - But common mode range rating cannot be exceeded.
- Common Mode Range (CMR)
  - Maximum voltage between either input and ground.
  - Not normally directly measured by the probe, but achieved through the probes topology
  - Can be verified by attaching negative input of suitably rated probe to ground / board reference and positive input to common-mode voltage.

Single-ended Range



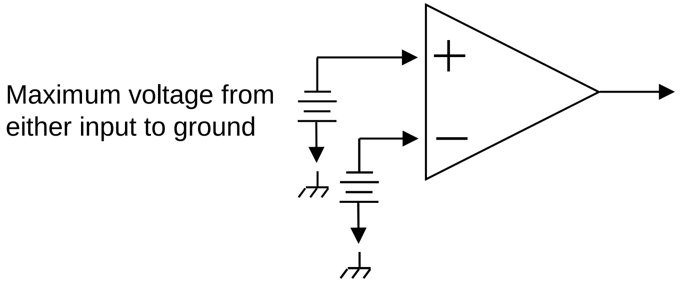
Maximum voltage from input to ground

Differential Mode Range



Maximum voltage between inputs

Common Mode Range



Maximum voltage from either input to ground

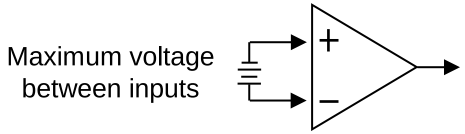
Voltage Dynamic Range

The Differential Amplifier vs. an Active Differential Probe

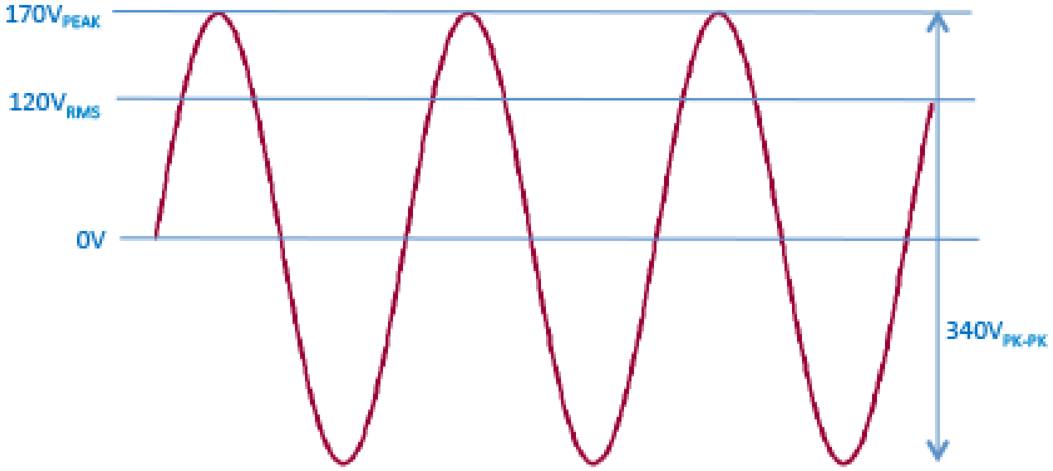
- A **Differential Amplifier** amplifies the voltage difference between the inputs, while ignoring any voltage common in amplitude and phase to the two inputs.
  - The two attenuating probes that comprise the probe pair must be precisely matched to achieve high CMRR
  - Typically, achieving the CMRR rating requires precise calibration to a particular probe pair
- An **Active Differential Probe** contains a differential amplifier near the probe tips.
  - The tips/leads are part of the overall probe design, and are typically shorter, making precise matching less critical to achieve good CMRR performance

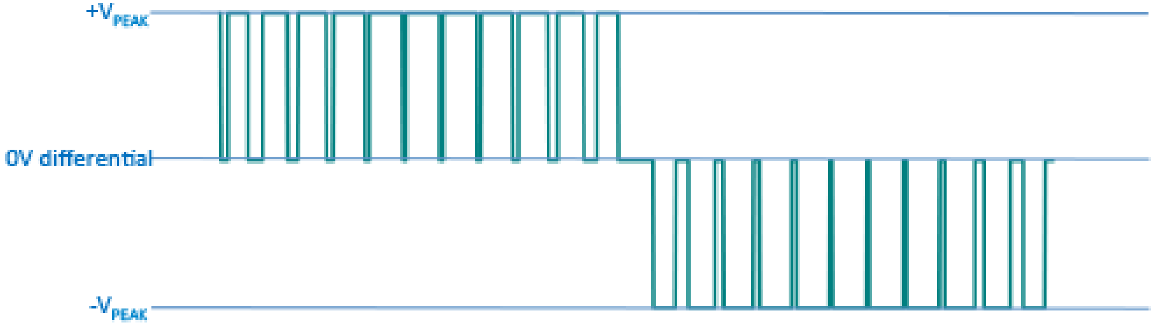
Voltage Dynamic Range

Differential Mode Range: Vpk-pk versus Vpk



- Differential Mode Range (DMR) = maximum instantaneous voltage which can appear between inputs.
  - Maximum voltage between + and - inputs.
  - Generally symmetrical with polarity (but not usually a requirement:
    - e.g., +5V and -1V
- Line AC Signals
  - Vpk-pk is required differential mode range
  - Example: A 120Vrms input is 170Vpk or 340Vpk-pk
- Inverter/Drive Output Line-Line PWM Outputs
  - Vpk is the required differential mode range
  - Typically, Vpk = DC bus voltage
  - Don’t forget to account for overshoot!





Voltage Offset Capability

- Provides the ability to negate some or all of the common-mode voltage of a measured signal
- Provides ability to “position” a signal below 0V on the oscilloscope grid
- But in adding offset, an additional offset inaccuracy in the probe and/or oscilloscope is incurred

Voltage Offset Capability

Comparison on a $V_{C\text{-}E}$ Measurement HVD3106 (yellow) and ADP305 (magenta)

- Lots of offset is needed for a $V_{C\text{-}E}$ measurement on an upper transistor
  - The offset needed = the DC bus voltage (~700Vdc for a 480V, 3ph drive)
  - And the signal amplitude = DC bus voltage + overshoot (fault conditions)

0V Offset
(the maximum allowed by the Teledyne LeCroy ADP305 at 350V/div)

-1500V Offset
(the maximum allowed by the Teledyne LeCroy HVD3206 at 500V/div)

C1 BwL DC 400 V/div -1.50127 kV

C2 BwL DC 350 V/div 0.00 V ofst

Timebase -80.0 µs 20.0 µs/div 250 kS 1.25 GS/s

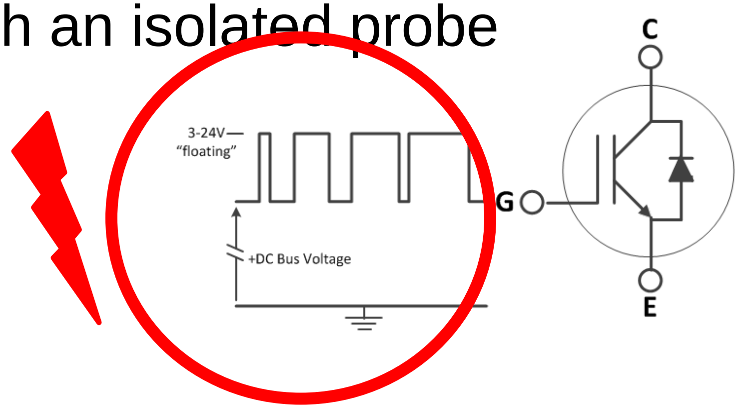
Trigger C1 DC Stop 325 V Edge Positive

7/1/2014 1:37:34 PM

High Voltage Isolation

The maximum common-mode voltage an attenuating probe can be safely used

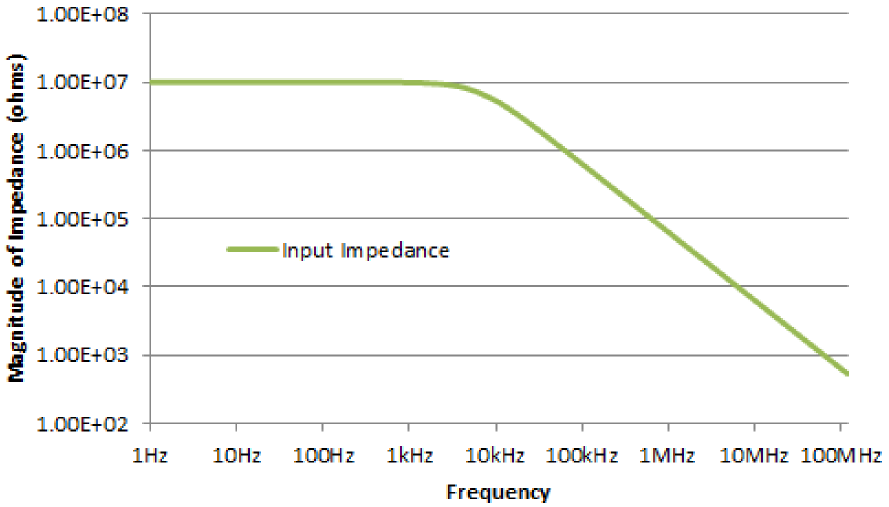
- In power electronics, the DC Bus voltage = the maximum common-mode voltage
  - Signals floating on the DC bus need to be measured with an isolated probe
    - upper-side gate drive signal
    - control or sensor signal
- Common DC bus voltages
  - 500 Vdc for 120/240Vac line inputs
  - 1000 Vdc for 600Vac class line inputs
  - 1500 Vdc for grid-tied solar PV inverters and UPS systems
  - 6000 Vdc for 4160Vac inputs
- Conventional high attenuation HV differential probes commonly have a UL (or other) safety rating
  - This indicates the maximum common-mode voltage the probe can be used at to ensure operator (for hand-held use), equipment and DUT safety

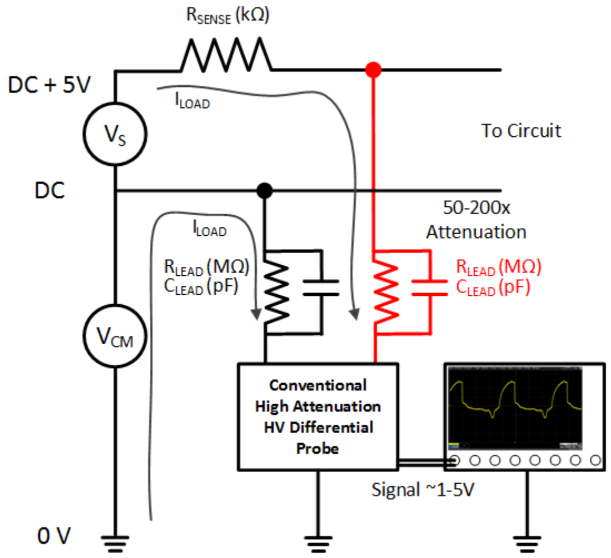


Input Impedance

- All probes will add a load to the test circuit, which will change the characteristics of the waveform.
  - High probe input impedance will add less load (draw less current)
  - The input impedance of all probes becomes lower as the frequency increases.
- Severe loading can alter the operation of the circuit
- High common-mode voltage will increase the capacitive loading
  - The full common-mode + floating signal voltage must charge the lead capacitance

Differential Input Impedance (Z_{IN}) of an HVD3106

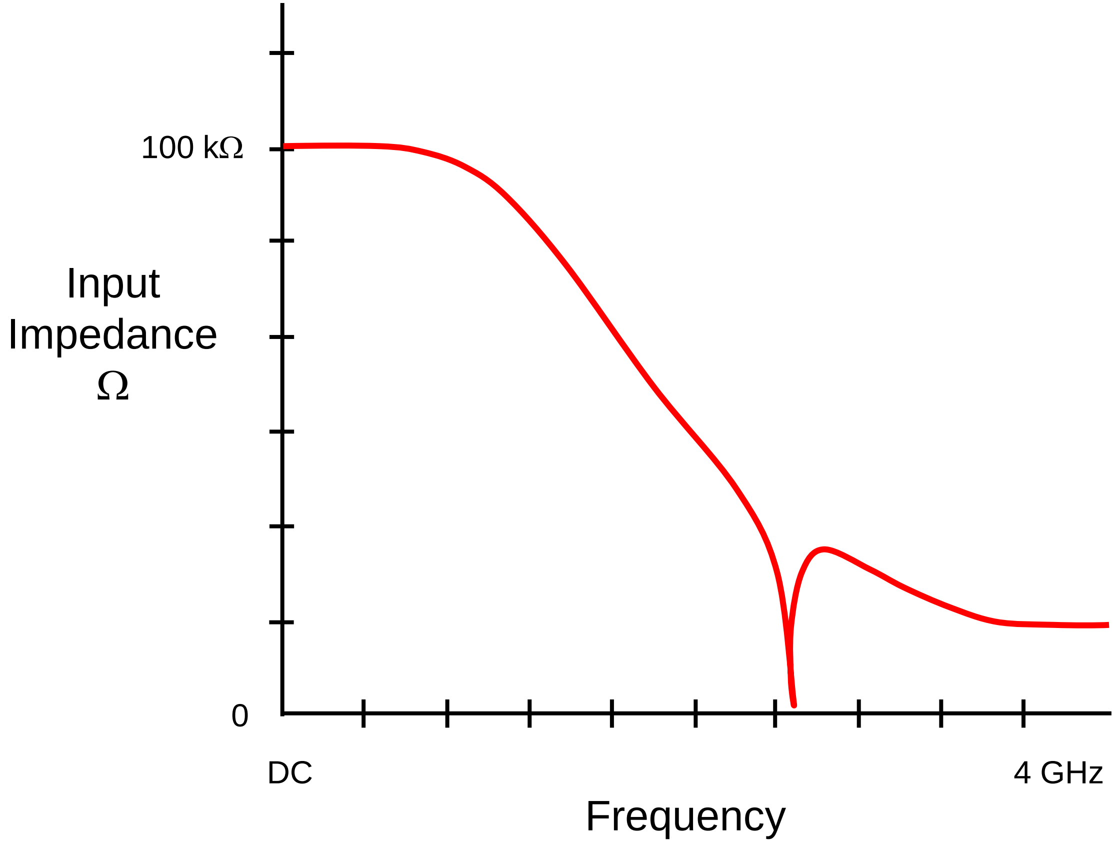




Input Impedance

Input Resonance

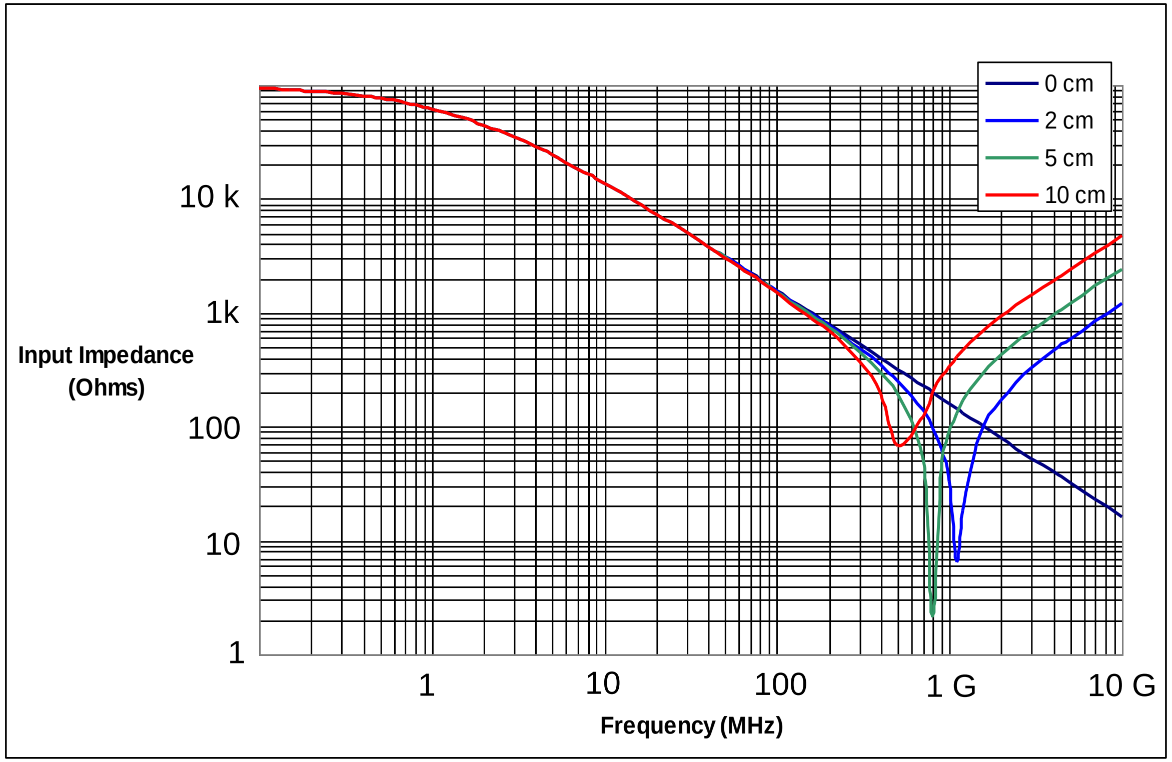
- The input capacitance of the probe, acting on the inductance of the input tip or leads, can form a series resonant circuit.
  - $\omega L = 1/\omega C$
- At resonance, the Z_{IN} drops very low.
- If the resonance is in the passband, serious waveform distortion can result.
- If the probe is operated per the manufacturer’s instructions, it is safe to assume that this won’t happen

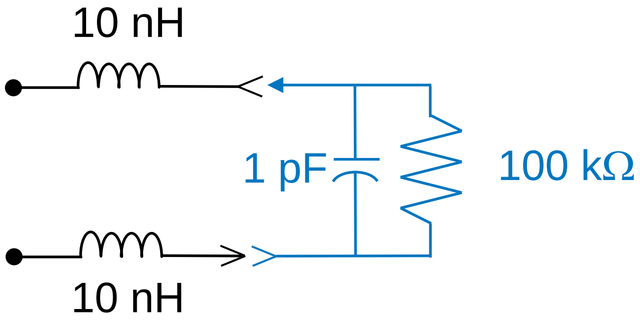


Input Impedance

So, Never Extend Input Leads !

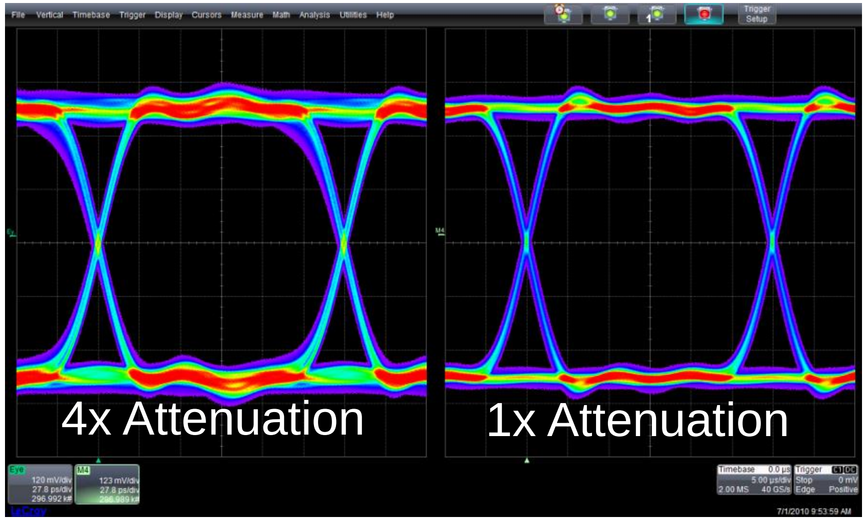
- Adding extension wires to probe input leads increases the inductance, lowering the resonant frequency.
  - In this high bandwidth probe example, only 1 cm added to tip and ground reduce Zin from 159 Ω to 8.3 Ω at 1 GHz!
- Long (added) input leads also increases loop inductance
  - Never a good thing in the presence of high common-mode voltages and high dV/dt signals
  - Will add noise (at the least) and unpredictable distortion effects (ringing).



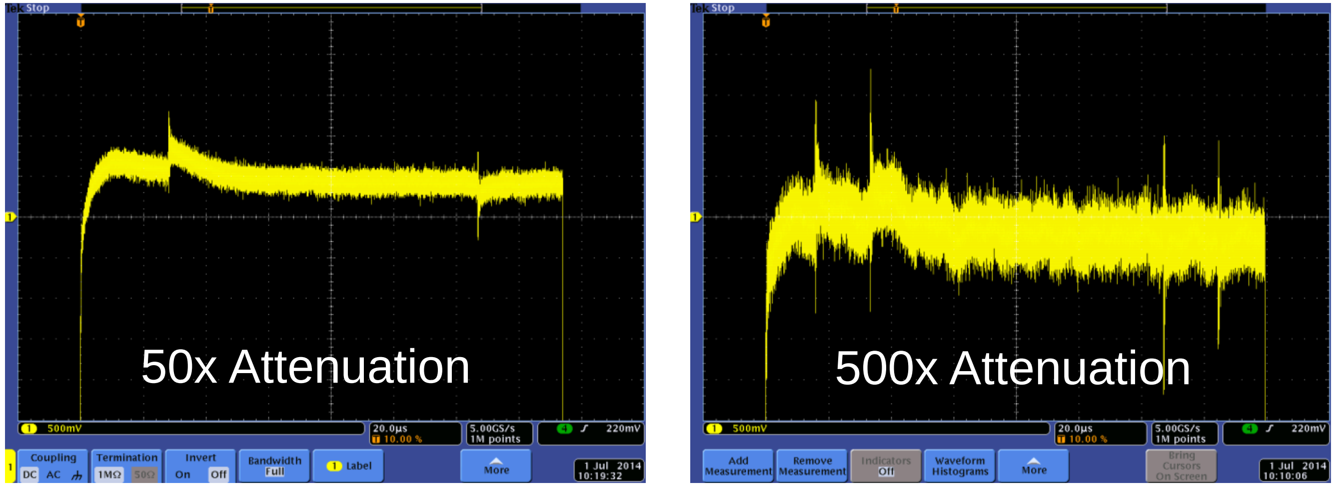


Attenuation

- Probe attenuation serves two primary purposes:
  - Reduces the measured voltage to a voltage safe to input to the oscilloscope
  - Reduces circuit loading
- However, what you attenuate, you then must amplify
  - More sensitive oscilloscope gain ranges have lower SNR, therefore…
  - Higher attenuation = higher noise (all other things being equal)
    - This does not mean that high attenuation is “bad” – it is necessary in some cases.



Serial data eye diagram with probe (left, 4x attenuation) and cable input (right, 1x attenuation)



Tektronix HV Differential Probe at 50x (left) and 500x (right). Note: This probe requires manual attenuation selection, which makes the comparison possible.

Common Mode Rejection Ratio (CMRR)

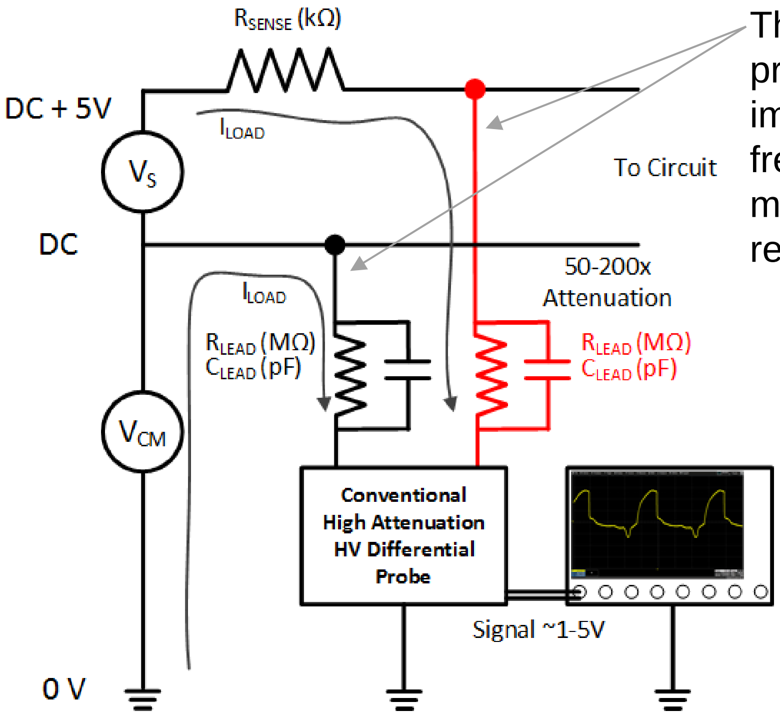
- **Common Mode Rejection** is the ability of the differential amplifier to ignore the component that is common to both inputs.
    - Real world differential amplifiers do not remove all of the common mode signal.
    - Additionally, differential probe leads/pairs must be perfectly matched for frequency response. This is hard to do with an attenuating probe lead set (but good results can still be obtained).
    - Common mode feedthrough sums with the V_{DM} (*signal of interest)* into the output of the differential amplifier, becoming indistinguishable from the true signal.
- The measure of how effective the differential amplifier + probe lead (pair) system is in removing common mode is **Common Mode Rejection Ratio (CMRR).**
    - You will see CMRR expressed both in dB units or as a ratio of rejected voltage. $20\log_{10}(V_{SIGNAL}/V_{MEASURED}) = CMRR_{dB}$
- Essentially, lower CMRR equates to greater noise and interference on the measured signal.
- High CMRR (100dB, or 100,000:1) at high frequencies is difficult to achieve with a conventional high voltage (high-attenuation) probe topology.

Common Mode Rejection Ratio (CMRR)

Comparison of a Conventional Differential Probe/Amp to a Fiber Optically-isolated Probe

Conventional HV Differential Probe or Amplifier

e.g., Teledyne LeCroy DA1855A+DXC100A, HVD3106, ADP305; Tektronix P5205, THDP0200

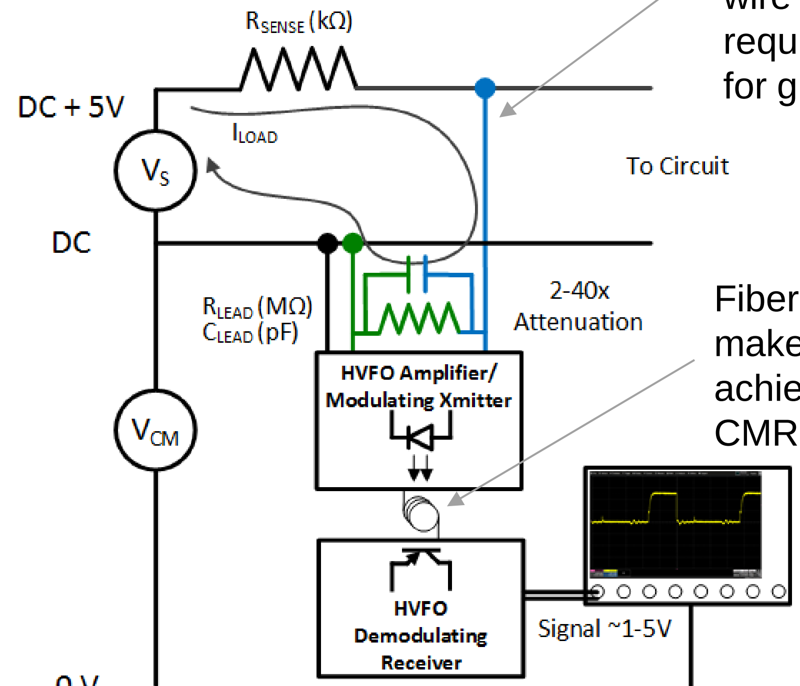


This probe pair must be precisely matched in impedance and frequency response to maintain CMRR – this is really hard to do!

A conventional high voltage differential probe topology requires that the probe measure small signal voltage + common-mode voltage across the lead capacitance = more probe loading on DUT, especially at high common-mode voltages.

HV Fiber Optic Probe

e.g., Teledyne LeCroy HVFO103



A coaxial signal wire does not require matching for great CMRR.

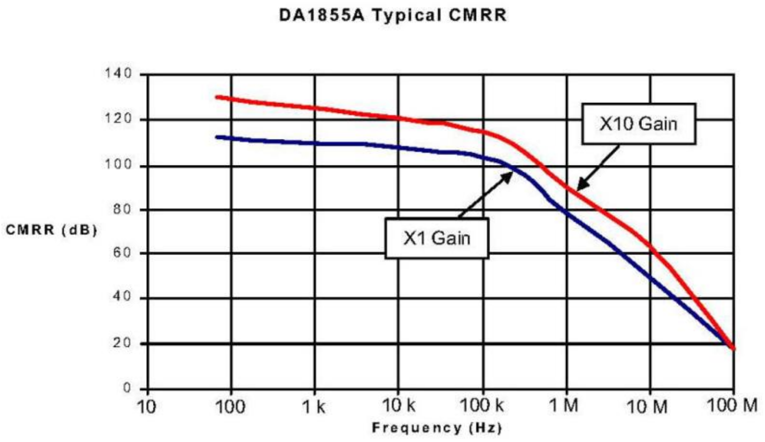
Fiber optic isolation makes it easy to achieve great CMRR

The high voltage fiber optic probe only measures the small signal voltage since the probe amplifier is floating (battery-powered). This reduces the voltage across the lead capacitance = less probe loading at high common-mode voltages.

Common Mode Rejection Ratio (CMRR)

CMRR of fiber-optically isolated HVFO103 is far better than conventional HV differential probes/amps

DA1855A (from Operator’s Manual)

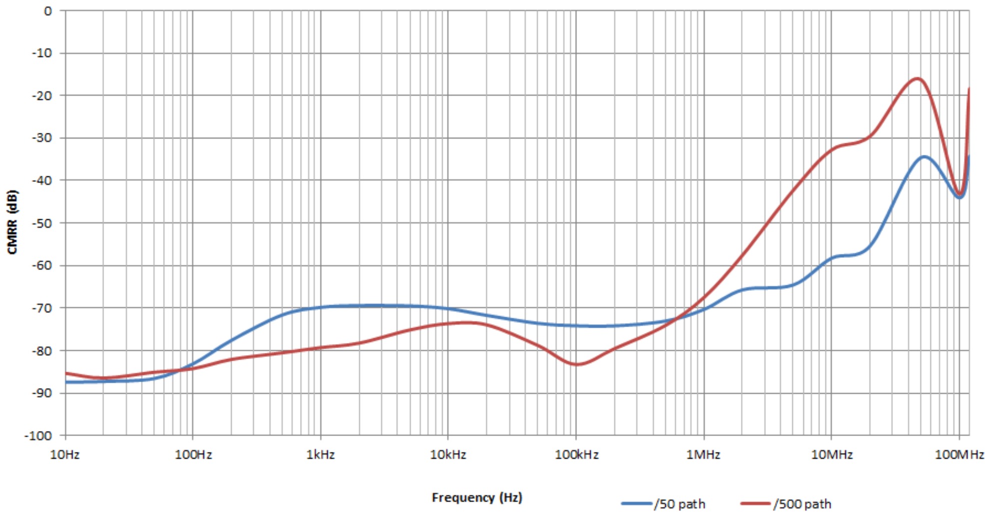


Specifications

100dB @ 100 kHz

50dB @ 10 MHz

HVD3106 (from Operator’s Manual)



Specifications

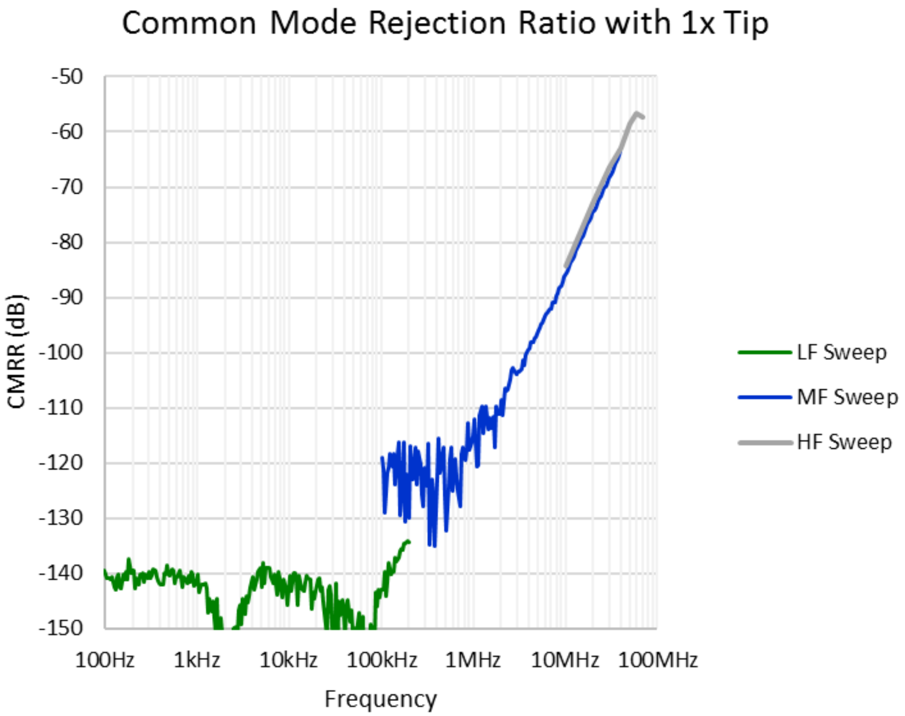
80dB @ 60 Hz

65dB @ 1 MHz

40dB @ 5 MHz

30dB @ 100 MHz

HVFO103



Specifications

140dB @ 100 Hz

120dB @ 1 MHz

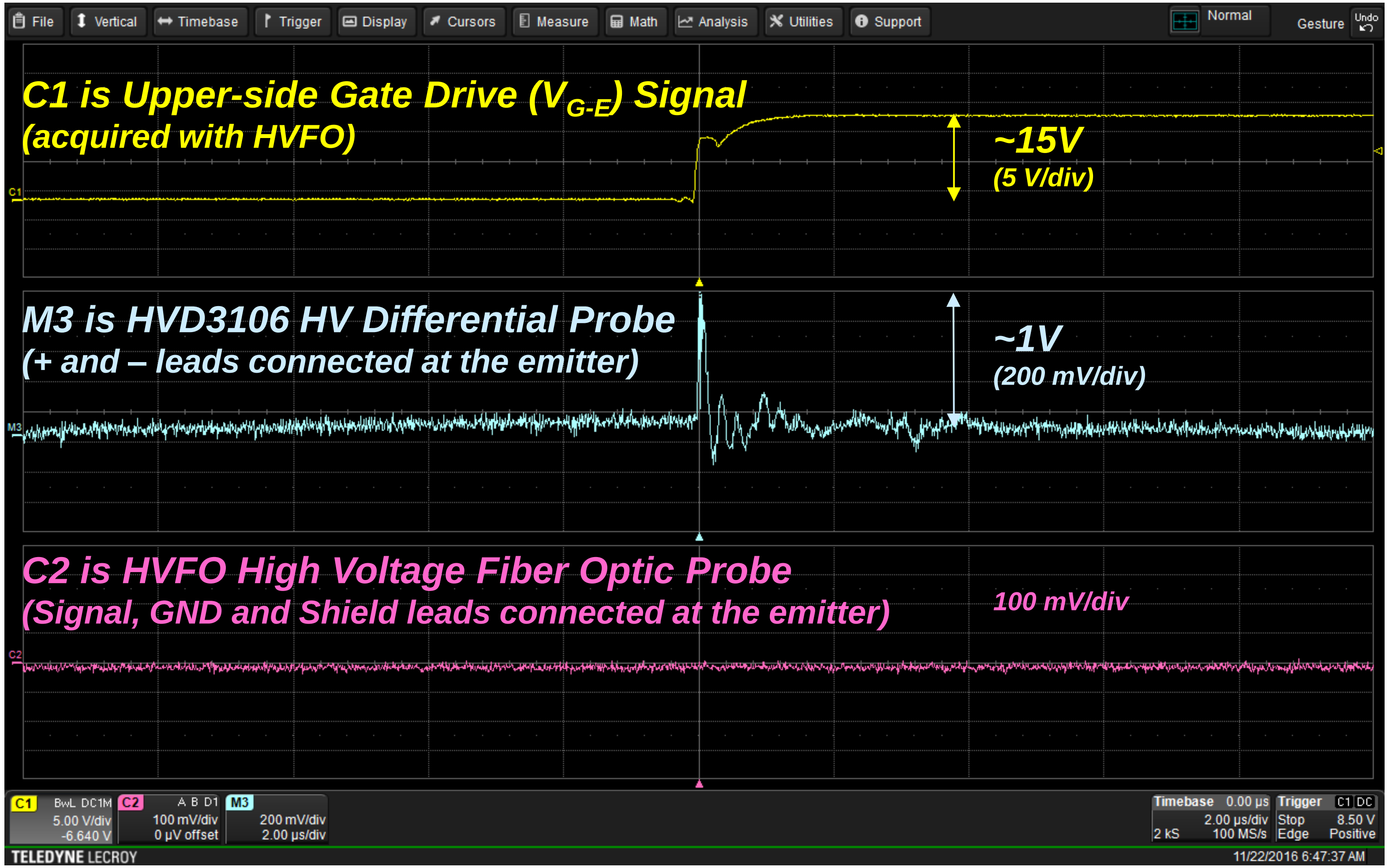
85dB @ 10 MHz

60dB @ 60 MHz

Common Mode Rejection Ratio (CMRR)

A simple test provides a reasonable measurement of your probe

- Connect the + and – leads together at the measurement reference location
  - e.g., the emitter or source location of an upper-side device.
- Acquire the signal
- View the interference
  - A measured transient during high dV/dt events indicates measured common-mode interference



C1 is Upper-side Gate Drive (V_{G-E}) Signal
(acquired with HVFO)

~15V
(5 V/div)

M3 is HVD3106 HV Differential Probe
(+ and – leads connected at the emitter)

~1V
(200 mV/div)

C2 is HVFO High Voltage Fiber Optic Probe
(Signal, GND and Shield leads connected at the emitter)

100 mV/div

C1 BwL DC1M 5.00 V/div -6.640 V
C2 A B D1 100 mV/div 0 µV offset
M3 200 mV/div 2.00 µs/div
Timebase 0.00 µs 2.00 µs/div 2 kS 100 MS/s
Trigger C1 DC Stop 8.50 V Edge Positive
11/22/2016 6:47:37 AM

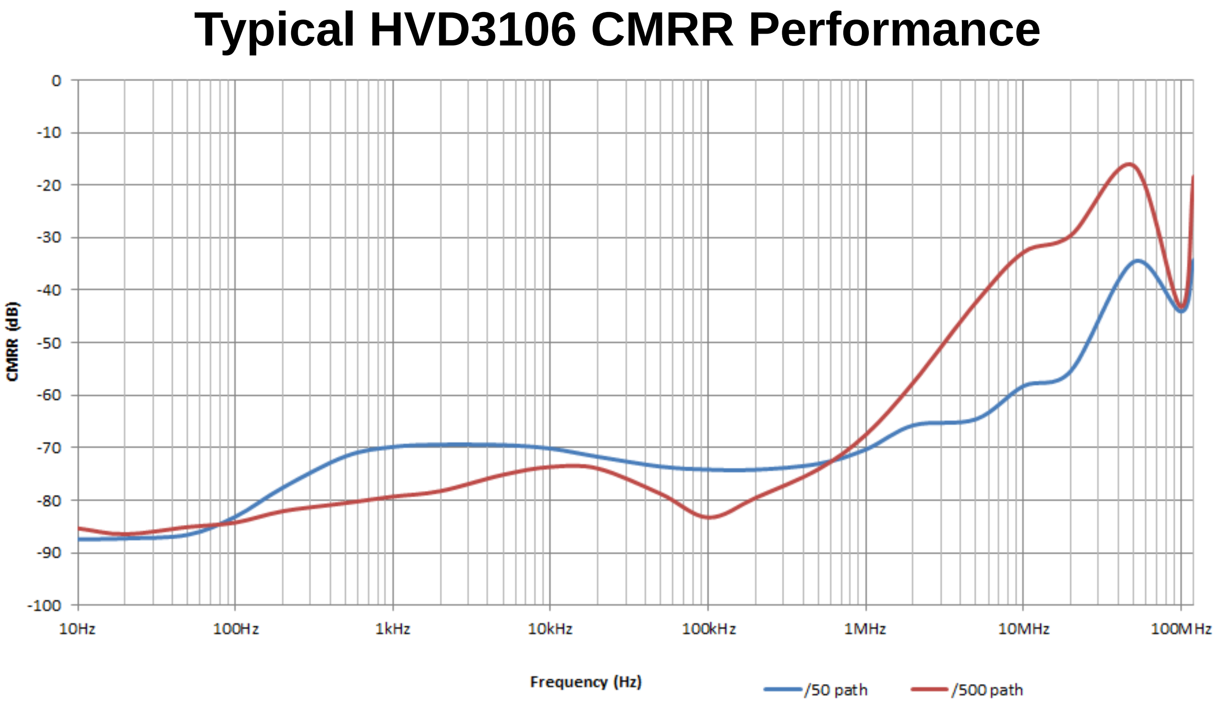
Common Mode Rejection Ratio (CMRR)

Comparing Field Measurement with Typical Factory-measured CMRR plot

15V high dV/dt event (~10 MHz step response)

1V common-mode interference (HVD)

No common-mode interference (HVFO), >100 dB CMRR



Typical HVD3106 CMRR Performance

C1 (yellow) is HVFO measuring an upper-side gate-drive signal (V_{G-E})

M3 (blue) is an HVD3106 HV differential probe with the + and – leads connected together at the emitter (V_E)

The measured 1V peak signal at the gate transition is the common-mode interference of the 15V signal. CMRR = 15:1 (24 dB) for this ~40ns rise time (BW = 0.35/T_{RISE} = 9 MHz).

Note that the HVD3106 has the best CMRR of any probe in it's class – but it can only be so good based on the topology of the design

Red line is 500x path (the attenuation used in the test at the left, required for this common-mode voltage)

Expected CMRR is ~32 dB at 9 MHz

Data above is taken in a controlled environment, parallel cables to minimize ground loops whereas test at the left is in "real-world" conditions.

Probe Types and Characteristics

High voltages present in power electronics requires care in selecting a probe that is safe to use. But just because a probe is safe to use does not mean that it will provide a good measurement result.

Types of Voltage Probes Commonly Used in Power Electronics

- Low Voltage
  1. Passive, Single-ended
  2. Active, Single-ended “FET”
  3. Active, Single-ended “Rail”
  4. Active Differential
- High Voltage “Isolated”
  5. Passive, Single-ended
  6. Active, Single-ended (fiber-optic isolated)
  7. Active, Differential (conventional high attenuation)
  8. Active, Differential Amplifier with matched probe pair (conventional high attenuation)

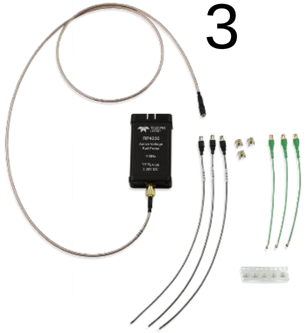
1

PP Series

2

ZS Series

3



RP4030

4

ZD Series

5

PPE or
HVP Series

6

HVFO103

7

HVD or ADP Series

8

DA1855A +
DXC100A

1 - Low Voltage Passive Single-ended Probes

Parameter	Value
Bandwidth	500 MHz
Voltage Range (SE) Voltage Range (DM) Voltage Range (CM)	~400Vpk N/A N/A
Voltage Offset	N/A
Loading	10MΩ || 15pF Z_{IN}=30Ω@500 MHz
Attenuation	10x
CMRR	N/A

- Rugged, reliable, inexpensive
- Ubiquitous

2 - Low Voltage Active Single-ended “FET” probes

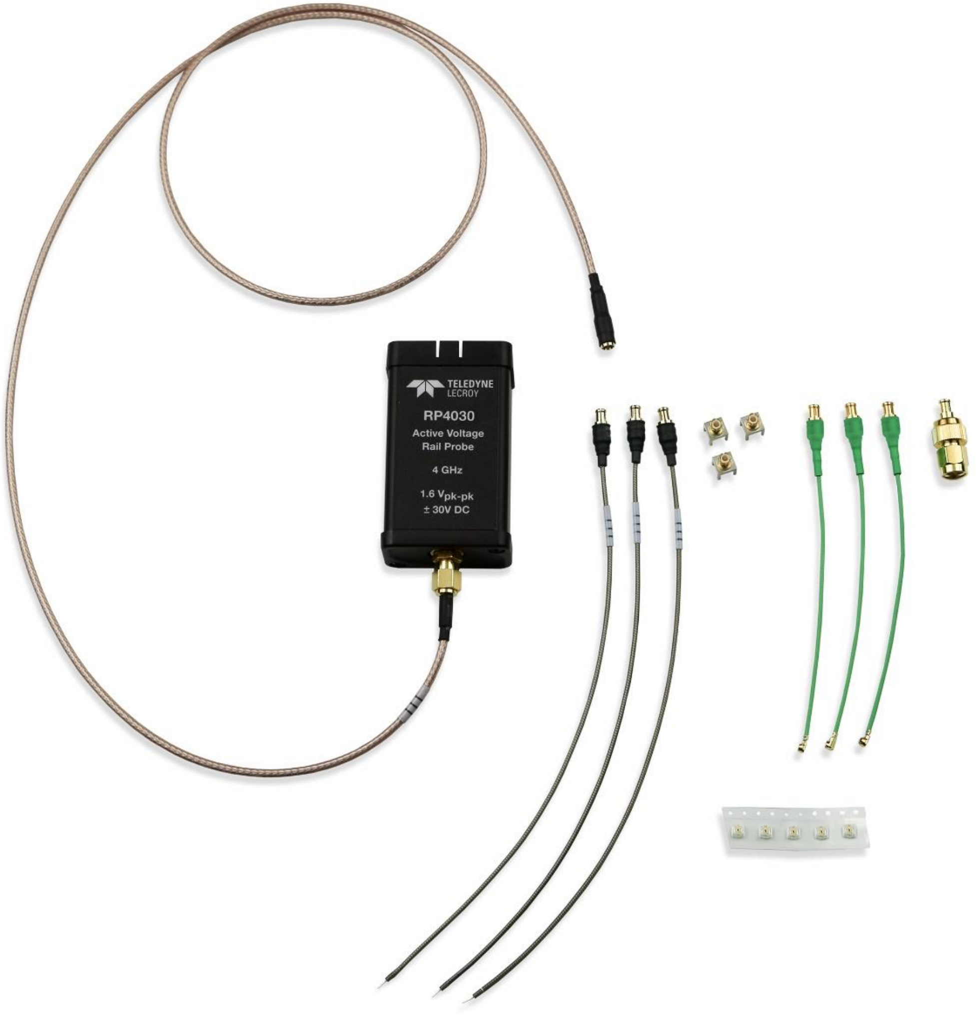
Parameter	Value
Bandwidth	Up to 4 GHz
Voltage Range (SE) Voltage Range (DM) Voltage Range (CM)	~10Vpk N/A N/A
Voltage Offset	N/A
Loading	1MΩ || 1pF Z_{IN}=400Ω@500 MHz
Attenuation	10x
CMRR	N/A

- Amplifier near the probe tip to isolate cable loading from test circuit.
- Less voltage range, fragile, can be expensive.

3 - Low Voltage Active (Voltage / Power) Rail Probes

Parameter	Value
Bandwidth	Up to 4 GHz
Voltage Range (SE) Voltage Range (DM) Voltage Range (CM)	800 mVpk N/A N/A
Voltage Offset	30V
Loading	50kΩ || 0.1μF
Attenuation	1.2x
CMRR	N/A

- Specifically used for probing DC power (voltage) rails (e.g., 1.1, 1.5, 1.8Vdc)
- Large voltage offset permits DC rail to be offset and gain to be set to high-sensitivity (e.g., 10 mV/div)



4 - Low Voltage Active Differential Probes

Parameter	Value
Bandwidth	0.2 to 1.5 GHz
Voltage Range (SE) Voltage Range (DM) Voltage Range (CM)	N/A 10-40V typical 10-60V
Voltage Offset	N/A
Loading	1MΩ || 3.5pF Z_{IN}=200Ω@500 MHz
Attenuation	10x
CMRR	50 dB at high freq.

- Some of the lower bandwidth differential probes have good V_{DM} and V_{CM} range for <50Vdc bus systems

5 - High Voltage Passive Single-ended Probes

Parameter	Value
Bandwidth	500 MHz
Voltage Range (SE) Voltage Range (DM) Voltage Range (CM)	Up to 6kV typical N/A N/A
Voltage Offset	N/A
Loading	10MΩ || 7.5pF Z_{IN}=50Ω@500 MHz
Attenuation	100x
CMRR	N/A

- A good option for some, but also have high attenuation values (so more noise)

6 - High Voltage Active Single-ended (Fiber Optic) Probes

Parameter	Value
Bandwidth	60 MHz
Voltage Range (SE) Voltage Range (DM) Voltage Range (CM)	2 to 80V N/A Virtually Unlimited
Voltage Offset	N/A
Loading	1-10MΩ || 34-22pF Z_{IN}=50kΩ@100 kHz
Attenuation	2x to 80x
CMRR	>140 dB

- A new topology specifically for measuring small signals floating on a HV DC bus

7 - High Voltage Active Differential Probes

Parameter	Value
Bandwidth	~100 MHz
Voltage Range (SE)	N/A
Voltage Range (DM)	2kV to 8kV
Voltage Range (CM)	1kV to 6kV
Voltage Offset	1kV to 6kV
Loading	10MΩ || 2.5pF Z_{IN}=1kΩ@100 MHz
Attenuation	50-2000x
CMRR	65 dB (HVD)

- Excellent all around choice for many applications, but has its limitations
- Some models perform better than others

8 - High Voltage Active Differential Amplifier with Matched Probe Pairs

Parameter	Value
Bandwidth	100 MHz
Voltage Range (SE) Voltage Range (DM) Voltage Range (CM)	N/A 0.5V to 2.5kV 155V to 2.5kV
Voltage Offset	Depends on probe
Loading	Depends on probe
Attenuation	1-1000x, with gain
CMRR	100 dB

- Exceptional overdrive recovery and fine offset adjust make this idea for device conduction loss and switching loss testing, and measuring small signal sensor values floating on a HV DC bus.

Probe-Application Comparisons

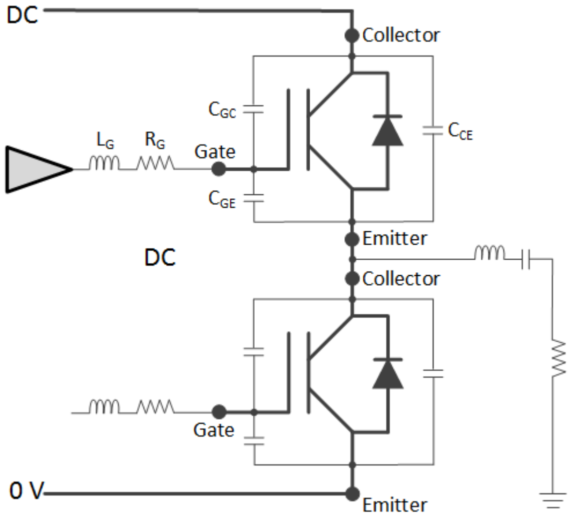
Some measurements are more difficult to make than others, and require high performance probes of the right topology for the measurement. The following comparisons highlight some of the more difficult measurements that power electronics engineers need to make.

TELEDYNE LECROY
Everywhereyoulook™

Comparisons for Upper Gate-drive Signal Measurements

These are challenging measurements. The upper gate-drive signal is floating at the DC bus voltage, requiring HV isolation. The high dV/dt from the lower-side switching can create a lot of measurement interference. And the high common-mode can cause probe loading problems when conventional probes are used.

TELEDYNE LECROY
Everywhereyoulook™



120/240Vac Half-bridge Upper-Side Gate-drive Signal (465Vdc bus)

A half-bridge LED driver with a fall-time of ~70ns and a 465Vdc bus voltage provides an ideal test for measurement fidelity of a number of HV differential probe topologies, vintages, and models.

