MULTI-PHASE POWER MEASUREMENTS WITH AN OSCILLOSCOPE

IEEE LI Power Electronics Symposium
2025 November 6

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Make ideas real

AGENDA

- Types of Multi-phase Measurements
- Power Measurements on an Oscilloscope
- Multi-Phase Buck Converter
- 1 and 3 Phase Inverter Measurements

Types of Multi-phase Measurements

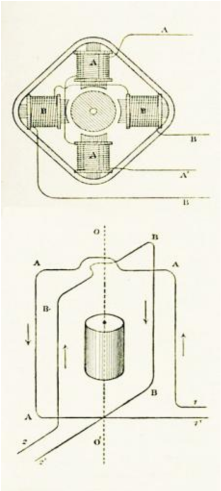
MULTI-PHASE APPLICATIONS

Oscilloscopes provide multiple channels that are time aligned, allowing easy measurement of timing events between different signals

In Power Applications, multiple phases are used in both power transmission and power conversion

AC Line Power – 3 phase (may be moving to 6 phase)

Inverters and Motor Drives – single and three phase are both common



FERRARIS' MOTOR (1885).

https://en.wikipedia.org/wiki/Three-phase_electric_power

MULTI-PHASE APPLICATIONS

Buck Converters – Multiple Phases in a single converter to provide more current output

2 Multiphase Buck Regulator Overview

A multiphase buck regulator is a parallel set of buck power stages as shown in Figure 2-1 and Figure 2-2, each with its own inductor and set of power MOSFETs. Collectively, these components are called a phase. These phases are connected in parallel and share both input and output capacitors. During steady-state operation, individual phases are active at spaced intervals equal to 360° / n throughout the switching period where n is the total number of phases. Figure 2-2 shows a TPS53679 multiphase controller demonstration board and TI power stages for a six-phase design.

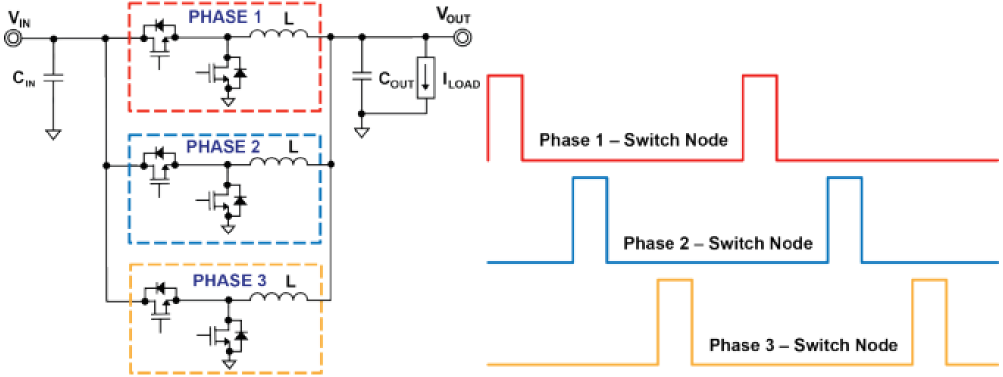


Figure 2-1. Multiphase Regulator Example

https://www.ti.com/lit/an/slva882/slva882.pdf

Power Measurements on an Oscilloscope

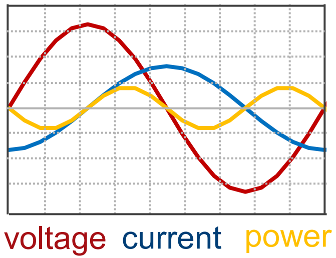
POWER BASICS

- ► What Voltage, and Current are used? (DC? Peak? Peak-to-Peak? Max? RMS?)
- ► What units is P given in?
- ► What if my supplied voltage is not DC or sinusoidal?
- ► What if my Load is not purely resistive?

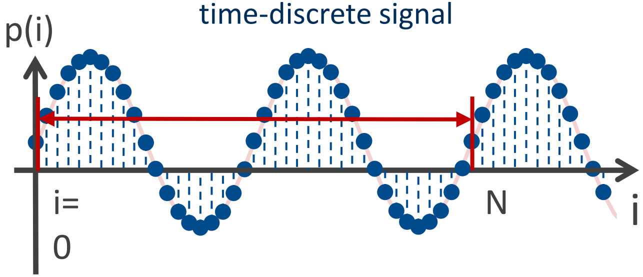
Oversimplification leads to errors. A DVM or DMM is not always an appropriate tool to make these measurements. You need an Oscilloscope!