Equipment Used in This Comparison

- Oscilloscopes + Probes
  - Teledyne LeCroy HDO6104 oscilloscope (4 channels, 1 GHz, 12-bits) with
    - Teledyne LeCroy ADP-305 High Voltage Differential Probe (100 MHz, 1990s)
    - Teledyne LeCroy HVD3106 High Voltage Differential Probe (120 MHz, 2014)
    - Teledyne LeCroy DA1855A Differential Amplifier with DXC100A HV probe pair
    - Teledyne LeCroy HVFO High Voltage Fiber Optic Probe (60 MHz, 2016)
- Customer-supplied half-bridge LED driver
  - ~70 ns fall time on gate-drive signals
  - 465 Vdc bus

Comparison 1 – Upper-side Gate Drive Measurement in an LED Driver

HVFO compared to DA1855A+DXC100A measuring high-side gate drive

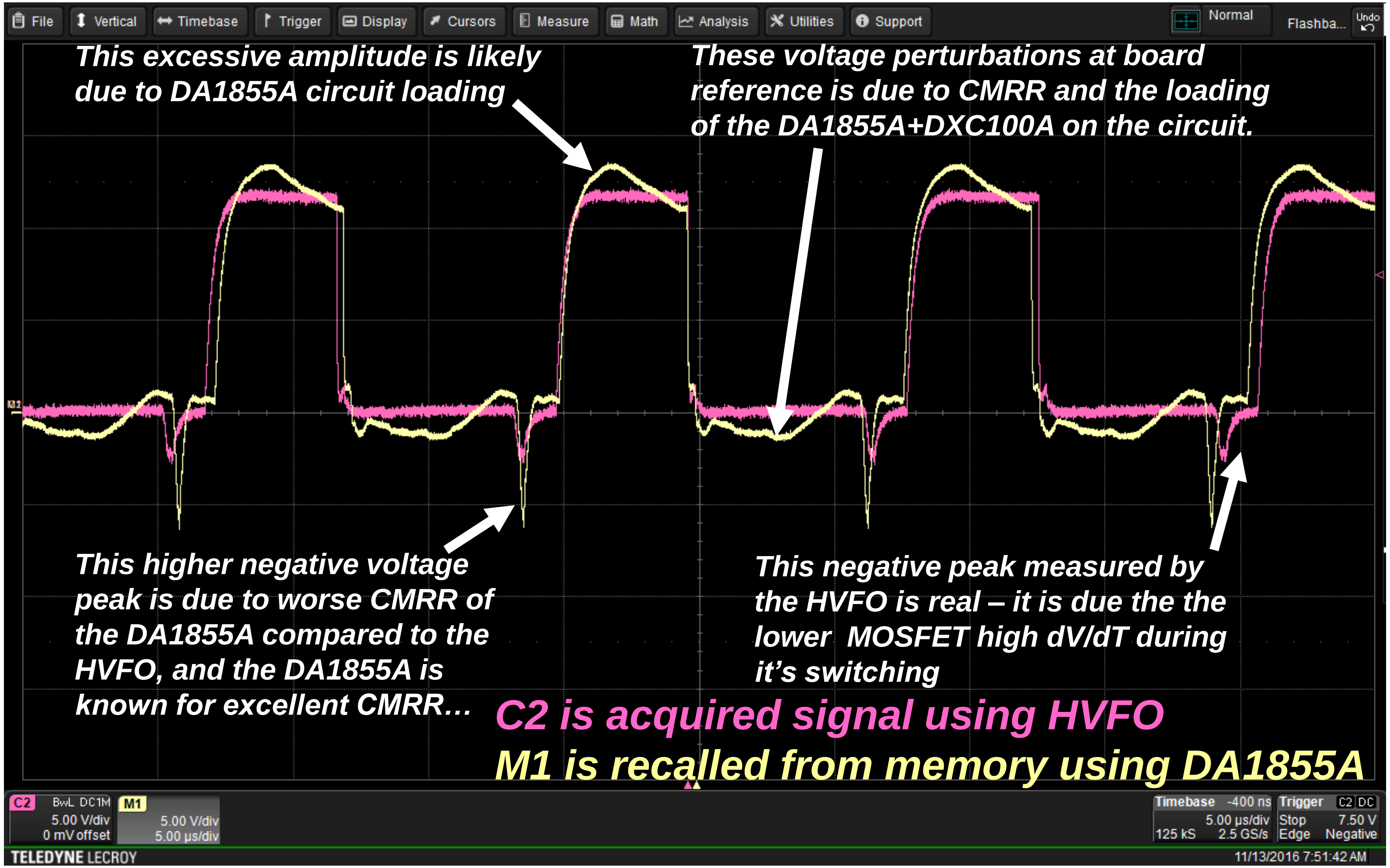
DA1855A in tan (M1)

HVFO in magenta (C2)

Note: both probes **NOT in circuit** at same time

HVFO exhibits less DUT loading, better CMRR

Notes: *Signals were acquired in separate acquisitions, which is why pulse widths are slightly different.*



This excessive amplitude is likely due to DA1855A circuit loading

These voltage perturbations at board reference is due to CMRR and the loading of the DA1855A+DXC100A on the circuit.

This higher negative voltage peak is due to worse CMRR of the DA1855A compared to the HVFO, and the DA1855A is known for excellent CMRR…

This negative peak measured by the HVFO is real – it is due the the lower MOSFET high dV/dT during it's switching

C2 is acquired signal using HVFO

M1 is recalled from memory using DA1855A

Comparison 1 – Upper-side Gate Drive Measurement in an LED Driver

DA1855A+DXC100A in the circuit at the same time as HVFO impacts measurement by HVFO

DA1855A in yellow (C1)

HVFO in magenta (C2)

Note: both probes **ARE in circuit** at same time

Loading of DA1855A affects HVFO measurement

DA1855A circuit loading impacts the HVFO measurement when they are both in circuit at the same time

C1 is DA1855A + DXC100A probe pair

C2 is HVFO High Voltage Fiber Optic Probe (now loaded by DA1855A+DXC100A)

Comparison 1 – Upper-side Gate Drive Measurement in an LED Driver

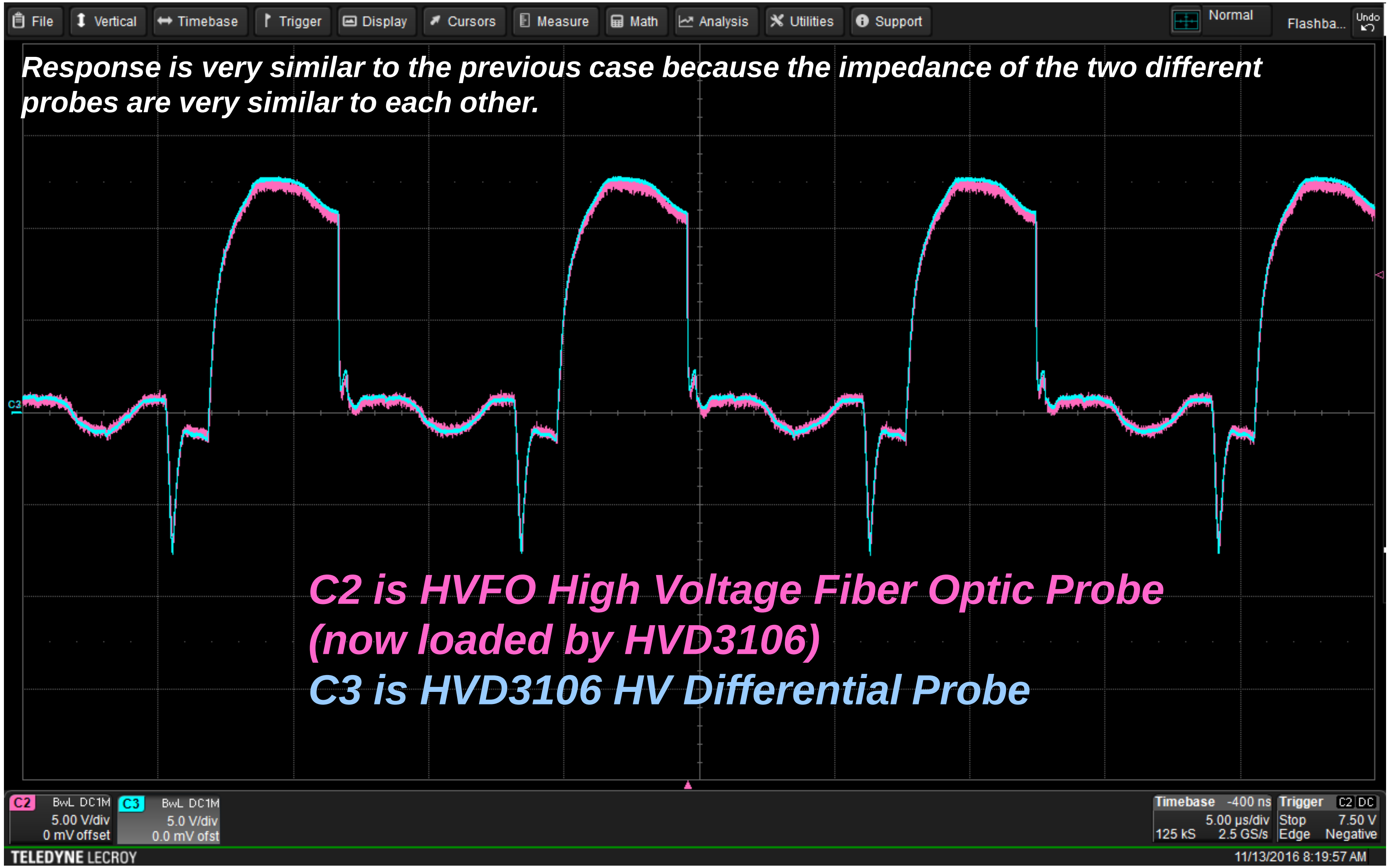
HVD3106 loading also affects HVFO measurement

HVD3106 in blue (C3)

HVFO in magenta (C2)

Note: both probes **ARE in circuit** at same time

Loading of HVD3106 also affects HVFO measurement



Response is very similar to the previous case because the impedance of the two different probes are very similar to each other.

C2 is HVFO High Voltage Fiber Optic Probe (now loaded by HVD3106)

C3 is HVD3106 HV Differential Probe

C2 BwL DC1M 5.00 V/div 0 mV offset

C3 BwL DC1M 5.0 V/div 0.0 mV ofst

Timebase -400 ns 5.00 µs/div 125 kS 2.5 GS/s

Trigger C2 DC Stop 7.50 V Edge Negative

11/13/2016 8:19:57 AM

Conclusions

Upper-Side Gate Drive Measurement On a HV (>200Vdc) Bus

- Choosing the right probe for the measurement is most important
  - Teledyne LeCroy HVFO Series is optimized for small-signal floating measurements
    - >140 dB CMRR over a wide frequency range
    - Low loading
    - Fiber optic isolation
  - Depending on the circuit, a ***good quality*** HV differential probe or amplifier ***may*** make a reasonable measurement.
- Newer probes of the same type can make much better measurements
  - Teledyne LeCroy HVD3106 (2014) compared to ADP305 (late 1990s)
- A probe that is great at one measurement may not be best for other measurements
  - Teledyne LeCroy DA1855A Differential Amplifier + DXC100A Probe Pair is optimized for switching/conduction loss and some sensor signal measurements
    - Great overdrive recovery
    - Very good CMRR
    - But conventional HV high-attenuation architecture results in more loading than desired on this small-signal gate-drive measurement

Cascaded H-Bridge (~400Vdc bus) Comparison of Instrument Isolated Inputs vs. HV Isolated Probes

It is a common misconception that “isolated inputs” are better than isolated probes. In fact, an instrument’s isolated input may provide safety to the instrument, user and DUT, but the long, capacitive, unshielded cable connections to the instrument are less than ideal for high frequency measurements.

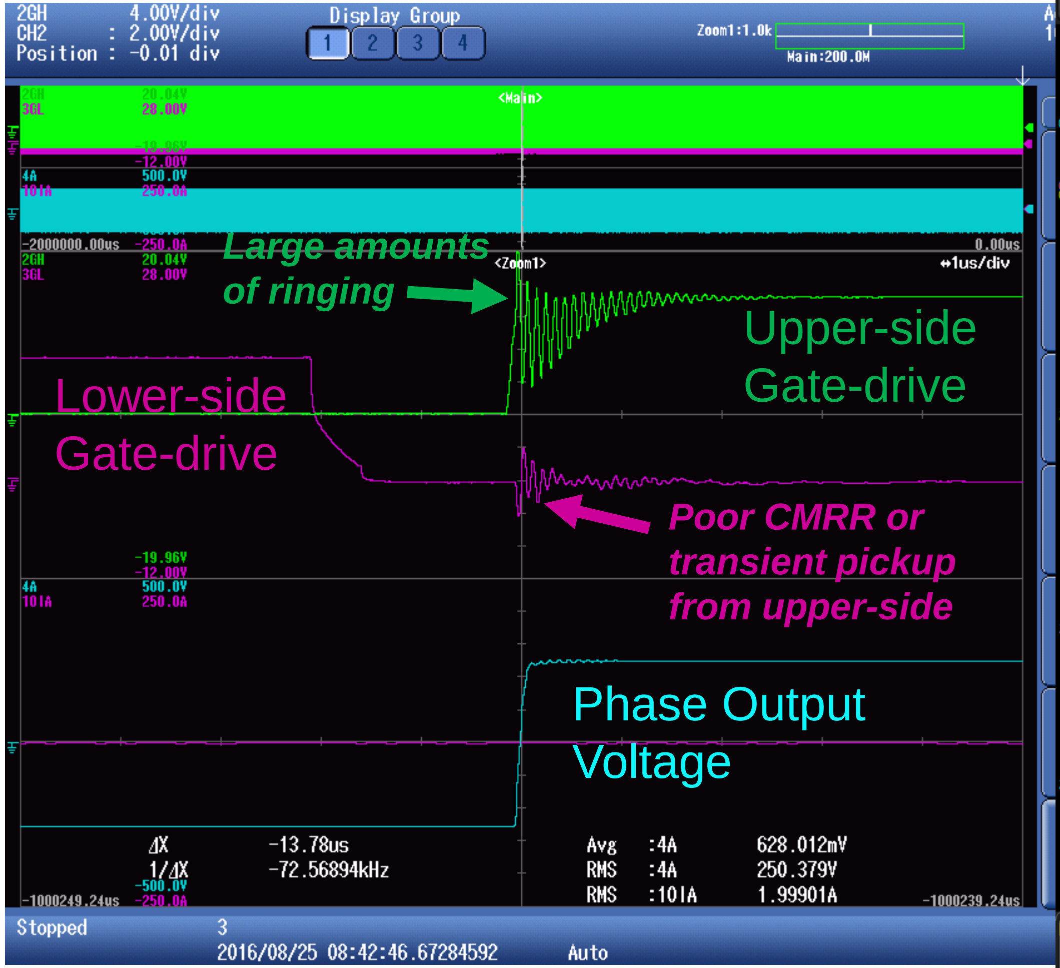
TELEDYNE LECROY
Everywhereyoulook™

Equipment Used in This Comparison

- Oscilloscopes + Probes
  - Teledyne LeCroy HDO6104 oscilloscope (4 channels, 1 GHz, 12-bits) with
    - Teledyne LeCroy HVFO High Voltage Fiber Optic Probe (60 MHz)
    - Teledyne LeCroy HVD3106 HV Differential Probe (120 MHz)
    - Teledyne LeCroy Passive Probe
      - for measuring $V_{L\text{-}REF}$ on mid-point of Cascaded H-Bridge half-bridge leg
  - Yokogawa DL850 ScopeCorder (20 MHz, 12-bit HV isolated inputs used)
    - With Yokogawa 720210 High Speed (100 MS/s, 20 MHz) 12-bit isolation module
    - 10:1 probe for isolated BNC input
- Customer-supplied Cascaded H-Bridge
  - Si devices
  - ~400 Vdc bus

Upper-side Gate-drive Measurement Comparison

Yokogawa DL850 “Isolated Inputs” Compared with Teledyne LeCroy



ΔX -13.78us
1/ΔX -72.56894kHz
Avg :4A 628.012mV
RMS :4A 250.379V
RMS :101A 1.99901A
2016/08/25 08:42:46.67284592

Large amounts of ringing

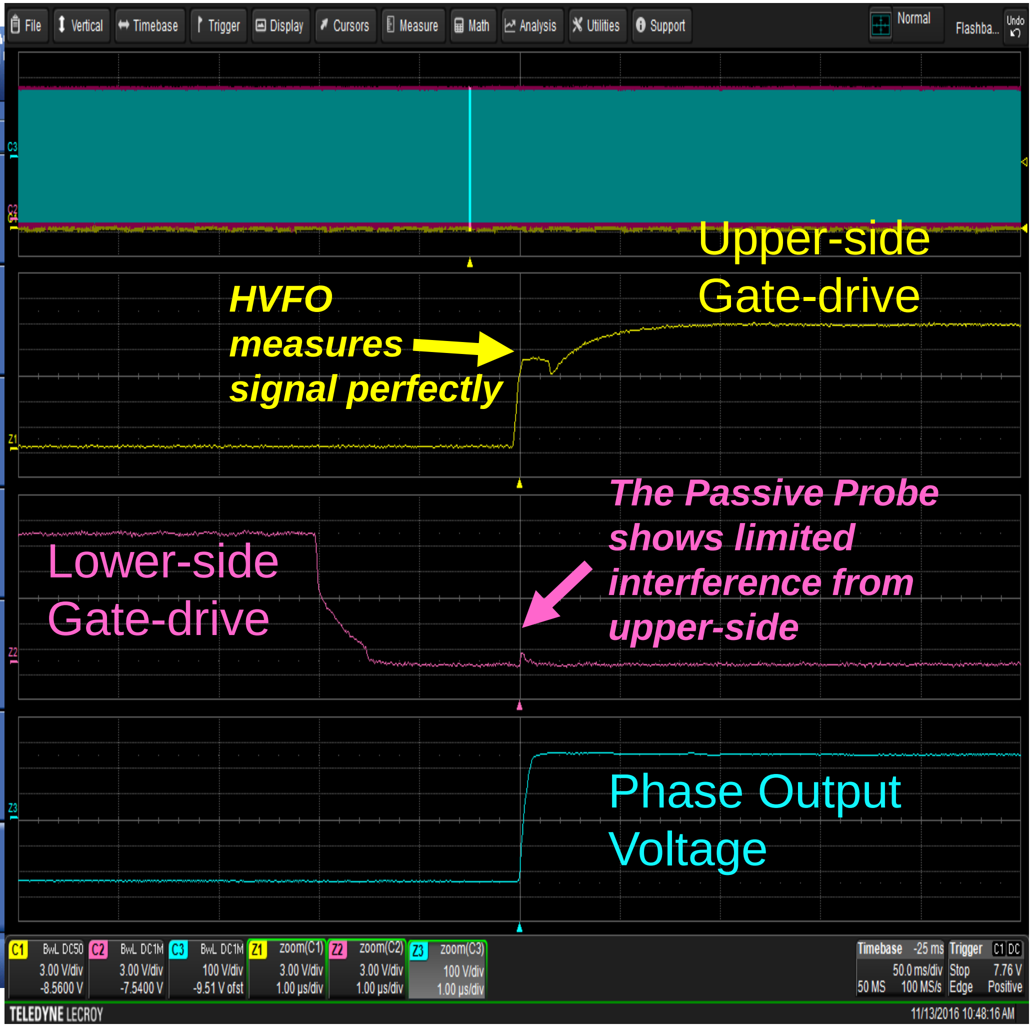
Upper-side Gate-drive

Lower-side Gate-drive

Poor CMRR or transient pickup from upper-side

Phase Output Voltage

Yokogawa DL850 – 100 MS/s, 20 MHz
Isolated input channels, high capacitance
long unshielded connections to DUT



Upper-side Gate-drive

HVFO measures signal perfectly

Lower-side Gate-drive

The Passive Probe shows limited interference from upper-side

Phase Output Voltage

Teledyne LeCroy HDO6104 with HVFO (yellow), passive probe (magenta) and HVD3106 (blue)

Conclusions

Instrument “Isolated Inputs” vs. Conventional Oscilloscope Inputs and Isolated Probes

- The attraction of an isolated oscilloscope input channel is well understood
  - Operator Safety
  - Instrument Safety
  - DUT Safety
- Very low bandwidth sensor signals may be adequately measured by these types of inputs.
- But the reality is that the measurement signal fidelity for high speed signals is often compromised
  - Bandwidth limitations
  - Use of unshielded cables/probes make measurements prone to transient pickup
  - High capacitance of unshielded cables can cause ringing in the measurement

Power Semiconductor Device Conduction Loss

This is a very difficult measurement to make. The signal of interest is the conduction voltage area of a PWM switching waveform, or ~1V in several hundred volts peak-peak. Great overdrive recovery of the measurement system is required, as well as output clamping and precision offset adjust (calibration).

Equipment Used in This Comparison

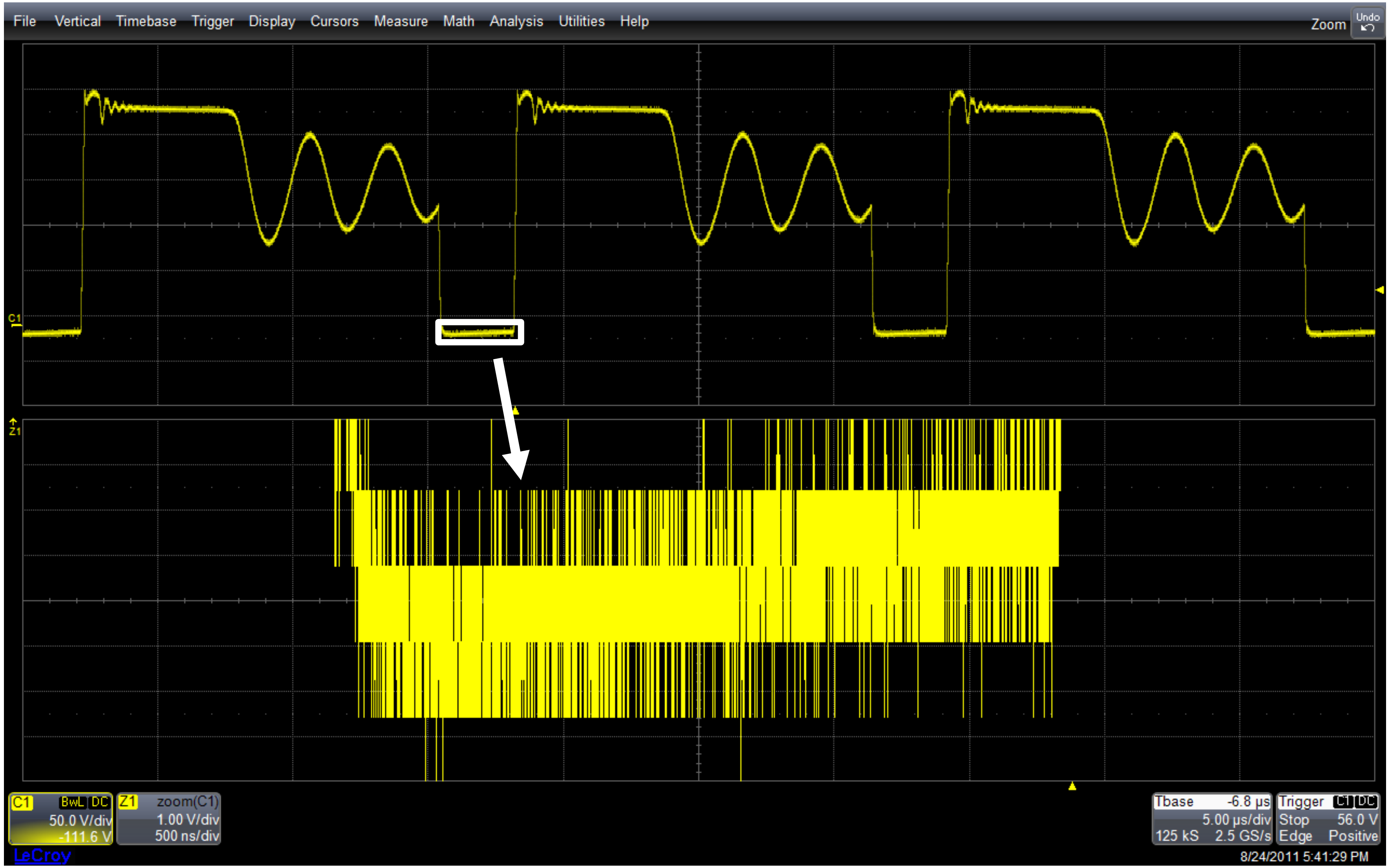
- Oscilloscopes
  - Teledyne LeCroy WaveRunner 610Zi oscilloscope (4 channels, 1 GHz, 8 bits)
  - Teledyne LeCroy WaveRunner 104Xi (4 channels, 1 GHz, 8 bits)
  - Teledyne LeCroy HDO6104 (4 channels, 1 GHz, 12 bits)
- Probes
  - Teledyne LeCroy ADP305 HV Differential Probe (100 MHz)
  - Teledyne LeCroy HVD3106 HV Differential Probe (120 MHz)
  - Teledyne LeCroy DA1855A Differential Amplifier + DXC100A Probe Pair (100 MHz)
- Flyback Switch-Mode Power Supply
  - Si devices
  - ~250 Vdc bus

Conduction Loss Measurement Challenge

8-bit digital oscilloscopes don’t have enough resolution to resolve 1V in 100s of volts

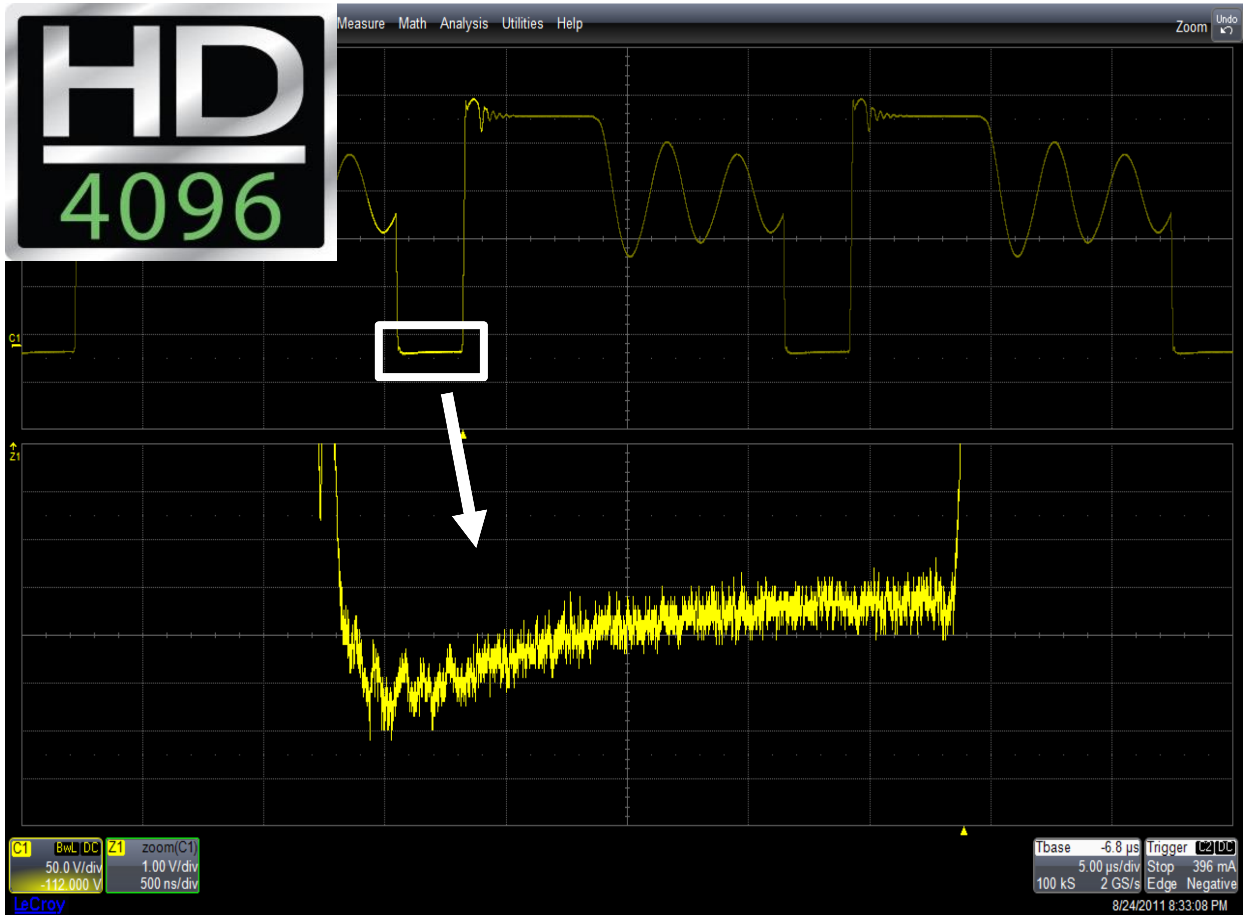
Although the peak to peak waveform may be hundreds of volts, during the conduction stage the voltage is close to zero.

Measuring the conduction loss or dynamic on resistance is a challenge due to the limited dynamic range of the oscilloscope



Switching Loss Measurement using ADP305 and HDO oscilloscope

Note: this is a vertical zoom in the bottom grid and not an overdriven signal



C1 BwL DC 50.0 V/div -112.000 V

Z1 zoom(C1) 1.00 V/div 500 ns/div

Tbase -6.8 µs 5.00 µs/div 100 kS 2 GS/s

Trigger C2 DC Stop 396 mA Edge Negative

8/24/2011 8:33:08 PM

- 12-Bit Capture with Vertical Zoom

C1 BwL DC 50.0 V/div -111.6 V

Z1 zoom(C1) 1.00 V/div 500 ns/div

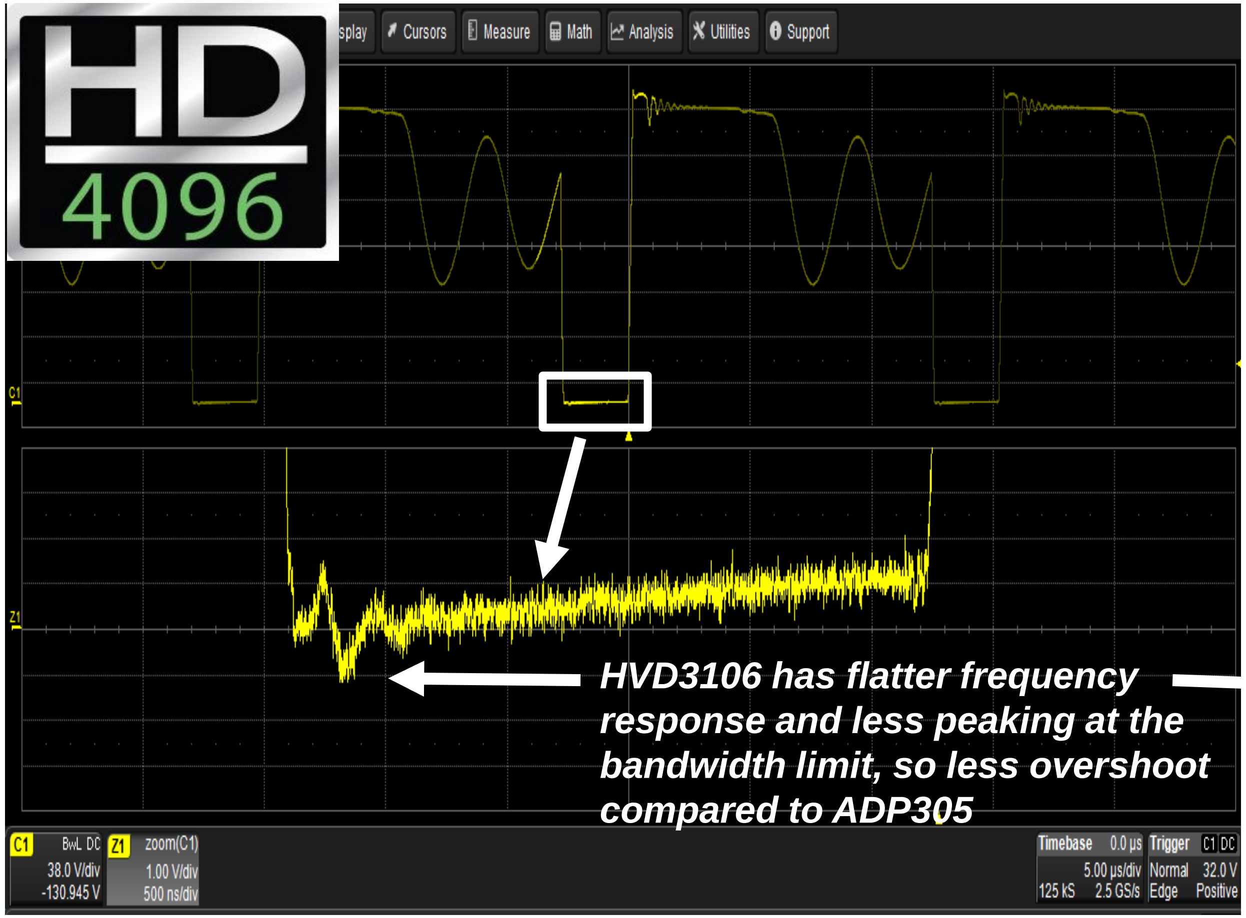
Tbase -6.8 µs 5.00 µs/div 125 kS 2.5 GS/s

Trigger C1 DC Stop 56.0 V Edge Positive

8/24/2011 5:41:29 PM

- 8-Bit Capture with Vertical Zoom

Comparison of HVD3106 to ADP305



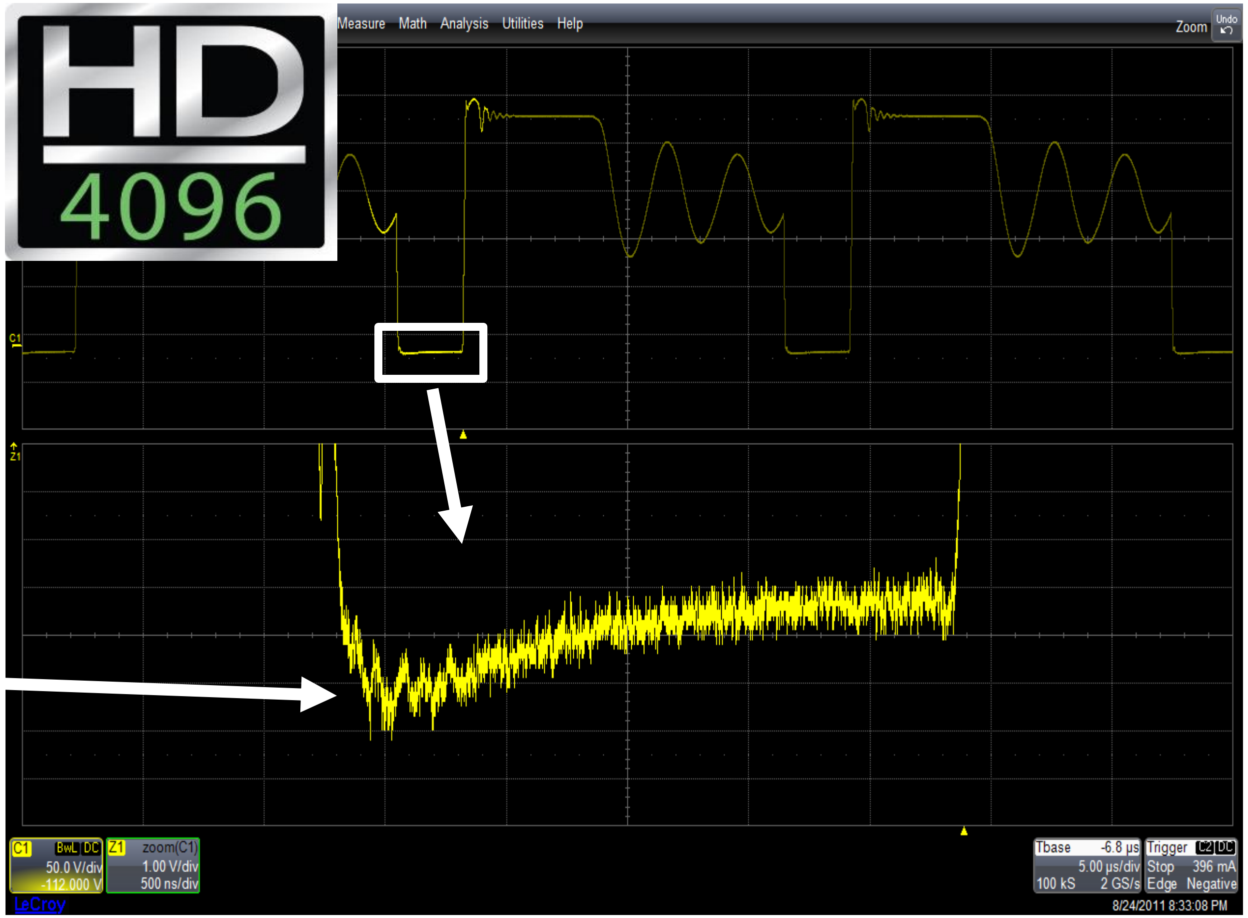
C1 BwL DC 38.0 V/div -130.945 V

Z1 zoom(C1) 1.00 V/div 500 ns/div

Timebase 0.0 µs 5.00 µs/div 125 kS 2.5 GS/s

Trigger C1 DC Normal 32.0 V Edge Positive

HVD3106 has flatter frequency response and less peaking at the bandwidth limit, so less overshoot compared to ADP305



C1 BwL DC 50.0 V/div -112.000 V

Z1 zoom(C1) 1.00 V/div 500 ns/div

Tbase -6.8 µs 5.00 µs/div 100 kS 2 GS/s

Trigger C2 DC Stop 396 mA Edge Negative

8/24/2011 8:33:08 PM

- 12-Bit Capture, 1% accuracy HVD3106 Probe

- 12-Bit Capture, 2% accuracy ADP305 Probe

Power Semiconductor Device Switching Loss

The large voltage swing required in this measurement requires reasonably good CMRR and excellent probe bandwidth flatness and gain accuracy with minimal added overshoot.

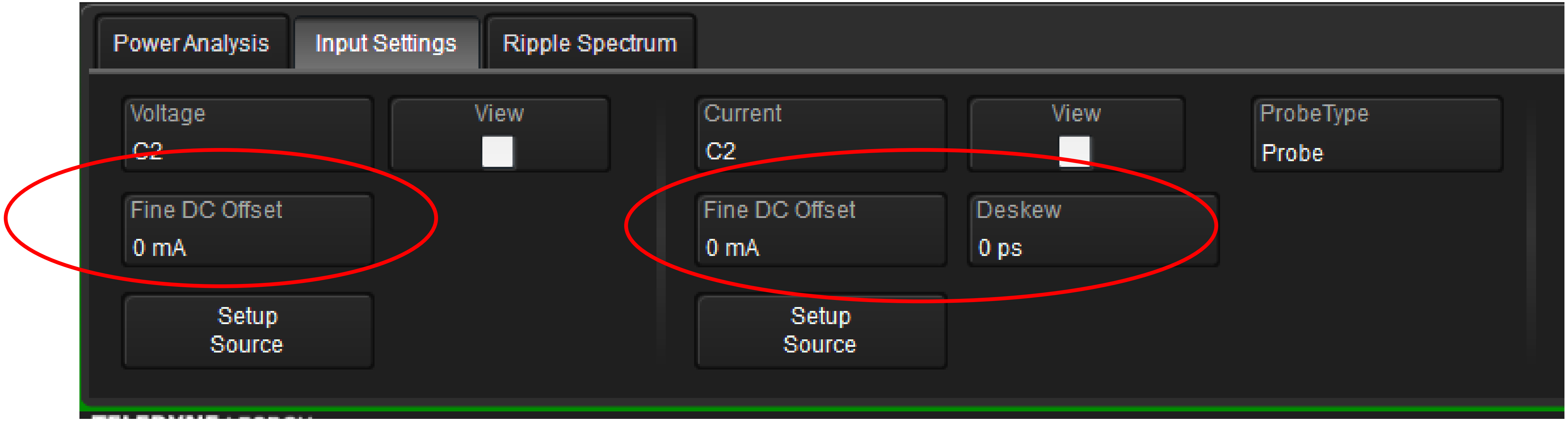
TELEDYNE LECROY
Everywhereyoulook™

Equipment Used in This Comparison

- Oscilloscopes
  - Teledyne LeCroy WaveRunner 610Zi oscilloscope (4 channels, 1 GHz, 8 bits)
  - Teledyne LeCroy WaveRunner 104Xi oscilloscope (4 channels, 1 GHz, 8 bits)
  - Teledyne LeCroy HDO6104 oscilloscope (4 channels, 1 GHz, 12 bits)
- Probes
  - Teledyne LeCroy ADP305 HV Differential Probe (100 MHz)
  - Teledyne LeCroy HVD3106 HV Differential Probe (120 MHz)
  - Teledyne LeCroy DA1855A Differential Amplifier + DXC100A Probe Pair (100 MHz)
- Flyback Switch-Mode Power Supply
  - Si devices
  - ~250 Vdc bus

Eliminating Sources of Error – DC Offsets, Deskew

- Before making detailed device loss measurements, fine adjust to eliminate DC offset errors and scope probe propagation delay differences



Voltage: C2

Fine DC Offset: 0 mA

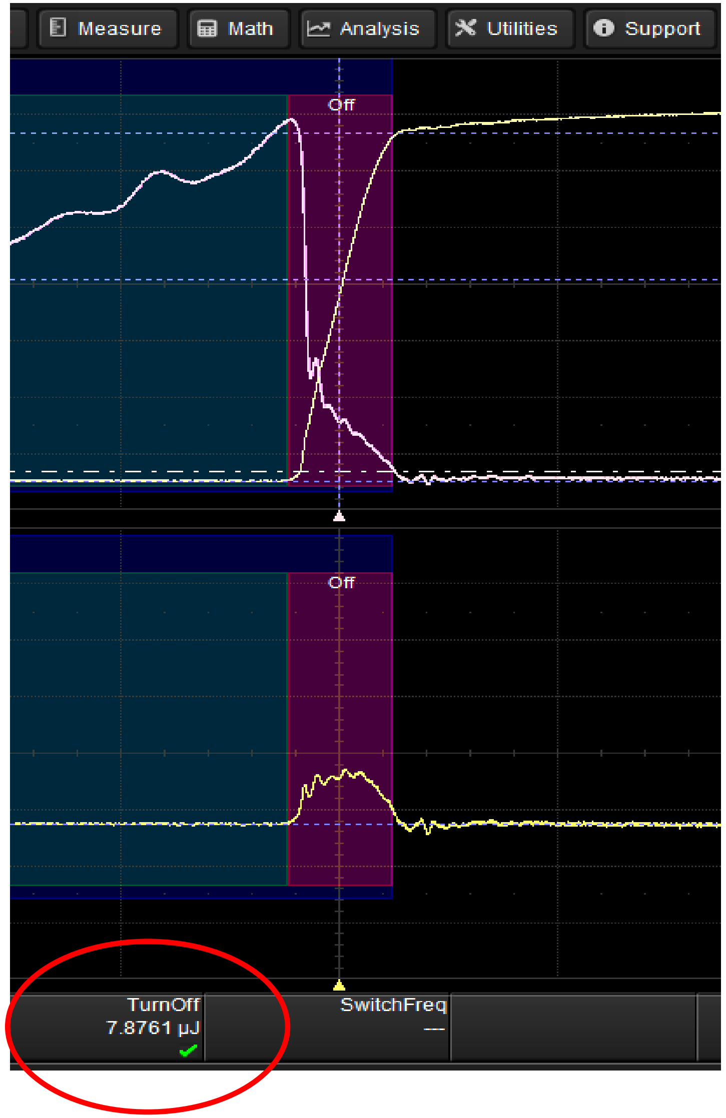
Current: C2

Fine DC Offset: 0 mA

Deskew: 0 ps

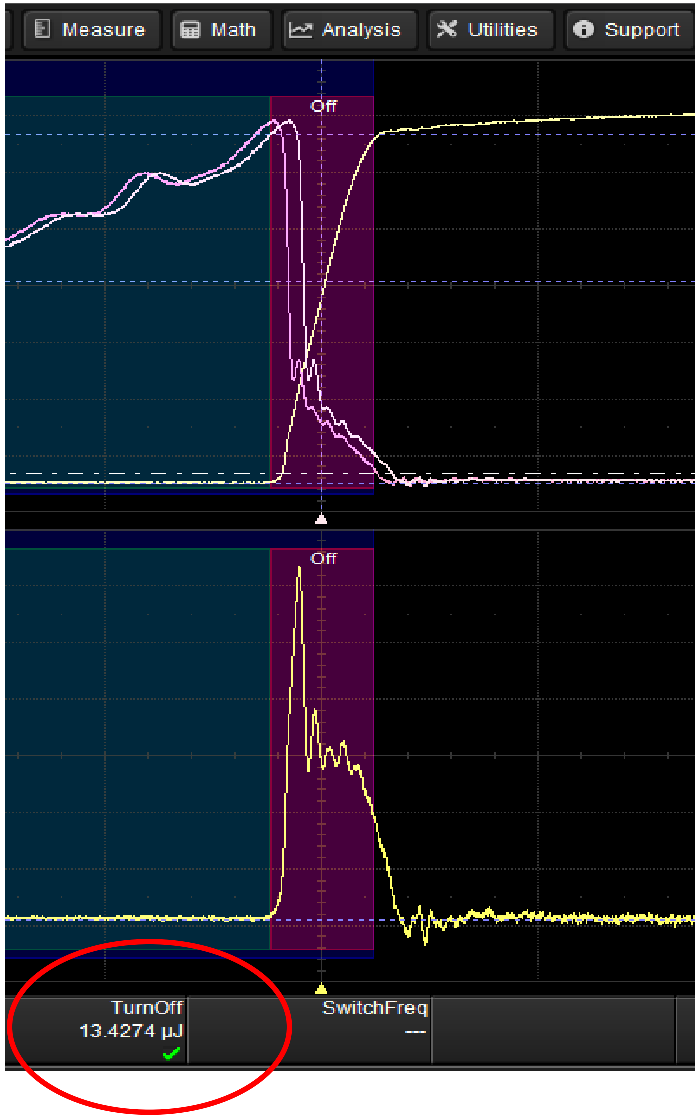
ProbeType: Probe

Sources of Error – Skew Between Voltage and Current Probes



TurnOff
7.8761 µJ ✓

SwitchFreq



TurnOff
13.4274 µJ ✓

SwitchFreq

- Timing skew between voltage and current probes results in measurement error

- Device turn-off transition loss, V x I, is properly measured at 7.88 nJ of energy versus 13.43 nJ without proper deskew

Conclusions

Switching losses can be accurately measured with a high quality HV differential probe

- A 12-bit digital oscilloscope is recommended for best accuracy (0.5%)
- The HVD3106 HV differential probe provides and is a good solution for switching loss measurements due to
  - 1% (guaranteed) accuracy (typically 0.6 to 0.7%)
    - Better than other 2% accurate HV differential probes
  - Flat frequency response with minimal peaking at bandwidth rating
    - Less overshoot and better signal fidelity compared to other HV differential probes
- The DA1855A differential amplifier with a suitable probe pair is the ultimate solution for switching loss measurements
  - Superior CMRR
- Regardless of the voltage measurement solution chosen, voltage and current probes must be deskewed for accurate switching loss measurements.
  - The Teledyne LeCroy DCS025 is ideal for this requirement

Upper-side Sensor Voltage (Resistor) Measurement in single device buck converter with ~450Vdc bus

These signals tend to be small (1-5Vpk) and are a challenge to measure accurately when floating on a high common-mode voltage. The low voltage value and conventional HV differential probe topology makes it difficult to achieve critically accurate signal fidelity on these signals.

TELEDYNE LECROY
Everywhereyoulook™

Equipment Used in This Comparison

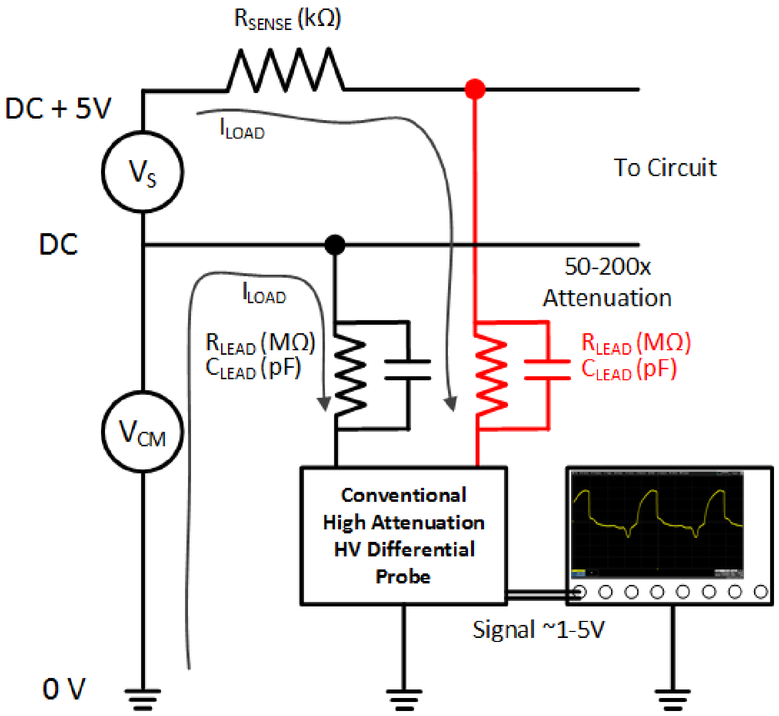
- Oscilloscopes
    - Teledyne LeCroy HDO6104 oscilloscope (4 channels, 1 GHz, 12 bits)
- Probes
    - Teledyne LeCroy HVFO Series HV Fiber Optic Probe (60 MHz)
    - Teledyne LeCroy HVD3106 HV Differential Probe (120 MHz)
- Customer-supplied Lighting Power Supply
    - Si devices
    - ~500 Vdc bus

Different Probe Topologies Provide Different Measurements

The HVFO is superior for “floating” small signal measurements

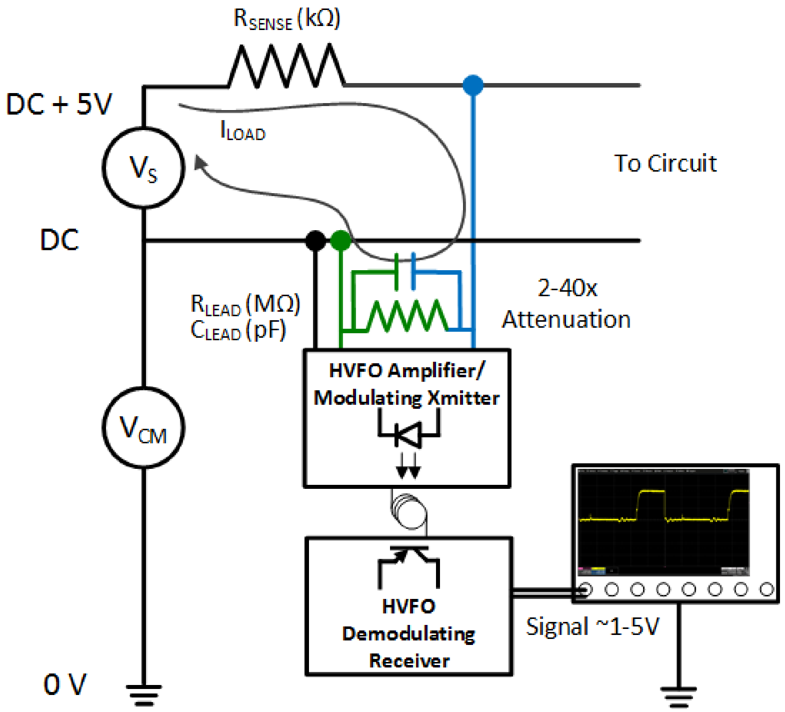
Conventional HV Differential Probe or Amplifier

e.g., Teledyne LeCroy DA1855A+DXC100A, HVD3106, ADP305; Tektronix P5205, THDP0200



HV Fiber Optic Probe

e.g., Teledyne LeCroy HVFO Series



Common-mode loading requires substantial current from circuit. CMRR is also more difficult to achieve at high frequencies.

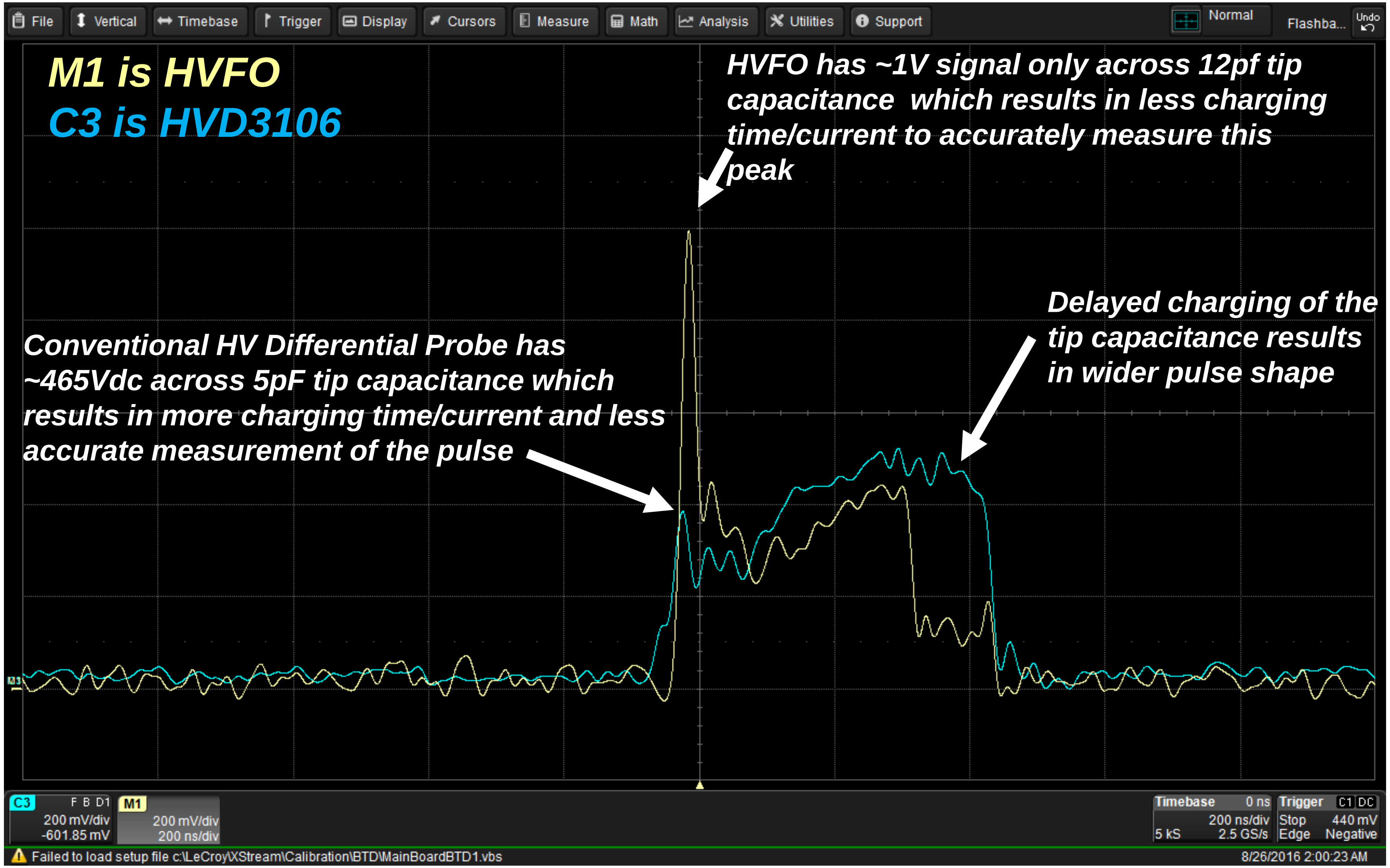
No common-mode loading reduces load current on circuit. CMRR is easier to achieve at high frequencies.