POWER BASICS

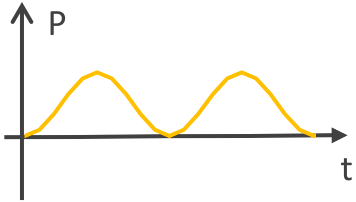
Oscilloscopes and Power Analyzers take advantage of ADCs that digitize the signal, and allow for analysis on full waveforms, characterizing correctly RMS values for current and voltage for non-ideal waveforms.



Yes, but!

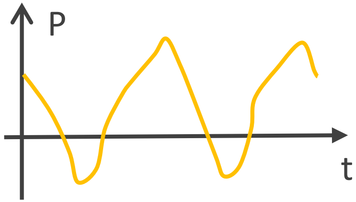


$$P = \frac{1}{N}\int_{i=0}^{N} p(i)$$



ideal world

no phase shift &
no distortion



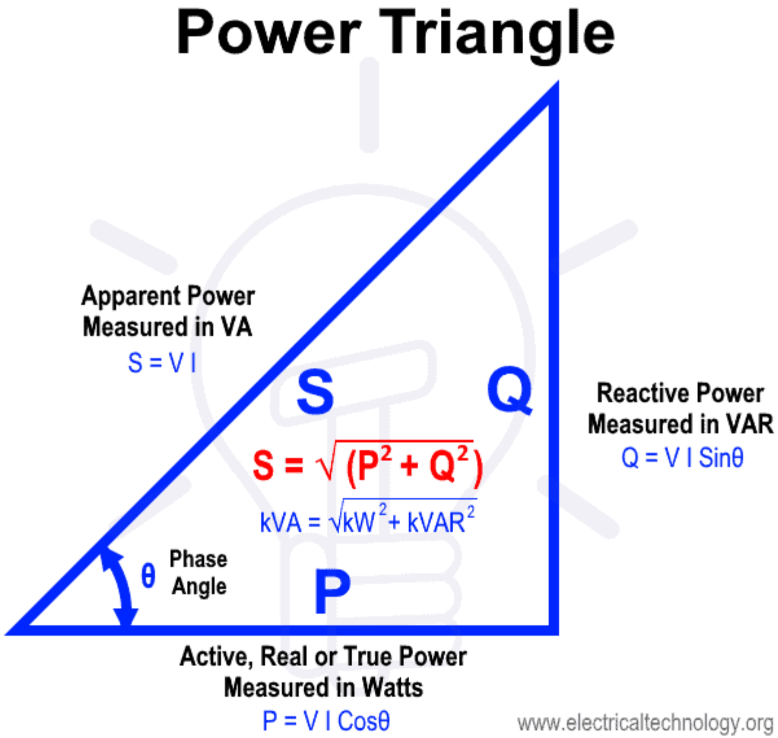
! real world !

phase shift &
distortion

POWER TRIANGLE – A MORE COMPLETE LOOK

These values can be manually measured with an Oscilloscope. Measurements made across 1 cycle.

- Apparent Power (S, in V*A) = Vrms * Irms
- Real (or Active or True) Power (P, in Watts) = Mean (V*I)
- Reactive Power (magnitude in Q) = $\sqrt{S^2 - P^2}$
- Power Factor (λ) = P/S
- Phase Angle = $\cos^{-1} \lambda$