HVFO Comparisons to Other Solutions

Compared to HVD3106 measuring floating current sense resistor (~1V) signal

Different probe topologies make a big difference in the measurements

- HVFO topology has tip capacitance at measured voltage only (~1V)
- Conventional HV differential probe has tip capacitance at ~465Vdc



M1 is HVFO

C3 is HVD3106

HVFO has ~1V signal only across 12pf tip capacitance which results in less charging time/current to accurately measure this peak

Conventional HV Differential Probe has ~465Vdc across 5pF tip capacitance which results in more charging time/current and less accurate measurement of the pulse

Delayed charging of the tip capacitance results in wider pulse shape

C3 F B D1 200 mV/div -601.85 mV

M1 200 mV/div 200 ns/div

Timebase 0 ns 200 ns/div 5 kS 2.5 GS/s

Trigger C1 DC Stop 440 mV Edge Negative

⚠ Failed to load setup file c:\LeCroy\XStream\Calibration\BTD\MainBoardBTD1.vbs

8/26/2016 2:00:23 AM

Conclusions

Conventional HV differential probe and amplifier topologies are superseded by fiber optics

- A 12-bit digital oscilloscope is recommended for best accuracy (0.5%)
- Probe tip capacitances charged to full common-mode voltage can have a significant impact on the signal fidelity
  - A conventional HV differential probe topology tip capacitance is exposed to the full common-mode + sensor voltage
    - This results in a significant charge current that will likely impact signal response time and signal fidelity
  - A HV fiber-optically isolated probe tip capacitance is exposed only to the sensor voltage
    - This results in a very small charge current and a more faithful signal response and signal fidelity
- Probe loading and CMRR performance of conventional HV differential probe topologies can also have important impacts on measured signal fidelity
  - The HV fiber optic probe is more immune to these effects by design.

Power (Voltage) Rail Measurement

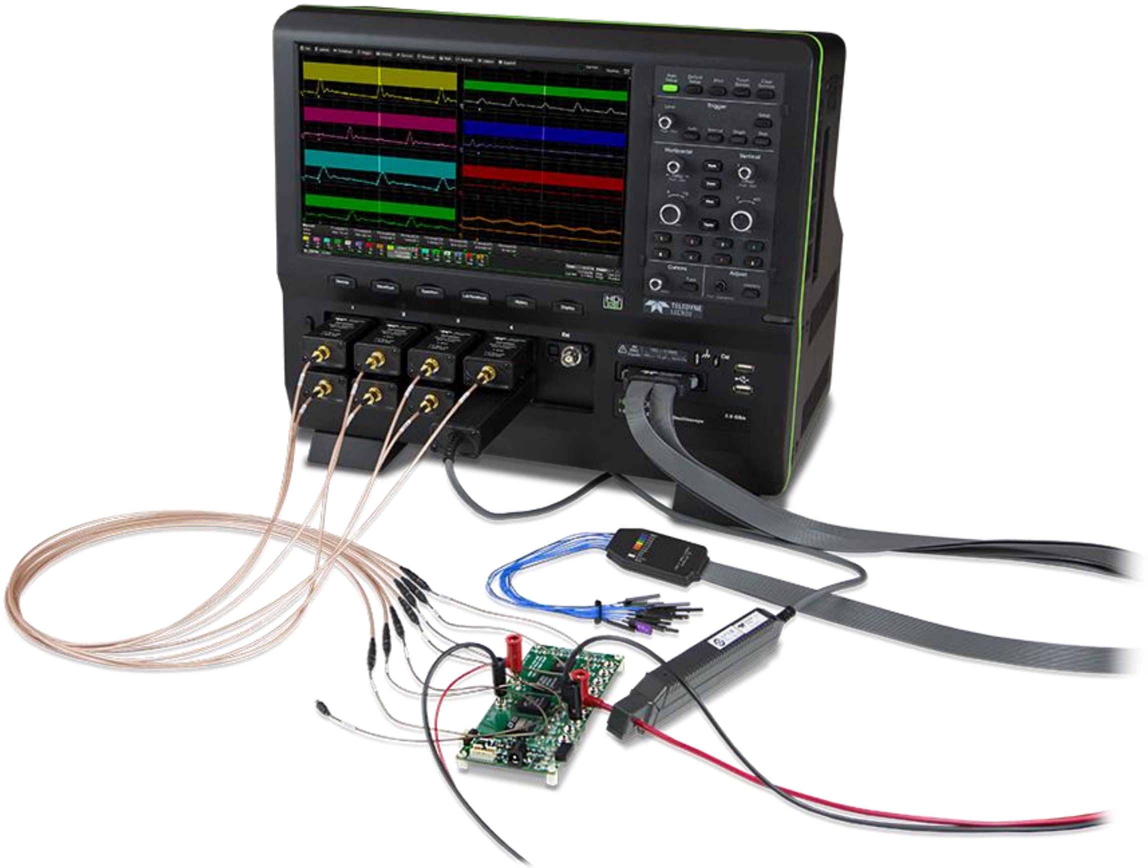
While the voltages present at the input or output of a DC-DC converter used in a power rail application generally do not exceed 50V, the requirement to measure small signal variations presents different challenges.

TELEDYNE LECROY
Everywhere**you**look™

Acquiring DC Power/Voltage Rails

There are three methods (but only one very good method)

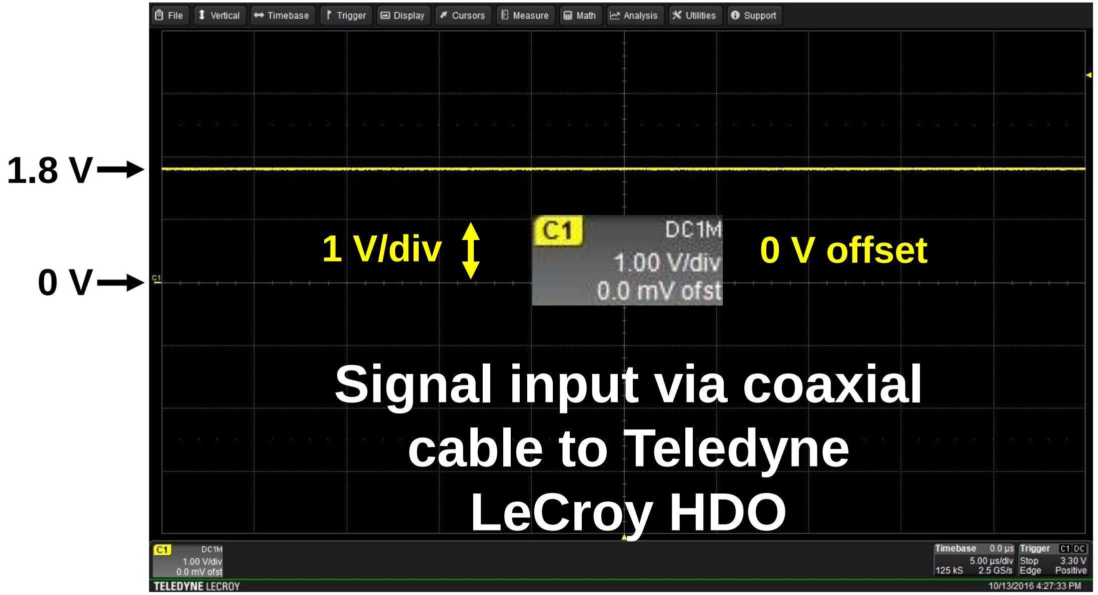
1. 50Ω Coaxial Cable Terminated at Oscilloscope Input with DC 1MΩ Coupling
    - Reasonable noise performance, but…
    - Requires high offset capability in the oscilloscope…. or requires use of a DC block (not ideal)
    - Reflections due to impedance mismatch
    - Bandwidth limitations
2. Conventional 10x Passive Probe
    - Poor noise performance
    - Bandwidth limitations
    - Maximum gain setting limitations
3. Use of Specialized Active Voltage Rail Probe
    - **Ideal solution** – lowest noise, highest bandwidth, lowest circuit loading



Acquiring DC Power/Voltage Rails

Using a coaxial cable input terminated in 1 MΩ at the oscilloscope input

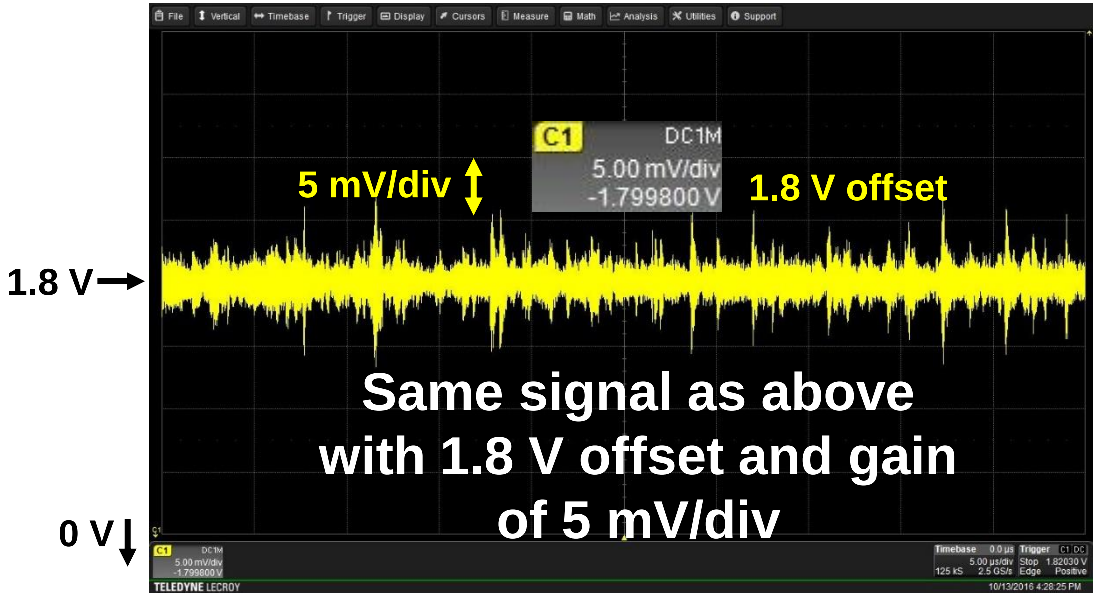
- Requires large native offset capability in the oscilloscope
  - HDO offset capability is very large (more than any other oscilloscope)
    - +/-1.6V (1mV to 4.95mV/div)
    - +/-4.0V (5mV to 9.9mV/div)
    - +/-8.0V (10mV to 19.8mV/div)
    - +/-10.0V (20mV to 1V/div)
- Or requires a DC block
  - DC blocks don't pass all AC frequencies
- 1 MΩ oscilloscope termination has limitations
  - Frequency response <1 GHz
  - Reflections due to impedance mismatch



C1 DC1M 1.00 V/div 0.0 mV ofst

Timebase 0.0 µs, 5.00 µs/div, 125 kS, 2.5 GS/s; Trigger C1 DC, Stop 3.30 V, Edge Positive

Signal input via coaxial cable to Teledyne LeCroy HDO



C1 DC1M 5.00 mV/div -1.799800 V

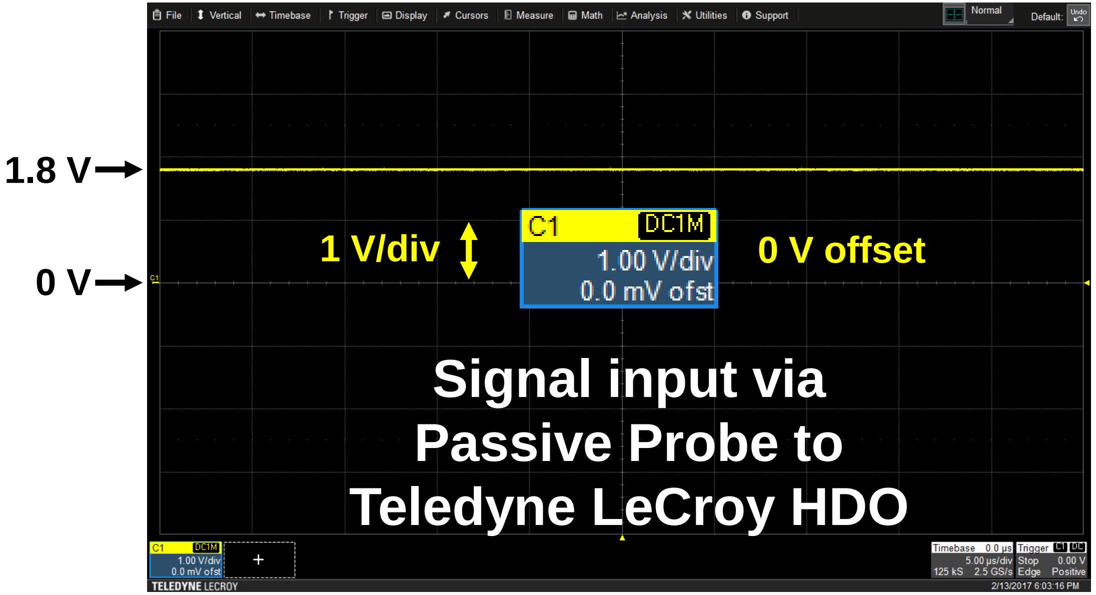
Timebase 0.0 µs, 5.00 µs/div, 125 kS, 2.5 GS/s; Trigger C1 DC, Stop 1.82030 V, Edge Positive

Same signal as above with 1.8 V offset and gain of 5 mV/div

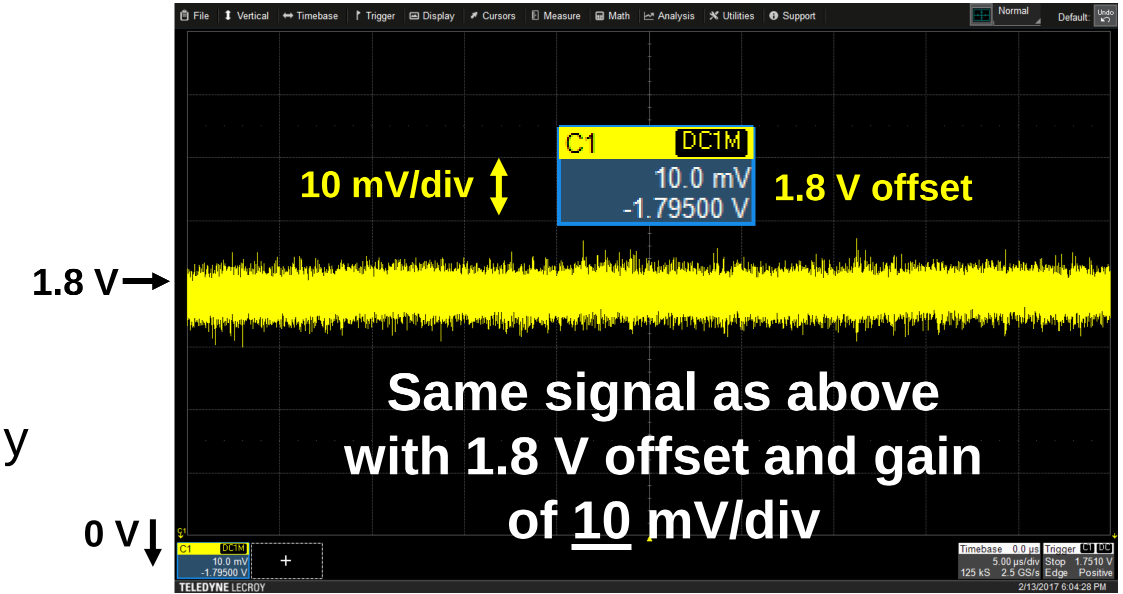
Acquiring DC Power/Voltage Rails

What's wrong with using a conventional 10x passive probe?

- Passive Probes have 10x attenuation
  - Therefore, the oscilloscope gain setting is 1/10th that of the desired gain setting
  - This has the following impacts on the measurement:
    - Increased noise
      - what is attenuated must be amplified
    - Reduced offset capabilities
      - Offset capability is determined by underlying oscilloscope gain setting
    - Higher maximum gain setting
      - i.e., an oscilloscope with a 1 mV/div maximum gain setting used with a 10x probe will have a 10 mV/div probe+oscilloscope maximum gain setting
- Additionally, the Passive Probe also has bandwidth limitations
  - 1 MΩ oscilloscope terminations limit frequency response to <1 GHz
  - Passive Probe frequency response is typically ~500 MHz (maximum)



Signal input via Passive Probe to Teledyne LeCroy HDO

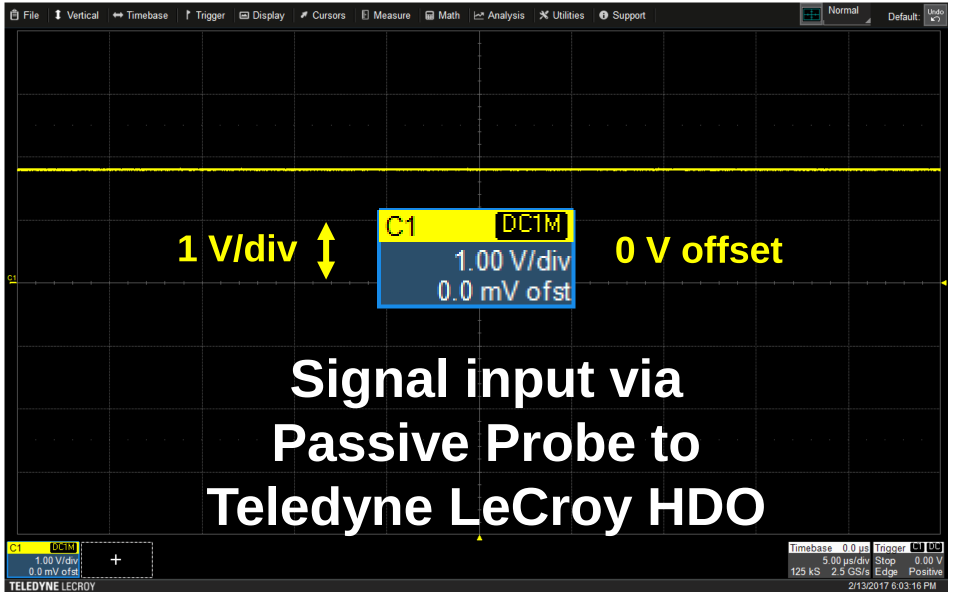


Same signal as above with 1.8 V offset and gain of 10 mV/div

Acquiring DC Power/Voltage Rails

What's wrong with using a conventional 10x passive probe? (continued)

- This is the same example as the previous slide, but with a vertical zoom of Channel 1
  - Z1 = Zoom(C1)
- Gain of vertical zoom is set to be equal to 5 mV/div
  - Creates direct comparison to previous coaxial cable input example and next (rail probe) example.



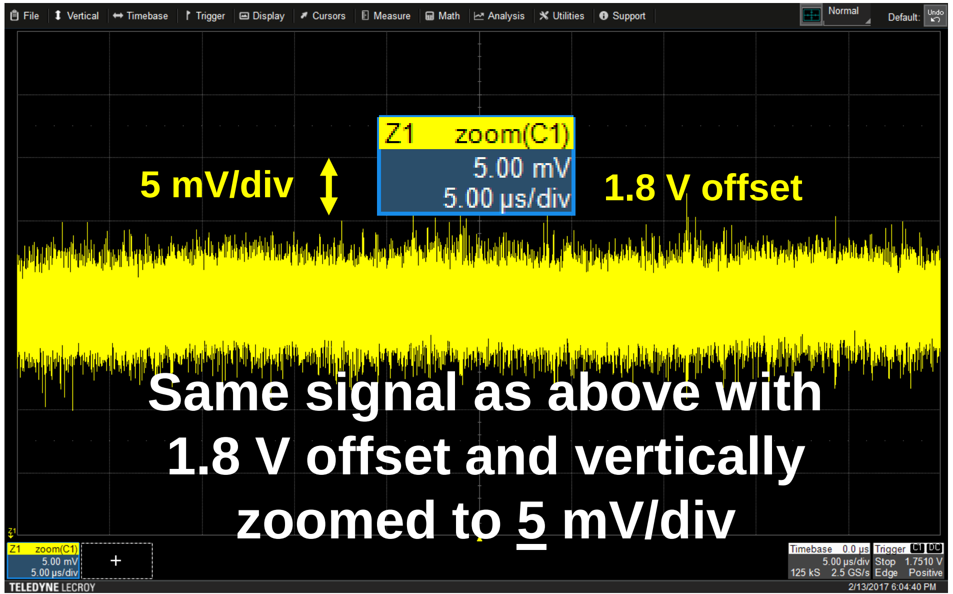
1.8 V→

0 V→

1 V/div

0 V offset

Signal input via Passive Probe to Teledyne LeCroy HDO



5 mV/div

1.8 V offset

1.8 V→

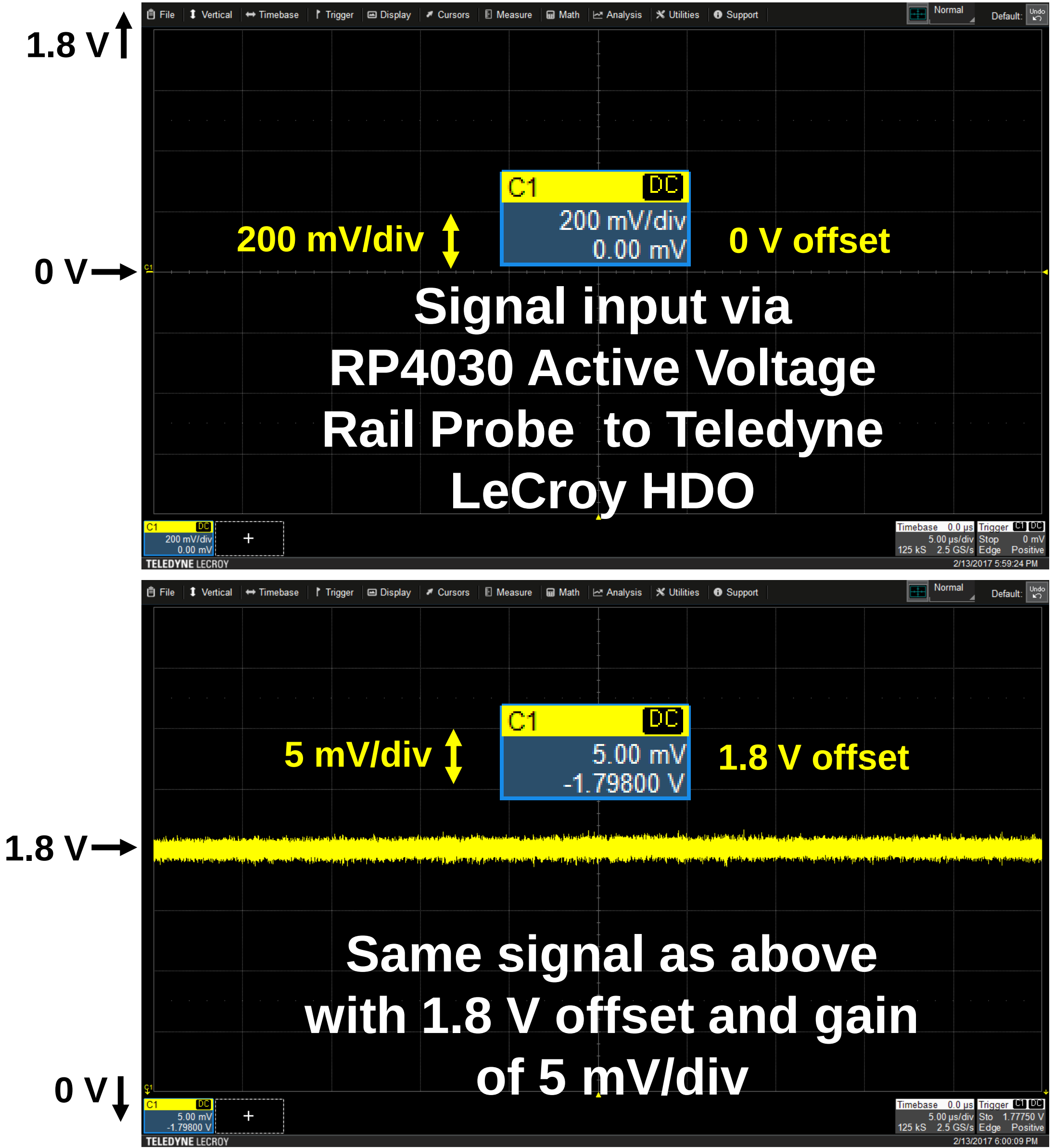
0 V↓

Same signal as above with 1.8 V offset and vertically zoomed to 5 mV/div

Acquiring DC Power/Voltage Rails

Using a specialized Rail Probe

- Provides four important capabilities for rail voltage acquisitions:
  - 50 kΩ Input Impedance
    - Very low circuit loading on the DC rail
  - 1.2x Attenuation
    - Keeps scope+probe noise very low
      - ~165 μVrms at 1 GHz and 1 mV/div (HDO)
  - +/-30V Offset built-in
    - Center a DC signal and use a high-sensitivity gain setting (e.g., 1-20 mV/div)
  - 4 GHz of bandwidth
- +/-800 mV dynamic/differential range
  - Offset *must* be applied or a >800mV signal will not appear on the oscilloscope grid
- Can also be re-purposed for full dynamic range voltage/power rail acquisitions
  - Use an SMA to BNC adapter and attach directly to BNC input with 1 MΩ coupling



200 mV/div

0 V offset

Signal input via RP4030 Active Voltage Rail Probe to Teledyne LeCroy HDO

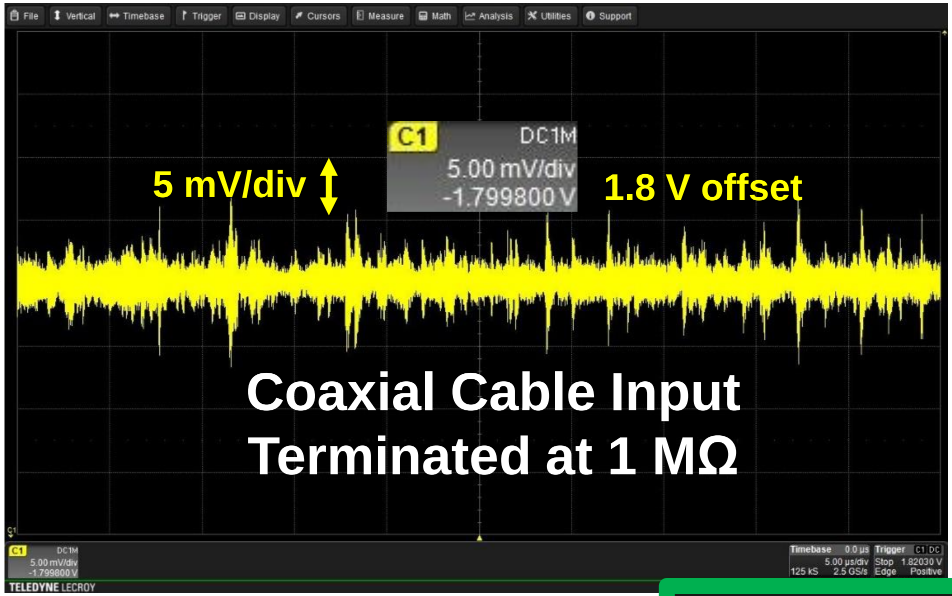
5 mV/div

1.8 V offset

Same signal as above with 1.8 V offset and gain of 5 mV/div

Acquiring DC Power/Voltage Rails

Comparison summary from previous four slides



C1 DC1M 5.00 mV/div -1.799800 V

Timebase 0.0 µs 5.00 µs/div 125 kS 2.5 GS/s

Trigger C1 DC Stop 1.82030 V Edge Positive

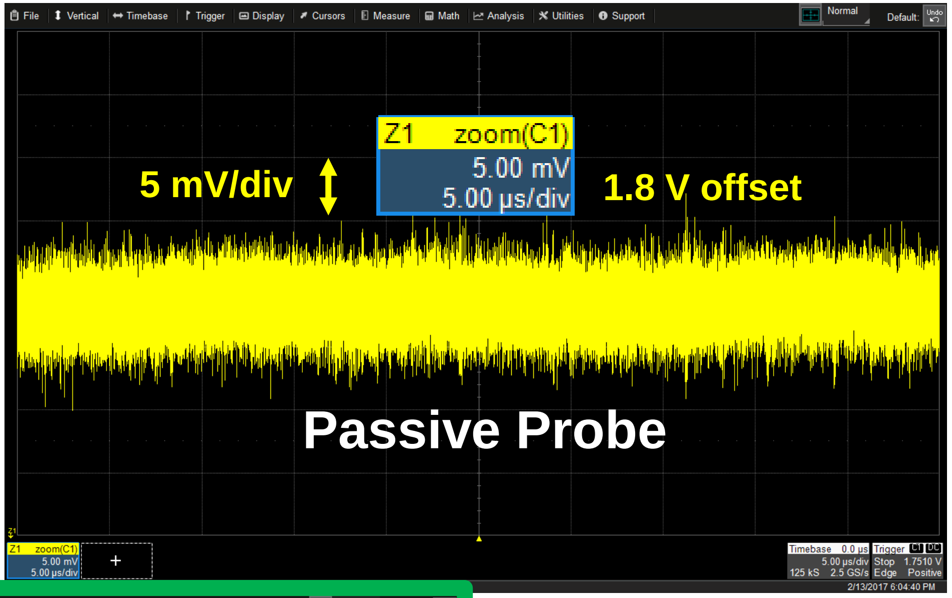
5 mV/div

1.8 V offset

1.8 V

0 V

Coaxial Cable Input Terminated at 1 MΩ



Z1 zoom(C1) 5.00 mV 5.00 µs/div

Timebase 0.0 µs 5.00 µs/div 125 kS 2.5 GS/s

Trigger C1 DC Stop 1.7510 V Edge Positive

2/13/2017 6:04:40 PM

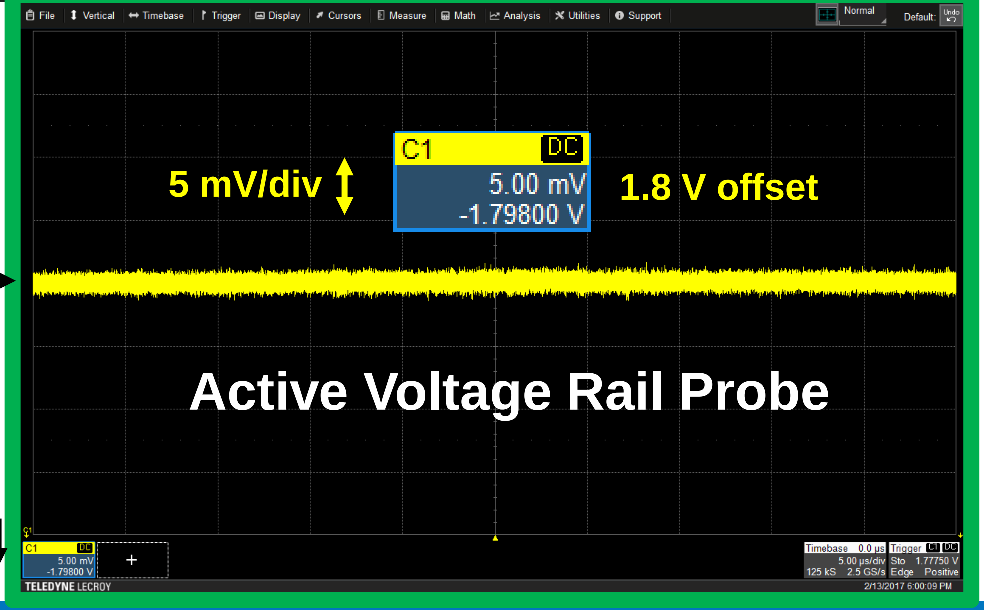
5 mV/div

1.8 V offset

1.8 V

0 V

Passive Probe



C1 DC 5.00 mV -1.79800 V

Timebase 0.0 µs 5.00 µs/div 125 kS 2.5 GS/s

Trigger C1 DC Sto 1.77750 V Edge Positive

2/13/2017 6:00:09 PM

5 mV/div

1.8 V offset

1.8 V

0 V

Active Voltage Rail Probe

Best Solution

Summary

TELEDYNE LECROY
Everywhereyoulook™

Summary

- In general, use a suitably rated HV probe UNLESS you know exactly why something that is LV rated will perform safely and suitably.

- Newer generation probes can perform a lot better than older generation probes. In many cases, you do get what you pay for.

- What you measure with a probe is not necessarily the signal you actually have in your circuit. It depends a lot on the characteristics of the circuit and the probe.

- Matching the right probe to the right application will give you the best possible result.

Short demo of Probe attenuation effect

TELEDYNE LECROY
Everywhereyoulook™

Device Characterization

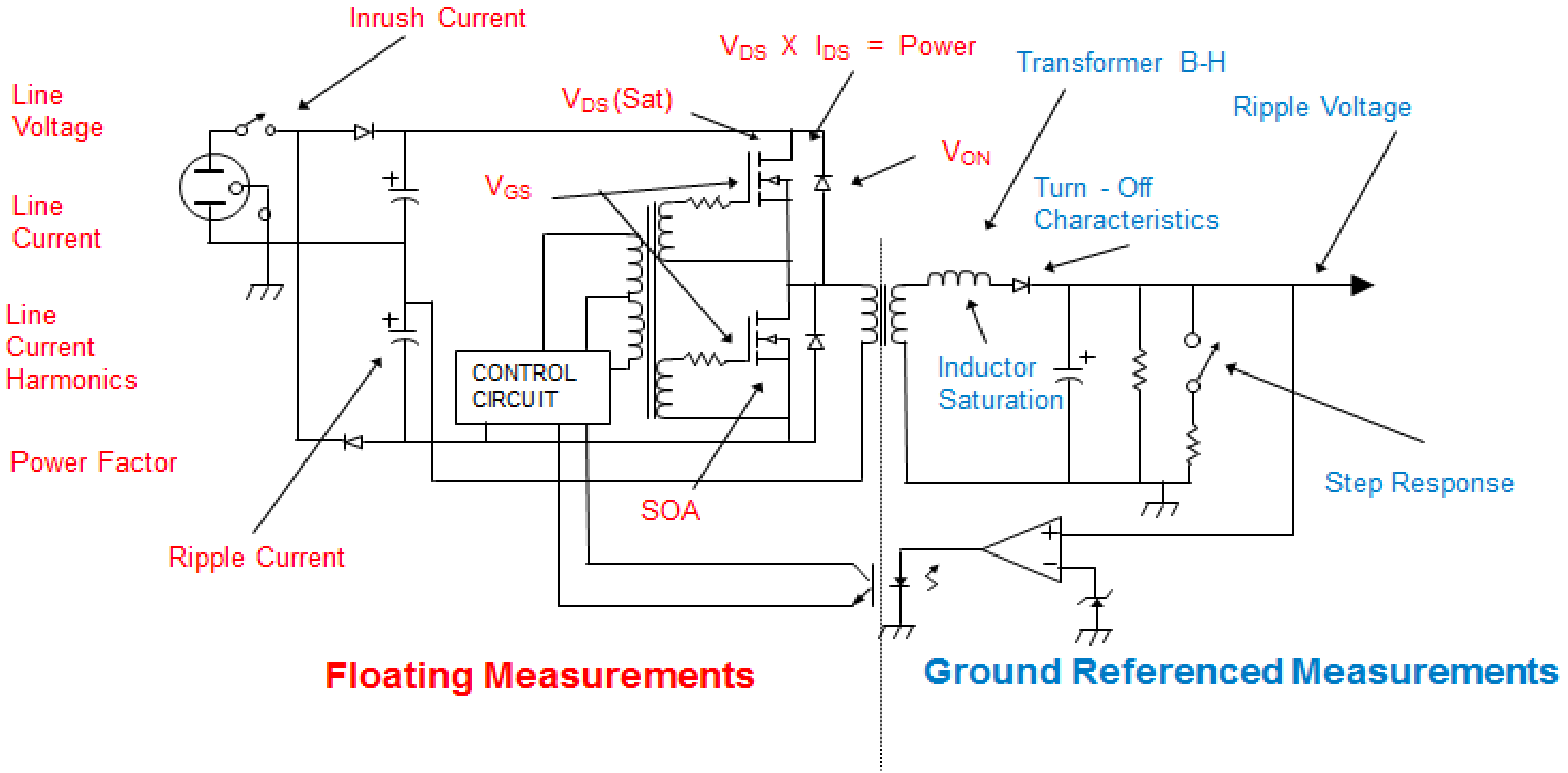
TELEDYNE LECROY
Everywhereyoulook™

Which measurements

- Device Measurements and Analysis
  - Measuring how much energy is being lost in the transition as the output transistor turns on and off, as well as how much is lost in conduction.
  - Improving Reliability of the Power Supply by monitoring device Stress Limits
  - Improving Rds(on) Measurement Accuracy
  - B-H Curve
  - Speed of a power device’s rate of change (dv/dt, di/dt) during turn-on and turn-off.

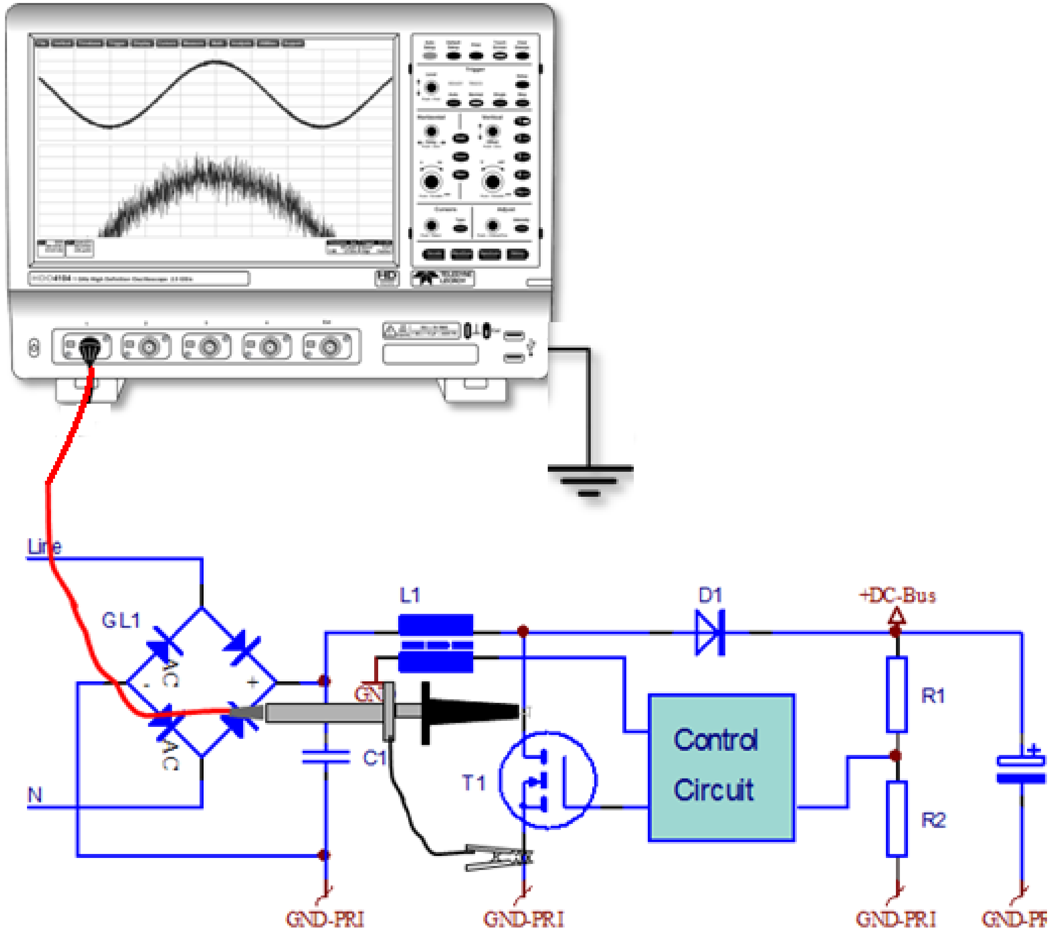
- Control Loop Analysis.
  - Measuring Feedback Loop Response in Power Systems

Which measurements



Examples of Power Measurements

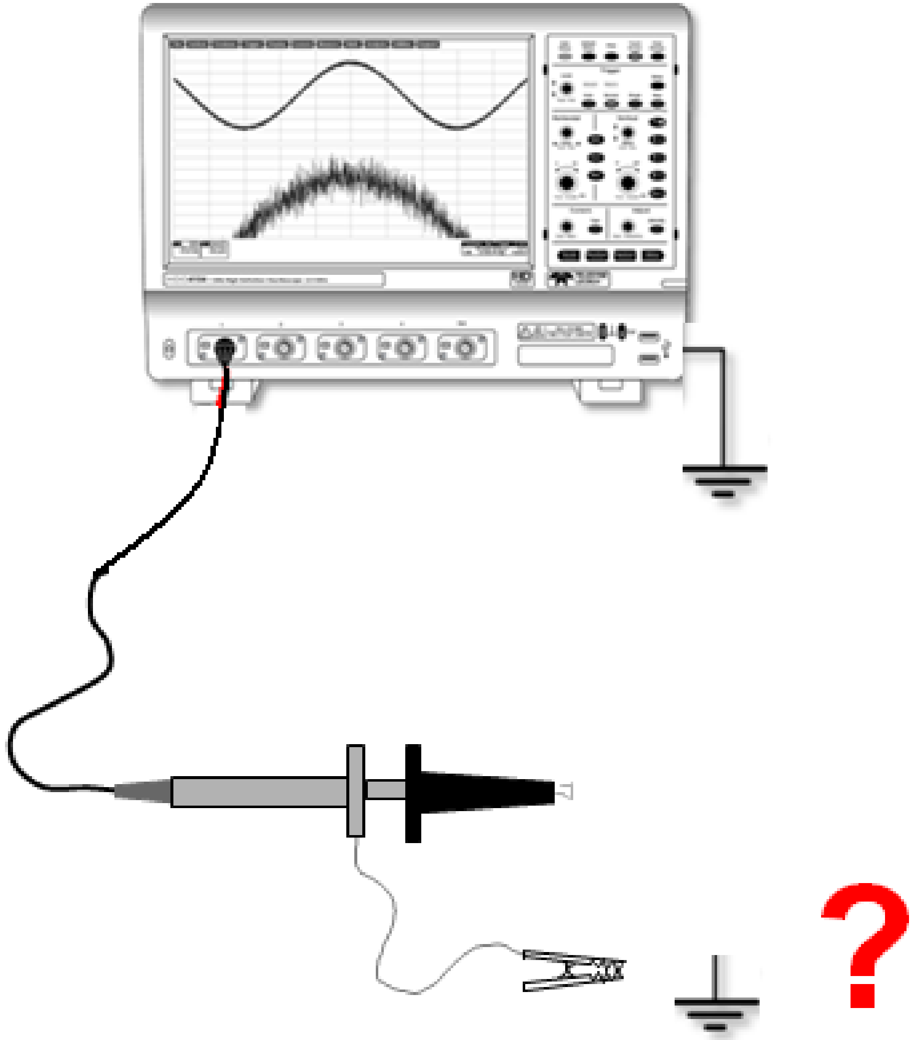
Ground Referenced Measurements



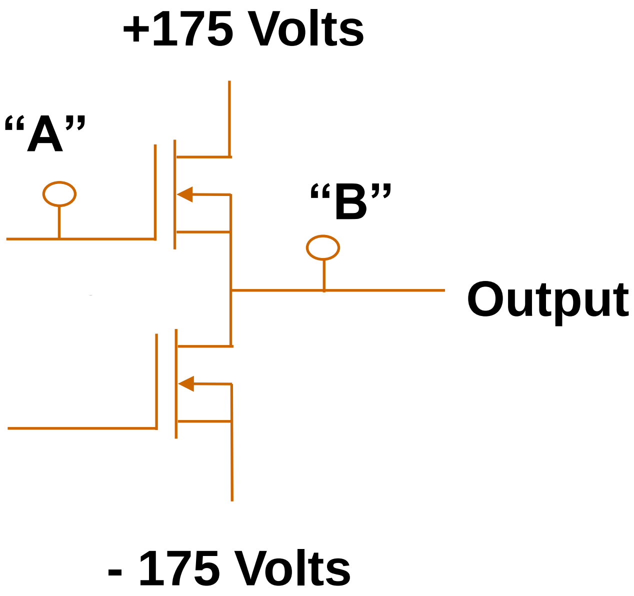
General Purpose oscilloscope can only measure “Ground Referenced” Voltage

While this configuration is adequate for many routine measurements, there are several applications where this restriction degrades the measurement quality, or prevents the measurement from being made altogether.

Non-ground Referenced Measurements

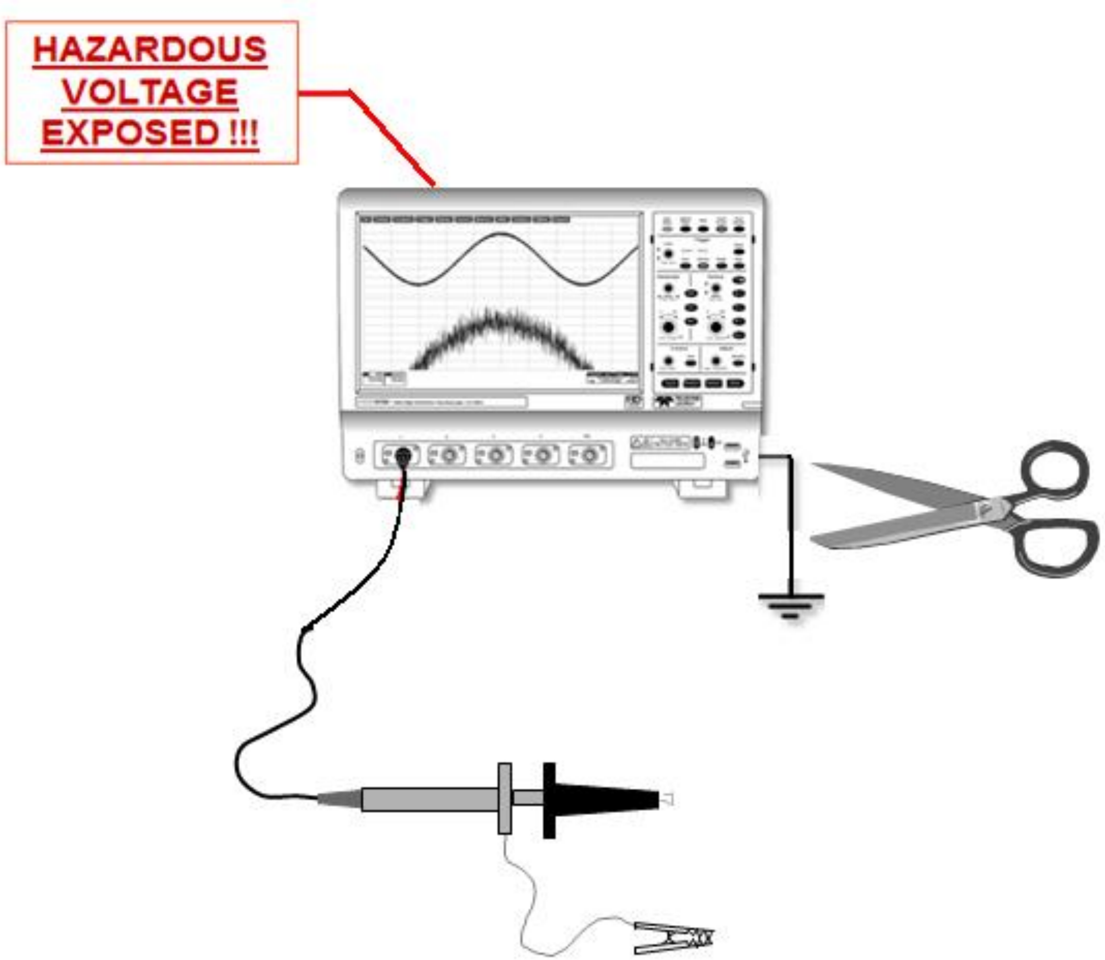


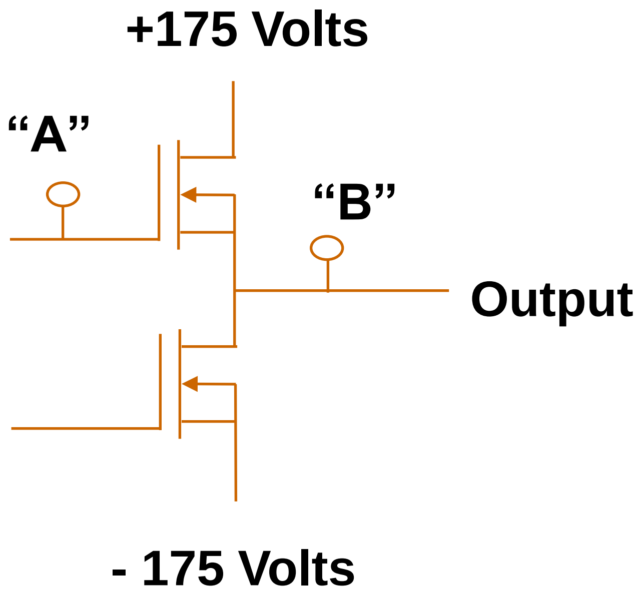
Upper V_{GS} Measurement Required between Point "A" and "B"



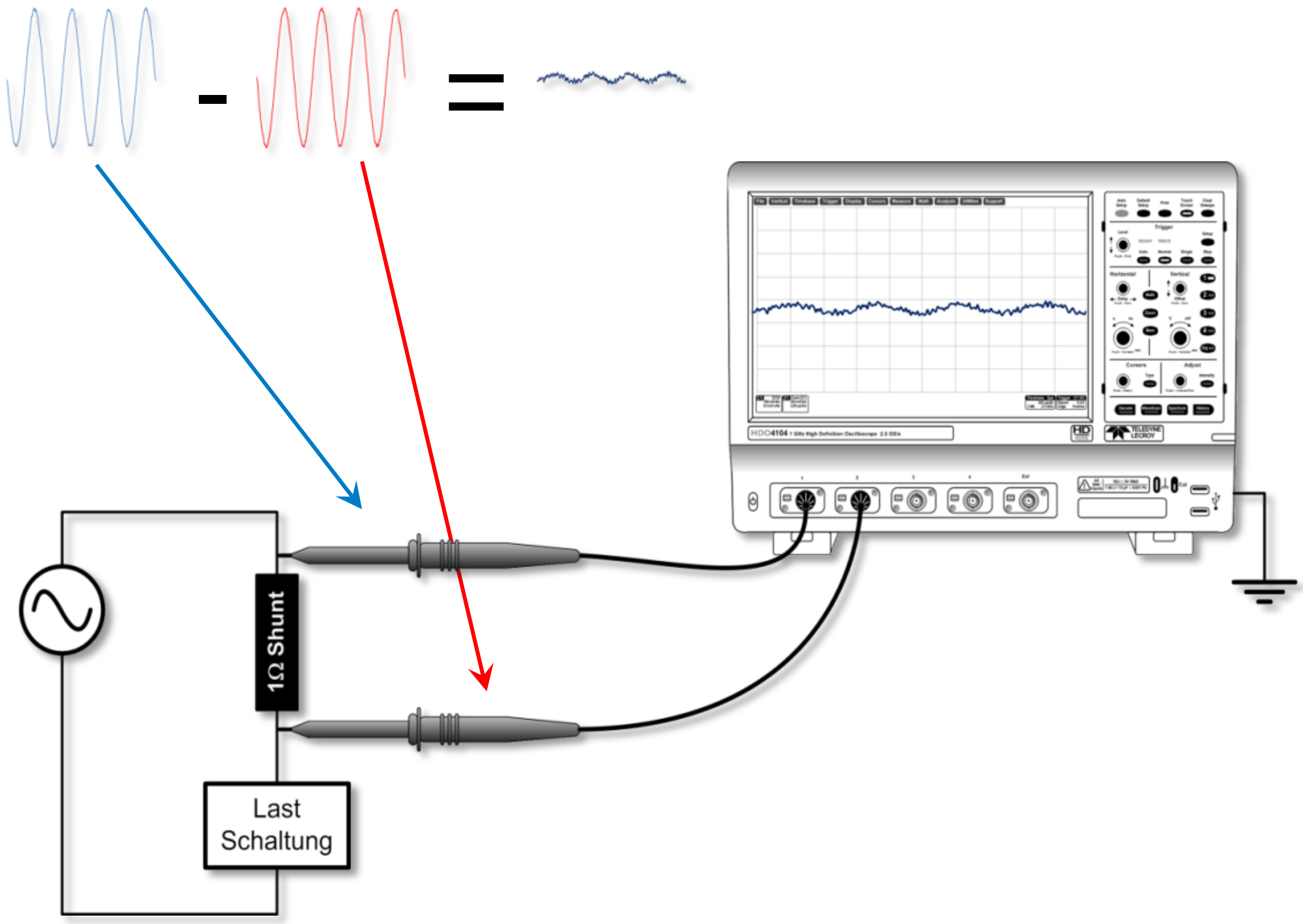
Non-ground Referenced Measurements-Cutting the scope’s ground

- “No problem, I’ll just float the scope!”





Non-ground Referenced Measurements- “Channel A” Minus “Channel B” Method



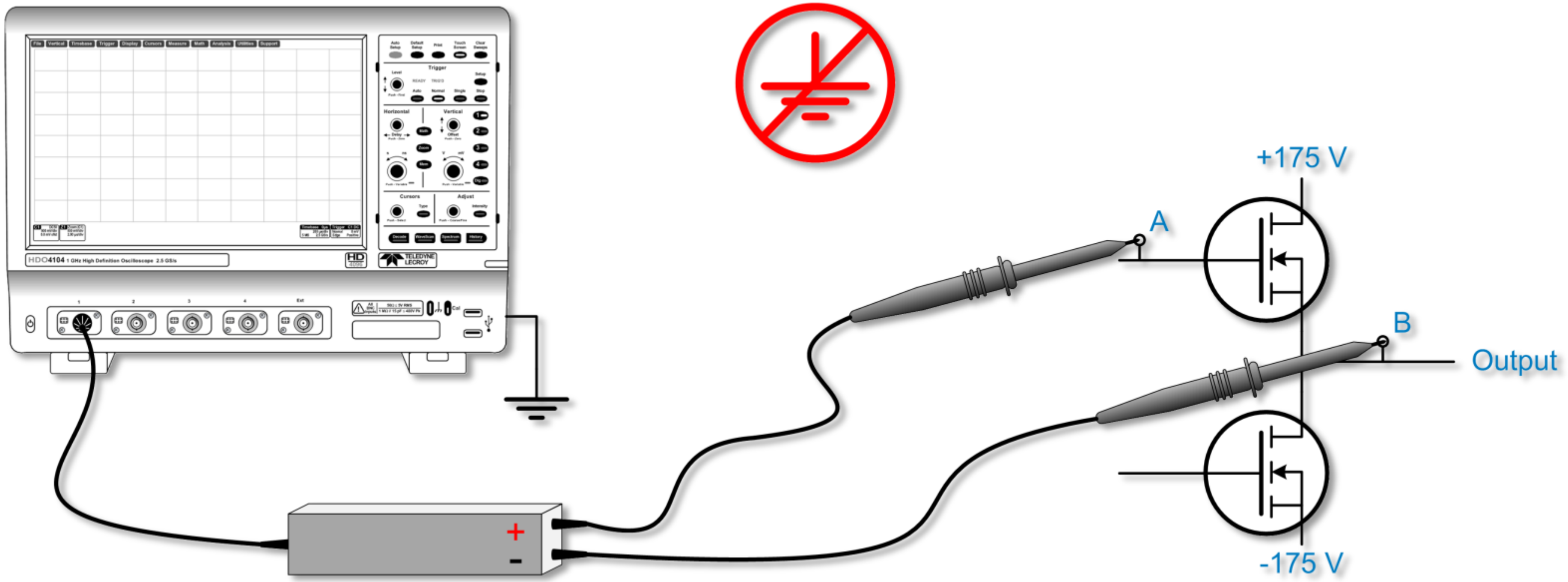
Both **A** & **B** must be on the screen.
This determines the maximum sensitivity the oscilloscope can be set at.

Limited channel accuracy matching severely limits the ability to “Reject” the signal that is “Common” to both **A** & **B**

Channel A – Channel B in not adequate when the common Mode Voltage >> Voltage being measured

Because oscilloscope amplifiers and passive probes are not precisely matched for higher frequency gain (or attenuation), CMRR above a few KHz will be very low

Non-ground Referenced Measurements- True Differential



Important Characteristics

- Common Mode Range
- Common Mode Rejection Ratio
- True Balanced Inputs

  Load “sees” high impedance

  Lead parasitic effects cancel out!

Differential probes are not all equals

Differential Mode and Common Mode

Differential amplifiers amplify the voltage difference which appears between the + input and – input. This voltage is referred to as the Differential Mode. The voltage component which is referenced to earth and is identical on both inputs is rejected by the amplifier.
This voltage is referred to as the Common Mode voltage and can be expressed as:

$$V_{CM} = (V_{+Input} + V_{-Input})/2$$

Differential Mode Range and Common Mode Range

Differential Mode Range is the maximum signal which can be applied between the + and – inputs without overloading the amplifier, which otherwise would result in clipping or distorting the waveform measured by the oscilloscope.
Common Mode Range is the maximum voltage with respect to earth ground which can be applied to either input. Exceeding the common mode range can result in unpredictable measurements. Because the Common Mode signal is normally rejected and not displayed on the oscilloscope, you must be careful to avoid accidentally exceeding the common mode range.

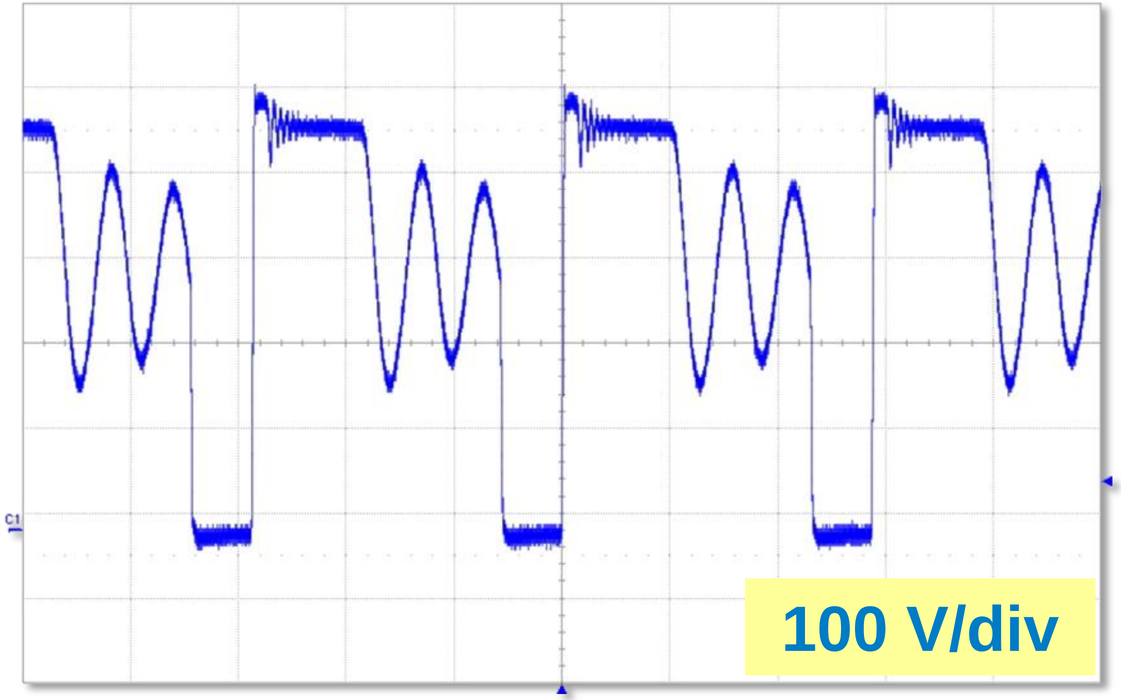
Common Mode Rejection Ratio

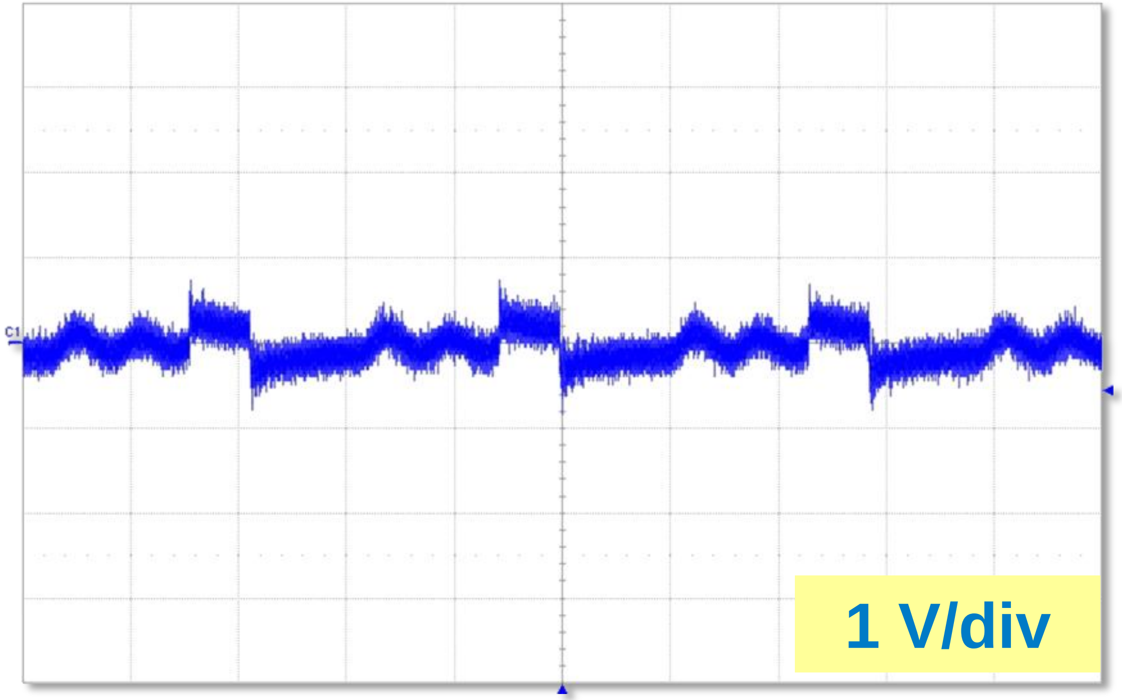
The ideal differential amplifier would amplify only the differential mode voltage component and reject all of the common mode voltage component. Real differential amplifiers are not perfect and a small portion of the common mode voltage component appears at the output. Common Mode Rejection Ratio (CMRR) is the measure of how much the amplifier rejects the common mode voltage component.

Common Mode Rejection Ratio

'Flyback'-Topology
Drain-Source Measurement

Remaining common mode in a high performance differential amplifier





Accuracy and Overdrive Recovery issues

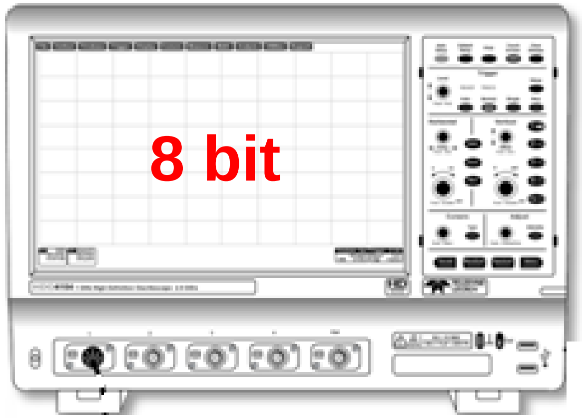
How do we make fine granularity measurements on high voltage signals, such as overshoot, undershoot, ripple saturation voltage, RdsON,..

A common technique is to use the channel knob of the oscilloscope to <u>increase the vertical sensitivity</u> and <u>offset</u> the signal under test.

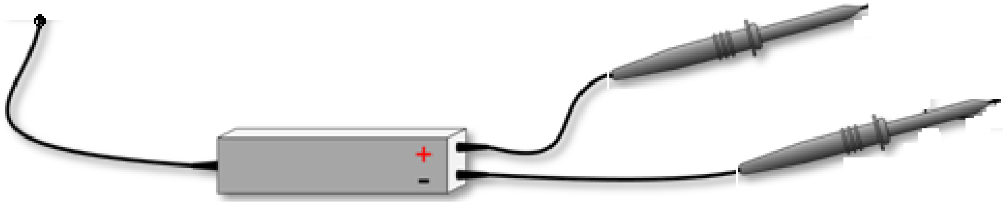
Whereas this does increase the vertical measurement granularity, and you would intuitively believe that it improves the accuracy, it also overloads the oscilloscope input channel amplifier.

Offsetting and expanding the signal over a wider range will drive major portions of the signal off-screen and beyond the dynamic range of the oscilloscope's input amplifier. Therefore the oscilloscope input amplifier can be driven into saturation causing waveform distortions and artefacts.

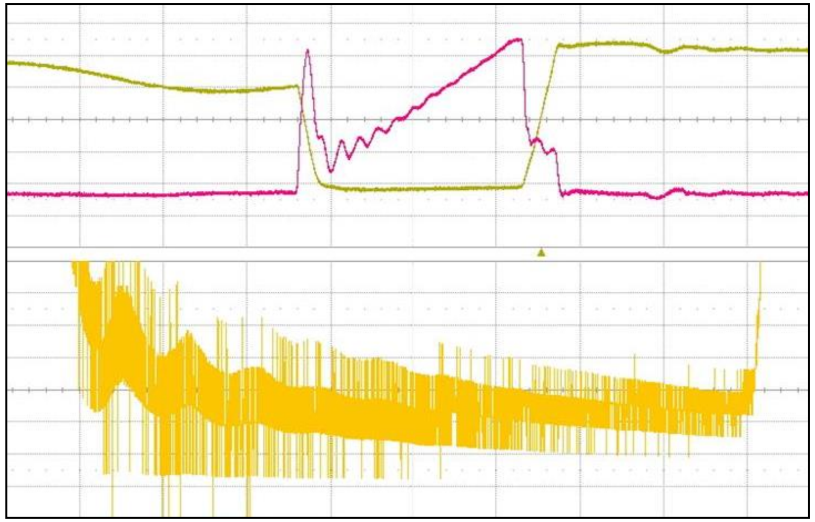
Accuracy and Overdrive Recovery issues



+



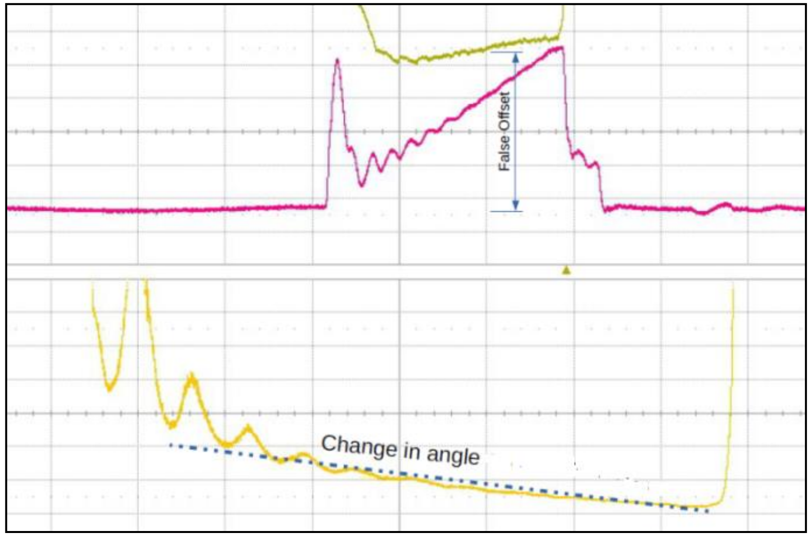
Differential probe



- No offset
- Not increased vertical sensitivity
- Only Zoom

⇩

- Poor accuracy
- High quantization error

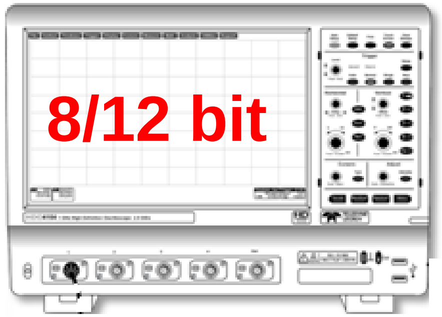


- Offset
- Increased vertical sensitivity

⇩

- Oscilloscope Input into Saturation
- Waveform distorted

Accuracy and Overdrive Recovery issues



+

External Fast Recovery Differential Clipping Amplifier

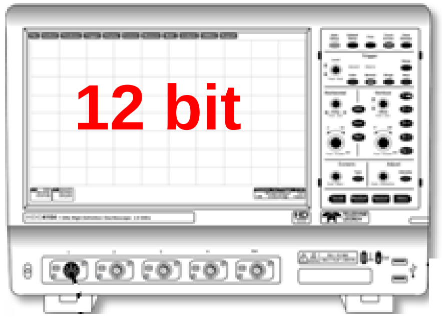
8 bit A/D Converter = 2^8 = 256 Levels

Precision Offset Generator

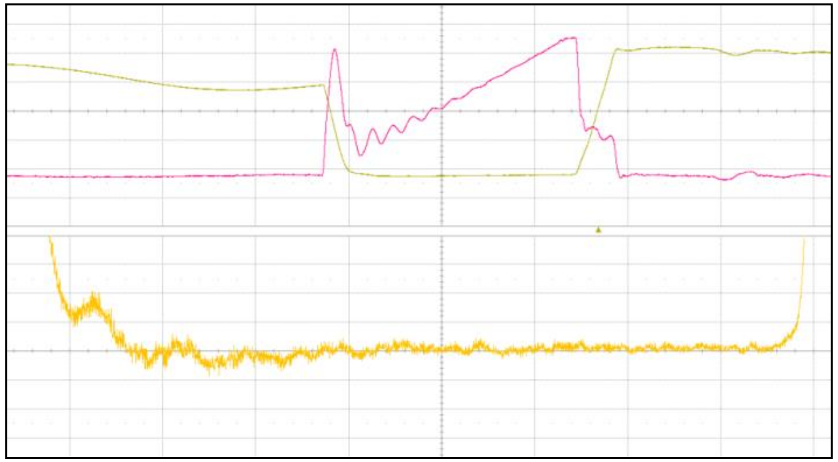
We don’t need to use the oscilloscope offset because the differential amplifier DA1855A features a built-in Precision Offset Generator.

Fast overdrive recovery

This unique capability allows the amplifier to make measurements that would normally be limited by oscilloscope input saturation because of poor overdrive recovery.



12 bit A/D Converter = 2^{12} = 4096 Levels

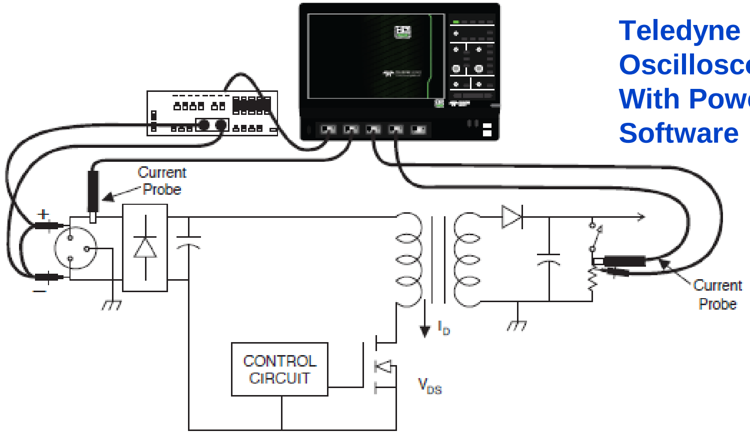


- No offset needed
- Not increased vertical sensitivity needed
- Only Zoom

⇩

- High accuracy
- High vertical resolution (12 bit = 4096 level)
- Waveform details

Performance Analysis : Efficiency

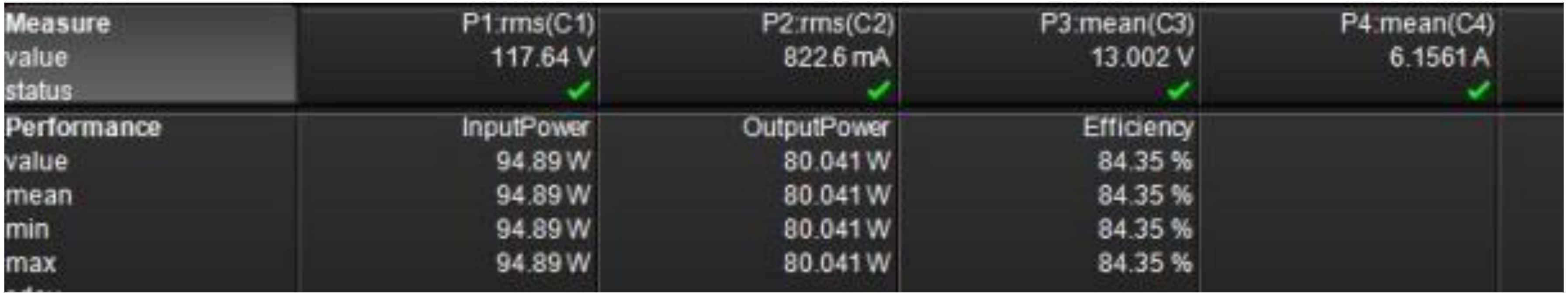


Teledyne LeCroy Oscilloscope HDO4000 With Power Analyzer Software

$$\text{Efficiency} = \frac{Pout}{Pin} = \frac{Vout\ x\ Iout}{Vin\ x\ Iin}$$

Measure	P1:rms(C1)	P2:rms(C2)	P3:mean(C3)	P4:mean(C4)	P5:---	P6:---	P7:apwr(C1,C2)	P8:---
value	117.64 V	822.6 mA	13.002 V	6.1561 A				
status	✓	✓	✓	✓				
Performance	InputPower	OutputPower	Efficiency					
value	94.89 W	80.041 W	84.35 %					
mean	94.89 W	80.041 W	84.35 %					
min	94.89 W	80.041 W	84.35 %					
max	94.89 W	80.041 W	84.35 %					
sdev	---	---	---					
num	1	1	1					
status	✓	✓	✓					

C1 BwL DC 60 V/div 49.60 V ofst
C2 BwL DC1M 455 mA/div -370.00 mA
C3 BwL DC1M 2.55 V/div -8.5500 V
C4 BwL DC1M 1.20 A/div -2.5000 A
InputPower 50.0 W/div 20.0 ms/div
OutputPower 500 mW/div 20.0 ms/div
Timebase 0.0 ms 20.0 ms/div 2.5 MS 12.5 MS/s
Trigger C1 DC Stop -8.6 V Edge Positive
TELEDYNE LECROY 2/26/2014 12:07:00 PM

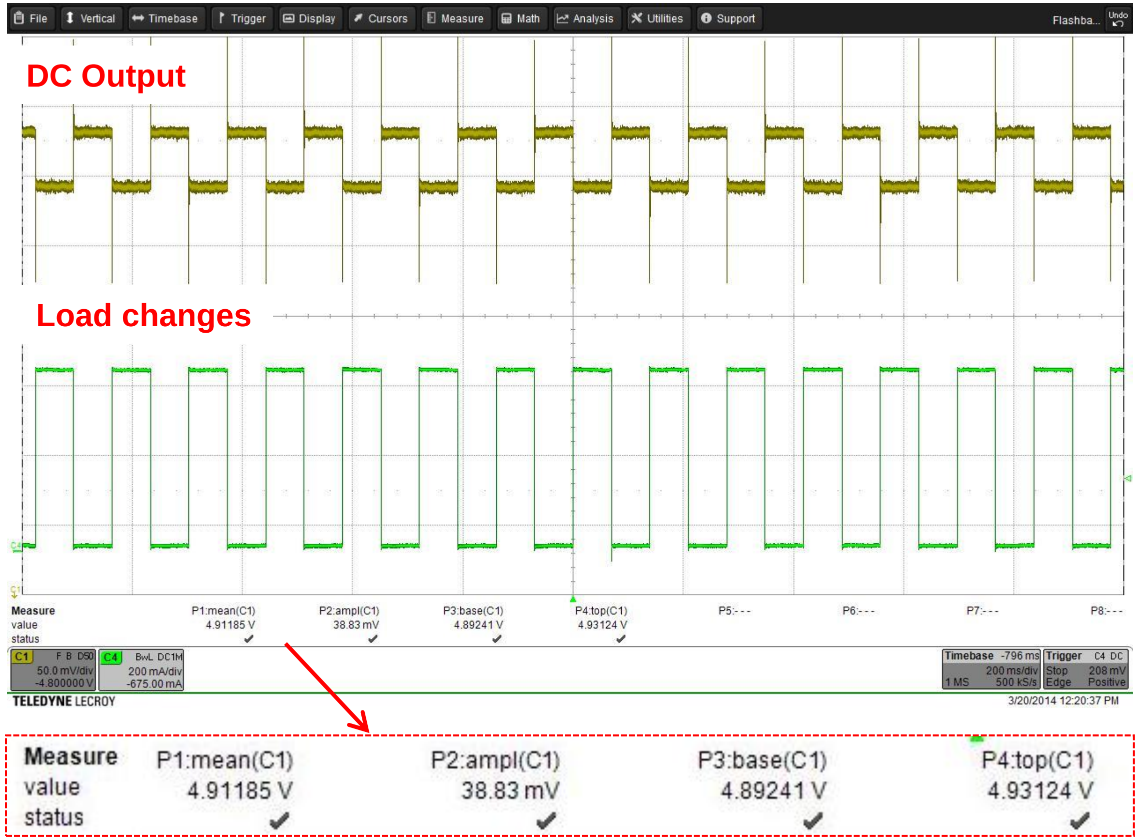


Measure	P1:rms(C1)	P2:rms(C2)	P3:mean(C3)	P4:mean(C4)
value	117.64 V	822.6 mA	13.002 V	6.1561 A
status	✓	✓	✓	✓
Performance	InputPower	OutputPower	Efficiency	
value	94.89 W	80.041 W	84.35 %	
mean	94.89 W	80.041 W	84.35 %	
min	94.89 W	80.041 W	84.35 %	
max	94.89 W	80.041 W	84.35 %	

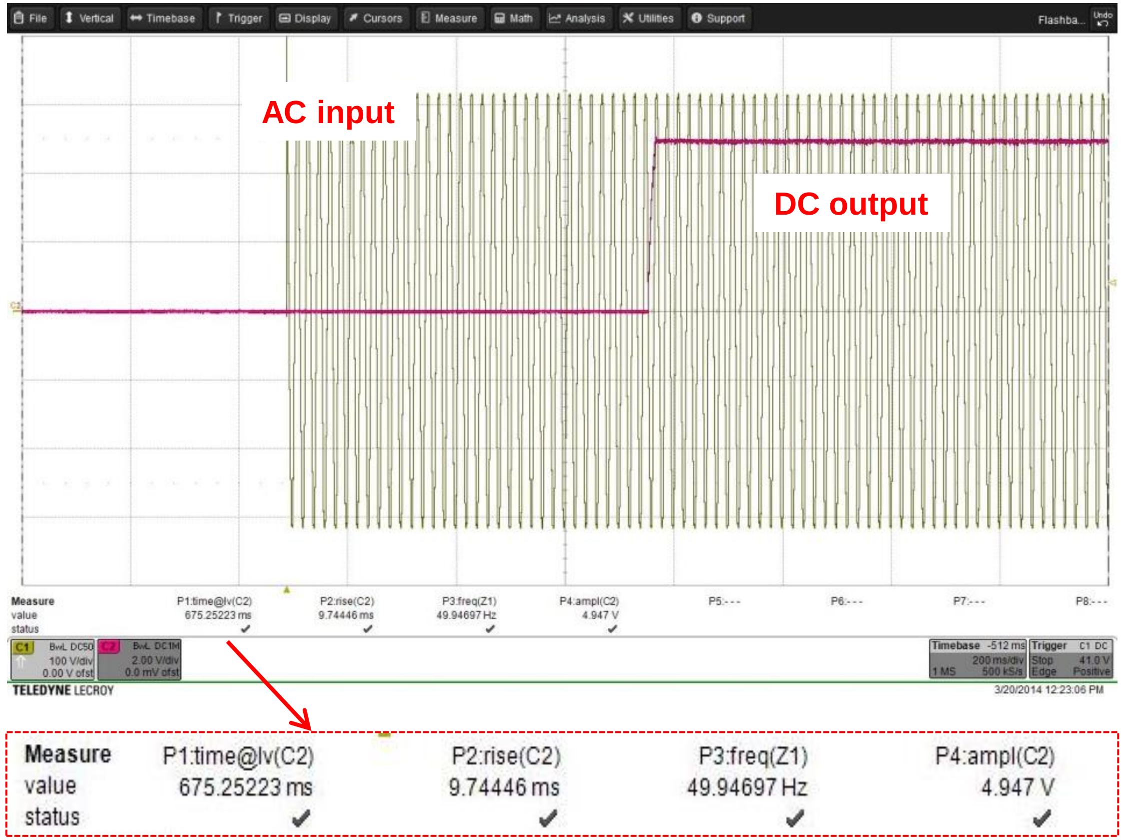
Performance Analysis : Load regulation, Turn-on/off Time

- **Load regulation** is the capability to maintain a constant voltage (or current) level on the output channel despite changes in the supply's load

Turn-on/off analysis measures the time between when power is initially switched on until the dc output reaches steady output voltage and vice versa.



```
Measure   P1:mean(C1)   P2:ampl(C1)   P3:base(C1)   P4:top(C1)   P5:---   P6:---   P7:---   P8:---
value     4.91185 V     38.83 mV      4.89241 V     4.93124 V
status    ✔             ✔             ✔             ✔

C1  F B D50   50.0 mV/div  -4.800000 V
C4  BwL DC1M  200 mA/div   -675.00 mA
Timebase -796 ms  200 ms/div  1 MS  500 kS/s
Trigger C4 DC  Stop  208 mV  Edge  Positive
3/20/2014 12:20:37 PM
```

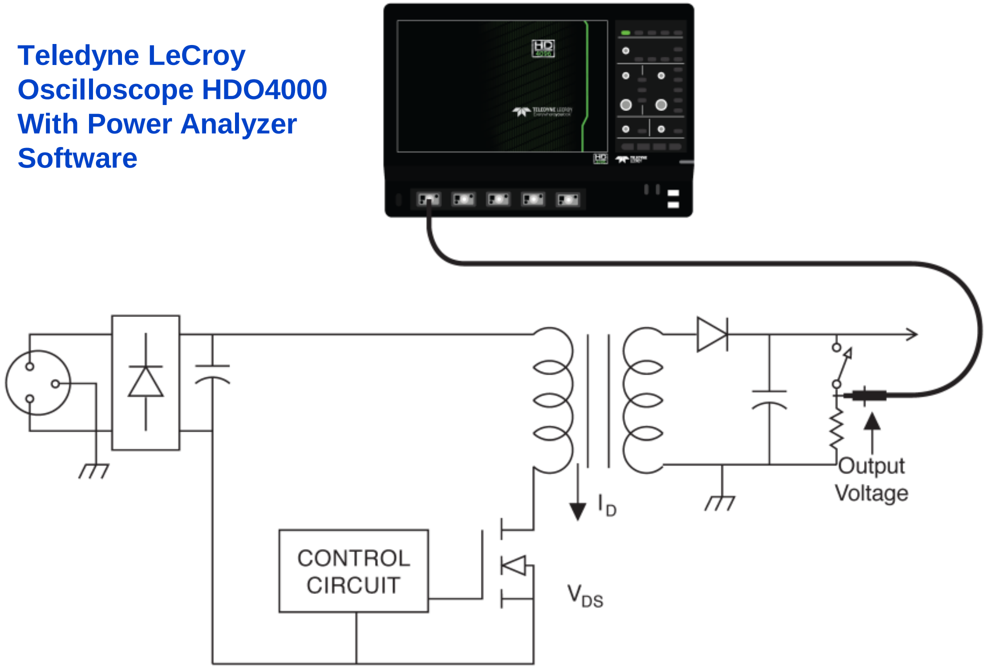


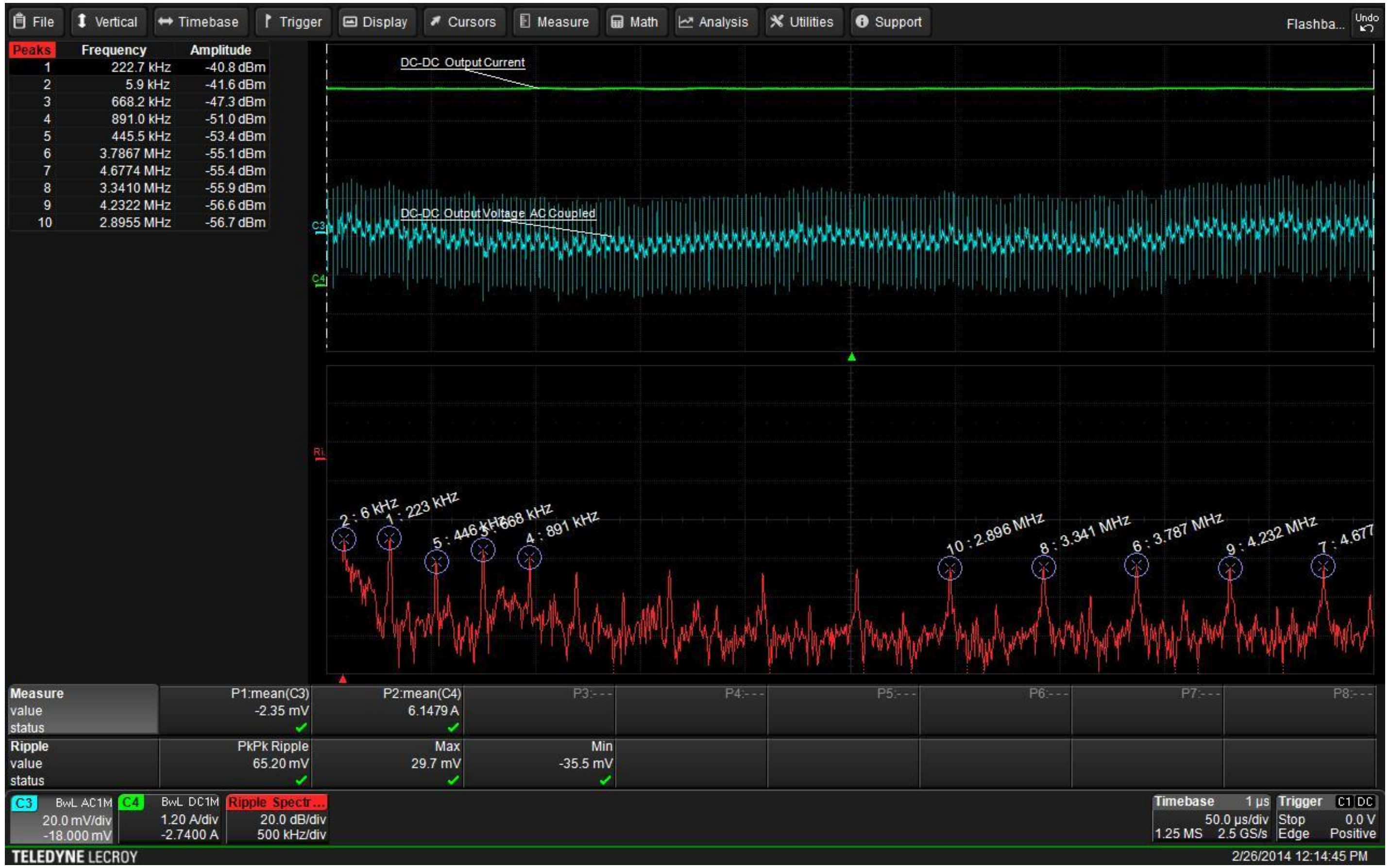
```
Measure   P1:time@lv(C2)   P2:rise(C2)   P3:freq(Z1)   P4:ampl(C2)   P5:---   P6:---   P7:---   P8:---
value     675.25223 ms     9.74446 ms    49.94697 Hz   4.947 V
status    ✔                ✔             ✔             ✔

C1  BwL DC50  100 V/div   0.00 V ofst
C2  BwL DC1M  2.00 V/div  0.0 mV ofst
Timebase -512 ms  200 ms/div  1 MS  500 kS/s
Trigger C1 DC  Stop  41.0 V  Edge  Positive
3/20/2014 12:23:06 PM
```

Performance Analysis : Output ripple and frequency analysis

- **Output ripple** : small unwanted AC components of the DC Output voltage
- Measurements include **the peak to peak ripple**, the **maximum and minimum values** of ripple, and the **spectral content** of ripple are provided

Teledyne LeCroy Oscilloscope HDO4000 With Power Analyzer Software





Peaks	Frequency	Amplitude
1	222.7 kHz	-40.8 dBm
2	5.9 kHz	-41.6 dBm
3	668.2 kHz	-47.3 dBm
4	891.0 kHz	-51.0 dBm
5	445.5 kHz	-53.4 dBm
6	3.7867 MHz	-55.1 dBm
7	4.6774 MHz	-55.4 dBm
8	3.3410 MHz	-55.9 dBm
9	4.2322 MHz	-56.6 dBm
10	2.8955 MHz	-56.7 dBm

Measure	P1:mean(C3)	P2:mean(C4)	P3:---	P4:---	P5:---	P6:---	P7:---	P8:---
value	-2.35 mV	6.1479 A						
status	✓	✓						

Ripple	PkPk Ripple	Max	Min
value	65.20 mV	29.7 mV	-35.5 mV
status	✓	✓	✓

C3 BwL AC1M 20.0 mV/div -18.000 mV

C4 BwL DC1M 1.20 A/div -2.7400 A

Ripple Spectr... 20.0 dB/div 500 kHz/div

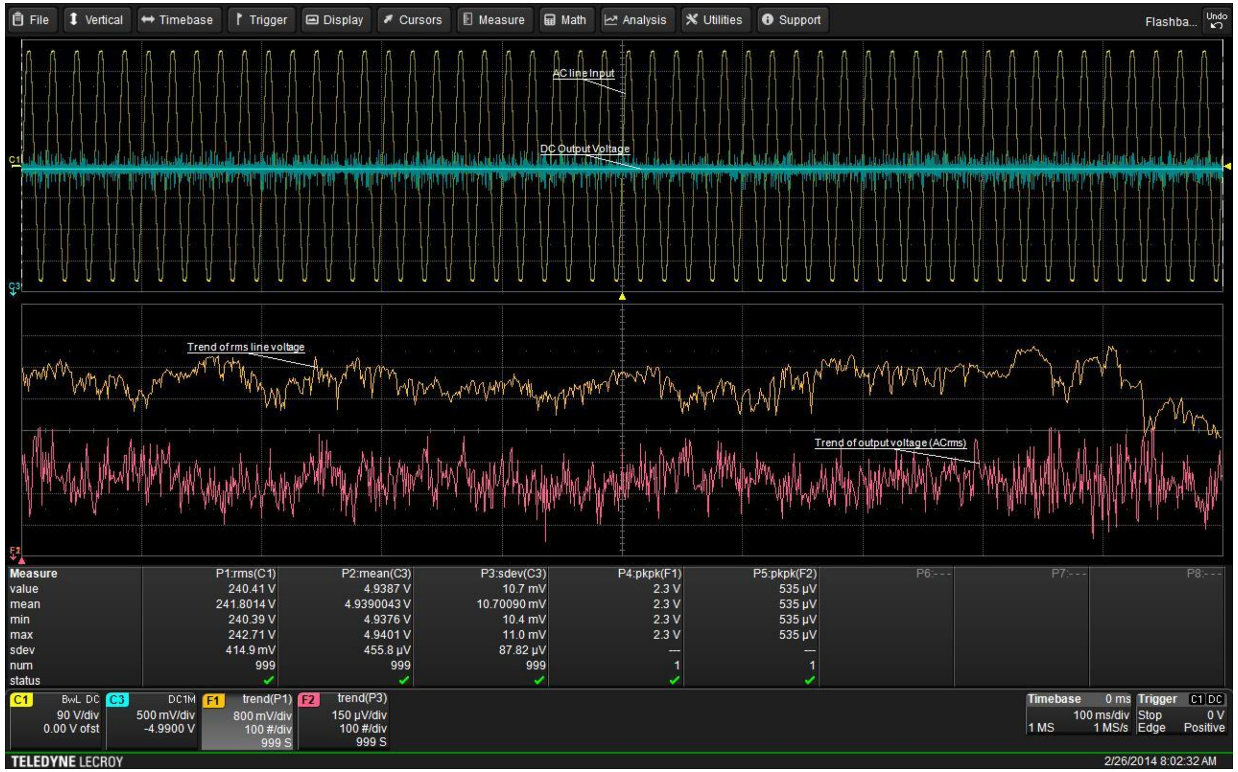
Timebase 1 µs 50.0 µs/div 1.25 MS 2.5 GS/s

Trigger C1 DC Stop 0.0 V Edge Positive

2/26/2014 12:14:45 PM

Performance Analysis : Power Line monitoring

- The Digital oscilloscope HDO4000 can be used for monitoring long term processes such as power supply input and output voltages.
- The **Trend function** is a waveform composed of a series of parameter measurement values presented in the order they were taken.



Measure	P1:rms(C1)	P2:mean(C3)	P3:sdev(C3)	P4:pkpk(F1)	P5:pkpk(F2)	P6:---	P7:---	P8:---
value	240.41 V	4.9387 V	10.7 mV	2.3 V	535 µV			
mean	241.8014 V	4.9390043 V	10.70090 mV	2.3 V	535 µV			
min	240.39 V	4.9376 V	10.4 mV	2.3 V	535 µV			
max	242.71 V	4.9401 V	11.0 mV	2.3 V	535 µV			
sdev	414.9 mV	455.8 µV	87.82 µV	---	---			
num	999	999	999	1	1			
status	✓	✓	✓	✓	✓			

AC input Voltage (Yellow trace) and DC output (Blue trace) are acquired and the trend functions are used to monitor their variations during a long acquisition, 17 min.

The parameters measure these variations

The Trend function is an ideal data logging tool, for applications like this, taking place over seconds, minutes, hours, or days.

Device Measurement – Power Losses

Device	TurnOn	Conduction	TurnOff	OffState	AllZones	SwitchFreq
value	4.8213 µJ	1.2035 µJ	8.0182 µJ	23.8 nJ	14.1575 µJ	140.022 kHz
mean	4.88683 µJ	1.15436 µJ	8.011493 µJ	16.677 nJ	14.07420 µJ	139.92983 kHz
min	4.8213 µJ	1.0592 µJ	8.0081 µJ	9.6 nJ	13.9909 µJ	139.838 kHz
max	4.9252 µJ	1.2035 µJ	8.0182 µJ	23.8 nJ	14.1575 µJ	140.022 kHz
sdev	46.56 nJ	67.30 nJ	4.758 nJ	7.102 nJ	83.26 nJ	92.06 Hz
num	3	3	3	2	2	2
status	✓	✓	✓	✓	✓	✓

C1 BwL DC1M 50.0 V/div -173.00 V

C2 DQ B D1 650 mA/div -1.9700 A

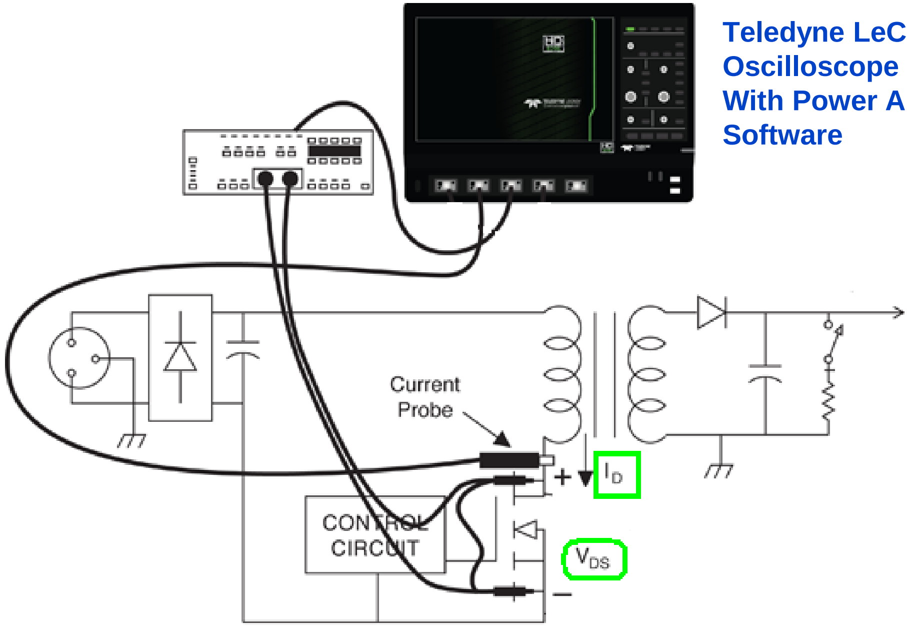
DevicePower 100 W/div 2.00 µs/div

Timebase 0.00 µs 2.00 µs/div 50 kS 2.5 GS/s

Trigger C1 DC Stop 154.5 V Edge Positive

2/27/2014 9:39:02 AM

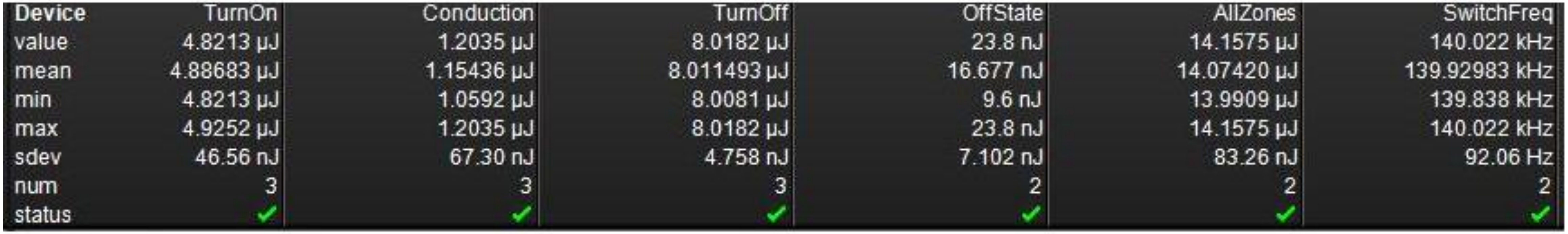
Power-supply efficiency is a measure of how much energy is wasted between the unit's input and output. **Turn-on, turn-off, and conduction losses** within the supply are converted into heat, which can compromise the health and longevity of the power supply itself as well as that of the system it powers. Thus, regardless of a power supply's efficiency, it's important to know how much energy is being lost in the transition as the output transistor turns on and off, as well as how much is lost in conduction.



Teledyne LeCroy Oscilloscope HDO4000 With Power Analyzer Software

Device Measurement – Power Losses

- Areas of power loss are automatically detected, measured and annotated across many cycles
- Color coded overlay highlights all areas of power losses on both power and voltage traces
- Measurements are automatically calculated and displayed with proper power terminology
- No manual gating of switching losses required



Device	TurnOn	Conduction	TurnOff	OffState	AllZones	SwitchFreq
value	4.8213 µJ	1.2035 µJ	8.0182 µJ	23.8 nJ	14.1575 µJ	140.022 kHz
mean	4.88683 µJ	1.15436 µJ	8.011493 µJ	16.677 nJ	14.07420 µJ	139.92983 kHz
min	4.8213 µJ	1.0592 µJ	8.0081 µJ	9.6 nJ	13.9909 µJ	139.838 kHz
max	4.9252 µJ	1.2035 µJ	8.0182 µJ	23.8 nJ	14.1575 µJ	140.022 kHz
sdev	46.56 nJ	67.30 nJ	4.758 nJ	7.102 nJ	83.26 nJ	92.06 Hz
num	3	3	3	2	2	2
status	✓	✓	✓	✓	✓	✓

Power Supply Efficiency

- User setup:
  - Input voltage and current
  - output voltage and current
- Analysis results:
  - input and output power waveforms
  - Parameters of input and output power, and efficiency
- Typically power efficiency measurements are done manually using power supply, multimeter, electronic load
- New feature in Power Analyzer option automates these measurements
- Measurement accuracy defined by scope and probes, approximately 3% - 4% when using 12-bit oscilloscope

Measure	P1:mean(C1)	P2:mean(C2)	P3:mean(C3)	P4:mean(C4)	P5:rms(C1)	P6:rms(C2)	P7:apwr(C1,C2)	P8:- - -
value	-108 mV	50.3 mA	13.002 V	6.1561 A	117.64 V	822.6 mA		
status	✓	✓	✓	✓	✓	✓		

Performance	InputPower	OutputPower	Efficiency
value	94.89 W	80.041 W	84.35 %
mean	94.8865 W	80.04086 W	84.3543 %
min	94.89 W	80.041 W	84.35 %
max	94.89 W	80.041 W	84.35 %
sdev	---	---	---
num	1	1	1
status	✓	✓	✓

C1 BwL AC1M	C2 BwL DC1M	C3 BwL DC1M	C4 BwL DC1M	InputPower	OutputPower
60 V/div	455 mA/div	2.55 V/div	1.20 A/div	50.0 W/div	5.00 W/div
49.60 V ofst	-370.00 mA	-8.5500 V	-2.5000 A	20.0 ms/div	20.0 ms/div

Timebase 0.0 ms 20.0 ms/div 2.5 MS 12.5 MS/s
Trigger C1 DC Stop -8.6 V Edge Positive

☑ Enable
Input Voltage C1
Input Current C2
Output Voltage C3
Output Current C4

Computes Efficiency of power conversion by computing power on output (mean of voltage*current) divided by power of input

☑ On
☐ Hist Icons

Improving Reliability by Monitoring Device Stress Limits.
Safe Operating Area (SOA)

- Every switching device has a maximum voltage, current and power specified by the device manufacturer, displayed on its technical application note. Reliability of the power supply is dependent on not exceeding these limits.
- Safe Operating Area (SOA) plot help to determine if the device exceeds its maximum voltage, current, or power ratings.
- Easily display SOA for comparison to component specs
- Power loss annotator identifies losses on all cycles in long captures
- Loss measurements calculated across all cycles with statistics

Device	TurnOn	Conduction	TurnOff	OffState	AllZones	SwitchFreq
value	5.71 W	413 mW	24.36 W	56 mW	398 mW	61.398 kHz
status	✓	✓	✓	✓	✓	✓

C1 BwL DC 50.0 V/div -112.50 V

C2 DQ B D1 100 mA/div -250.00 mA

XY X:Vo Y:Cu 100 mA/div 50.0 V/div

DevicePower 10.0 W/div 50.0 µs/div

Timebase 0 µs 50.0 µs/div 1.25 MS 2.5 GS/s

Trigger C2 DC Stop 379 mV Edge Positive

TELEDYNE LECROY 2/26/2014 11:52:14 AM

Improving Rds(on) Measurements accuracy

This is the measurement of the conduction resistance of the switching FET or IGBT.
The overall calculation accuracy depends on accurate current and voltage measurements, and therefore fine granularity in the oscilloscope vertical resolution.

Benefits of 12 bit Oscilloscope vs 8 bit Oscilloscope
The enhanced resolution is relatively straight forward, an 8 bit A/D converter has 2^8 discrete levels, therefore 256 levels, whereas a 12 bit A/D converter has 2^12 discrete levels, therefore 4096 levels. Quite a difference!