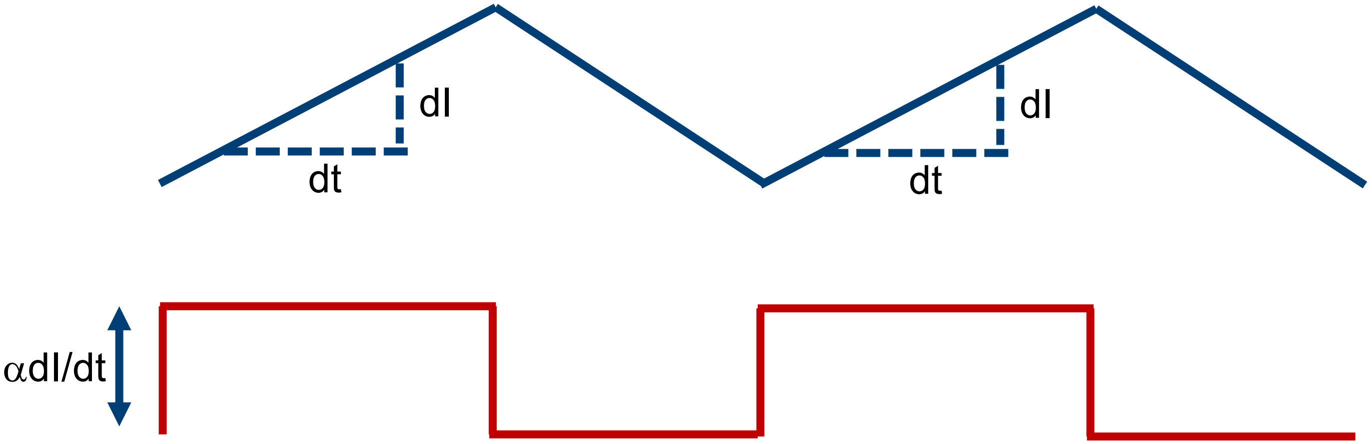


Multi-Phase Buck Converter

IN-SITU INDUCTOR CURRENT MEASUREMENT IN MULTI-PHASE BUCK CONVERTERS

- Application
  - Measure current loading of multi-phase buck converter
  - Observe PMIC control function
- Problem
  - Access is generally limited due to the placement of many PMIC's and inductors
  - Standard probes such as clamp-on, Rogowski, shunt resistor, etc. cannot be used
- Solution
  - Measure H-field using a near-field probe (non-invasive)
  - Signal is a pulse proportional to the inductor current slope

MEASURING CURRENT USING A NEAR FIELD PROBE

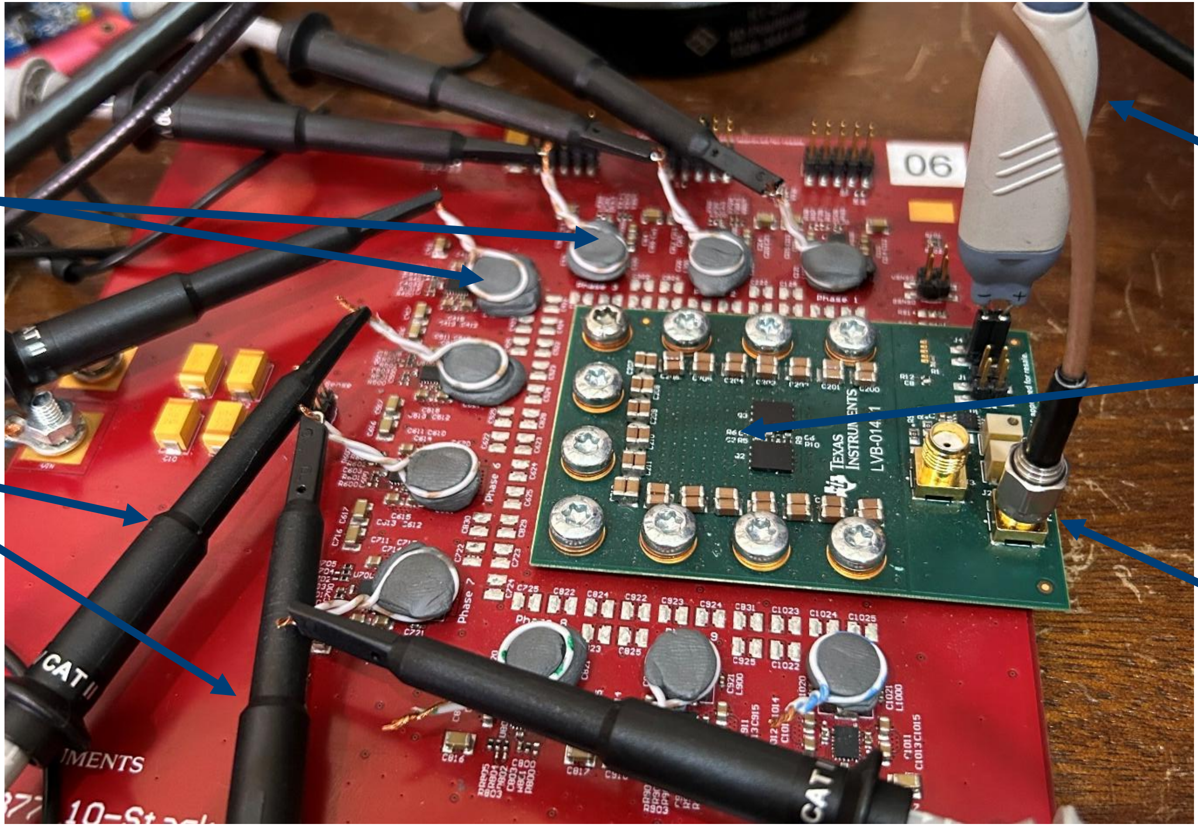


α is a function of the probe geometry and gain

EXAMPLE MEASUREMENT ON A 10-PHASE BUCK CONVERTER

Wire loops used to sense H-field

Passive voltage probes



Differential voltage probe

Load step generator board

Pulse generator input to gate drivers

MEASUREMENT RESULTS – LOAD STEP

Near field signal for each phase (7 phases measured)