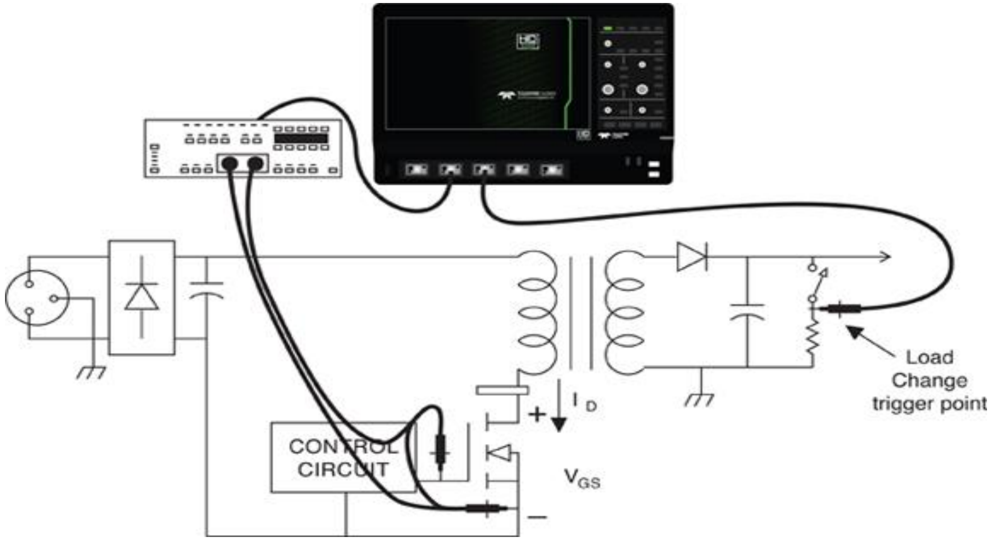
Measure	P1:pkpk(C1)	P2:pkpk(C2)	P3:min(F1)	P4:min(C1)	P5:- - -	P6:- - -	P7:- - -	P8:- - -
value	448.8 V	494.4 mA	6 Ω	1.3 V				
status	✓	✓	✓	✓				

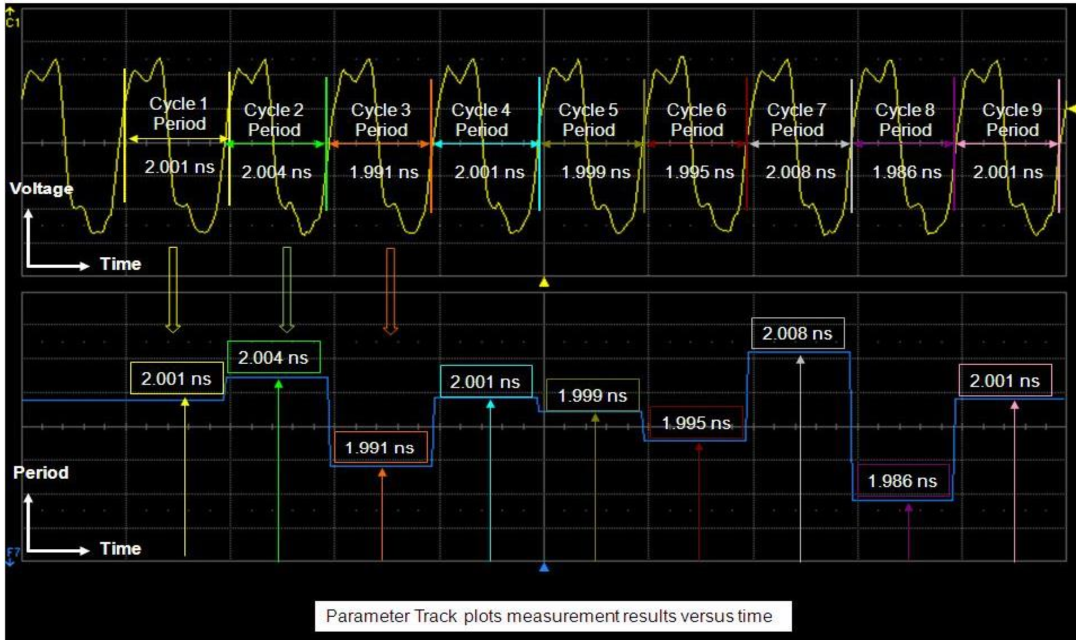
12 bit Oscilloscope

8 bit Oscilloscope

Control Loop Analysis – Feedback Loop Response

- Every power supply has a feedback loop that monitors the output voltage or current and keeps the device's on-time appropriate to the load.
- Output regulation is achieved by modulating the amount of energy transferred in each cycle. The most common method is Pulse Width Modulation (PWM) but other methods, such as frequency modulation, are also used.
- Modulation analysis can be used to characterize power supply stability under load changes, line changes, soft-starts, dropouts and short circuits.
- We can see on a cycle-by-cycle basis, the behaviour of the entire control loop by demodulating the PWM signal and extracting the underlying modulation signal in order to assess the correct tracking and linearity in PWM regulator/controller.





Parameter Track plots measurement results versus time

Control Loop Analysis – Feedback Loop Response

ControlLoop	Frequency	Period	Width	Duty
value	140.9435 kHz	7.09504 µs	2.39332 µs	33.727 %
status	⚠	⚠	⚠	⚠

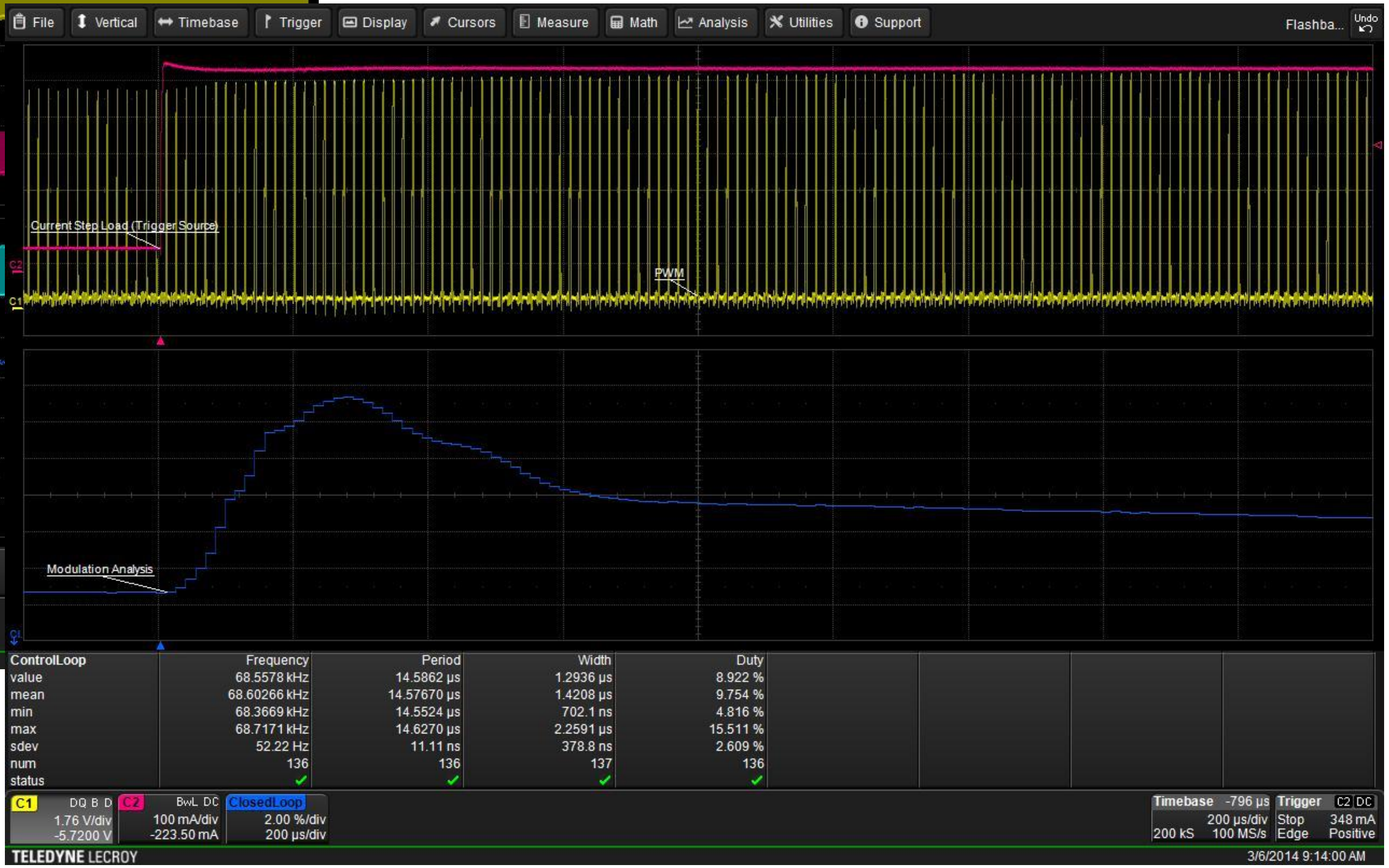
C1 BwL DC1M 200 V/div 140.00 V

C2 BwL DC1M 4.25 A/div -13.4000 A

C3 DC1M 10.0 V/div 21.840 V

ClosedLoop 10.0 %/div 1.00 ms/div

Measuring the start-up in a switched mode power supply



ControlLoop	Frequency	Period	Width	Duty
value	68.5578 kHz	14.5862 µs	1.2936 µs	8.922 %
mean	68.60266 kHz	14.57670 µs	1.4208 µs	9.754 %
min	68.3669 kHz	14.5524 µs	702.1 ns	4.816 %
max	68.7171 kHz	14.6270 µs	2.2591 µs	15.511 %
sdev	52.22 Hz	11.11 ns	378.8 ns	2.609 %
num	136	136	137	136
status	✓	✓	✓	✓

C1 DQ B D 1.76 V/div -5.7200 V

C2 BwL DC 100 mA/div -223.50 mA

ClosedLoop 2.00 %/div 200 µs/div

Timebase -796 µs 200 µs/div 200 kS 100 MS/s

Trigger C2 DC Stop 348 mA Edge Positive

3/6/2014 9:14:00 AM

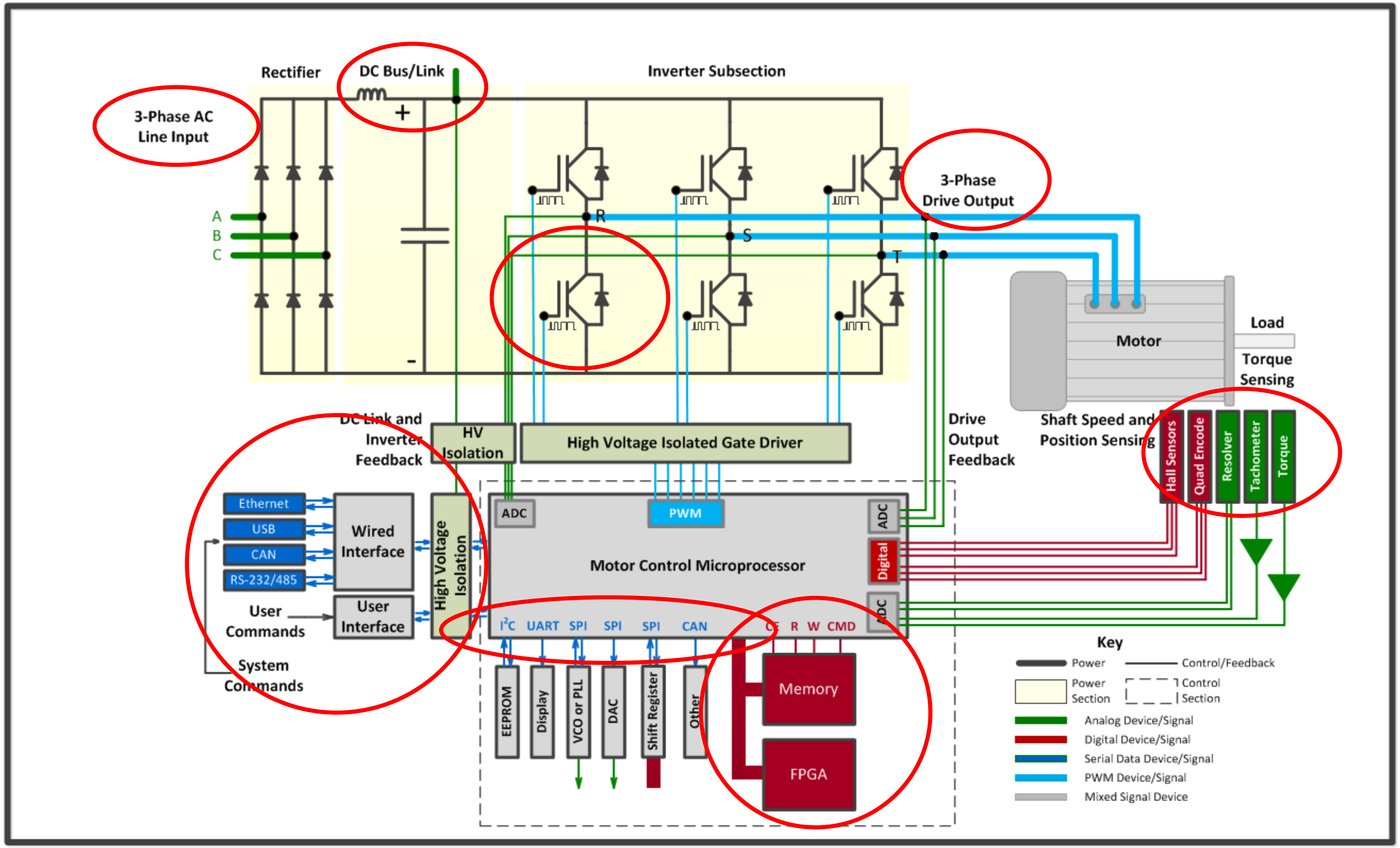
Measuring the step load response in a switched mode power supply

System Power Applications (Three-phase, motor,..)

TELEDYNE LECROY
Everywhereyoulook™

Complex Power system component

- Power Section Measurements
  - Line input
  - PWM output
  - Efficiencies
- Motor Integration
  - Torque
  - Speed
  - Position
  - Power
- Embedded Control Debug
  - Analog
  - Digital
  - Serial Data
  - Control Loop
  - PWM



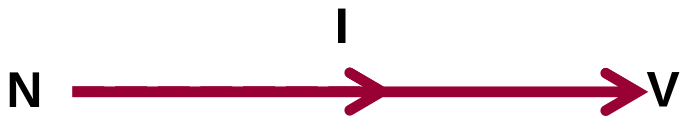
Line Power

TELEDYNE LECROY
Everywhereyoulook™

“AC” Power – The Basics

Single-phase, resistive loads

- Electric Power
    - “The rate at which energy is transferred to a circuit”
    - Units = Watts (one Joule/second)
- For purely resistive loads
    - $P = I^2R = V^2/R$ = instantaneous V*I
    - The current vector and voltage vector are in perfect phase



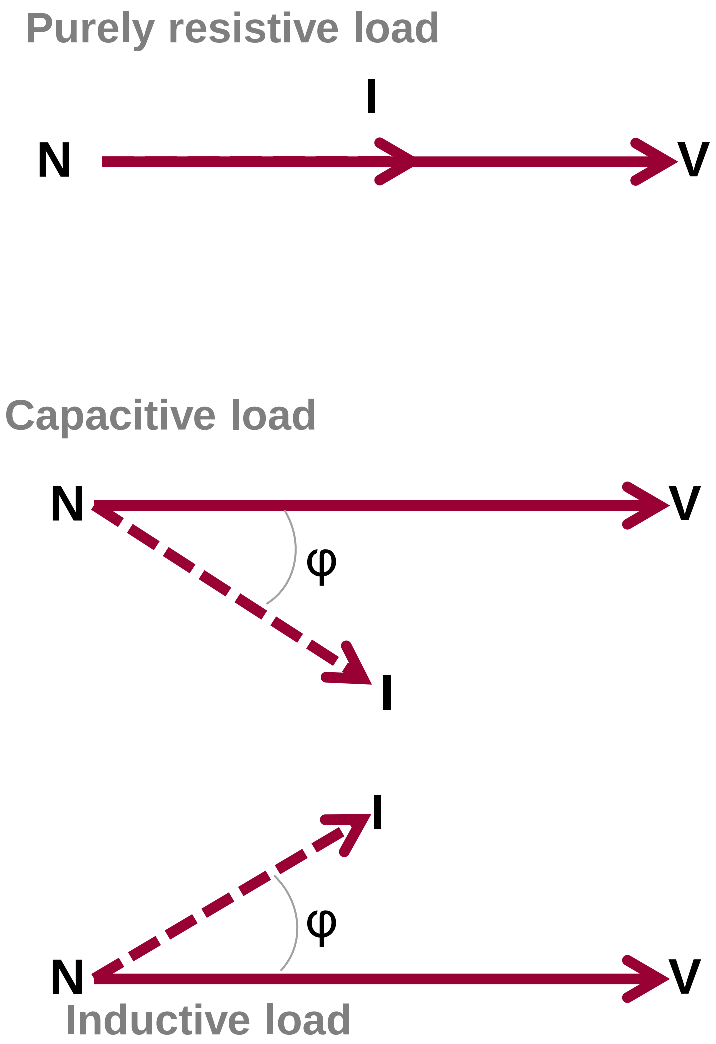
Purely resistive load

P = V*I

“AC” Power – The Basics

Introducing Power Factor

- Phase Angle (φ)
  - Indicates the angular difference between the current and voltage vectors
    - Degrees: - 90° to +90°
    - or radians: -π/2 to + π/2
- Power Factor (PF, or λ)
  - Cos(φ) *for purely sinusoidal waveforms*
  - Unitless, 0 to 1,
    - 1 = V and I in phase, purely resistive load
    - 0 = 90° out of phase, purely capacitive or purely inductive load
    - Not typically “signed” – current either leads (capacitive load) or lags (inductive load) the voltage



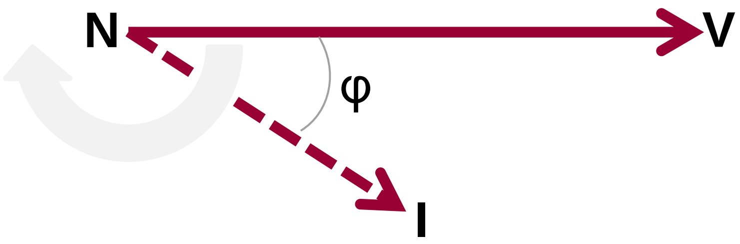
“AC” Power – The Basics

Single-phase, non-resistive loads

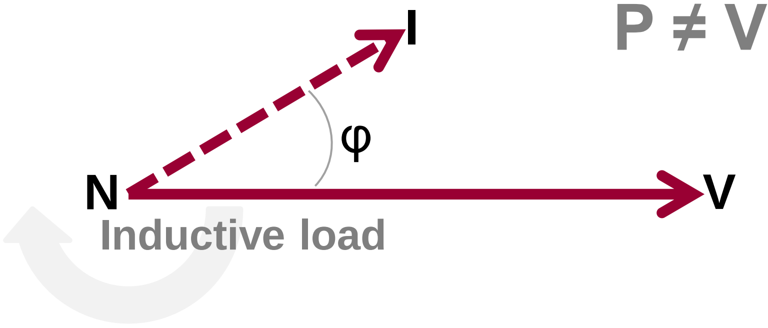
- For capacitive and inductive loads
  - P ≠ I^2R since voltage and current are not in phase
    - Capacitive Loads
      - The current vector “leads” the voltage vector by angle φ
      - Purely capacitive load has angle φ = 90°
    - For inductive loads
      - The current vector “lags” the voltage vector angle φ
      - Purely inductive load has angle φ = 90°

P ≠ V*I

Capacitive load



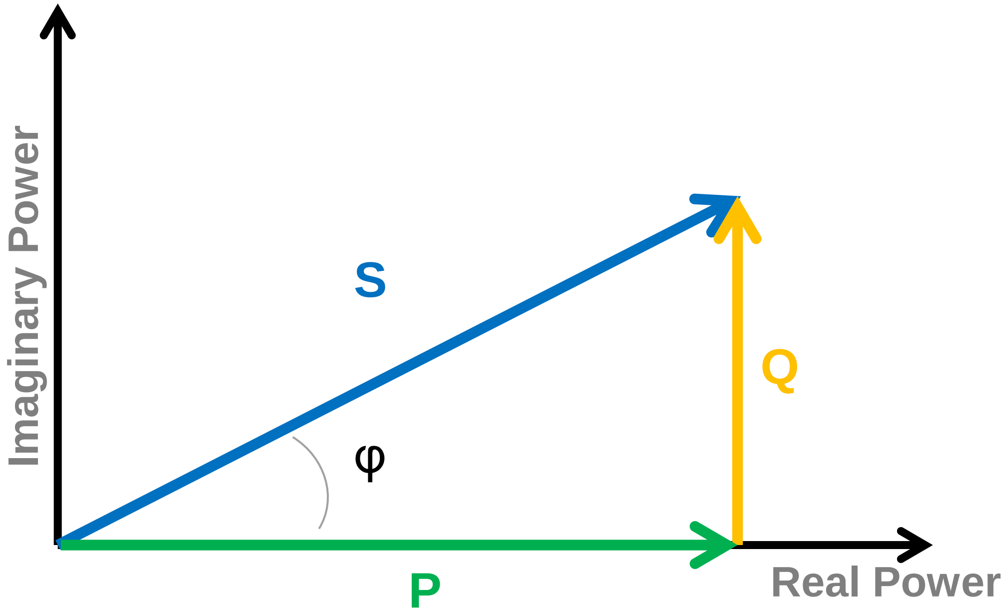
P ≠ V*I



"AC" Power – The Basics

Introducing Single-phase Real, Apparent and Reactive Power

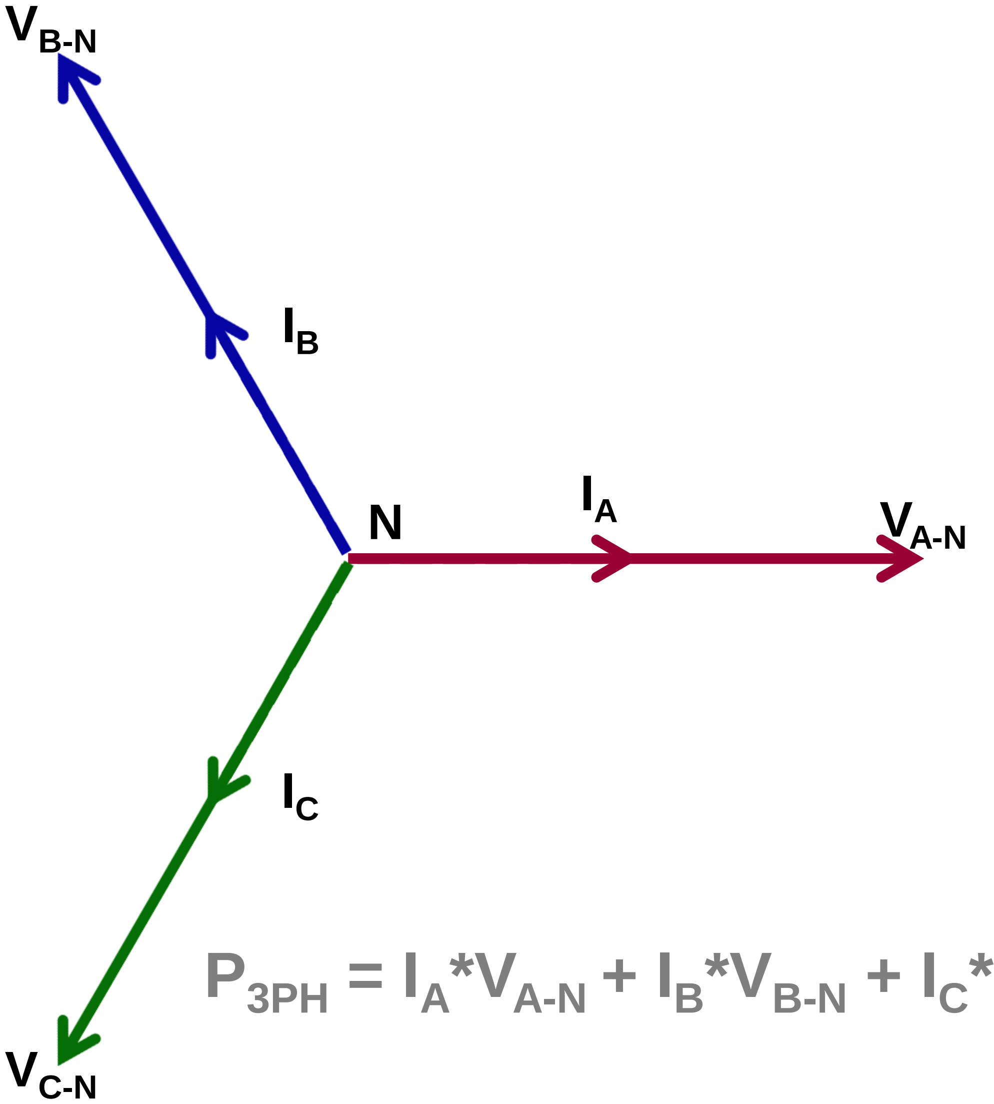
- **Real Power**
  - P, in Watts
  - = instantaneous V*I
- **Apparent Power**
  - |S|, in Volt-Amperes, or VA
  - = V_{RMS}*I_{RMS} for a given power cycle
- **Reactive Power**
  - Q, in Volt-Amperes reactive, or VAr
  - Q = $\sqrt{(S^2-P^2)}$
  - Does not "transfer" to load during a power cycle, just "moves around" in the circuit
  - Some Q is necessary in AC transmission
    - Too much causes various problems
    - Utilities control Q in transmission and distribution



"AC" Power – The Basics

Three-phase, resistive loads

- For purely resistive loads
  - $P_{PHASE\ A}$ = instantaneous $V_{A\text{-}N}*I_A$
  - $P_{PHASE\ B}$ = instantaneous $V_{B\text{-}N}*I_B$
  - $P_{PHASE\ C}$ = instantaneous $V_{C\text{-}N}*I_C$
  - $P_{3PHASE} = P_A + P_B + P_C$
- If Voltages are not referenced to Neutral
  - This formula is not valid
  - A voltage "conversion" must be performed from line-line to line-neutral

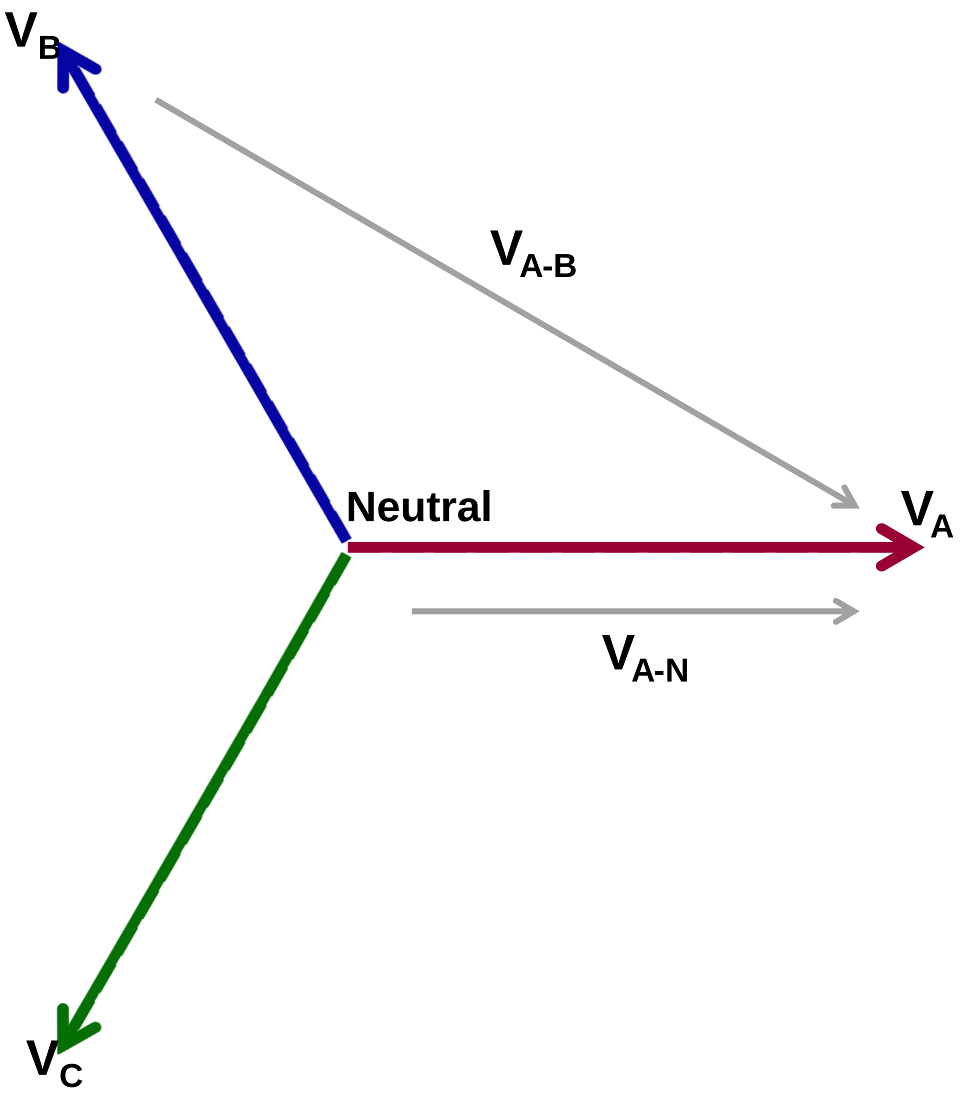


$P_{3PH} = I_A*V_{A\text{-}N} + I_B*V_{B\text{-}N} + I_C*V_{C\text{-}N}$

“AC” Power – The Basics

Line-Line to Line-Neutral Voltage Magnitude and Phase Conversion

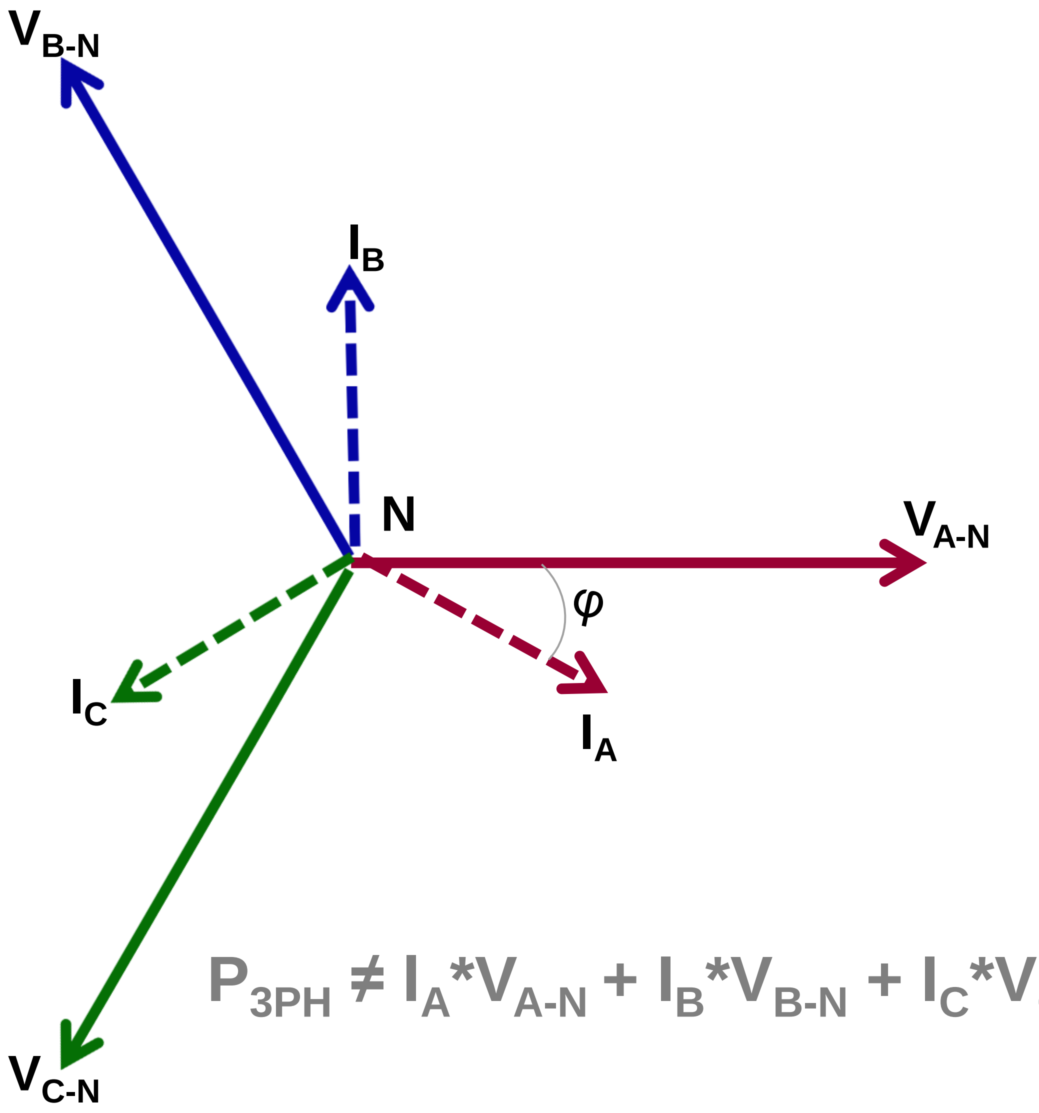
- Mathematically, V_{A-B} and V_{A-N} are related as follows:
  - Magnitude $V_{A-B} = V_{A-N} * \sqrt{3}$
  - Phase $V_{A-B} = V_{A-N} - 30°$
- This is true for all three phases



“AC” Power – The Basics

Three-phase, non-resistive loads

- As with the single-phase case, Power is not the simple multiplication of voltage and current, and summation for all three phases

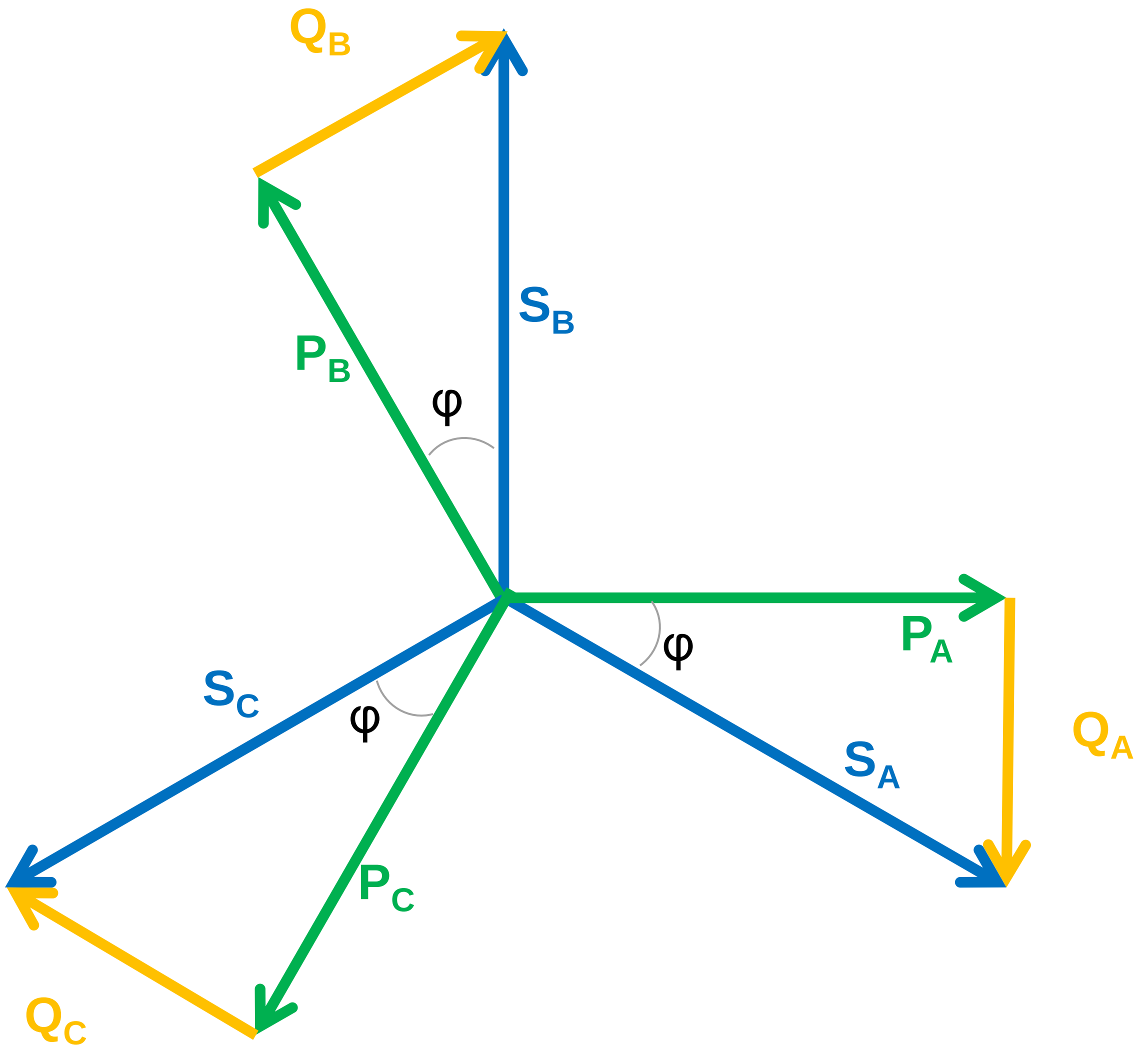


$$P_{3PH} \neq I_A{*}V_{A-N} + I_B{*}V_{B-N} + I_C{*}V_{C-N}$$

“AC” Power – The Basics

Three-phase, non-resistive loads

- **Real Power for each Phase**
  - P, in Watts
  - = instantaneous V*I
- **Apparent Power for each Phase**
  - |S|, in Volt-Amperes, or VA
  - = $V_{RMS}*I_{RMS}$ for a given power cycle
- **Reactive Power for each Phase**
  - Q, in Volt-Amperes reactive, or VAr
  - $Q = \sqrt{(S^2-P^2)}$
- $P_{Total} = P_A + P_B + P_C$
- $S_{Total} = S_A + S_B + S_C$
- $Q_{Total} = Q_A + Q_B + Q_C$



The Basics – Power Conversion

Power electronics circuits are used to “convert” line power to different voltages and frequencies, depending on user and application requirements.

TELEDYNE LECROY
Everywhereyoulook™

Power Conversion – The Basics

- “Power Conversion” is the conversion of electric power from one form to another, from one voltage to another, or one frequency to another, or some combination of these
  - AC-AC
    - AC line voltage conversion to a different voltage and/or frequency
  - AC-DC or DC-AC
    - AC line voltage conversion to a specified DC voltage, or vice-a-versa
  - DC-DC
    - DC voltage conversion to a different specified DC voltage

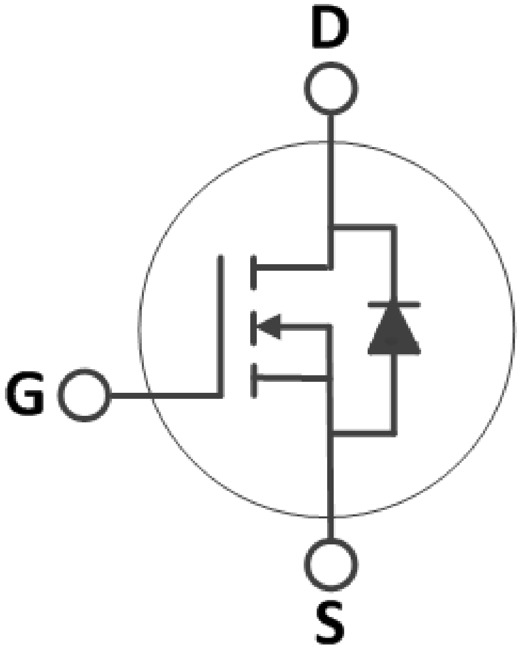
- For our purposes, “Power Conversion” involves use of fast power electronics “switching” devices to enable the conversion in the most efficient manner
  - 20 kHz (typical) switching frequencies
  - 50/60 Hz core/coil device would not be considered “power conversion” devices

- “High Power” and “Three-Phase” Power Conversion is our focus
  - >1 kW, or Three-phase, or both
  - DC-DC (“converters”), AC-AC (“drives”), or DC-AC (“inverters”)
  - This is where the money is – follow the money

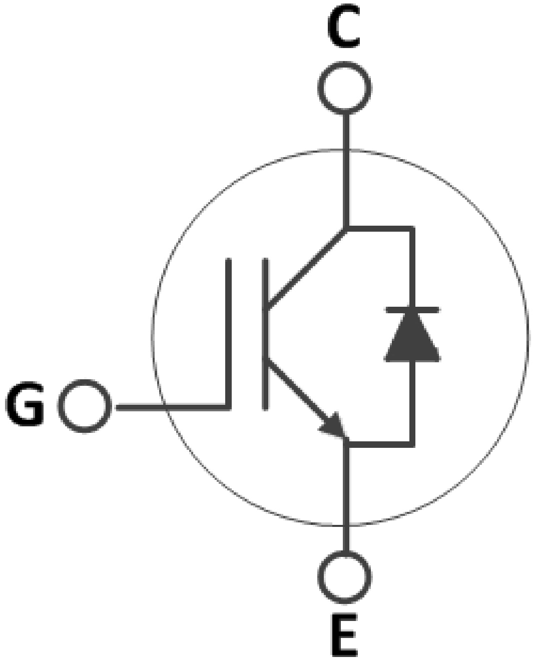
Power Semiconductor Device "Building Blocks"

Different nomenclature, but same functions

- Power MOSFET
  - Gate (G)
  - Drain (D)
  - Source (S)



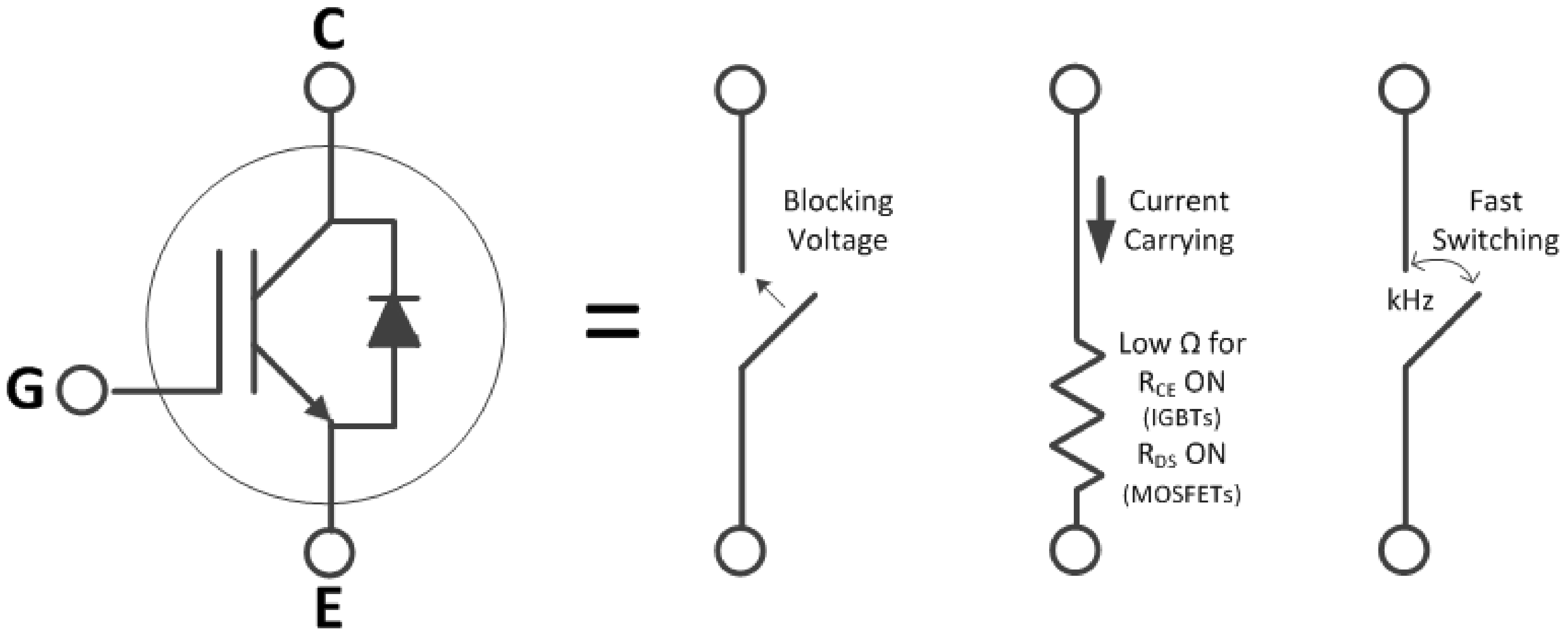
- IGBT
  - Gate (G)
  - Collector (C)
  - Emitter (E)



Power Semiconductor Device Operation

Think of a Power MOSFET or an IGBT as a fast switch

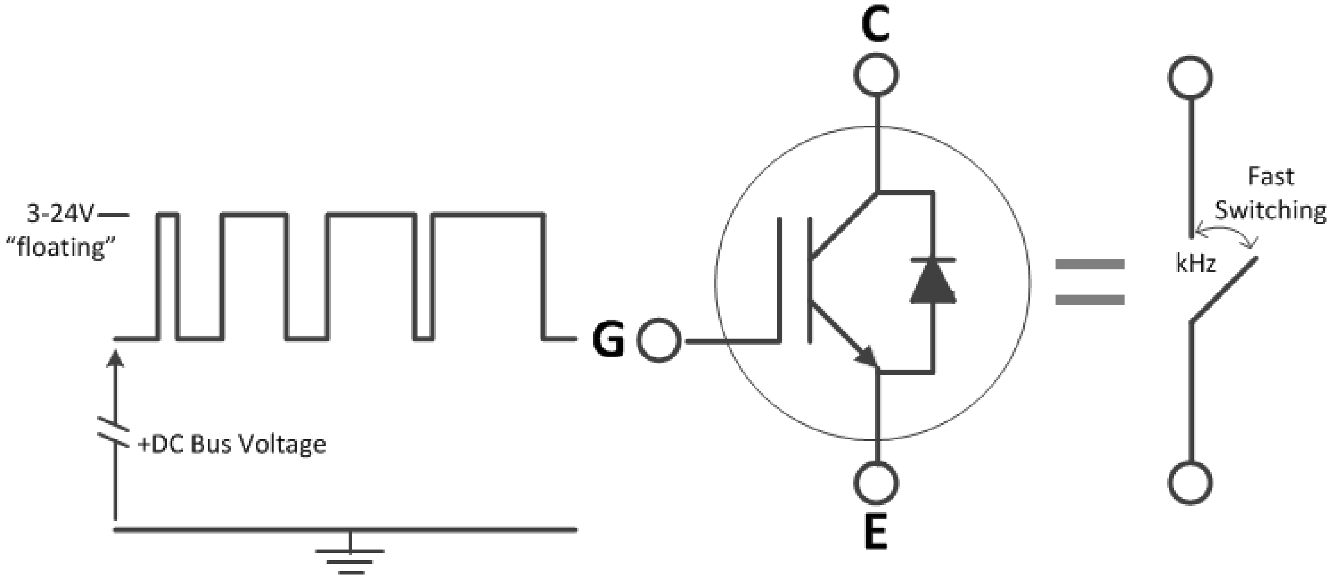
- The power semiconductor can be simply thought of as a very fast switch
  - With a rated “withstand (blocking) voltage
  - That can carry (handle) a lot of current
  - With low losses (low forward voltage drop)
  - That can switch very fast (kHz)



Power Semiconductor Device Operation

The switching is easily controllable with a varying pulse width signal

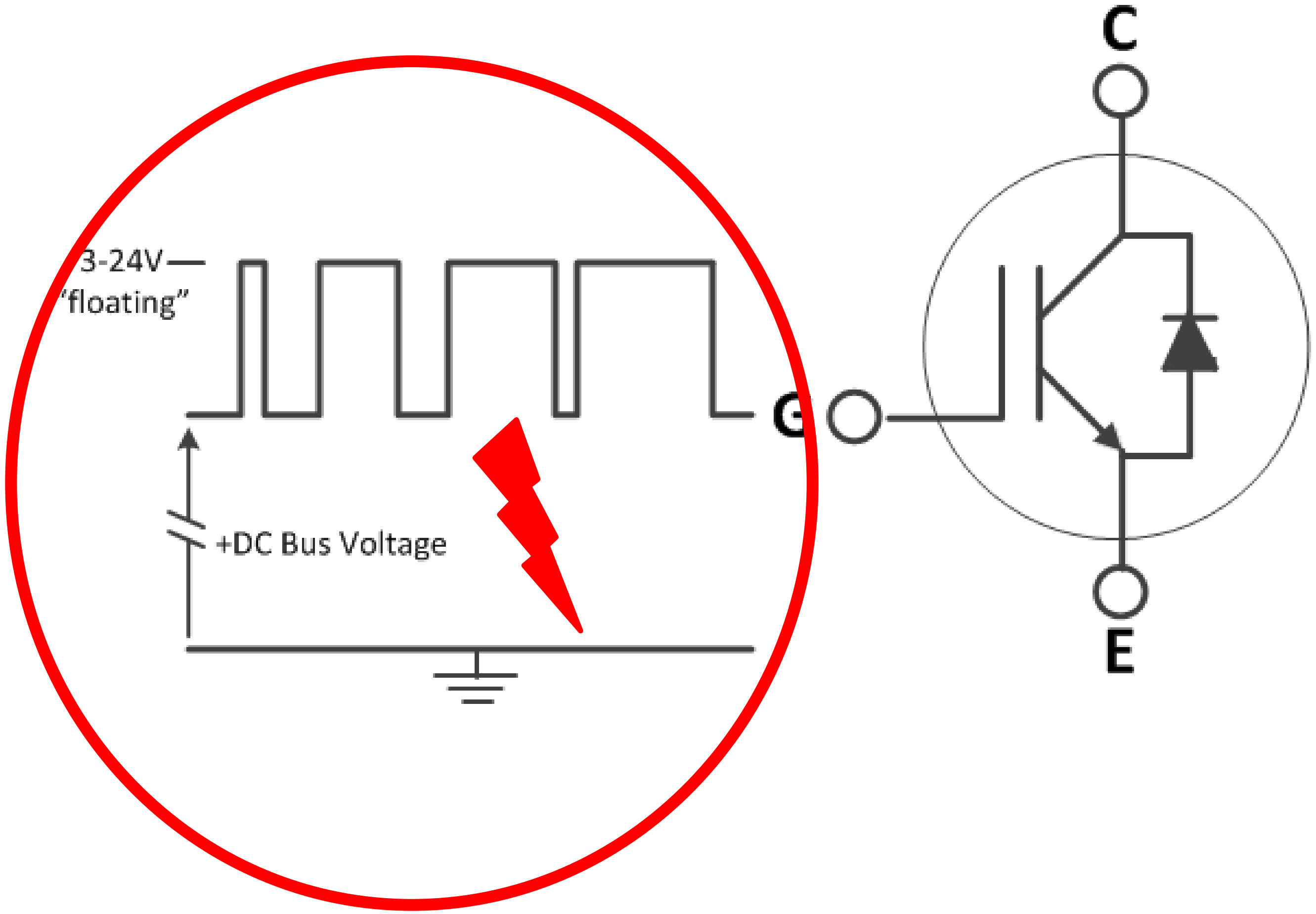
- The Gate (G) controls the switching
- A pulse-width modulated (PWM) signal is applied at the gate to control the switching
  - This signal is usually from 3-24V in amplitude, depending on the power semiconductor
  - This signal is usually called the “Gate Drive Signal” or “Gate Driver”
- The power semiconductor then performs the same switching at a higher voltage/current level



Power Semiconductor Device Operation

The gate drive signal is “floating” and requires HV isolation to measure

- This gate drive signal is floating at full or half of DC bus voltage, depending on inverter topology
    - This usually requires an isolated input channel on the oscilloscope
        - 1000Vrms Ch-Ch and Ch-Gnd
    - Or a high voltage differential probe (HVD3000 series) with a similar rating
    - For ≤50V drive designs (MOSFETS), a passive probe with an HDO (400V max input) is often used

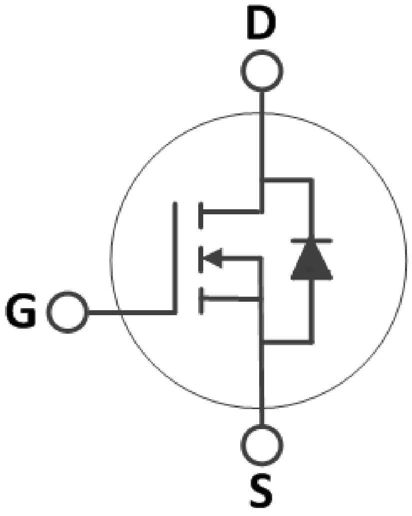


Silicon (Si) Power Semiconductor Device Types

These two devices are dominant in most applications for switching at high frequencies

Silicon Power MOSFET

Metal Oxide Semiconductor
Field- Effect Transistor

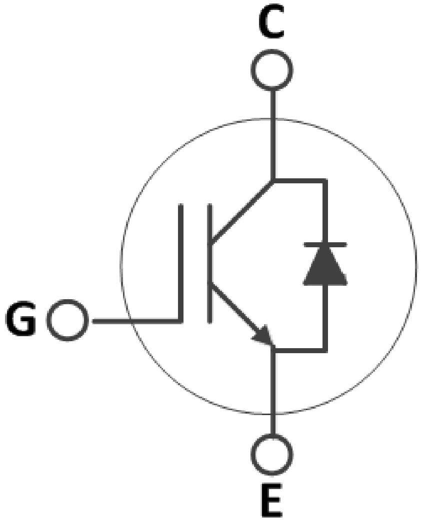


Characteristics

200V blocking voltage (typical) – up to 500V
10s of amperes current handling capability
Higher forward voltage drop at higher voltages
Higher switching speeds – 20 to 100 kHz typical
Widely deployed in 50V/120/240V applications

Silicon IGBT

Insulated Gate
Bipolar Transistor



Characteristics

1200V blocking voltage (typical) – up to 6000V
100s of amperes current handling capability
Lower forward voltage drop – 2 volt typical
Lower switching speeds – 1.5 to 10 kHz typical
Widely deployed in 600V class applications

Silicon Carbide (SiC) Power Semiconductor Device Types

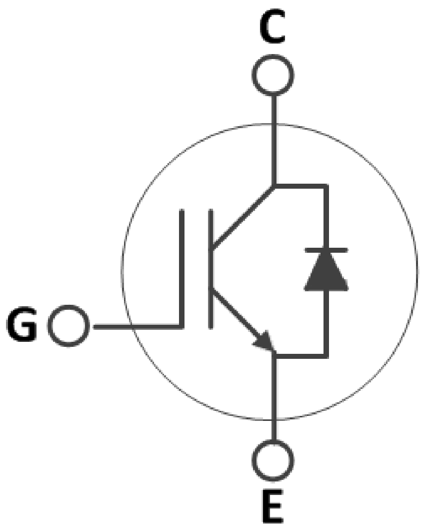
This is an emerging device material for higher power designs

- Silicon Carbide (SiC) and Gallium Nitride (GaN)
  - Higher breakdown voltages
  - Faster switching speeds
  - Lower leakage currents
  - Lower thermal resistance

- Advantages to the design
  - Better reliability and more compact power conversion designs
  - Reduced heat-sink sizes
  - Reduced size filter components (capacitors, inductors)
  - Lower weight
  - Higher power density
  - Higher efficiencies

Silicon Carbide (SiC) IGBT

Insulated Gate Bipolar Transistor



Characteristics

12 kV blocking voltage

100s of amperes current handling capability

Lower forward voltage drop – <1 volt typical

Faster switching speeds – 20 kHz to 100 kHz

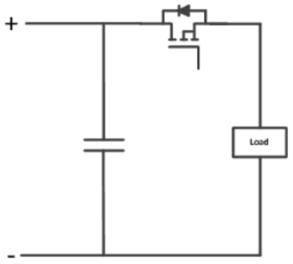
Will be increasingly adopted in ≥600V class designs

Typical Inverter/Drive Topologies

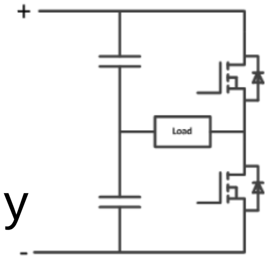
These are the typical “building blocks” for power conversion circuits

Low Power
Low Voltage
Low Transistor Count
4 channels scope

- Single-stage (Boost)
  - MOSFET-based
- Applications
  - LED driver

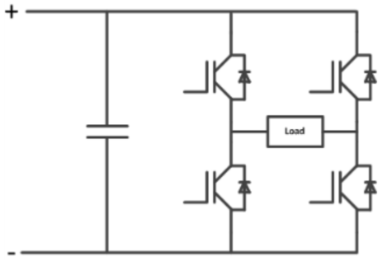


- Half-Bridge
  - Usually MOSFET-based
- Applications
  - CFL lighting ballast
  - Switch-mode power supply (SMPS)
  - Low power DC-DC converter

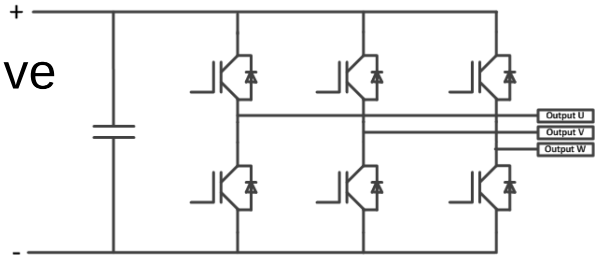


Higher Power
Higher Voltage
High Transistor Count
8 channels scope

- Full-Bridge (H-Bridge)
  - MOSFET or IGBT-based
- Applications
  - 1-phase grid-tied inverter
  - 1-phase motor drive
  - UPS
  - Vehicle DC-DC converter



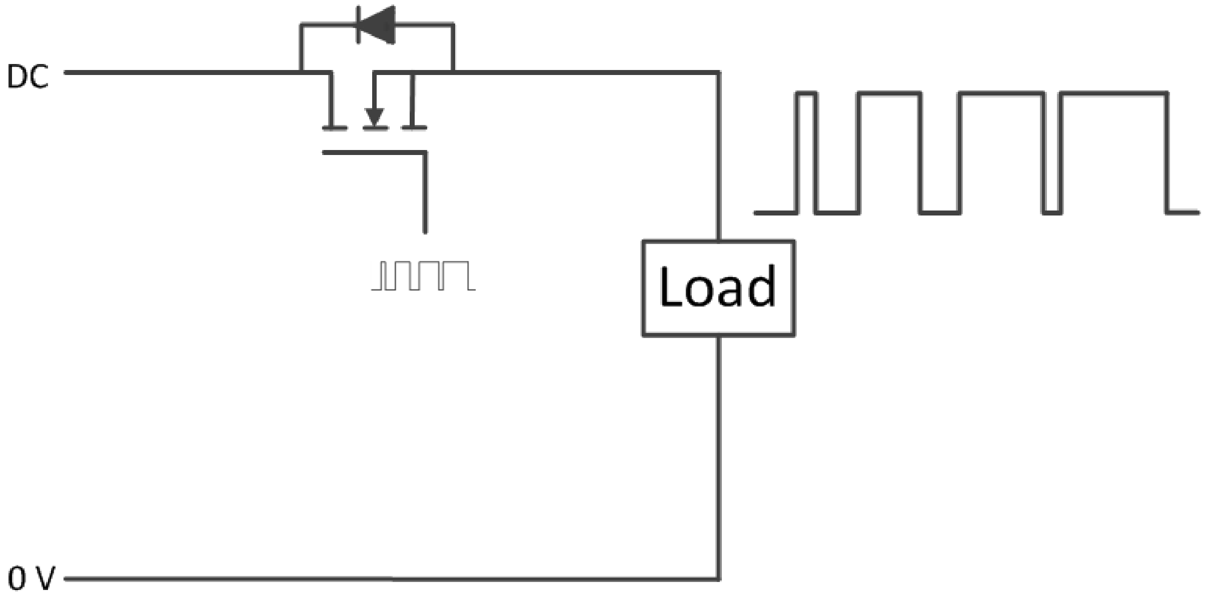
- (Three-Phase) Cascaded H-Bridge
  - MOSFET or IGBT-based
- Applications
  - Motor Drive
  - Grid-tied inverter

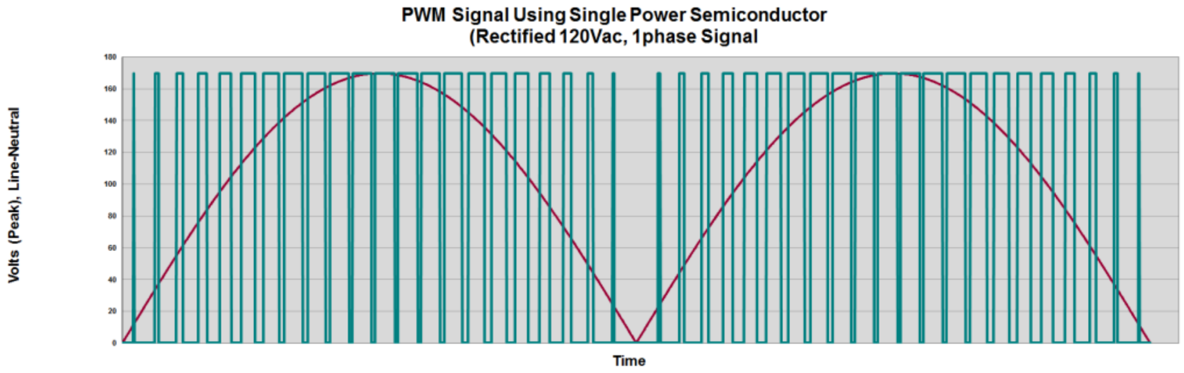


Single-stage (Boost) Implementation

Let’s understand this operation as a foundation for more complicated topologies

- Power semiconductor “opens” and “closes” based on gate-drive signal to supply DC voltage and current at load
    - Assume DC voltage = 170Vdc
- PWM signal at Gate creates PWM signal at load
    - “1” level = 170Vdc
    - “0” level = 0 Vdc
- If PWM signal is modulated as AC sinusoid, then fundamental frequency of PWM signal on load is rectified AC sinusoid 0-170Vpk

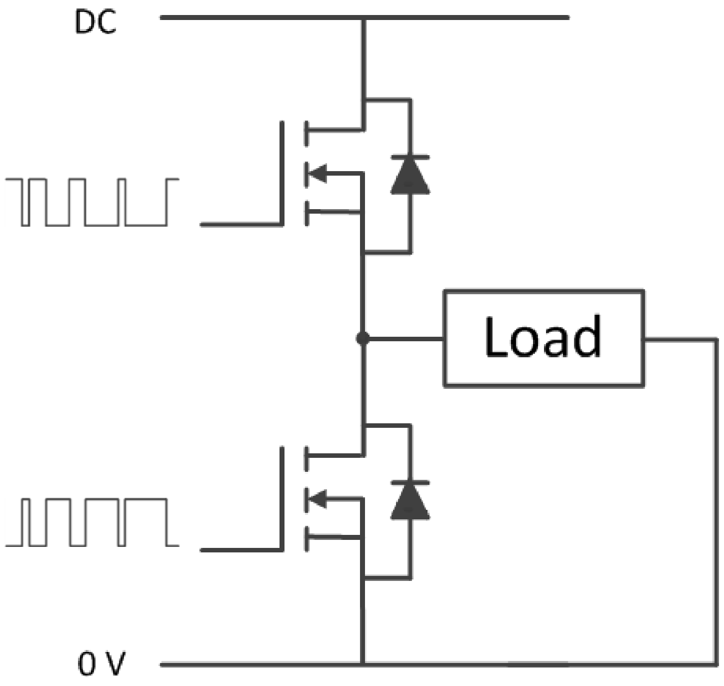


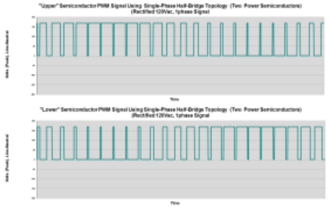


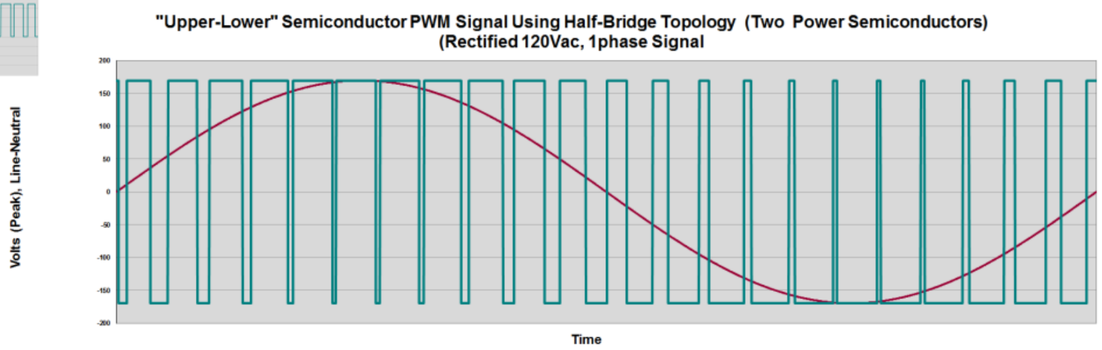
Half-Bridge (Series Connection) Implementation

Higher voltage AC sinusoidal output, single-direction power flow via load termination

- Load is connected at midpoint of circuit and could be terminated at either
  - The upper rail (DC)
  - The lower rail (0V) (as shown)
- Complementary PWM signals are applied at the Upper Device and Lower Device gate
  - Both devices can not be "on" (conducting) at the same time or there will be a short circuit
- Upper and Lower Devices Both
  - "1" level = 170Vdc
  - "0" level = 0 Vdc
- Upper-Lower Device = Load
  - +170Vpk to -170Vpk







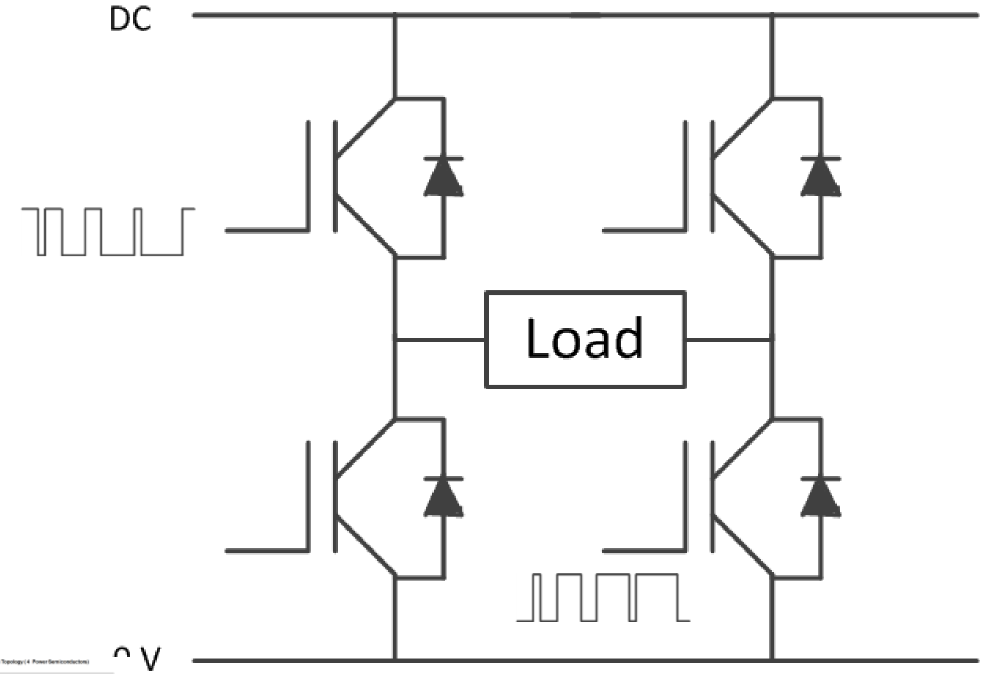
Full-Bridge (H-Bridge) Implementation

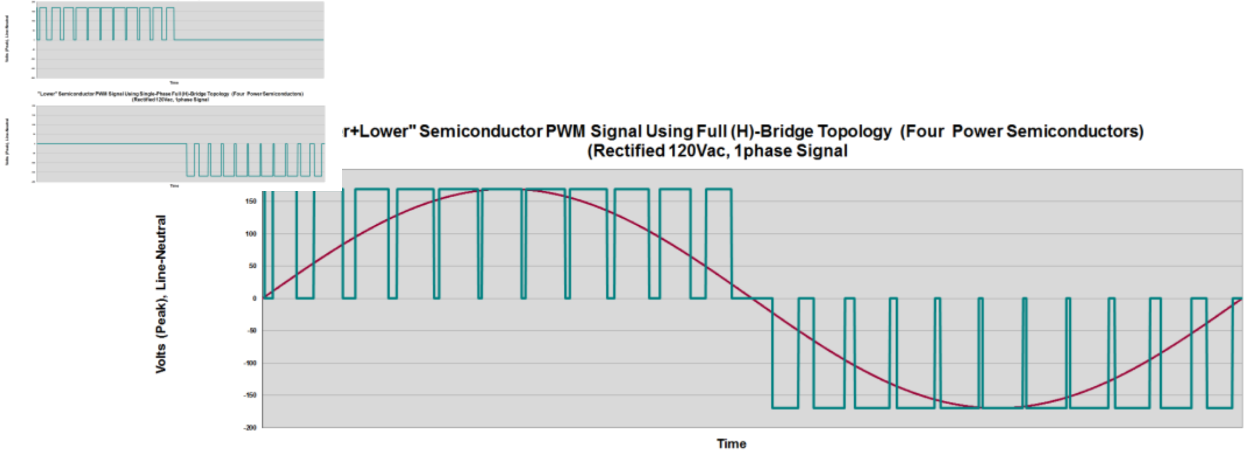
Higher voltage AC sinusoidal output, bi-directional power flow and braking

- A Full-Bridge is essentially two Half-Bridges in Parallel with the load connected at the midpoint of each

- Device switching can be programmed to provide
  - "Forward" current flow through load
  - "Reverse" current flow through load
  - "Braking" from forward direction
  - "Braking" from reverse direction
  - "Stop" (no current flow)

- Gate drive signals are complementary, but…
  - Upper device is modulated for positive half of sinewave and lower device is modulated for negative half of sinewave
  - Load sees +170Vpk to -170Vpk

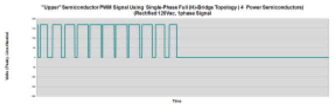


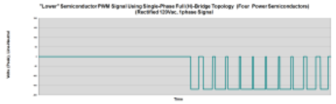


Full-Bridge (H-Bridge) Implementation

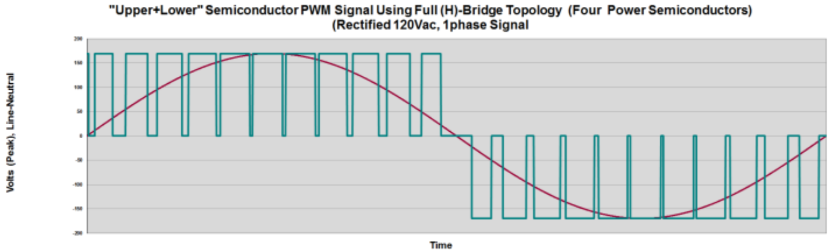
Positive Direction Current Flow

- Upper left and lower right devices are switched ON with PWM gate drives
  - As with the Half-bridge, gate drives are complementary

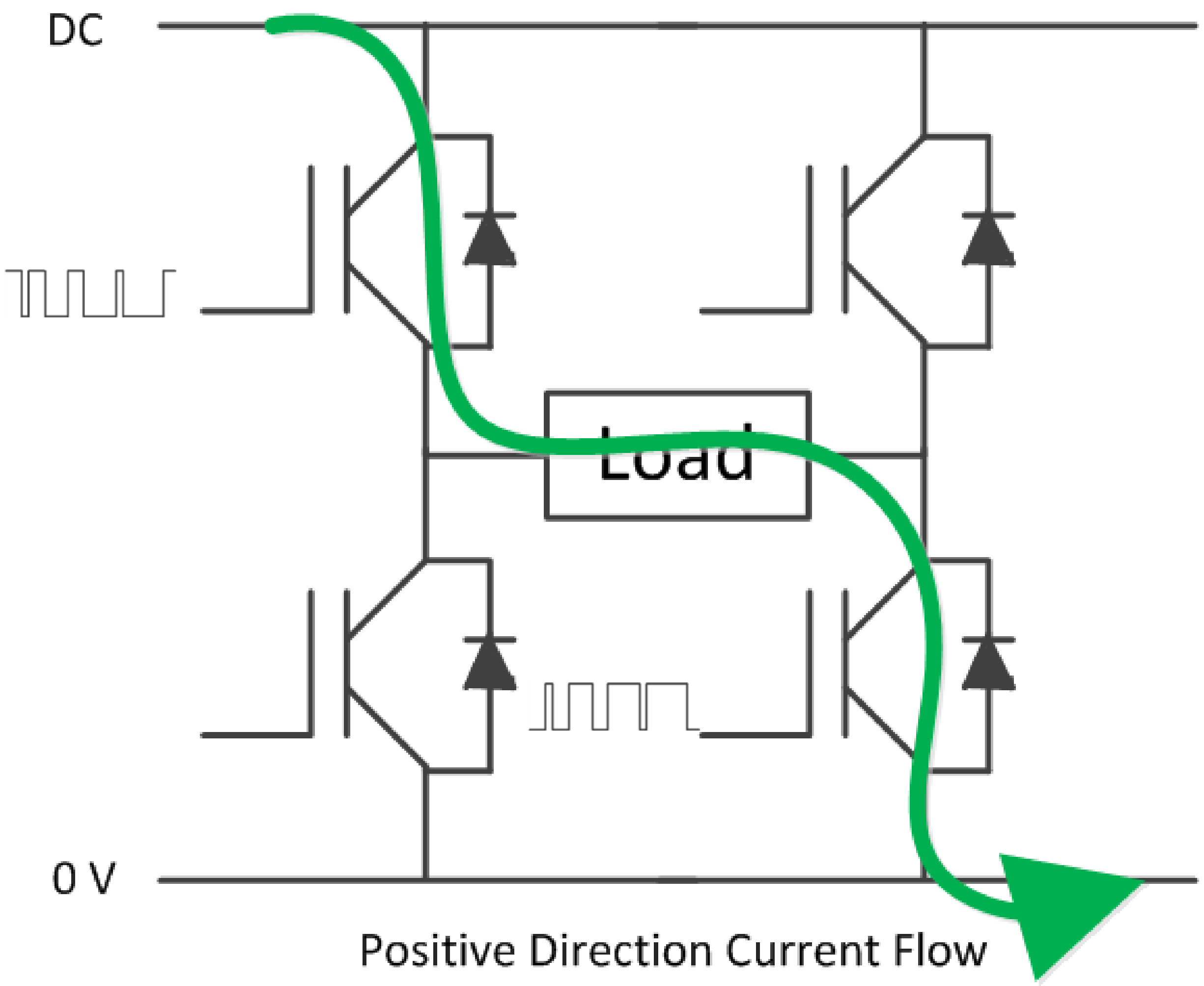




  - Output across load is Upper-Lower = +170Vpk to -170Vpk PWM signals



- Lower left and upper right devices are OFF (open)

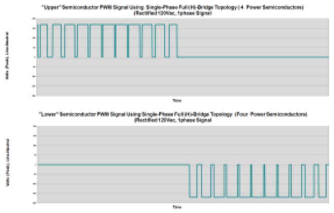


Positive Direction Current Flow

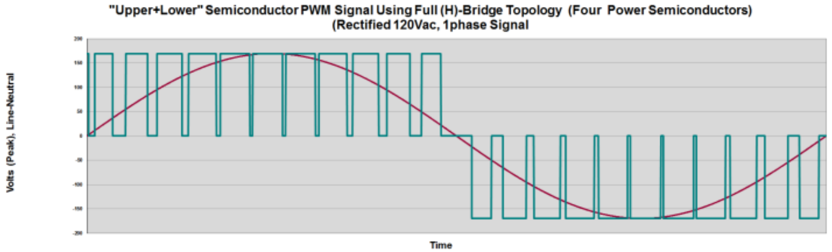
Full-Bridge (H-Bridge) Implementation

Negative Direction Current Flow

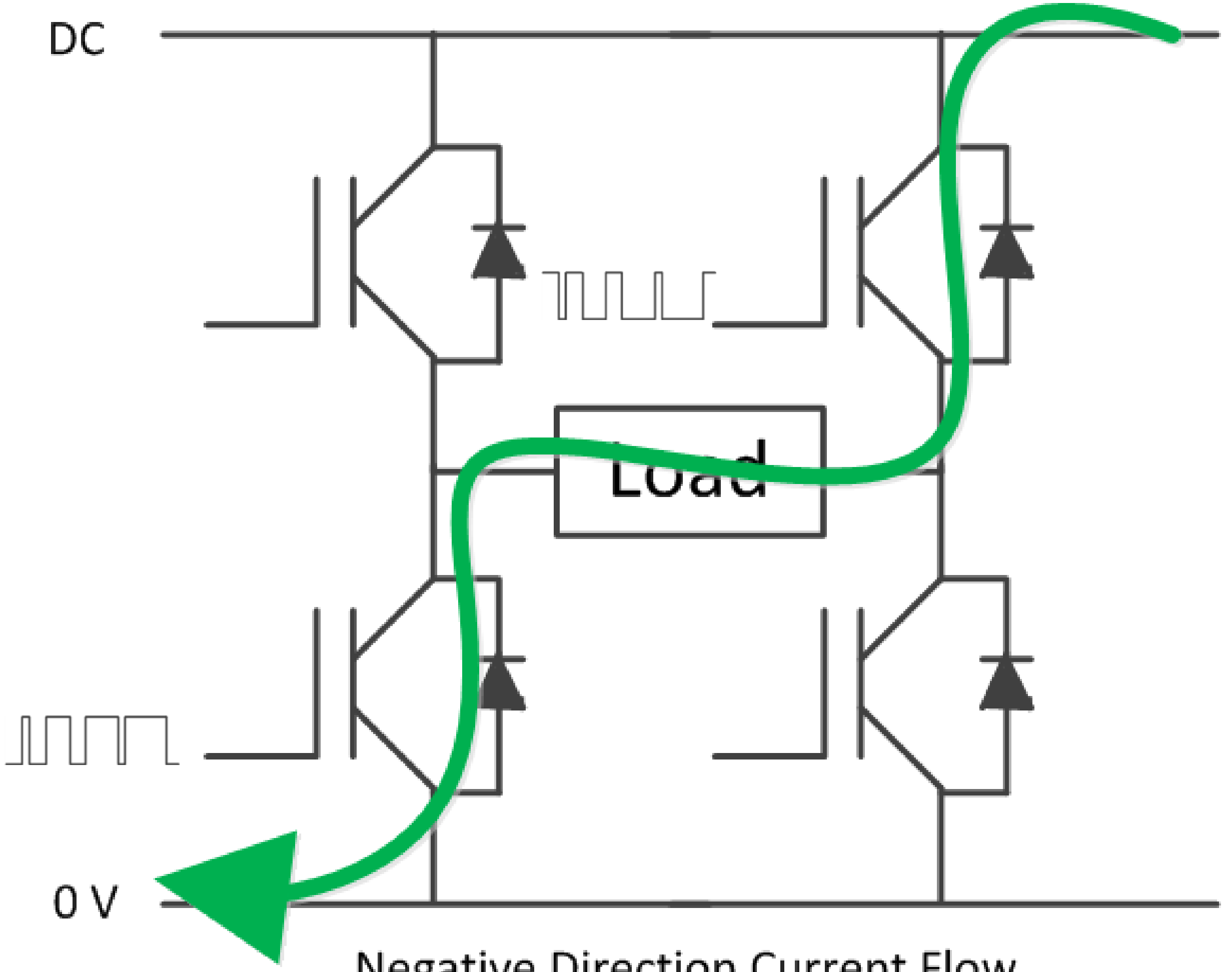
- Upper right and lower left devices are switched ON with PWM gate drives
  - As with the Half-bridge, gate drives are complementary



  - Output across load is Upper-Lower = +170Vpk to -170Vpk PWM signals



- Lower left and upper right devices are OFF (open)

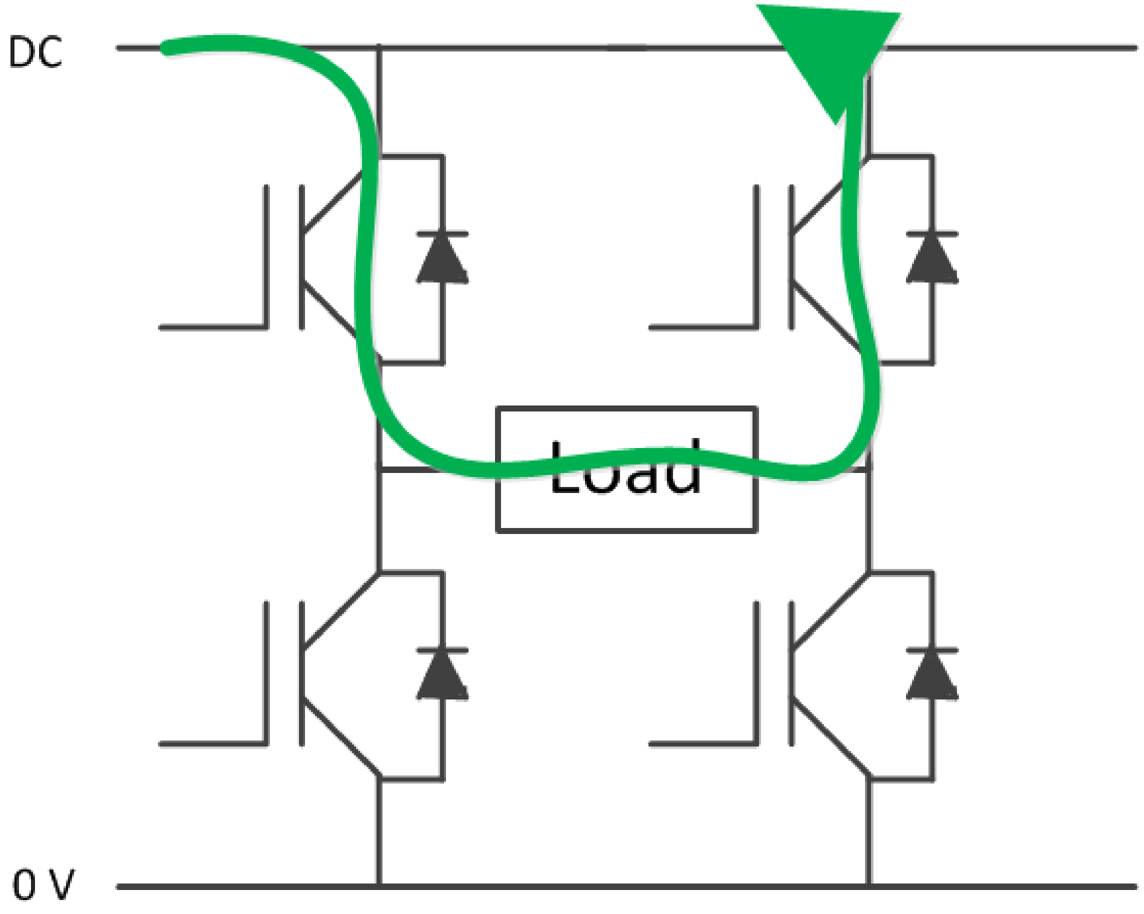


Negative Direction Current Flow

Full-Bridge (H-Bridge) Implementation

Braking a motor from a positive current flow direction

- Upper left and upper right devices are switched ON (conducting) creating a path for current to flow from the motor terminals back to the DC supply
  - “Static” braking – motor simply spins down delivering energy to DC supply
  - “Dynamic” braking – PWM signals are applied to brake the motor faster or in a controlled fashion
- Lower left and lower right devices are switched OFF (open)

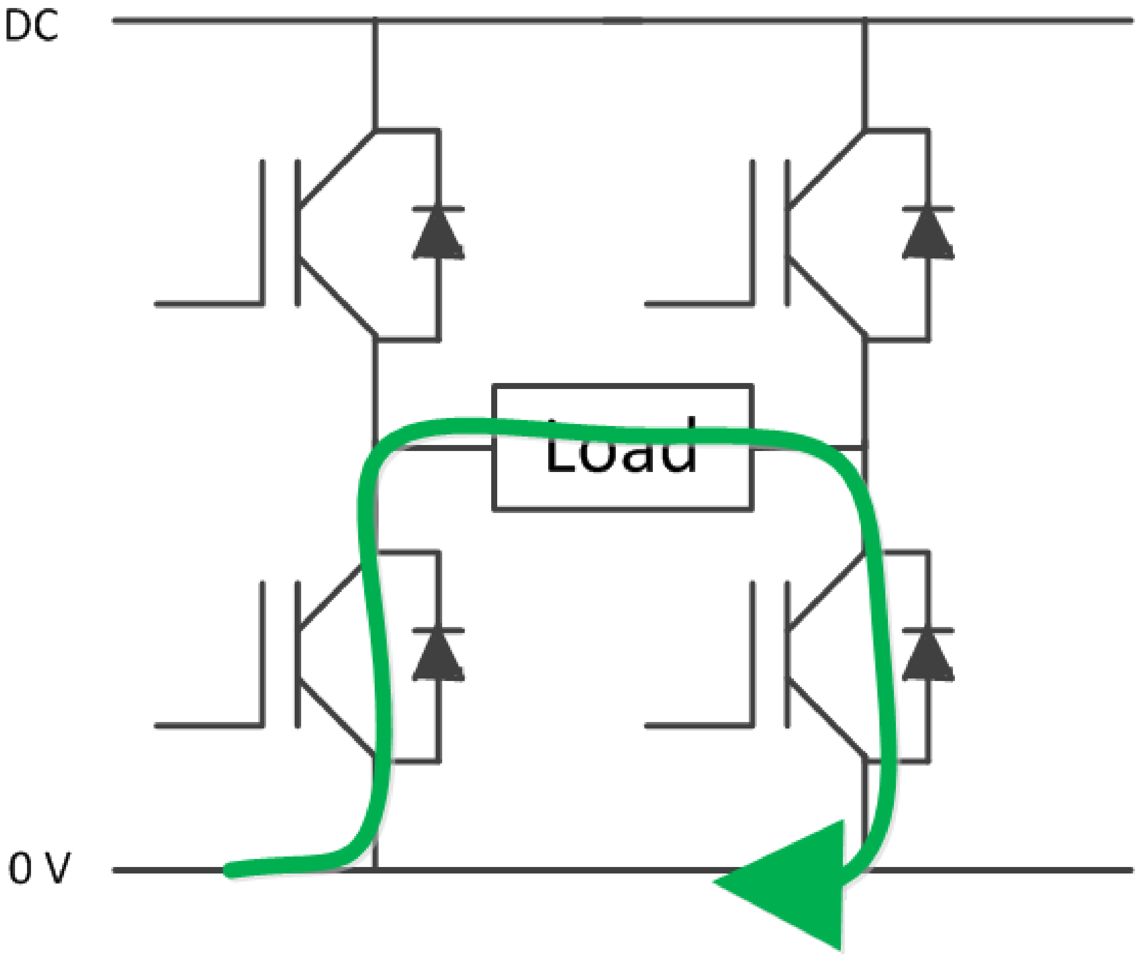


Braking Enabled When Motor is Running in Positive Direction

Full-Bridge (H-Bridge) Implementation

Braking a motor from a negative current flow direction

- Low left and lower right devices are switched ON (conducting) shorting the motor terminals to ground
    - “Static” braking – motor simply spins down delivering energy to DC supply
    - “Dynamic” braking – PWM signals are applied to brake the motor faster or in a controlled fashion
- Upper left and upper right devices are switched OFF (open)

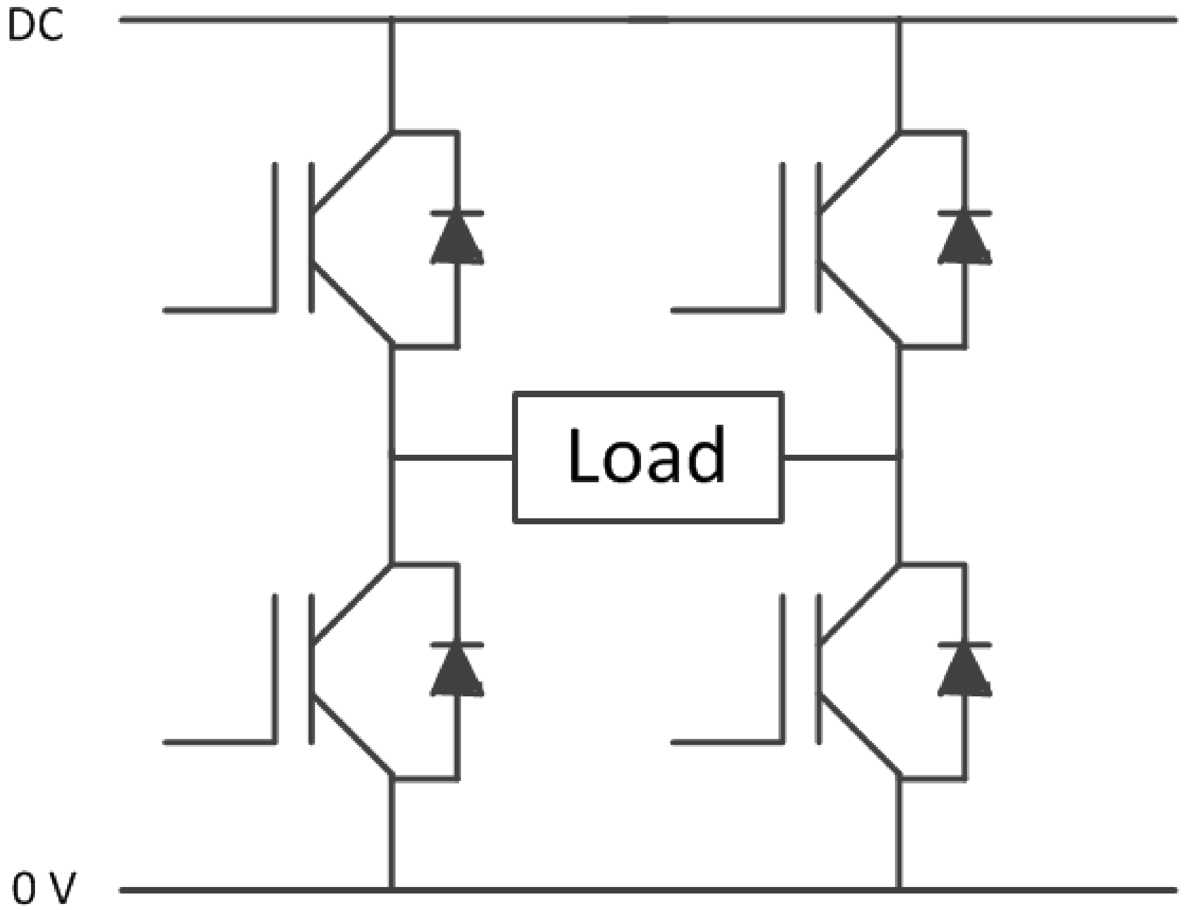


Braking Enabled When Motor is Running in Negative Direction

Full-Bridge (H-Bridge) Implementation

Holding a motor in a “stopped” position

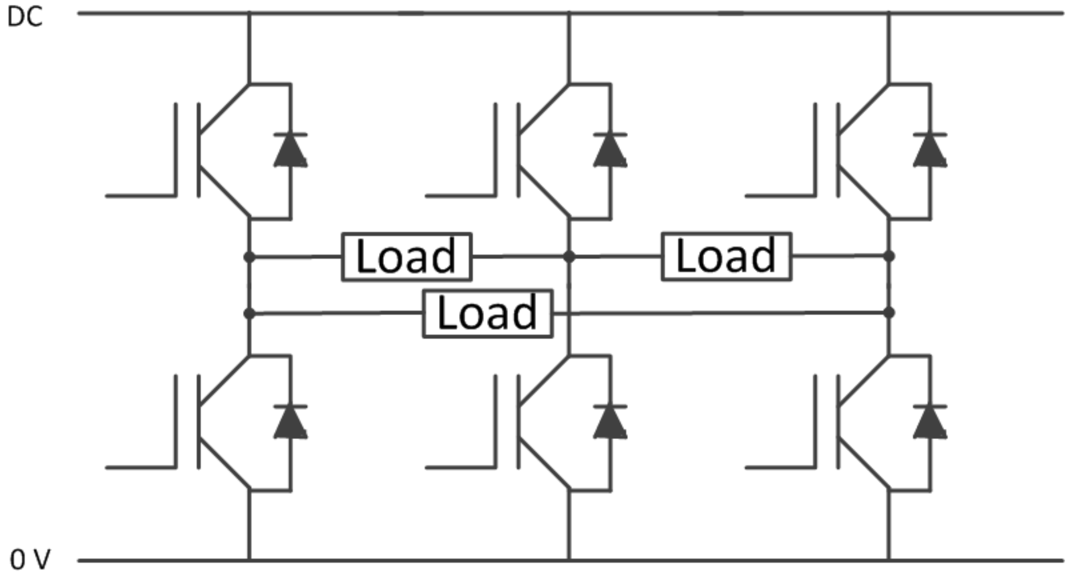
- All devices are switched OFF (open)
  - No current flows in the circuit



Cascaded H-Bridge Implementation

Three-phase AC sinusoidal output, bi-directional power flow and braking

- A Cascaded H-Bridge is essentially three H-Bridges with three loads (phases) connected across each series pair
  - These loads are the three “phases”
  - The loads are connected “line-line”
    - e.g. U-V, V-W, W-U; or R-S, S-T, T-R depending on the nomenclature used

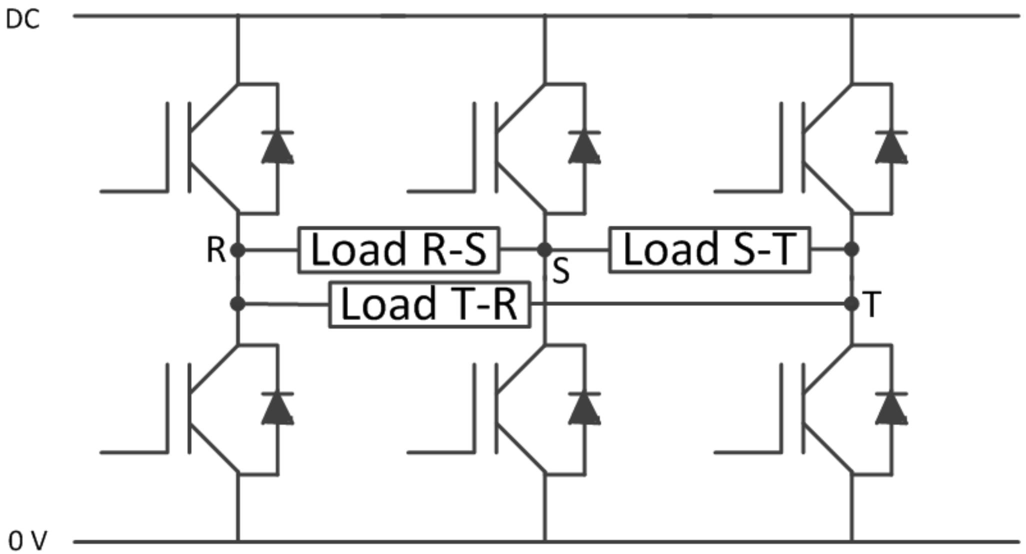


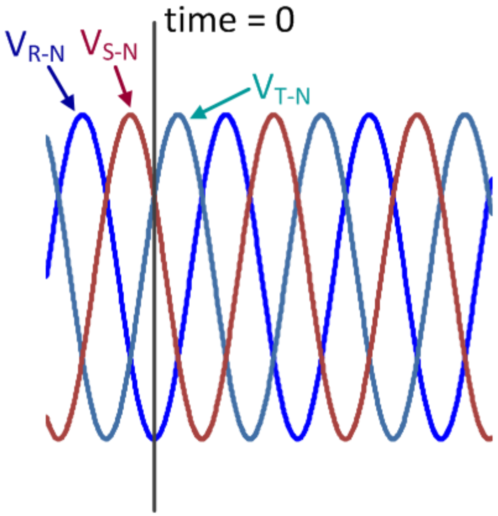
- There are two basic methods to create the three-phase output waveforms
  - “Sine” modulated
    - Carrier-based PWM
    - Space Vector Modulation (SVM)
  - Six-step commutated

Cascaded H-Bridge Implementation

“Sine” modulated control

- Voltage is generated across all three loads (phases) at all times using three sinewave modulating signals 120° apart
- At time=0, output voltages are desired to be
  - V_R = -170V
  - V_S = +85V
  - V_T = +85V
- Gate drive signals can be calculated to create current flow consistent with these voltages





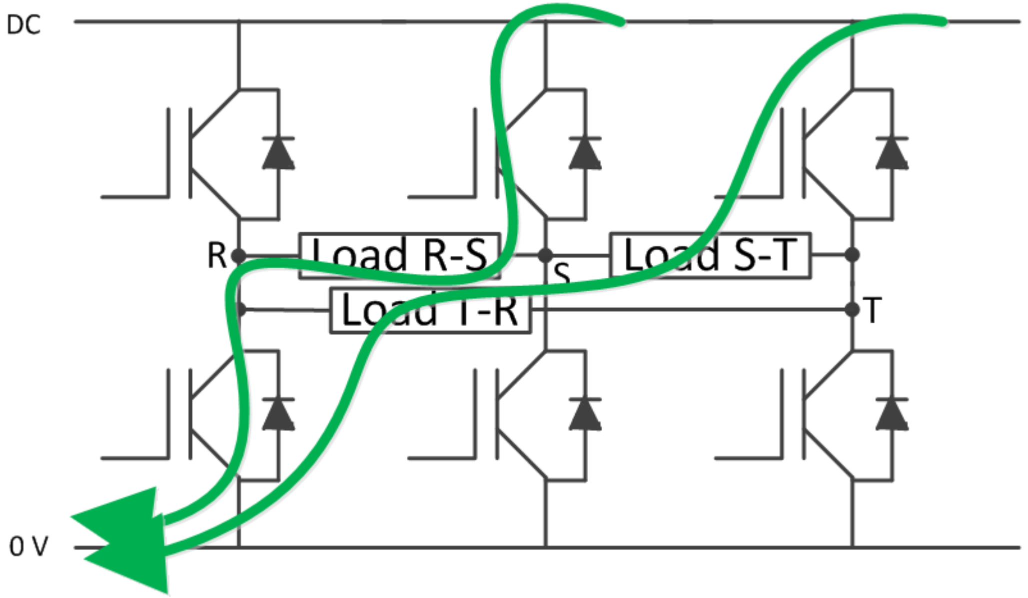
Cascaded H-Bridge Implementation

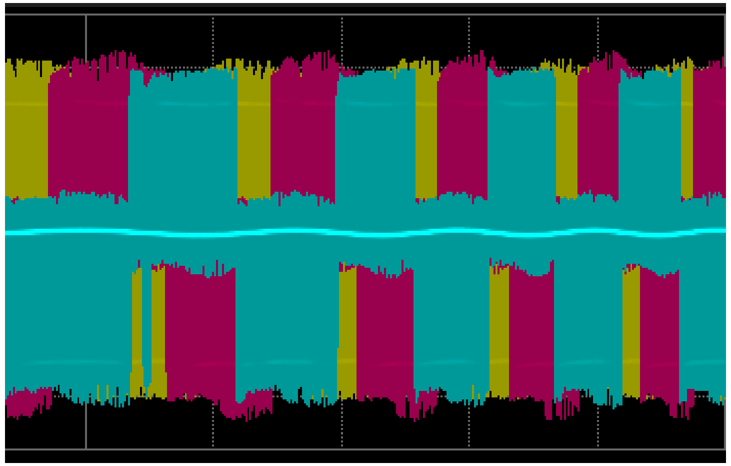
“Sine” modulated control

- Devices switch “on” (conducting) or “off” (open)
  - Upper R device is “off”
  - Lower R device is “on”
  - Upper S device is “on”
  - Lower S device is “off”
  - Upper T device is “on”
  - Lower T device is “off”

- PWM carrier frequency defines switching interval

- PWM outputs appear as in an H-Bridge, but for three-phases
  - At right, is three line-line output PWM waveforms for a sine-modulated Cascaded H-Bridge





MDA800 Motor Drive Analyzer

(and HDO8000 Series Oscilloscopes)

TELEDYNE LECROY
Everywhereyoulook™

MDA800 – Motor Drive Analyzer

- Complete Motor Drive System Debug and Validation
- Three-Phase Power Measurements (Real , Apparent and Reactive)
- Efficiency Measurements
- Per-Cycle Time-Correlated Waveforms From Power Values
- Dynamic Drive response Analysis, from Startup to Overload
- Complete Motor Integration (Torque, Speed, Position)
- User-Configurable Power Table and Graphical User Interface
- Unique Zoom+Gate Mode

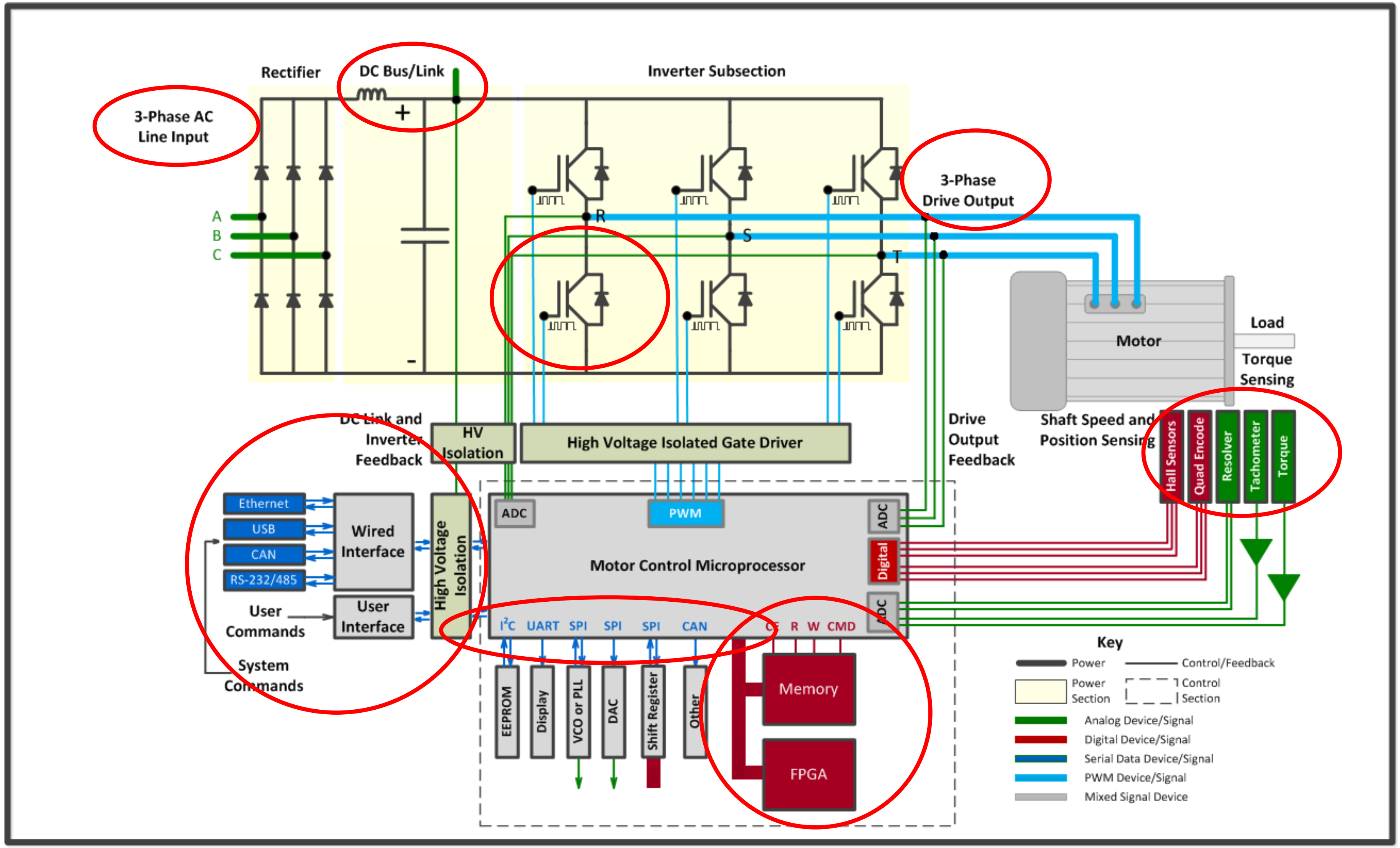
MDA support the complete design and debug challenge

for the motor drive engineer

- Power Section Measurements
  - Line input
  - PWM output
  - Efficiencies

- Motor Integration
  - Torque
  - Speed
  - Position
  - Power

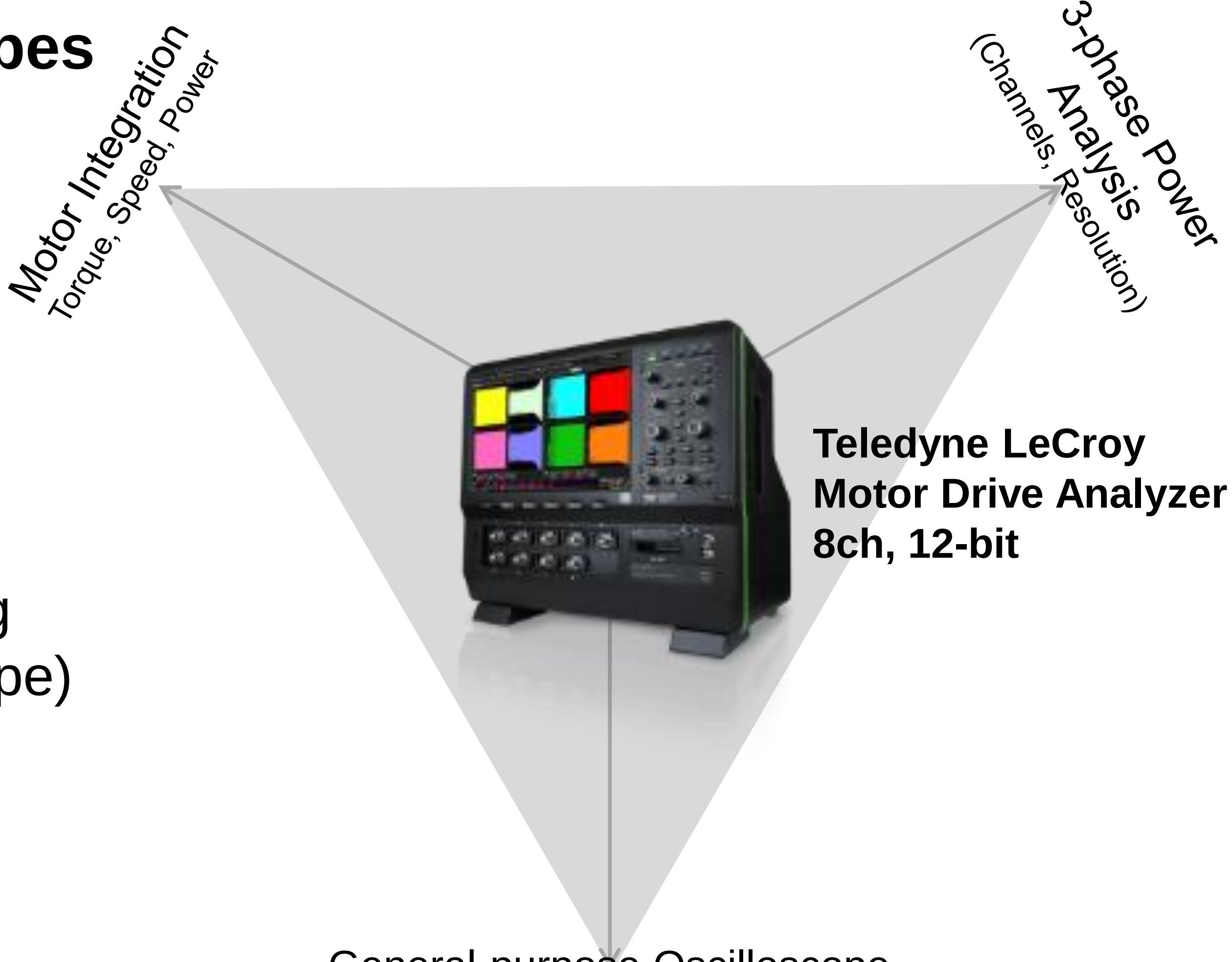
- Embedded Control Debug
  - Analog
  - Digital
  - Serial Data
  - Control Loop
  - PWM