Track of pulse width

Slope times increase in response to load step. Track amplitude shows imbalance

MEASUREMENT RESULTS – LOAD STEP REMOVED

Near field signal for each phase (7 phases measured)

Track of pulse width

Switching stops when load is removed (discontinuous conduction)

MEASUREMENT RESULTS – NO LOAD

Near field signal for each phase (7 phases measured)

Track of pulse width

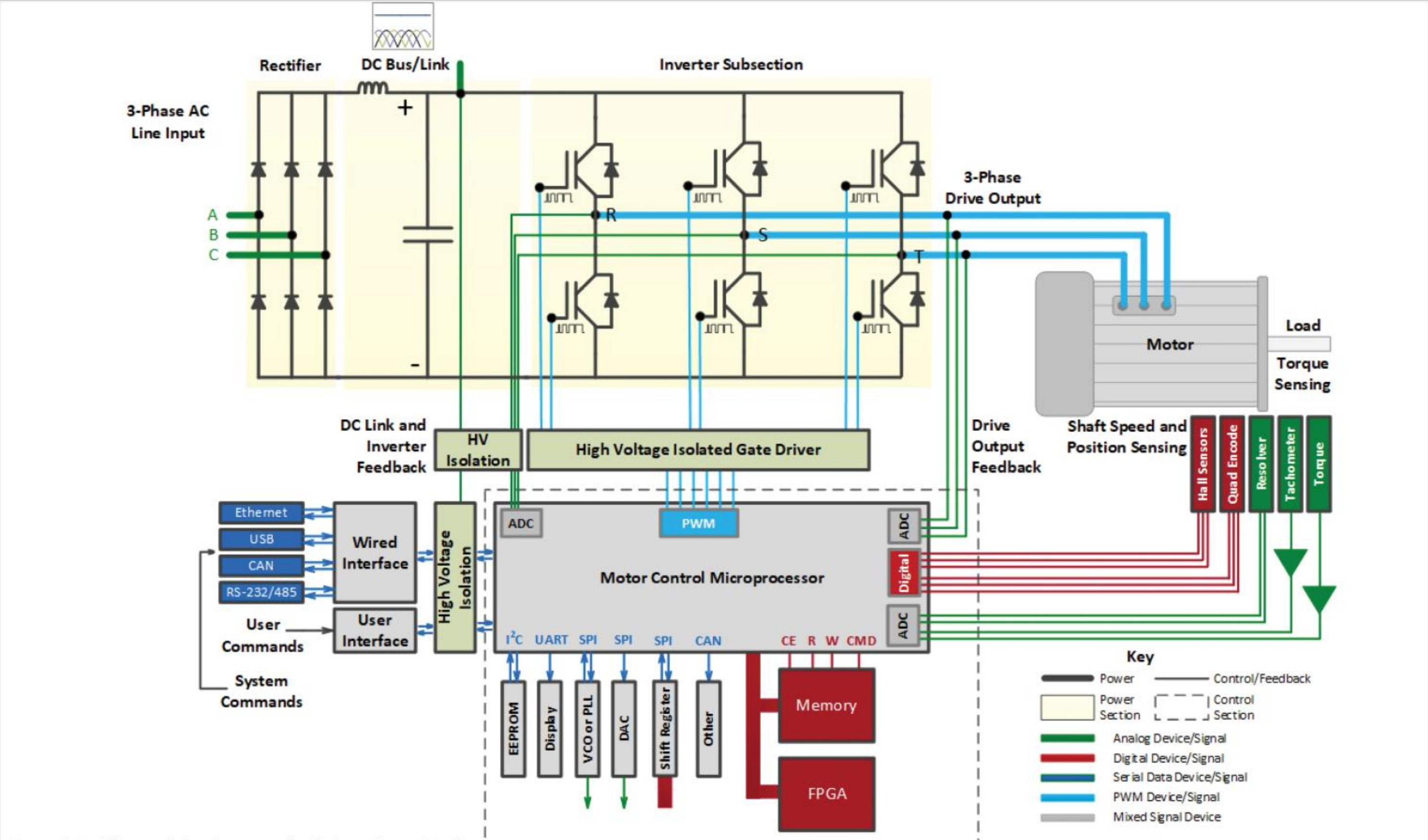
Constant switching pulse width

PHASE INTERLEAVING – NO LOAD

Not all phases measured

1 and 3 Phase Inverter Measurements

TYPICAL MOTOR DRIVE (POWER INVERTER)



Source: https://www.teledynelecroy.com/static-dynamic-complete/

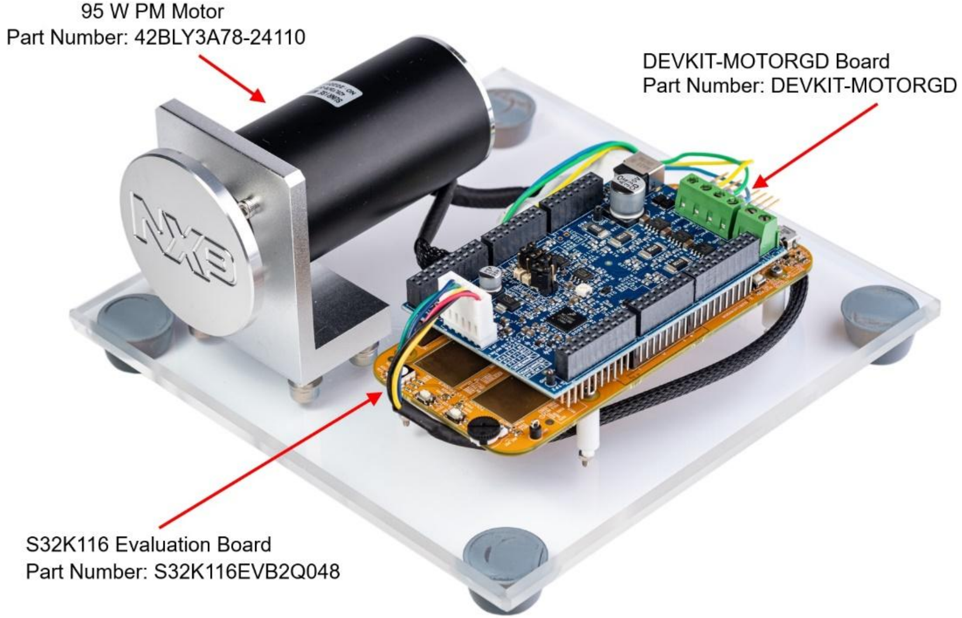
3-PHASE PMSM MOTOR
S32K116 BLDC/PMSM DEVELOPMENT KIT