Motor Drive Analyzers – Unique Positioning

It's an Oscilloscope, and it's also a Power Analyzer with Motor Integration

- **General-purpose 8 ch, 12-bit scopes up to 1 GHz plus 32 Digital Channels**
- **Motor Drive Analyzers perform**
  - **Static** (steady-state) "mean value" tables, like a power analyzer
  - **Dynamic** (transient) analysis
  - **Complete** embedded control debug (i.e. it is a fully-functional oscilloscope)
    - High SR, BW, Memory
    - Mixed Signal
    - Serial Trigger & Decode
  - More complete motor integration

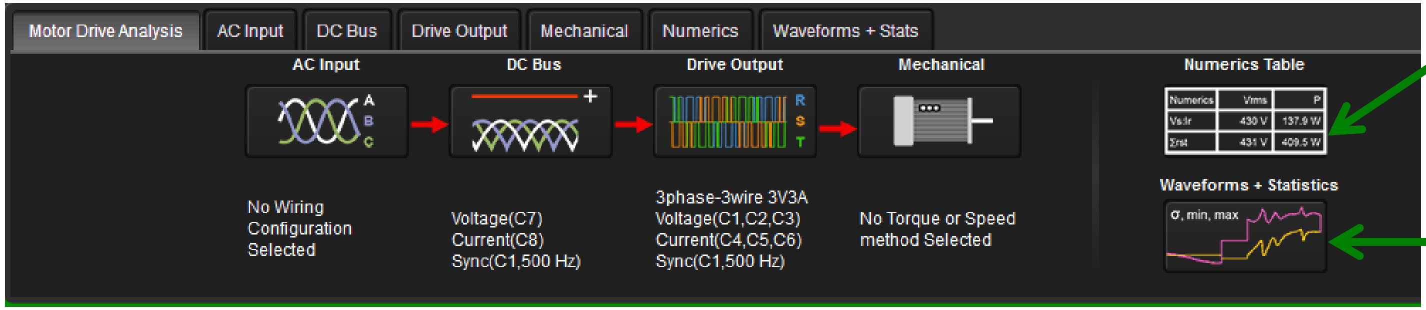


Teledyne LeCroy Motor Drive Analyzer 8ch, 12-bit

General-purpose Oscilloscope
(BW, SR, Memory, MSO, Serial Trigger/Decode, IGBT/MOSFET Device Test)

Motor Drive Analyzer Graphical User Interface

- Simple , Intuitive user interface



No Wiring Configuration Selected

Voltage(C7)
Current(C8)
Sync(C1,500 Hz)

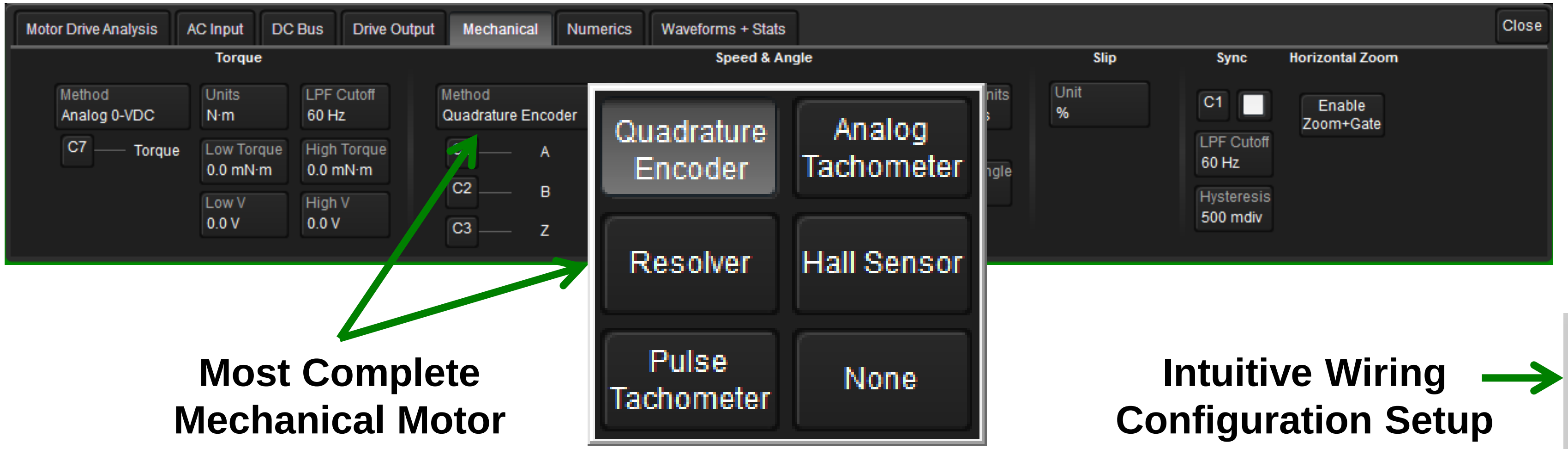
3phase-3wire 3V3A
Voltage(C1,C2,C3)
Current(C4,C5,C6)
Sync(C1,500 Hz)

No Torque or Speed method Selected

Numerics	Vrms	P
Vs:lr	430 V	137.9 W
Σrst	431 V	409.5 W

Numerics Table for short record power analysis, like a Power Analyzer

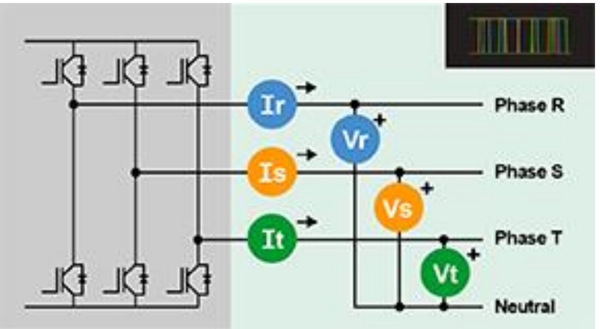
Long Record Dynamic Analysis toolsets that Power Analyzers don't have



Method: Analog 0-VDC
Units: N·m
LPF Cutoff: 60 Hz
Low Torque: 0.0 mN·m
High Torque: 0.0 mN·m
Low V: 0.0 V
High V: 0.0 V
Method: Quadrature Encoder
Unit: %
LPF Cutoff: 60 Hz
Hysteresis: 500 mdiv

Most Complete Mechanical Motor Integration

Intuitive Wiring Configuration Setup Diagrams
"This is much nicer than a power analyzer"



Powerful Analysis : Brushless DC Power Tool

Numerics	Vrms	Irms	P	S	Q	PF	Φ	Torque	Speed	η_1	η_2
Bus	19.9318 V	3.4189 A	36.359 W	68.026 VA	-5.322 VAR	520e-3	-1.9590 °				
Σrst	7.880 V	4.386 A	29.21 W	70.518 VA	64.11 VAR	399e-3	66.4259 °			779e-3	779e-3
Mechanical			9.85741 W					732.6 mN·m	127.930 rpm	444.7e-3	339.70e-3

MDA800 Motor Drive Analyzer Key Capabilities

- **Static**
  - It can calculate three-phase power and motor mechanical torque/speed values for short record, static (steady-state) operating conditions.

- **Dynamic**
  - It can capture long record, dynamic operating events and contains advanced tools for per-cycle analysis and correlation to other events. **Unique capabilities !**

- **Complete**
  - It’s an 8-channel (+16 digital), high definition (12-bit) oscilloscope that can perform complex debug of the embedded control system
  - **MDO800 can debug anything** in the full drive system:
    - Motor (mechanical) measurements
    - Motor Drive input/output (AC Line Input, DC Bus, Drive Output) measurements
    - Inverter subsection characterization and debug (e.g. power semiconductor device loss/operation, switching problems)
    - Embedded control system debug
    - All of the above working together as a complete Drive System

MDA : 3-phase Power and Motor Interface

Feature Set and Capability Comparison

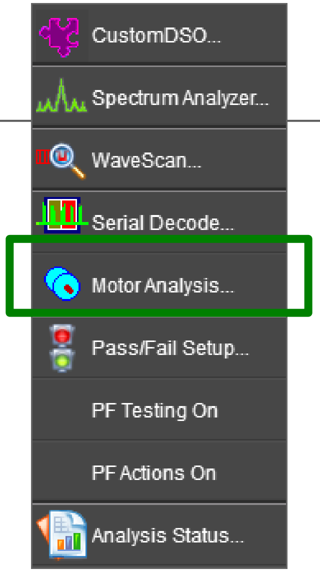
Capability		 
“Static” Power Analysis (Numeric table)	**Numeric Values + Table**	**Yes**
	Each Phase and Σ3-ph values	**Yes**
	Line-Line to Line-Neutral Conversion	**Yes (standard)**
	Efficiency Calculations	**Yes**
	Per-cycle Values	**Yes**
“Dynamic” Power Analysis	**Per Cycle V, I, PWR Waveforms**	**Yes**
	Per-cycle Values and Statistics	**Yes**
Harmonics	**Drive Input/Output Harmonics**	**Yes**
Motor Integration	**Torque**	**Yes**
	Speed, Direction, Position	**Yes (standard, comprehensive)**

Motor Drive Analizer - MDA
Software Capability Overview

TELEDYNE LECROY
Everywhereyoulook™

Motor Drive Analysis Setup Dialog Overview

Push "Drive Setup" button or Select "Motor Analysis" from Analysis pull-down



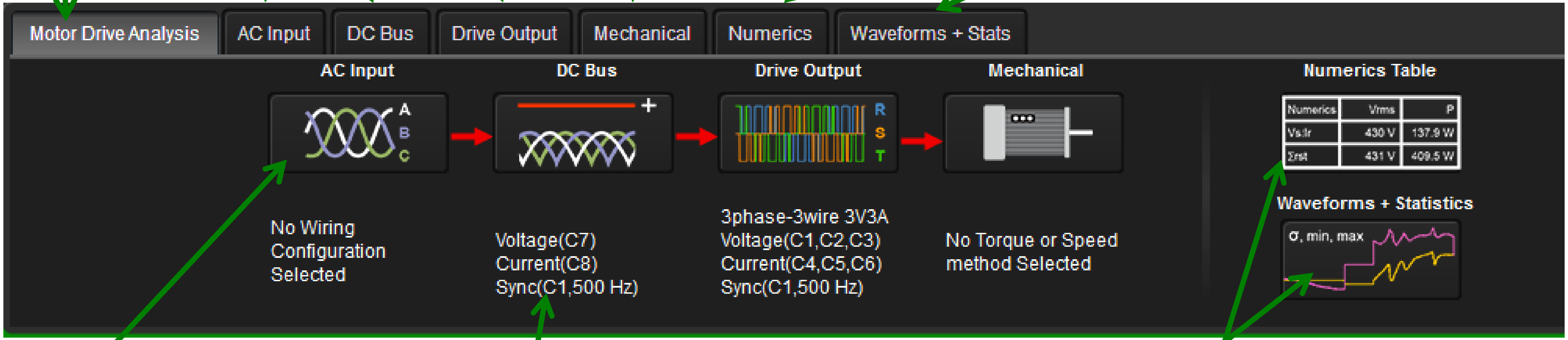
Multi-tab structure, like SDAIII

Wiring diagram and channel assignments – 1 for each power section

Mechanical (torque and speed) selections and channel assignments

3-phase Power and Motor Measurements numerics table setup

Per-cycle "synthesized" Waveforms and Statistics



Numerics	Vrms	P
Vs:Ir	430 V	137.9 W
Σrst	431 V	409.5 W

No Wiring
Configuration
Selected

Voltage(C7)
Current(C8)
Sync(C1,500 Hz)

3phase-3wire 3V3A
Voltage(C1,C2,C3)
Current(C4,C5,C6)
Sync(C1,500 Hz)

No Torque or Speed
method Selected

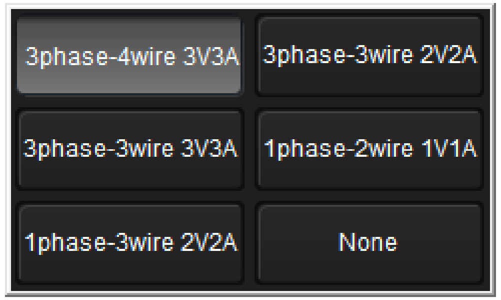
Combined iconic setup indication and shortcut button to dialog/tab

Setup summary

Shortcut buttons to dialog/tab

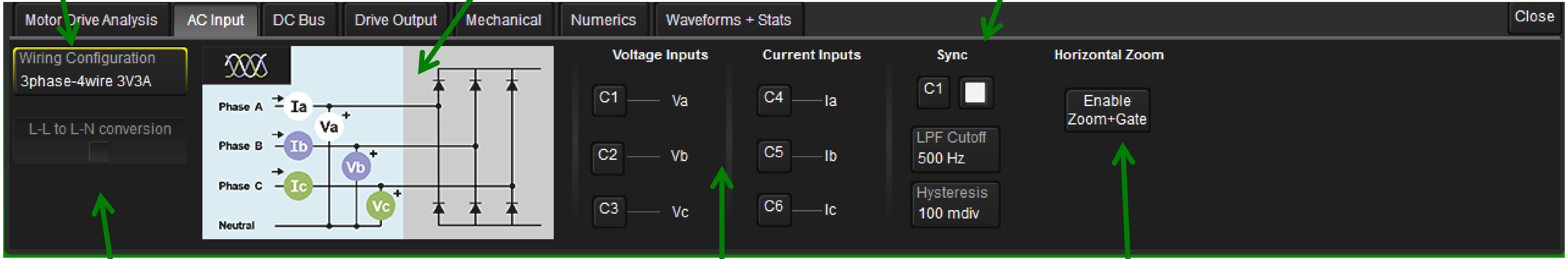
AC Input Setup Dialog Overview

Wiring configuration selection



Wiring setup image changes dynamically with selected wiring configuration

Waveform period synchronization setup (for per-cycle measurement analysis)



Wiring Configuration: 3phase-4wire 3V3A

C1 — Va

C2 — Vb

C3 — Vc

C4 — Ia

C5 — Ib

C6 — Ic

Sync: C1

LPF Cutoff: 500 Hz

Hysteresis: 100 mdiv

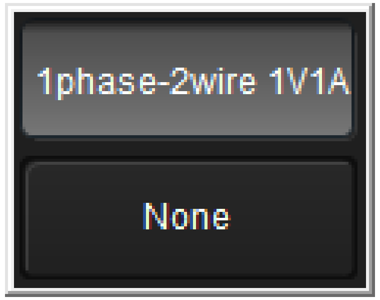
L-L to L-N voltage conversion (when applicable, selectable individually for each power section tab)

AC Input Voltage and Current Assignments

Enable **Zoom+Gate** – button and indicator (gray when “ON”)

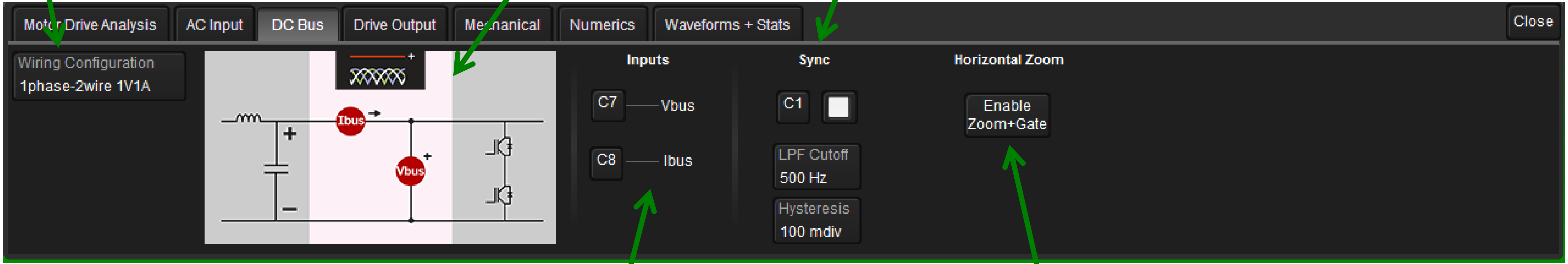
DC Bus Setup Dialog Overview

Wiring configuration selection



Wiring setup image changes dynamically with selected wiring configuration

Waveform period synchronization setup (for per-cycle measurement analysis)



Wiring Configuration
1phase-2wire 1V1A

C7 Vbus
C8 Ibus

C1 ☐

LPF Cutoff
500 Hz

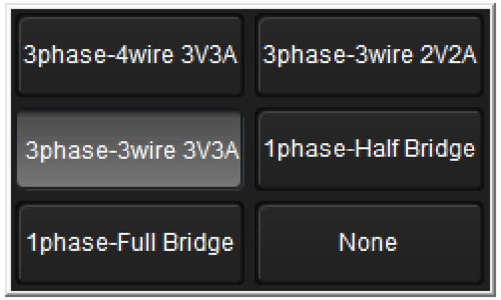
Hysteresis
100 mdiv

DC Bus Voltage and Current Assignments

Enable **Zoom+Gate** – button and indicator (gray when "ON")

Drive Output Setup Dialog Overview

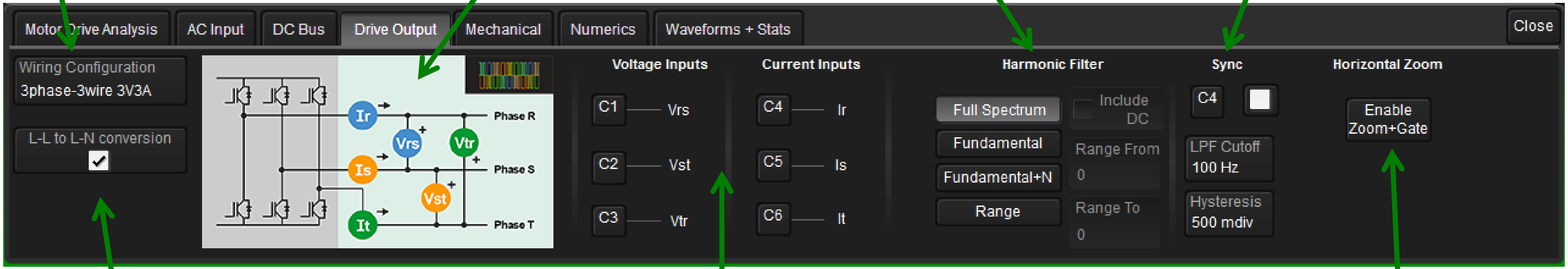
Wiring configuration selection



Wiring setup image changes dynamically with selected wiring configuration

Harmonic Filter Setup

Waveform period synchronization setup (for per-cycle measurement analysis)



Wiring Configuration: 3phase-3wire 3V3A

L-L to L-N conversion ☑

C1 — Vrs

C2 — Vst

C3 — Vtr

C4 — Ir

C5 — Is

C6 — It

Range From: 0

Range To: 0

Sync: C4

LPF Cutoff: 100 Hz

Hysteresis: 500 mdiv

L-L to L-N voltage conversion (when applicable, selectable individually for each power section tab)

Drive Output Voltage and Current Assignments

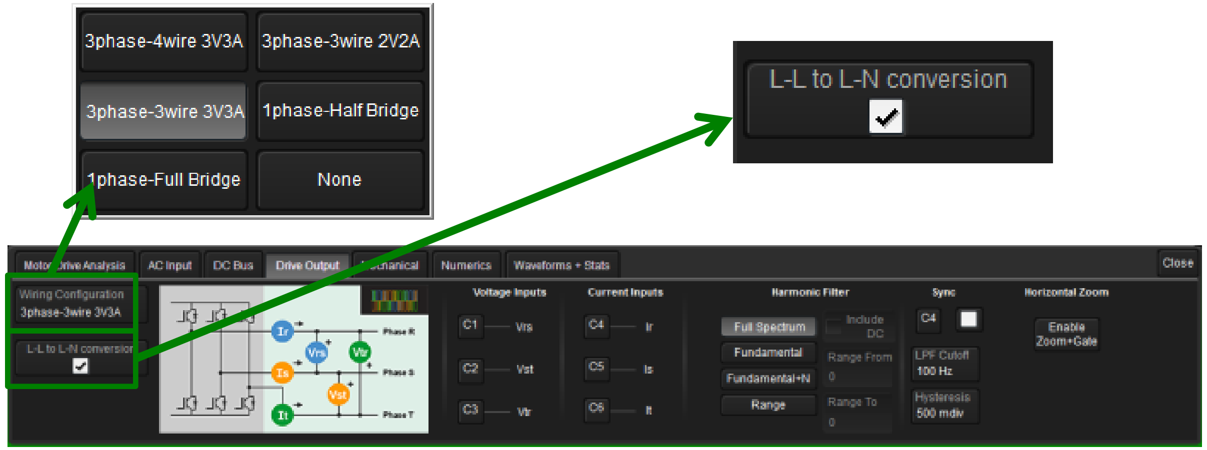
Enable **Zoom+Gate** – button and indicator (gray when “ON”)

Wiring Configuration - Setup

Complete wiring configuration selection, with L-L to L-N voltage conversion standard

- Wiring configuration is user-selectable
  - We support the same 1-phase and 3-phase configurations
- Line-Line (L-L) to Line-Neutral (L-N) conversion is a standard feature

- Intuitive, graphical UI makes for better understanding of required three-phase connections
  - “That’s nice !



Wiring Configuration 3phase-3wire 3V3A

L-L to L-N conversion ☑

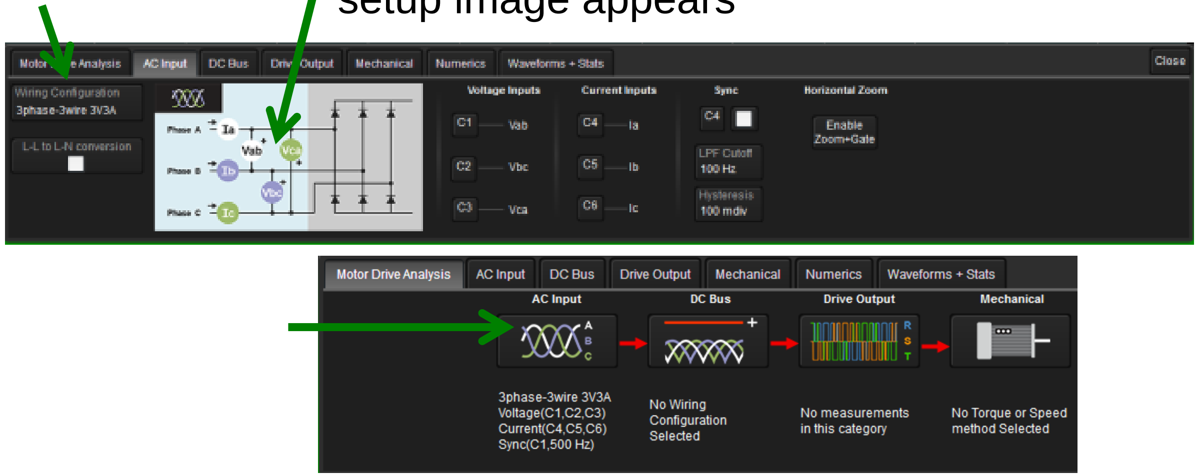
C1 Vrs, C2 Vst, C3 Vtr

C4 Ir, C5 Is, C6 It

Include DC ☐ Range From 0 Range To 0

C4 ☐ LPF Cutoff 100 Hz Hysteresis 500 mdiv

Corresponding graphical setup image appears



Wiring Configuration 3phase-3wire 3V3A

L-L to L-N conversion ☐

C1 Vab, C2 Vbc, C3 Vca

C4 Ia, C5 Ib, C6 Ic

C4 ☐ LPF Cutoff 100 Hz Hysteresis 100 mdiv

AC Input: 3phase-3wire 3V3A Voltage(C1,C2,C3) Current(C4,C5,C6) Sync(C1,500 Hz)

DC Bus: No Wiring Configuration Selected

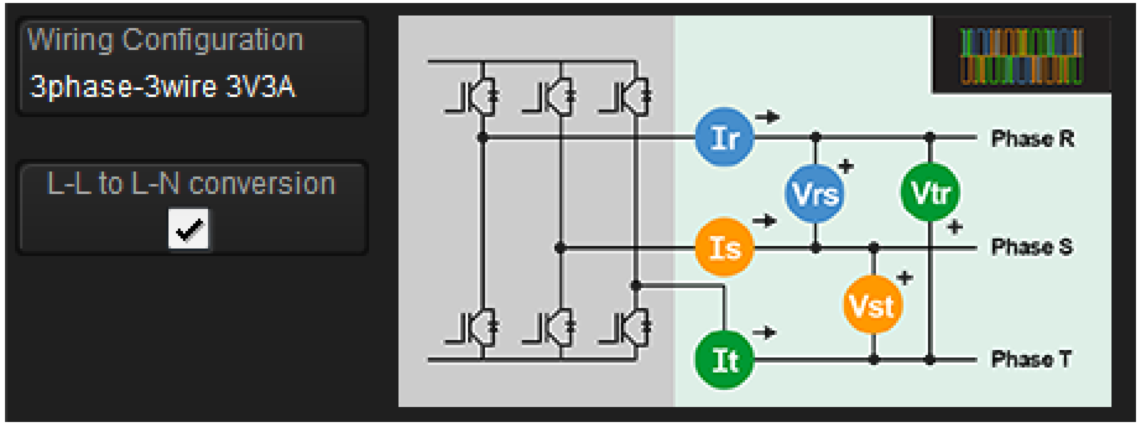
Drive Output: No measurements in this category

Mechanical: No Torque or Speed method Selected

Intuitive 3-phase, 3-wire (3V3A) Associations

Voltages and Currents Associate in an Intuitive Fashion

- More intuitive line-line voltage and line current associations
  - V_{RS} -› I_R
  - V_{ST} -› I_S
  - V_{TR} -› I_T



Wiring Configuration: 3phase-3wire 3V3A

L-L to L-N conversion ☑

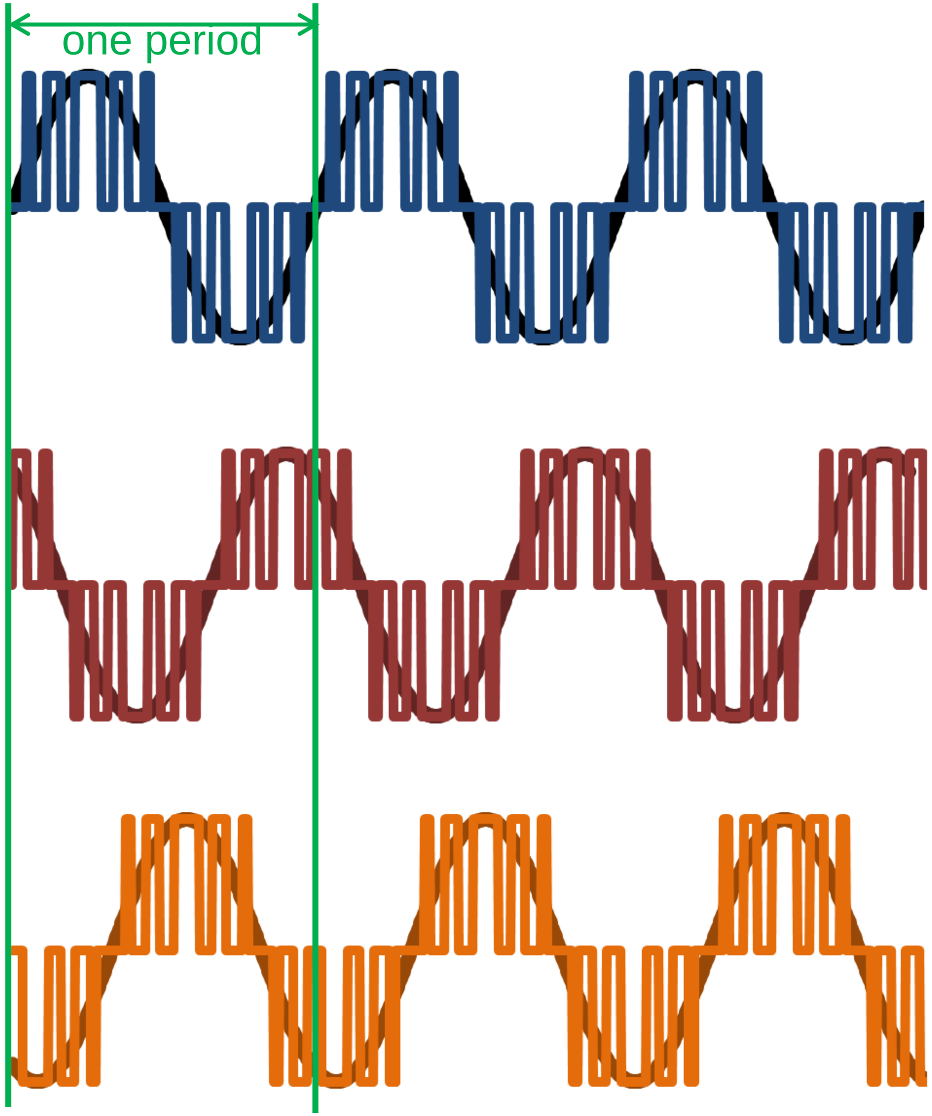
- It’s easy to remember how to set up the wiring assignments

- When acquired, L-L voltage and L-N currents “associate” in an expected way

“Per Cycle” Measurement Technique for Power Analysis

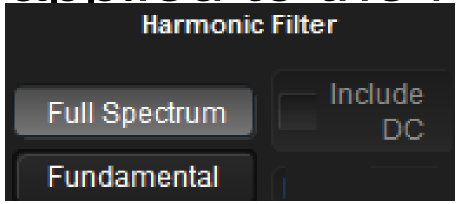
The selected Sync signal determines the measurement period

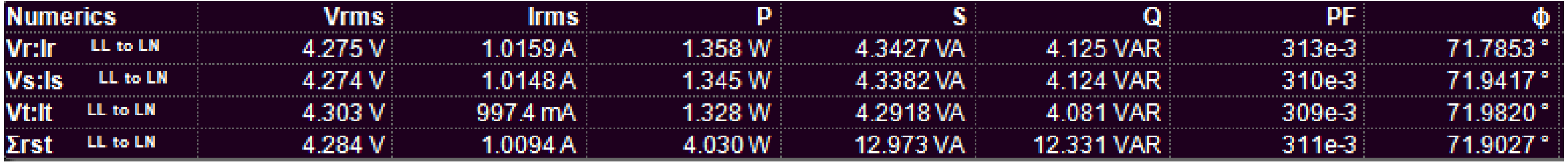
- Take a long acquisition
  - Only two cycles are shown, to the right, as an example
- Detect the cyclical period, and “slice” the waveforms into these periods
  - We know how to do this – this is what we in serial data jitter analysis
- In each “sliced” period
  - Calculate Real Power (P) as instantaneously V * I sampled data
  - Calculate Apparent Power (S) as V_{rms} * I_{rms} for each cyclical period
  - “N” measurement values for “N” cyclical periods in each acquisition
  - Solve for Q, as before.
- Calculate V_{DC}, I_{DC}, I_{peak}, $V_{peak,}$ etc. as well on a per-cycle basis



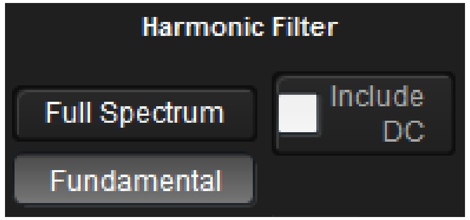
Drive Output Harmonic Filter

- Drive PWM Output contains a lot of high frequency “harmonic” content
- Motors are by nature LC filters – they filter this content out
- Capability to look at Numerics data with a filter applied at the output
- This is a line-line voltage probed example with a L-L to L-N conversion applied to the Numerics data





Numerics		Vrms	Irms	P	S	Q	PF	ϕ
Vr:Ir	LL to LN	4.275 V	1.0159 A	1.358 W	4.3427 VA	4.125 VAR	313e-3	71.7853 °
Vs:Is	LL to LN	4.274 V	1.0148 A	1.345 W	4.3382 VA	4.124 VAR	310e-3	71.9417 °
Vt:It	LL to LN	4.303 V	997.4 mA	1.328 W	4.2918 VA	4.081 VAR	309e-3	71.9820 °
Σrst	LL to LN	4.284 V	1.0094 A	4.030 W	12.973 VA	12.331 VAR	311e-3	71.9027 °



Numerics		Vrms	Irms	P	S	Q	PF	ϕ
Vr:Ir	LL to LN	1.357 V	1.0139 A	1.331 W	1.3756 VA	349 mVAR	967e-3	14.6983 °
Vs:Is	LL to LN	1.355 V	1.0131 A	1.318 W	1.3725 VA	382 mVAR	961e-3	16.1353 °
Vt:It	LL to LN	1.361 V	995.0 mA	1.305 W	1.3537 VA	361 mVAR	964e-3	15.4474 °
Σrst	LL to LN	1.357 V	1.0073 A	3.953 W	4.1018 VA	1.093 VAR	964e-3	15.4385 °

- At fundamental only, Apparent Power and Reactive Power values are reduced, Power Factor goes up, and Phase Angle goes down (as expected)

Zoom+Gate Operation

Push “Zoom+Gate” button to create Zooms and Gate the Numerics table to zoomed area

Zoomed Area in Acquisition

Original, Full Record Length Acquisitions

All table data is calculated on zoomed area only

Numerics	Vrms	Irms	P	S	Q	PF	ϕ
Vrs:Ir	12.5562 V	2.7784 A	---	---	---	---	---
Vst:Is	12.6712 V	2.7040 A	---	---	---	---	---
Vtr:It	13.3013 V	2.7633 A	---	---	---	---	---
Σrst	12.8429 V	2.7486 A	19.690 W	73.916 VA	71.029 VAR	266e-3	74.5242 °

Statistics	P(Σrst)	PF(Σrst)
value	30.808 W	257e-3
mean	19.69 W	266.16e-3
min	10.537 W	127e-3
max	43.396 W	395e-3
sdev	10.56 W	67.73e-3
num	12	12
status	✓	✓

Zooms

Displayed Sync Signal is Zoomed

Per-cycle “synthesized” Waveforms are Zoomed

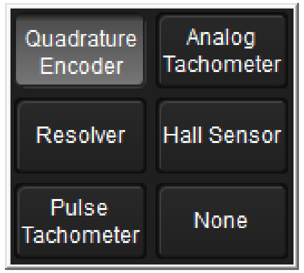
Light Glows “ON” when in Zoom+Gate mode

Mechanical Setup Dialog Overview

Torque Sensing Method Selection

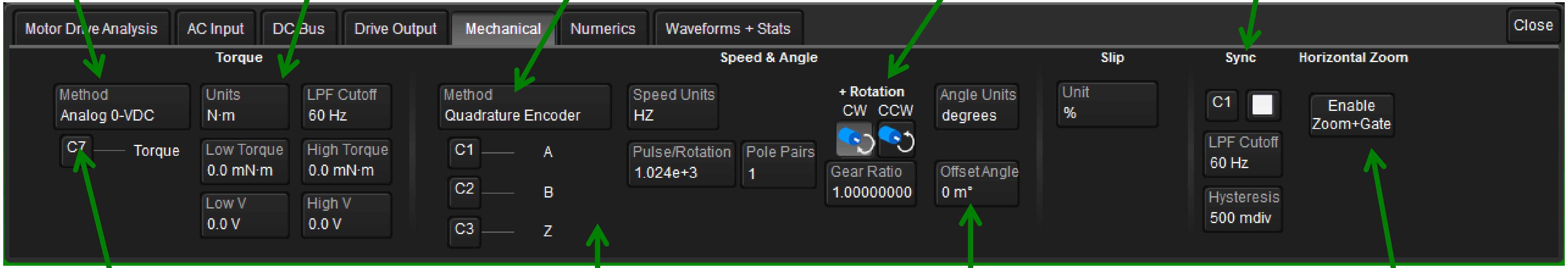
Select Units, Filter Cutoff, and Scaling

Speed, Angle, Direction Method Selection



Rotation direction is arbitrary – select one of these to get correct sign of rotation parameter

Waveform period synchronization setup (for per-cycle measurement analysis)



Torque

Method: Analog 0-VDC
C7 — Torque
Units: N·m
LPF Cutoff: 60 Hz
Low Torque: 0.0 mN·m
High Torque: 0.0 mN·m
Low V: 0.0 V
High V: 0.0 V

Speed & Angle

Method: Quadrature Encoder
C1 — A
C2 — B
C3 — Z
Speed Units: HZ
Pulse/Rotation: 1.024e+3
Pole Pairs: 1
Gear Ratio: 1.00000000
Angle Units: degrees
Offset Angle: 0 m°

Slip

Unit: %

Sync

C1
LPF Cutoff: 60 Hz
Hysteresis: 500 mdiv

Select the analog channel to use for Torque sensing input

Speed & Angle setup changes depending on Method selected

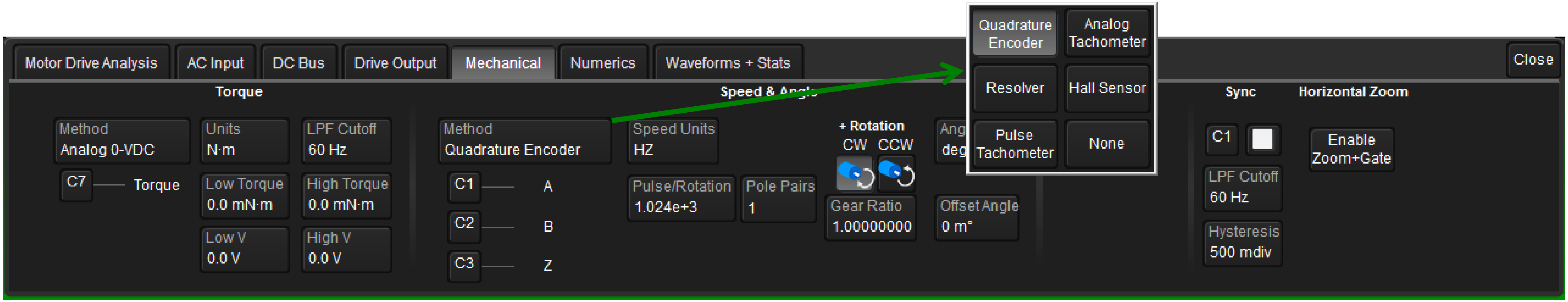
“Angle” is the arbitrary shaft rotation angle. “Offset Angle” allows correction to something not arbitrary (e.g. rotor field)

Enable **Zoom+Gate** – button and indicator (gray when “ON”)

Mechanical Setup – The Most Complete Motor Sensor Integration

Standard with MDA – Teledyne LeCroy

- Torque Load Cells
- Analog and Digital Speed Sensors
  - Analog/Pulse Tachometer (speed)
  - Hall Sensor (speed and direction)
  - Resolver (speed and direction)
  - Quadrature Encoder Interface (speed, direction, absolute position)



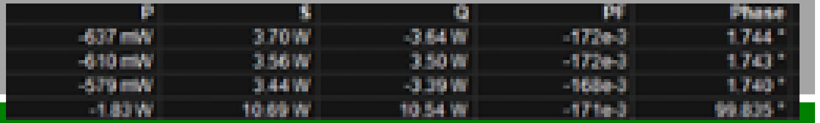
Torque:
Method: Analog 0-VDC
Units: N·m
LPF Cutoff: 60 Hz
C7 — Torque
Low Torque: 0.0 mN·m
High Torque: 0.0 mN·m
Low V: 0.0 V
High V: 0.0 V

Speed & Angle:
Method: Quadrature Encoder
Speed Units: HZ
C1 — A
C2 — B
C3 — Z
Pulse/Rotation: 1.024e+3
Pole Pairs: 1
+ Rotation: CW CCW
Gear Ratio: 1.00000000
Ang: deg
Offset Angle: 0 m°

Sync:
C1
LPF Cutoff: 60 Hz
Hysteresis: 500 mdiv

Mechanical Setup – The Most Complete Motor Sensor Integration

Speed x Torque = Mechanical Power, so complete sensor support is critical

Sensor Type	Sensing Capability	 
Analog Tachometer	**Speed**	**Fully-supported.**
Digital (Pulse) Tachometer		**Fully-supported.**
Hall Effect Sensors	**Speed + Direction**	**Fully-supported.** **Commonly used in BLDC applications. Signals are digital, so MSO inputs can be used for sensing, preserving analog channels for other needs.**
Resolver		**Fully-supported.** **Commonly used in Vector FOC motor drives where high-precision and reliability is required (e.g. hybrid/EV vehicle propulsion)**
Quadrature Encoder Interface (QEI)	**Speed + Direction + Absolute Position**	**Fully-supported.** **Commonly used in Vector FOC motor drives as it provides absolute position of rotor field. Engineers may debug with QEI even when production drives use Resolvers.**
Analog Load Cell	**Torque**	**Fully-supported.**

P	S	Q	PF	Phase
-637 mW	3.70 W	-3.64 W	-172e-3	1.744 °
-610 mW	3.56 W	3.50 W	-172e-3	1.743 °
-579 mW	3.44 W	-3.39 W	-168e-3	1.740 °
-1.83 W	10.69 W	10.54 W	-171e-3	99.835 °

Numeric Table Setup Dialog Overview

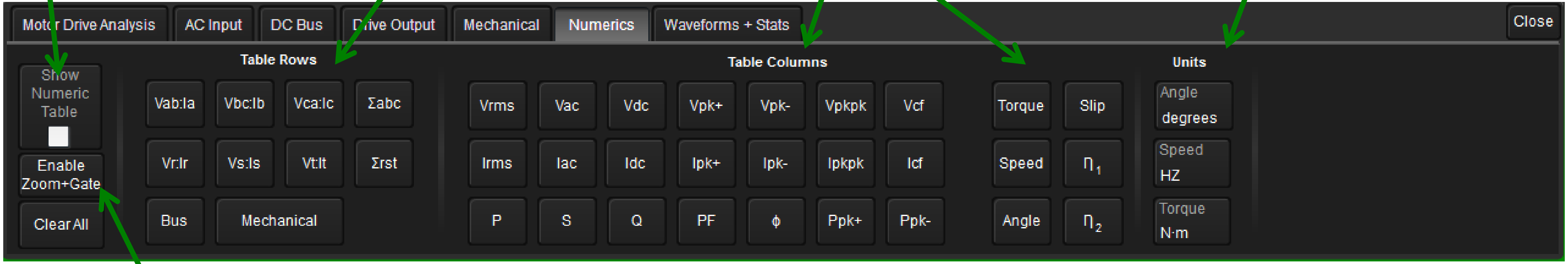
Push “Numerics” button to open setup dialog and/or display Numerics table

Check the box to display the table

Table row (source) selections dynamically change based on wiring configuration

Table column (measurement) selections are made here

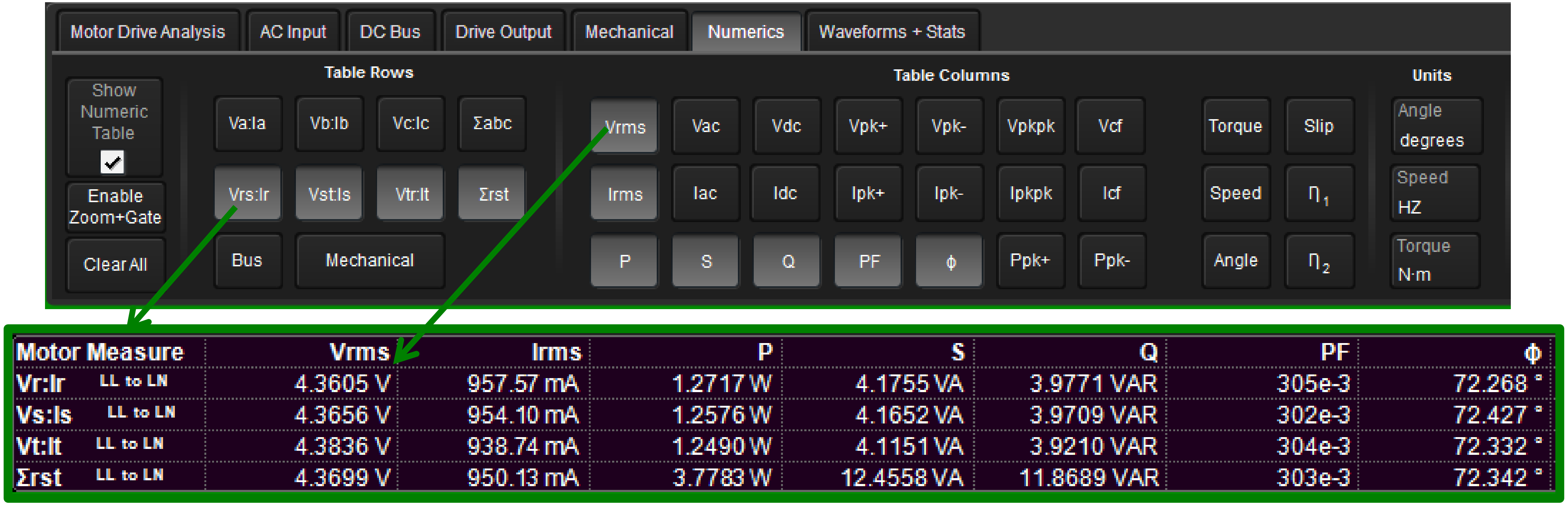
Mechanical Units Selection



Enable **Zoom+Gate** – button and indicator (gray when “ON”)

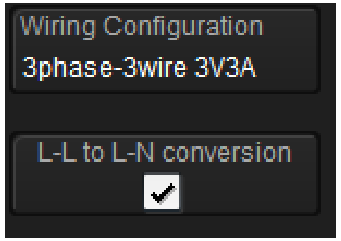
Numeric Voltage, Current and Power Results Table

- User-Configurable "Power" Results Table (up to 10 rows and 12 columns)



Motor Measure	Vrms	Irms	P	S	Q	PF	ϕ
Vr:Ir LL to LN	4.3605 V	957.57 mA	1.2717 W	4.1755 VA	3.9771 VAR	305e-3	72.268 °
Vs:Is LL to LN	4.3656 V	954.10 mA	1.2576 W	4.1652 VA	3.9709 VAR	302e-3	72.427 °
Vt:It LL to LN	4.3836 V	938.74 mA	1.2490 W	4.1151 VA	3.9210 VAR	304e-3	72.332 °
Σrst LL to LN	4.3699 V	950.13 mA	3.7783 W	12.4558 VA	11.8689 VAR	303e-3	72.342 °

- Selection of Rows and Columns Populates the Results Table
- Probe Line-Line (L-L) and Display Results in Line-Neutral (L-N)
  - Using L-L to L-N conversion



Wiring Configuration
3phase-3wire 3V3A

L-L to L-N conversion ☑

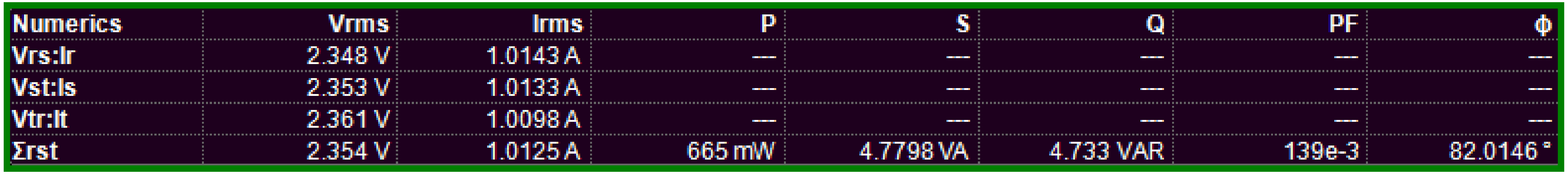
Waveform (Voltage and Current) Acquisition

with Numeric Voltage, Current and Power Results Table Shown

- Displays the mean value of parameter for the complete acquisition
- Single table, easy to configure
  - Up to 10 rows x 12 columns
    - 120 measurements in one table
  - Inherently customizable
    - Populates as selections made

⚠ Failed to load setup file c:\LeCroy\XStream\Calibration\BTD\MainBoardBTD1.vbs

1/26/2015 11:00:42 PM



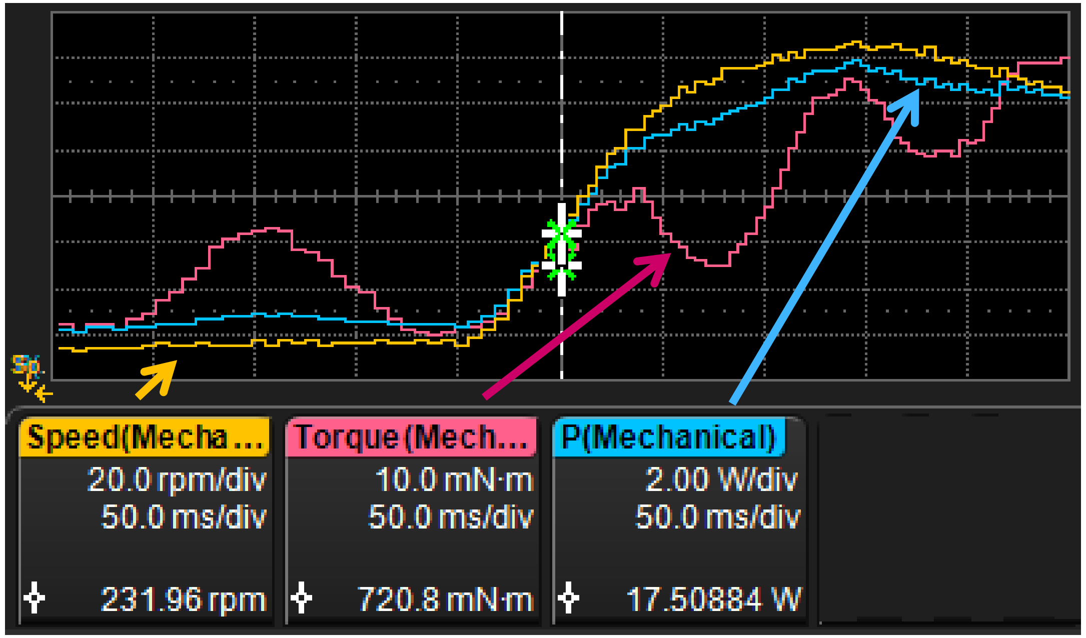
Numerics	Vrms	Irms	P	S	Q	PF	ϕ
Vrs:Ir	2.348 V	1.0143 A	---	---	---	---	---
Vst:Is	2.353 V	1.0133 A	---	---	---	---	---
Vtr:It	2.361 V	1.0098 A	---	---	---	---	---
Σrst	2.354 V	1.0125 A	665 mW	4.7798 VA	4.733 VAR	139e-3	82.0146 °

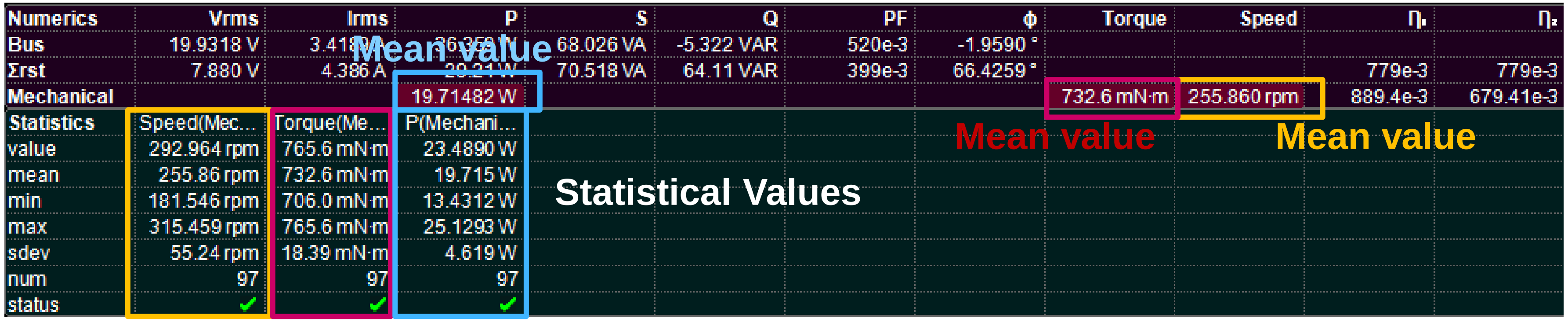
Per-Cycle “Synthesized” Waveforms and Statistics

Unique Teledyne LeCroy features!