Motor

- 42BLY3A78-24110: 3-phase PM motor, 24 V, 95 W, 9000 rpm, 6 A, 2 pole pairs

Power supply

- PSD-1270APL05: 12 V, 7 A + universal AC plug adapter



Permanent-Magnet Synchronous Motors

3-PHASE PMSM MOTOR
S32K116 BLDC/PMSM DEVELOPMENT KIT

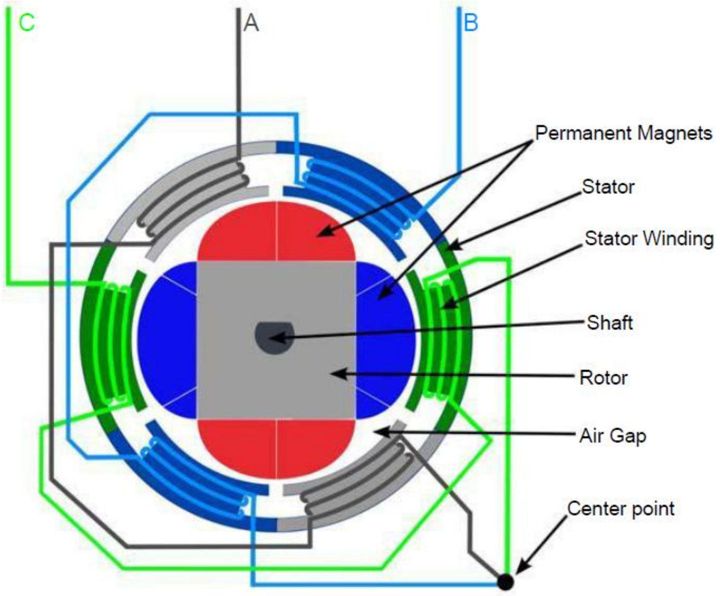


Figure 1. **BLDC motor – cross-section**

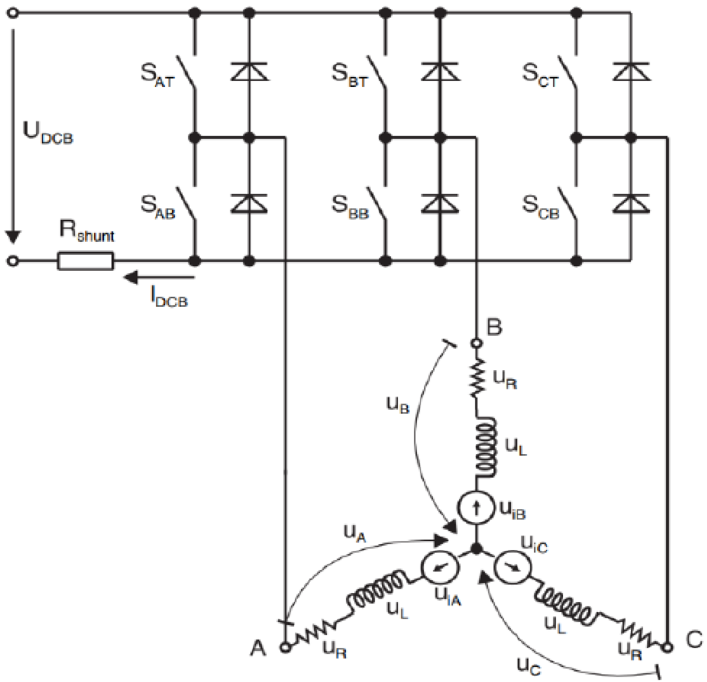
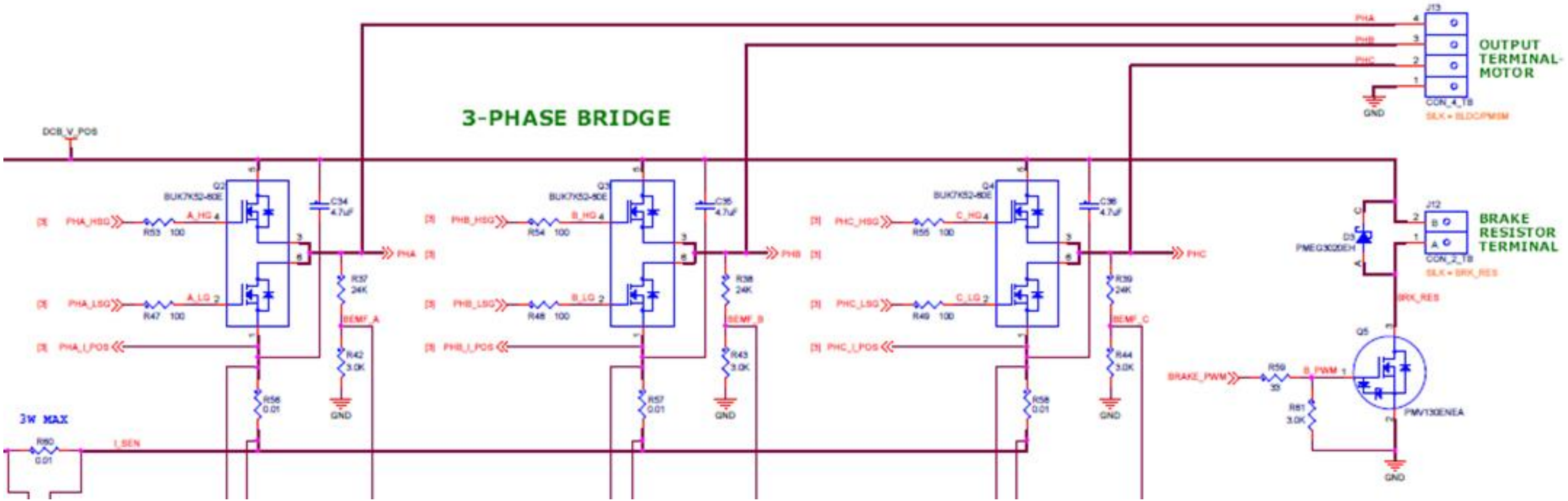


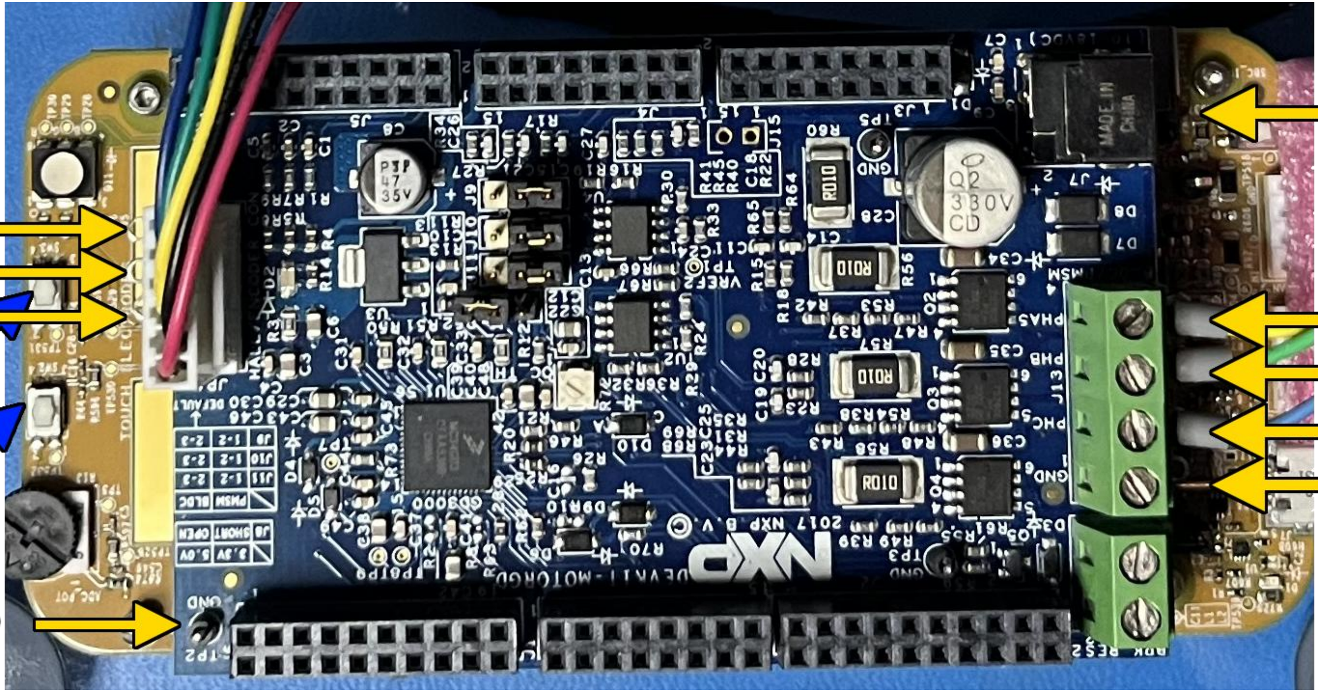
Figure 3. **Power stage and motor topology**

3-PHASE INVERTER OF THE S32K116

Note that this motor uses Half H-Bridge

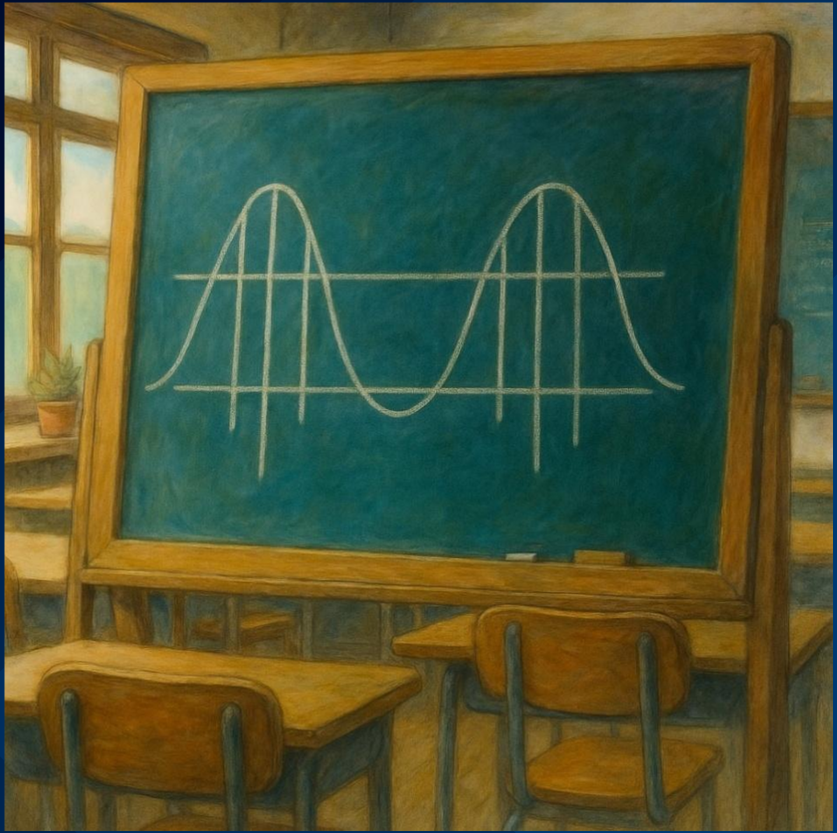


3-PHASE PMSM MOTOR
S32K116 BLDC/PMSM DEVELOPMENT KIT



What Measurements Can We Make?