- Click on a Numeric table mean value
- Get detailed statistics on all cycles in the Statistics table
- Create a Waveform of the data over time

Time-correlated waveforms indicate drive system behavior over time





Numerics	Vrms	Irms	P	S	Q	PF	ϕ	Torque	Speed	η₁	η₂
Bus	19.9318 V	3.418[illegible]	36.35[illegible]	68.026 VA	-5.322 VAR	520e-3	-1.9590 °				
Σrst	7.880 V	4.386 A	20.21 W	70.518 VA	64.11 VAR	399e-3	66.4259 °			779e-3	779e-3
Mechanical			19.71482 W					732.6 mN·m	255.860 rpm	889.4e-3	679.41e-3

Statistics	Speed(Mec…	Torque(Me…	P(Mechani…
value	292.964 rpm	765.6 mN·m	23.4890 W
mean	255.86 rpm	732.6 mN·m	19.715 W
min	181.546 rpm	706.0 mN·m	13.4312 W
max	315.459 rpm	765.6 mN·m	25.1293 W
sdev	55.24 rpm	18.39 mN·m	4.619 W
num	97	97	97
status	✓	✓	✓

Mean value

Mean value

Mean value

Statistical Values

Conclusions

- The MDA address a complex world of applications
- The system, thanks to the acquisition capabilities and the application software allows a relatively simple approach giving results which are useful for debugging and characterization
- There is a unique capability to analyze the system in dynamic condition and not only static one.

- It is still a general purpose oscilloscope …

- Questions?

Application 2: Brushless DC Power Tool Analysis

TELEDYNE LECROY
Everywhereyoulook™

Brushless DC Power Tool Analysis

C3 F B D 8.4 V/div 0.0 mV ofst 23.1781 V
C6 F B D 10.0 A/div 0.0 mA ofst -12.3962 A
Z3 zoom(C3) 1.00 V/div 50.0 ms/div 23.1781 V
Z6 zoom(C6) 5.00 A/div 50.0 ms/div -12.3962 A

C7 F B D 200 mV/div -265.00 mV 722.750 mV
C8 F B D 500 mV/div -1.29500 V 816.44 mV
Digital1 [3] 12.5 MS/s 25.0 MS 0x3
Z7 zoom(C7) 200 mV/div 50.0 ms/div 722.750 mV
Z8 zoom(C8) 500 mV/div 50.0 ms/div 816.44 mV
Z9 zoom(Dig[3] 12.5 MS/s 6.25 MS 0x3

C1 B D 8.0 V 0 mV 26.5 V
C2 B D 8.0 V 0 mV 24.0 V
C4 B D 10.0 A 0 mA -14.1 A
C5 B D 10.0 A 0 mA 1.65 A
Z1 zoo... 8.0 V 50 ms 26.5 V
Z2 zoo... 8.0 V 50 ms 24.0 V
Z4 zoo... 10.0 A 50 ms -14.1 A
Z5 zoo... 10.0 A 50 ms 1.65 A

Speed(Mecha... 10.0 rpm/div 50.0 ms/div 115.98 rpm
Torque(Mech... 10.0 mN·m 50.0 ms/div 720.8 mN·m
P(Mechanical) 1.00 W/div 50.0 ms/div 8.754422 W
XY2 C8,C7 200 mV/div 500 mV/div
XY1 Speed(... 10.0 mN·m 10.0 rpm/div
XY3 Z8,Z7 200 mV/div 500 mV/div

Numerics	Vrms	Irms	P	S	Q	PF	ϕ	Torque	Speed	η_1	η_2
Bus	19.9318 V	3.4189 A	36.359 W	68.026 VA	-5.322 VAR	520e-3	-1.9590 °				
Σrst	7.880 V	4.386 A	29.21 W	70.518 VA	64.11 VAR	399e-3	66.4259 °			779e-3	779e-3
Mechanical			9.85741 W					732.6 mN·m	127.930 rpm	444.7e-3	339.70e-3

Timebase -920 ms 200 ms/div 25 MS 12.5 MS/s
Trigger C1 DC Stop 7.7 V Edge Positive
X1= 648.5356 ms

1/22/2015 4:01:10 PM

Numerics	Vrms	Irms	P	S	Q	PF	ϕ	Torque	Speed	η_1	η_2
Bus	19.9318 V	3.4189 A	36.359 W	68.026 VA	-5.322 VAR	520e-3	-1.9590 °				
Σrst	7.880 V	4.386 A	29.21 W	70.518 VA	64.11 VAR	399e-3	66.4259 °			779e-3	779e-3
Mechanical			19.71482 W					732.6 mN·m	255.860 rpm	889.4e-3	679.41e-3

Timebase -920 ms
200 ms/div
25 MS 12.5 MS/s
Trigger C1 DC
Stop 7.7 V
Edge Positive
X1= 648.5356 ms

Torque

Method: Analog 0-VDC
Units: N·m
LPF Cutoff: 500 Hz
C7 — Torque
Low Torque: -10.00 N·m
High Torque: 10.000 N·m
Low V: -10.00000 V
High V: 10.00000 V

Speed & Angle

Method: Hall Sensor
Speed Units: RPM
D1 — Hall R
D2 — Hall S
D3 — Hall T
Pole Pairs: 1
Hall Angle: 120 °
+ Rotation: CW CCW
Gear Ratio: 48.5300000
Angle Units: degrees

Slip

Unit: %

Sync

C1
LPF Cutoff: 100 Hz
Hysteresis: 20 mdiv

Horizontal Zoom

Numerics	Vrms	Irms	P	S	Q	PF	ϕ	Torque	Speed	η_1	η_2
Bus	19.9318 V	3.4189 A	36.359 W	68.026 VA	-5.322 VAR	520e-3	-1.9590 °				
Σrst	7.880 V	4.386 A	29.21 W	70.518 VA	64.11 VAR	399e-3	66.4259 °			779e-3	779e-3
Mechanical			19.71482 W					732.6 mN·m	255.860 rpm	889.4e-3	679.41e-3

Timebase -920 ms
200 ms/div
25 MS 12.5 MS/s
X1= 648.5356 ms

Trigger C1 DC
Stop 7.7 V
Edge Positive

1/22/2015 4:01:52 PM

Numerics	Vrms	Irms	P	S	Q	PF	ϕ	Torque	Speed	η₁	η₂
Bus	19.9318 V	3.4189 A	36.359 W	68.026 VA	-5.322 VAR	520e-3	-1.9590 °				
Σrst	7.880 V	4.386 A	29.21 W	70.518 VA	64.11 VAR	399e-3	66.4259 °			779e-3	779e-3
Mechanical			19.71482 W					732.6 mN·m	255.860 rpm	889.4e-3	679.41e-3

Statistics	Speed(Mec...	Torque(Me...	P(Mechani...
value	292.964 rpm	765.6 mN·m	23.4890 W
mean	255.86 rpm	732.6 mN·m	19.715 W
min	181.546 rpm	706.0 mN·m	13.4312 W
max	315.459 rpm	765.6 mN·m	25.1293 W
sdev	55.24 rpm	18.39 mN·m	4.619 W
num	97	97	97
status	✓	✓	✓

Timebase -920 ms 200 ms/div 25 MS 12.5 MS/s
Trigger C1 DC Stop 7.7 V Edge Positive
X1= 648.5356 ms

FrontPanelExtender :

1/22/2015 4:02:01 PM

Numerics	Vrms	Irms	P	S	Q	PF	ϕ	Torque	Speed	η₁	η₂
Bus	19.9318 V	3.4189 A	36.359 W	68.026 VA	-5.322 VAR	520e-3	-1.9590 °				
Σrst	7.880 V	4.386 A	29.21 W	70.518 VA	64.11 VAR	399e-3	66.4259 °			779e-3	779e-3
Mechanical			19.71482 W					732.6 mN·m	255.860 rpm	889.4e-3	679.41e-3

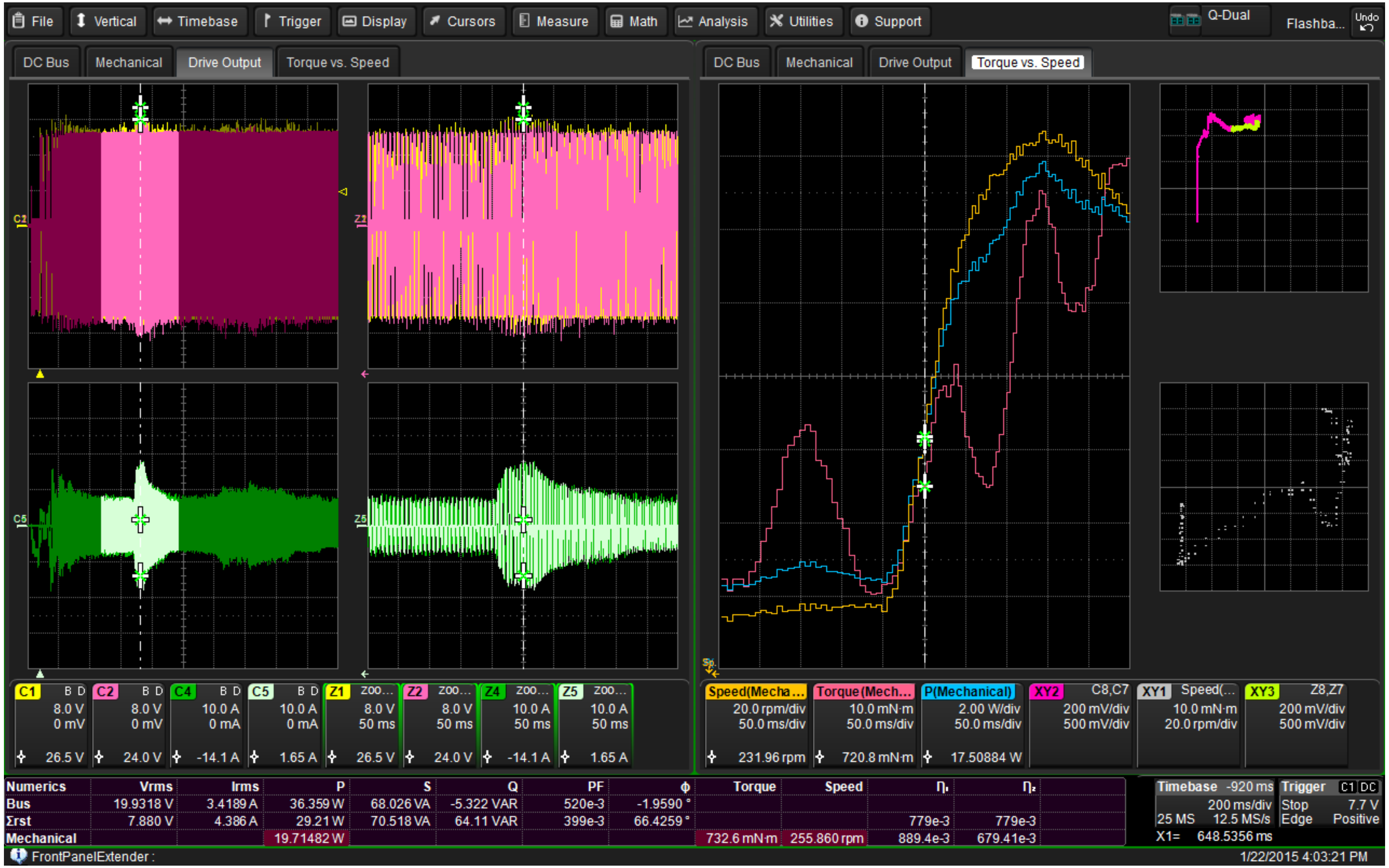
Statistics	Speed(Mec...	Torque(Me...	P(Mechani...
value	292.964 rpm	765.6 mN·m	23.4890 W
mean	255.86 rpm	732.6 mN·m	19.715 W
min	181.546 rpm	706.0 mN·m	13.4312 W
max	315.459 rpm	765.6 mN·m	25.1293 W
sdev	55.24 rpm	18.39 mN·m	4.619 W
num	97	97	97
status	✓	✓	✓

Timebase	-920 ms	Trigger	C1 DC
	200 ms/div	Stop	7.7 V
25 MS	12.5 MS/s	Edge	Positive

X1= 648.5356 ms

FrontPanelExtender :

1/22/2015 4:03:04 PM



Numerics	Vrms	Irms	P	S	Q	PF	ϕ	Torque	Speed	η_1	η_2
Bus	19.9318 V	3.4189 A	36.359 W	68.026 VA	-5.322 VAR	520e-3	-1.9590 °				
Σrst	7.880 V	4.386 A	29.21 W	70.518 VA	64.11 VAR	399e-3	66.4259 °			779e-3	779e-3
Mechanical			19.71482 W					732.6 mN·m	255.860 rpm	889.4e-3	679.41e-3

Timebase -920 ms
200 ms/div
25 MS 12.5 MS/s
X1= 648.5356 ms

Trigger C1 DC
Stop 7.7 V
Edge Positive

FrontPanelExtender :

1/22/2015 4:03:21 PM

Numerics	Vrms	Irms	P	S	Q	PF	ϕ	Torque	Speed	η_1	η_2
Bus	19.7852 V	7.4611 A	80.306 W	147.616 VA	-39.104 VAR	544e-3	-19.4869 °				
Σrst	8.138 V	9.780 A	66.55 W	159.208 VA	144.62 VAR	418e-3	65.2956 °			829e-3	829e-3
Mechanical			17.6119 W					722.0 mN·m	232.935 rpm	264.8e-3	219.41e-3

Timebase -920 ms
200 ms/div
25 MS 12.5 MS/s
Trigger C1 DC
Stop 7.7 V
Edge Positive
X1= 648.5356 ms

FrontPanelExtender :

1/22/2015 4:04:15 PM

C1 B D 8.0 V 0 mV 26.5 V
C2 B D 8.0 V 0 mV 24.0 V
C4 B D 10.0 A 0 mA -14.1 A
C5 B D 10.0 A 0 mA 1.65 A
Z1 ZOO... 8.0 V 5.0 ms 26.5 V
Z2 ZOO... 8.0 V 5.0 ms 24.0 V
Z4 ZOO... 10.0 A 5.0 ms -14.1 A
Z5 ZOO... 10.0 A 5.0 ms 1.65 A

Speed(Mecha... 10.0 rpm/div 5.00 ms/div 231.96 rpm
Torque(Mech... 5.00 mN·m 5.00 ms/div 720.8 mN·m
P(Mechanical) 1.00 W/div 5.00 ms/div 17.50887 W
XY2 C8,C7 200 mV/div 500 mV/div
XY1 Speed(... 5.00 mN·m 10.0 rpm/div
XY3 Z8,Z7 200 mV/div 500 mV/div

Numerics	Vrms	Irms	P	S	Q	PF	ϕ	Torque	Speed	η_1	η_2
Bus	19.7870 V	7.4184 A	80.627 W	146.780 VA	-59.532 VAR	549e-3	-28.8124 °				
Σrst	8.169 V	9.707 A	67.01 W	158.718 VA	143.85 VAR	421e-3	65.0734 °			830e-3	830e-3
Mechanical			17.9678 W					724.7 mN·m	236.628 rpm	268.7e-3	223.01e-3

Timebase -920 ms
200 ms/div
25 MS 12.5 MS/s
Trigger C1 DC
Stop 7.7 V
Edge Positive
X1= 648.5356 ms

FrontPanelExtender :
1/22/2015 4:04:41 PM

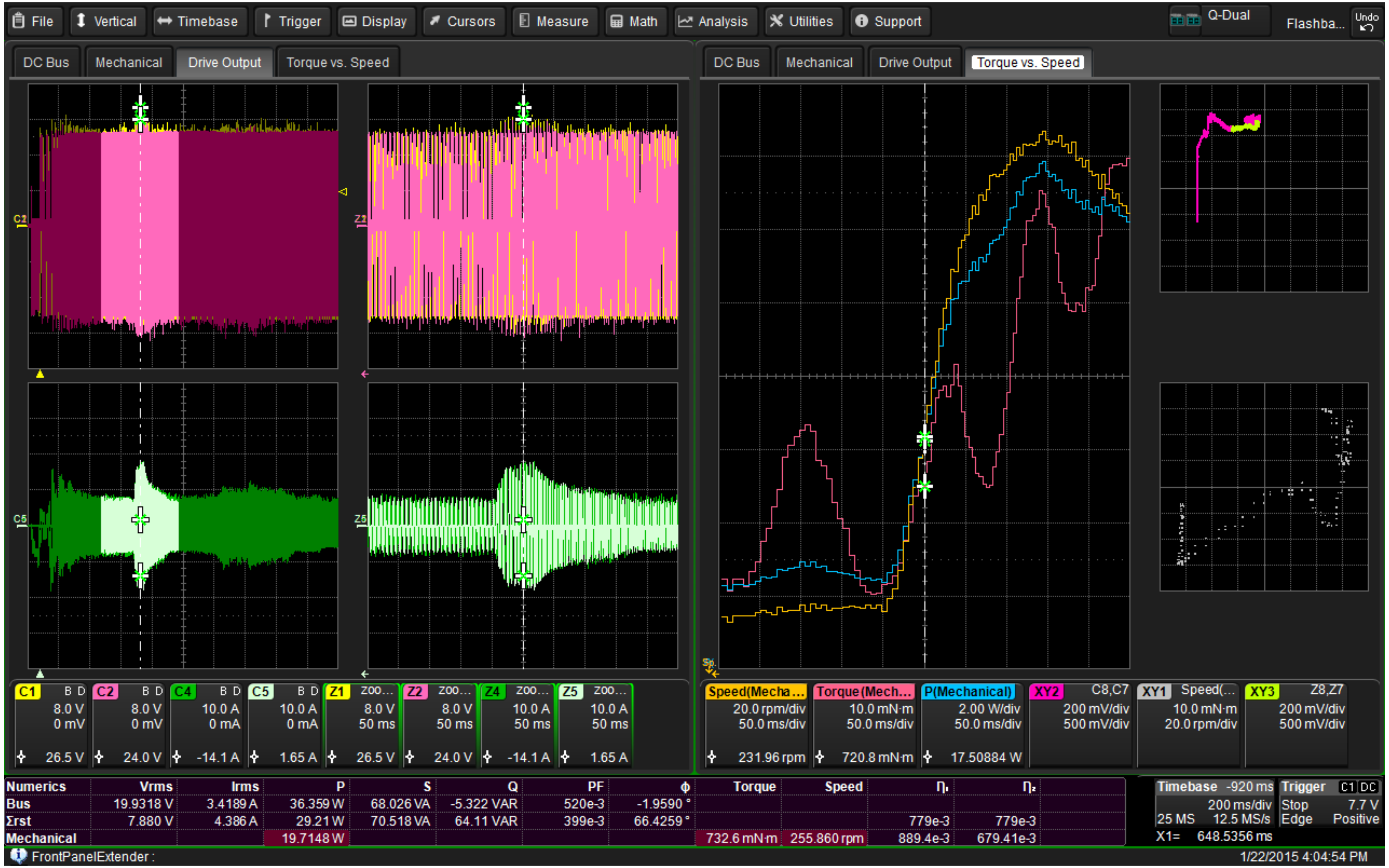
C1 B D 8.0 V 0 mV 26.5 V
C2 B D 8.0 V 0 mV 24.0 V
C4 B D 10.0 A 0 mA -14.1 A
C5 B D 10.0 A 0 mA 1.65 A
Z1 ZOO... 8.0 V 20 ms 26.5 V
Z2 ZOO... 8.0 V 20 ms 24.0 V
Z4 ZOO... 10.0 A 20 ms -14.1 A
Z5 ZOO... 10.0 A 20 ms 1.65 A
Speed(Mecha... 20.0 rpm/div 20.0 ms/div 231.96 rpm
Torque(Mech... 5.00 mN·m 20.0 ms/div 720.8 mN·m
P(Mechanical) 2.00 W/div 20.0 ms/div 17.50885 W
XY2 C8,C7 200 mV/div 500 mV/div
XY1 Speed(... 5.00 mN·m 20.0 rpm/div
XY3 Z8,Z7 200 mV/div 500 mV/div

Numerics	Vrms	Irms	P	S	Q	PF	ϕ	Torque	Speed	η_1	η_2
Bus	19.8725 V	4.9290 A	53.635 W	97.817 VA	-18.957 VAR	538e-3	-12.5347 °				
Σrst	8.043 V	6.346 A	44.19 W	103.840 VA	93.89 VAR	416e-3	65.4093 °			806e-3	806e-3
Mechanical			18.7093 W					721.2 mN·m	247.242 rpm	536.1e-3	419.55e-3

Timebase -920 ms 200 ms/div 25 MS 12.5 MS/s
Trigger C1 DC Stop 7.7 V Edge Positive
X1= 648.5356 ms

FrontPanelExtender :

1/22/2015 4:04:48 PM



C1 B D 8.0 V 0 mV 26.5 V
C2 B D 8.0 V 0 mV 24.0 V
C4 B D 10.0 A 0 mA -14.1 A
C5 B D 10.0 A 0 mA 1.65 A
Z1 ZOO... 8.0 V 50 ms 26.5 V
Z2 ZOO... 8.0 V 50 ms 24.0 V
Z4 ZOO... 10.0 A 50 ms -14.1 A
Z5 ZOO... 10.0 A 50 ms 1.65 A
Speed(Mecha... 20.0 rpm/div 50.0 ms/div 231.96 rpm
Torque(Mech... 10.0 mN·m 50.0 ms/div 720.8 mN·m
P(Mechanical) 2.00 W/div 50.0 ms/div 17.50884 W
XY2 C8,C7 200 mV/div 500 mV/div
XY1 Speed(... 10.0 mN·m 20.0 rpm/div
XY3 Z8,Z7 200 mV/div 500 mV/div

Numerics	Vrms	Irms	P	S	Q	PF	ϕ	Torque	Speed	η_1	η_2
Bus	19.9318 V	3.4189 A	36.359 W	68.026 VA	-5.322 VAR	520e-3	-1.9590 °				
Σrst	7.880 V	4.386 A	29.21 W	70.518 VA	64.11 VAR	399e-3	66.4259 °			779e-3	779e-3
Mechanical			19.7148 W					732.6 mN·m	255.860 rpm	889.4e-3	679.41e-3

Timebase -920 ms 200 ms/div 25 MS 12.5 MS/s
Trigger C1 DC Stop 7.7 V Edge Positive
X1= 648.5356 ms

FrontPanelExtender :

1/22/2015 4:04:54 PM

C1 B D 8.0 V 0 mV 26.5 V
C2 B D 8.0 V 0 mV 24.0 V
C4 B D 10.0 A 0 mA -14.1 A
C5 B D 10.0 A 0 mA 1.65 A
Z1 ZOO... 8.0 V 100 ms 26.5 V
Z2 ZOO... 8.0 V 100 ms 24.0 V
Z4 ZOO... 10.0 A 100 ms -14.1 A
Z5 ZOO... 10.0 A 100 ms 1.65 A
Speed(Mecha... 50.0 rpm/div 100 ms/div 231.95 rpm
Torque(Mech... 20.0 mN·m 100 ms/div 720.8 mN·m
P(Mechanical) 5.00 W/div 100 ms/div 17.50869 W
XY2 C8,C7 200 mV/div 500 mV/div
XY1 Speed(... 20.0 mN·m 50.0 rpm/div
XY3 Z8,Z7 200 mV/div 500 mV/div

Numerics	Vrms	Irms	P	S	Q	PF	ϕ	Torque	Speed	η₁	η₂
Bus	19.9531 V	2.9062 A	29.838 W	57.909 VA	-2.151 VAR	505e-3	-670.6 m°				
Σrst	7.624 V	3.824 A	23.28 W	58.938 VA	54.08 VAR	383e-3	67.4382 °			760e-3	760e-3
Mechanical			18.9039 W					737.7 mN·m	243.904 rpm	1.0002	753.86e-3

Timebase -920 ms
200 ms/div
25 MS 12.5 MS/s
Trigger C1 DC
Stop 7.7 V
Edge Positive
X1= 648.5356 ms

FrontPanelExtender :

1/22/2015 4:05:03 PM

Three-Phase Power Analysis Software

- Complete 3-phase System Debug and Validation
- Support for 1-phase and 3-phase measurements
- Two-wattmeter and Three-wattmeter Methods Supported
- Per-cycle Time-correlated Waveforms From Power Values

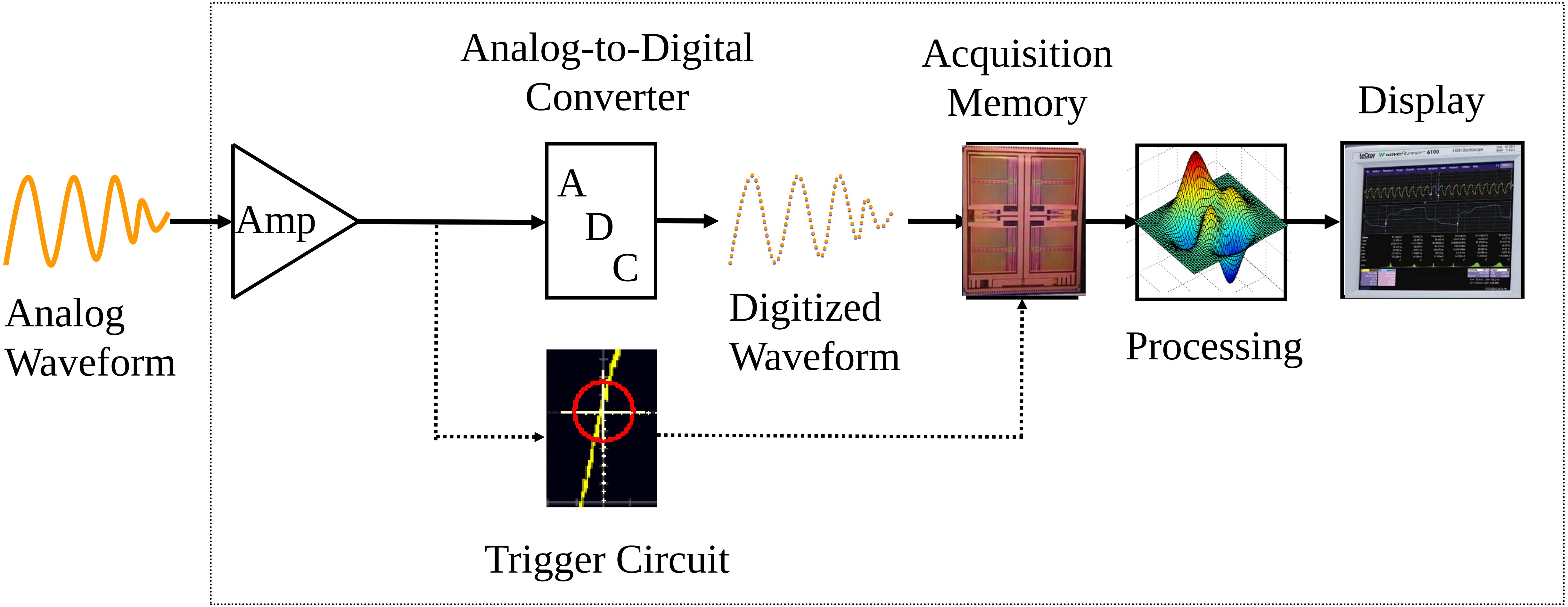
- Available on 4 channels scopes two (using Two-Wattmeter method - **Blondel’s** Theorem)!!!

Video, Application and Posters at : https://teledynelecroy.com/static-dynamic-complete/

HD4096 High Definition Technology

- Combination of
  - High Sample Rate 12-bit ADCs
  - High signal-to-noise input amplifiers
  - Low noise system architecture
- 16 times more resolution than any other oscilloscope on the market
- Capture high frequency signals with 1GHz bandwidth
- Benefits
  - Clean, Crisp Waveforms
  - More Signal Details
  - Precise Waveform Measurements

Waveform Signal Path

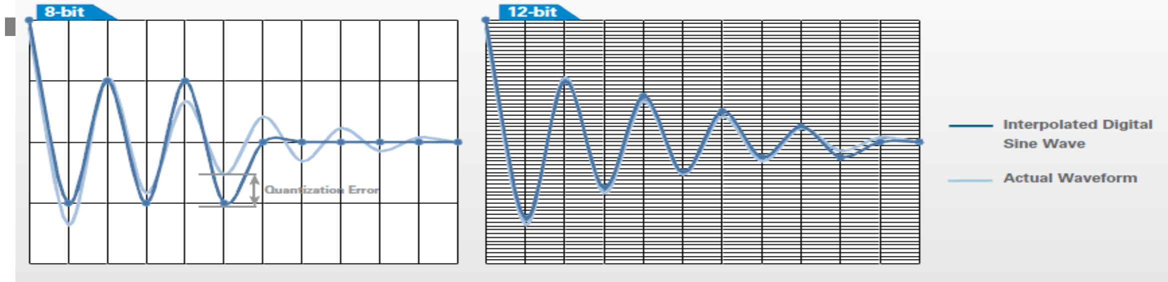


SIMPLIFIED OSCILLOSCOPE BLOCK DIAGRAM

High Definition Oscilloscopes

- Available Quantization Levels in an ADC = **$2^{\text{N bits}}$ of Resolution**

ADC Resolution	Number of Steps	Dynamic Range
8	256	~48 dB
12	4096	~72 dB



- **LeCroy oscilloscopes with high resolution ADCs are the next generation of oscilloscopes providing 16 times more resolution than traditional 8 bit instruments**

16x

LeCroy HRO 6 Zi
8-bit ADC becomes
12-bit ADC

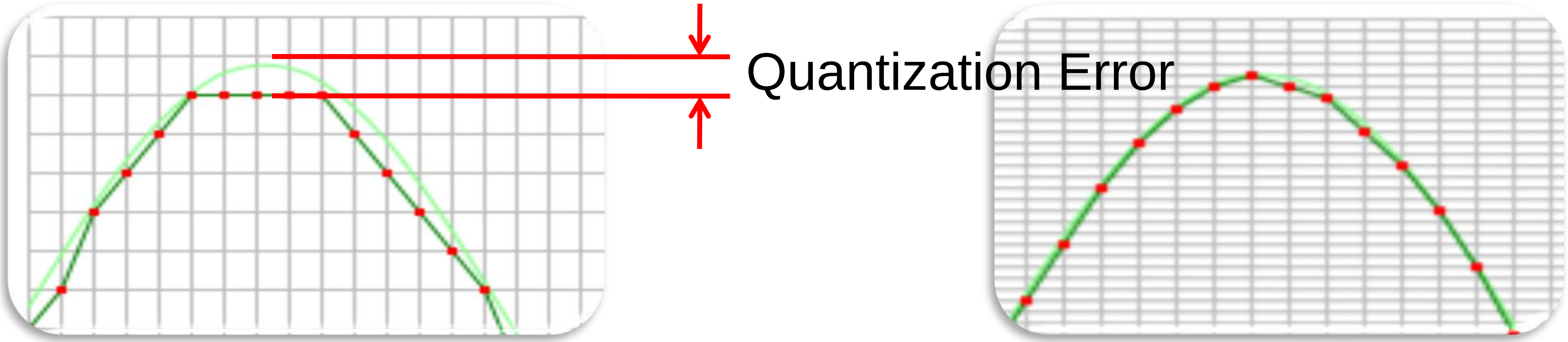
HDO4000 &
HDO6000
12-bit ADC

Highest Resolution
12-bits provides 16 times resolution compared to 8-bits

- Resolution = The number of available levels

$$= 2^{\text{bits of Resolution}}$$

ADC Resolution	Number of Steps	Dynamic Range
8	256	48 dB
12	4096	72 dB



Quantization Error

Scope with low resolution

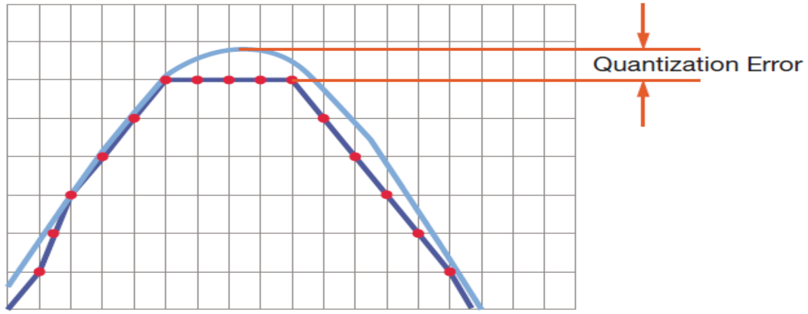
Scope with high resolution

Highest Resolution
12-bit allows detection of smaller signal variations

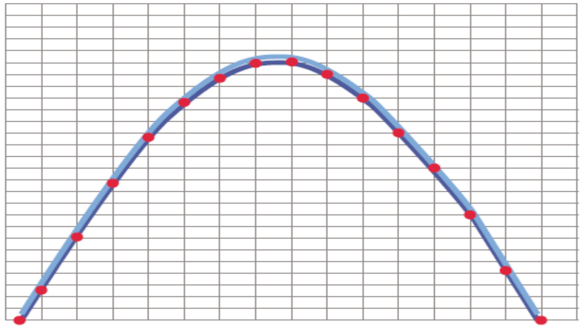
- The higher number of bits means the lower measurable voltage

Full Scale	Smallest Voltage Step	
	8 bits	12 bits
80 V	312.5 mV	19.5 mV
40 V	156.2 mV	9.76 mV
20 V	78.1 mV	4.88 mV
8 V	31.3 mV	1.95 mV
4 V	15.6 mV	976 µV
1.6 V	6.3 mV	390 µV
800 mV	3.1 mV	195 µV
400 mV	1.56 mV	97.6 µV
160 mV	625 µV	39 µV
80 mV	313 µV	19.5 µV
40 mV	156 µV	9.76 µV
16 mV	62.5 µV	3.9 µV
8 mV	31.2 µV	1.95 µV

- When measuring an 8 V signal, the smallest detectable voltage variation is 1.95 mV, compared to 31.3 mV on an 8-bit ADC.



Lower resolution



Higher resolution

8-Bit Scope Baseline Noise

12-Bit Scope Baseline Noise

Measure	P1:pkpk(C1)	P2:pkpk(M1)	P3:pkpk(C1)	P4:sdev(M1)	P5:sdev(M2)	P6:pkpk(M1)	P7:sdev(M1)	P8:- - -
value				214 µV	98 µV			
mean				214.2 µV	98.15 µV			
min				214 µV	98 µV			
max				214 µV	98 µV			
sdev				---	---			
num				1	1			
status				✓	✓			

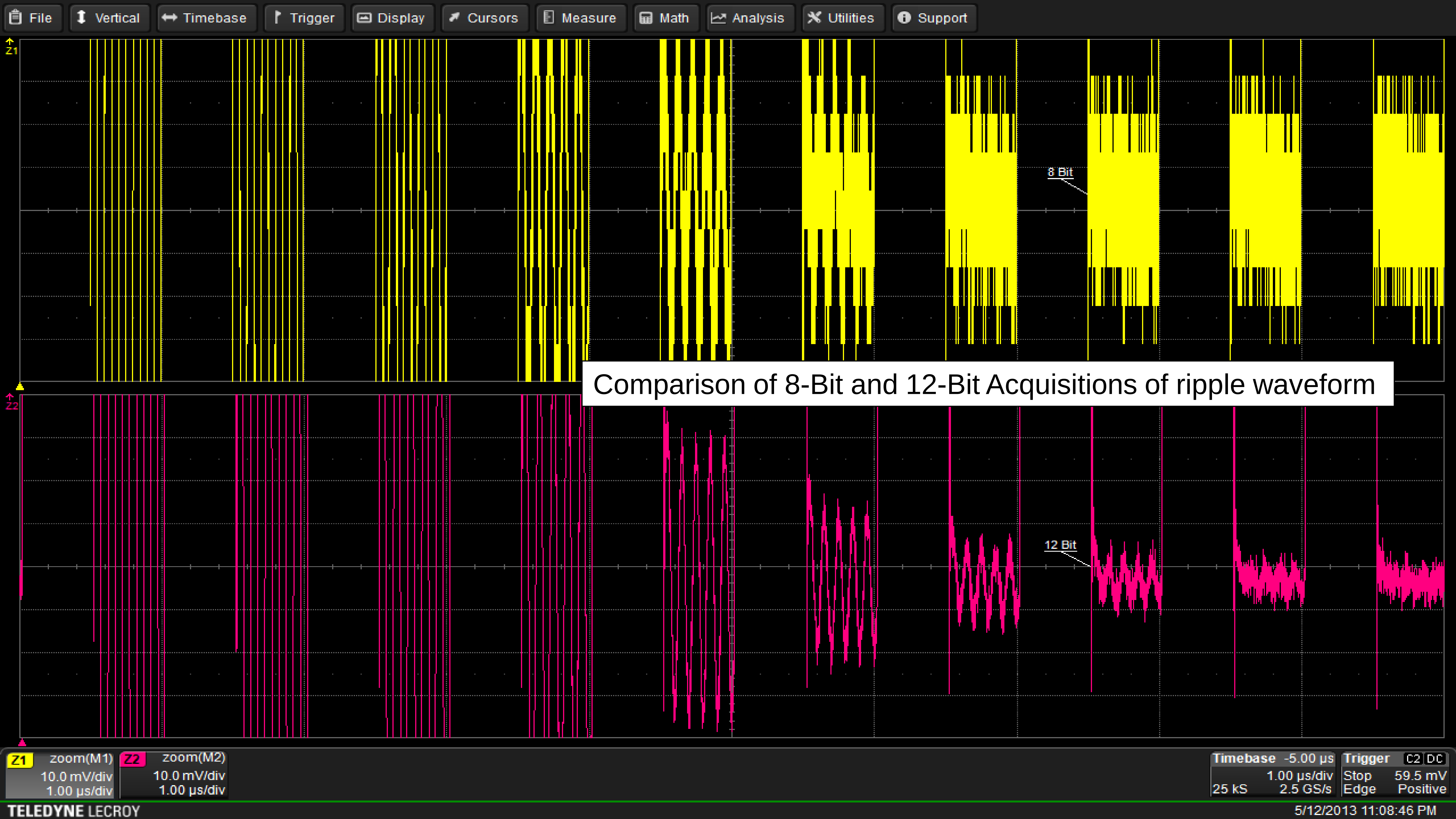
M1
5.00 mV/div
2.00 µs/div

M2
5.00 mV/div
2.00 µs/div

Timebase 0.00 µs
2.00 µs/div
25 kS 1.25 GS/s

Trigger C1 DC
Stop 0.00 mV
Edge Positive

5/12/2013 10:59:18 PM



Comparison of 8-Bit and 12-Bit Acquisitions of ripple waveform

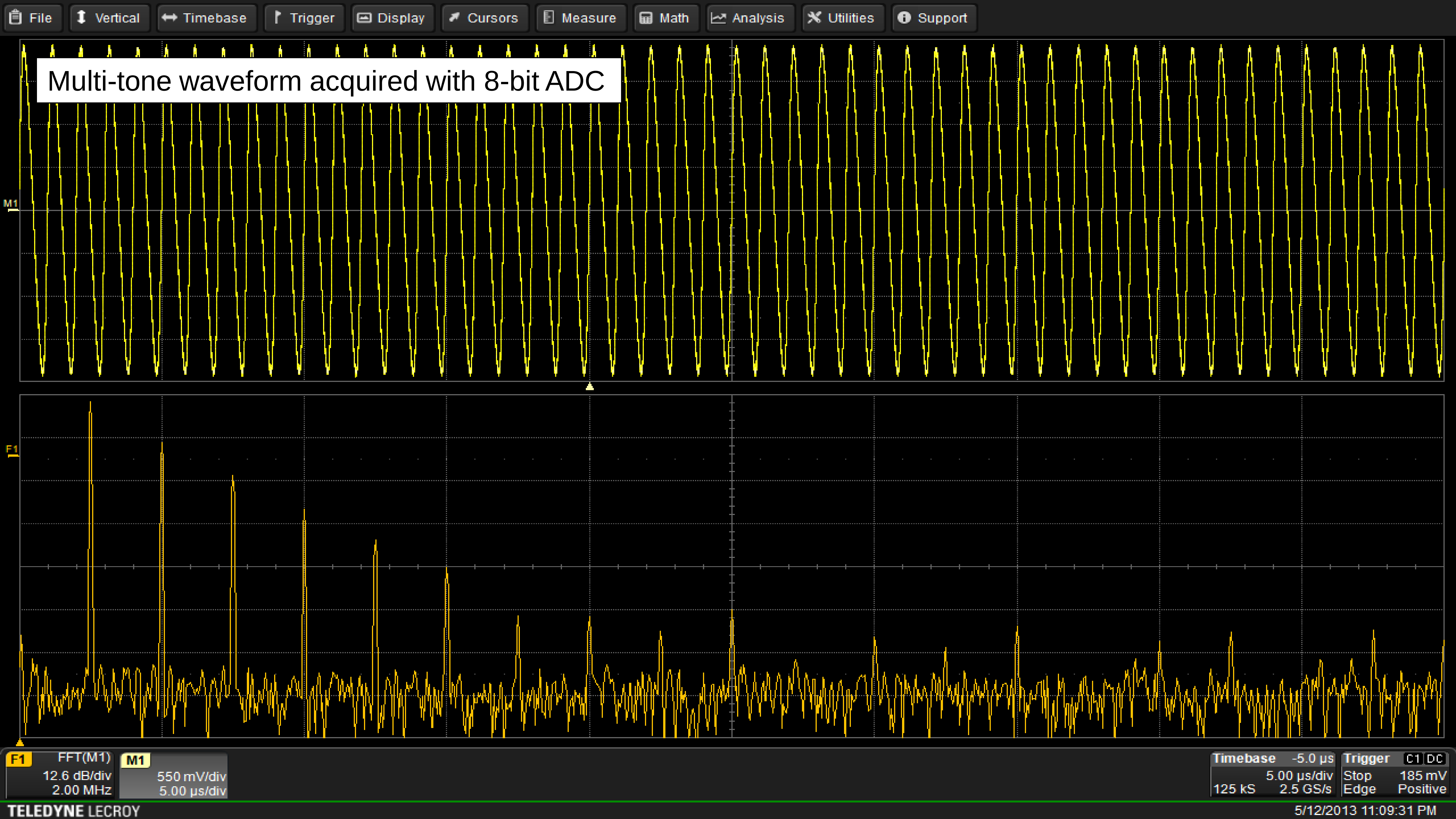
Z1 zoom(M1)
10.0 mV/div
1.00 µs/div

Z2 zoom(M2)
10.0 mV/div
1.00 µs/div

Timebase -5.00 µs
1.00 µs/div
25 kS 2.5 GS/s

Trigger C2 DC
Stop 59.5 mV
Edge Positive

5/12/2013 11:08:46 PM



Multi-tone waveform acquired with 8-bit ADC

F1 FFT(M1)
12.6 dB/div
2.00 MHz

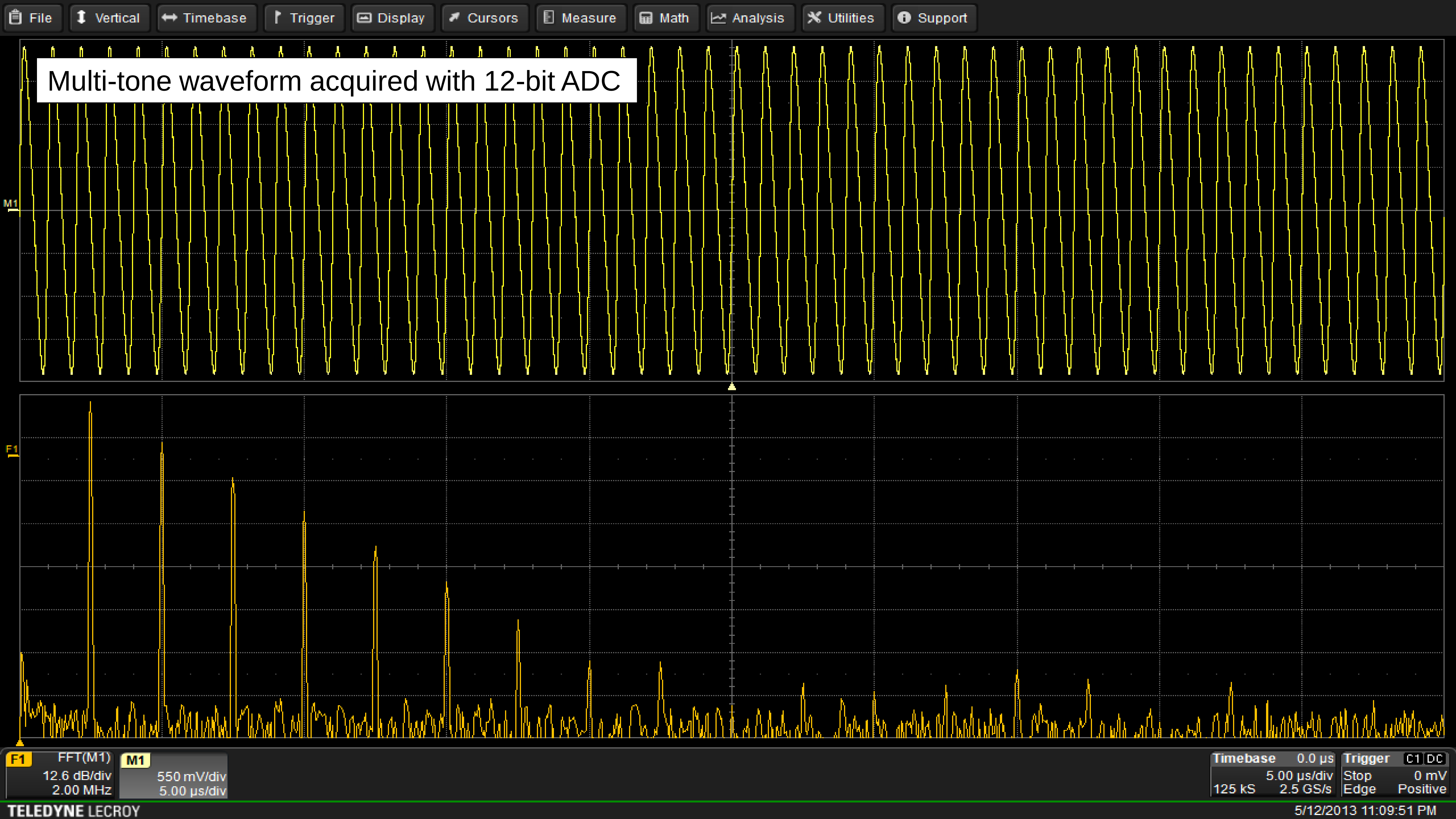
M1
550 mV/div
5.00 µs/div

Timebase -5.0 µs
5.00 µs/div
125 kS 2.5 GS/s

Trigger C1 DC
Stop 185 mV
Edge Positive

5/12/2013 11:09:31 PM

Multi-tone waveform acquired with 12-bit ADC



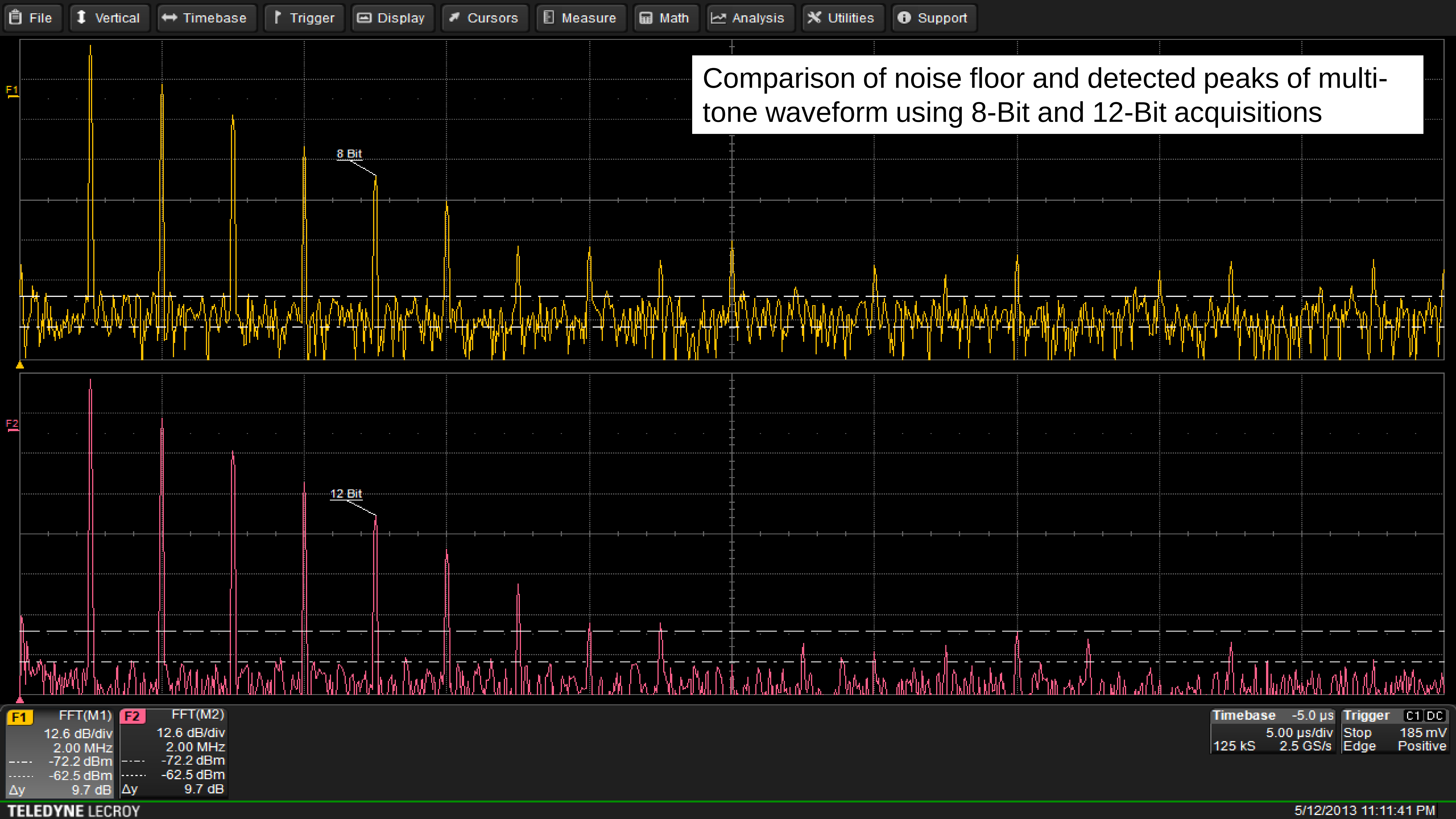
F1 FFT(M1)
12.6 dB/div
2.00 MHz

M1
550 mV/div
5.00 µs/div

Timebase 0.0 µs
5.00 µs/div
125 kS 2.5 GS/s

Trigger C1 DC
Stop 0 mV
Edge Positive

5/12/2013 11:09:51 PM



Comparison of noise floor and detected peaks of multi-tone waveform using 8-Bit and 12-Bit acquisitions

F1 FFT(M1)
12.6 dB/div
2.00 MHz
---- -72.2 dBm
...... -62.5 dBm
Δy 9.7 dB

F2 FFT(M2)
12.6 dB/div
2.00 MHz
---- -72.2 dBm
...... -62.5 dBm
Δy 9.7 dB

Timebase -5.0 µs
5.00 µs/div
125 kS 2.5 GS/s

Trigger C1 DC
Stop 185 mV
Edge Positive

5/12/2013 11:11:41 PM