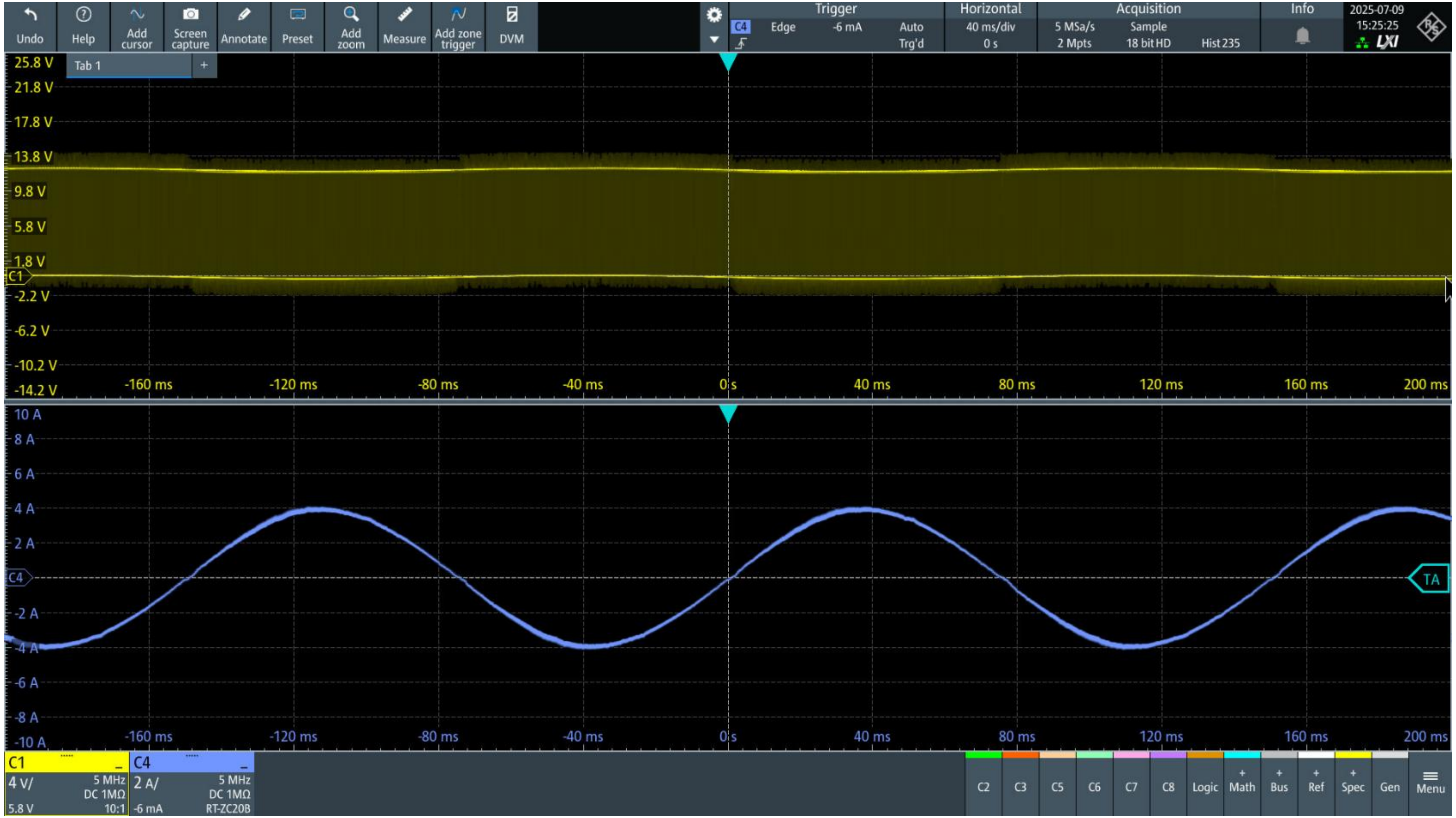
1 Phase



WHAT MEASUREMENTS CAN WE MAKE?

View of Phase A

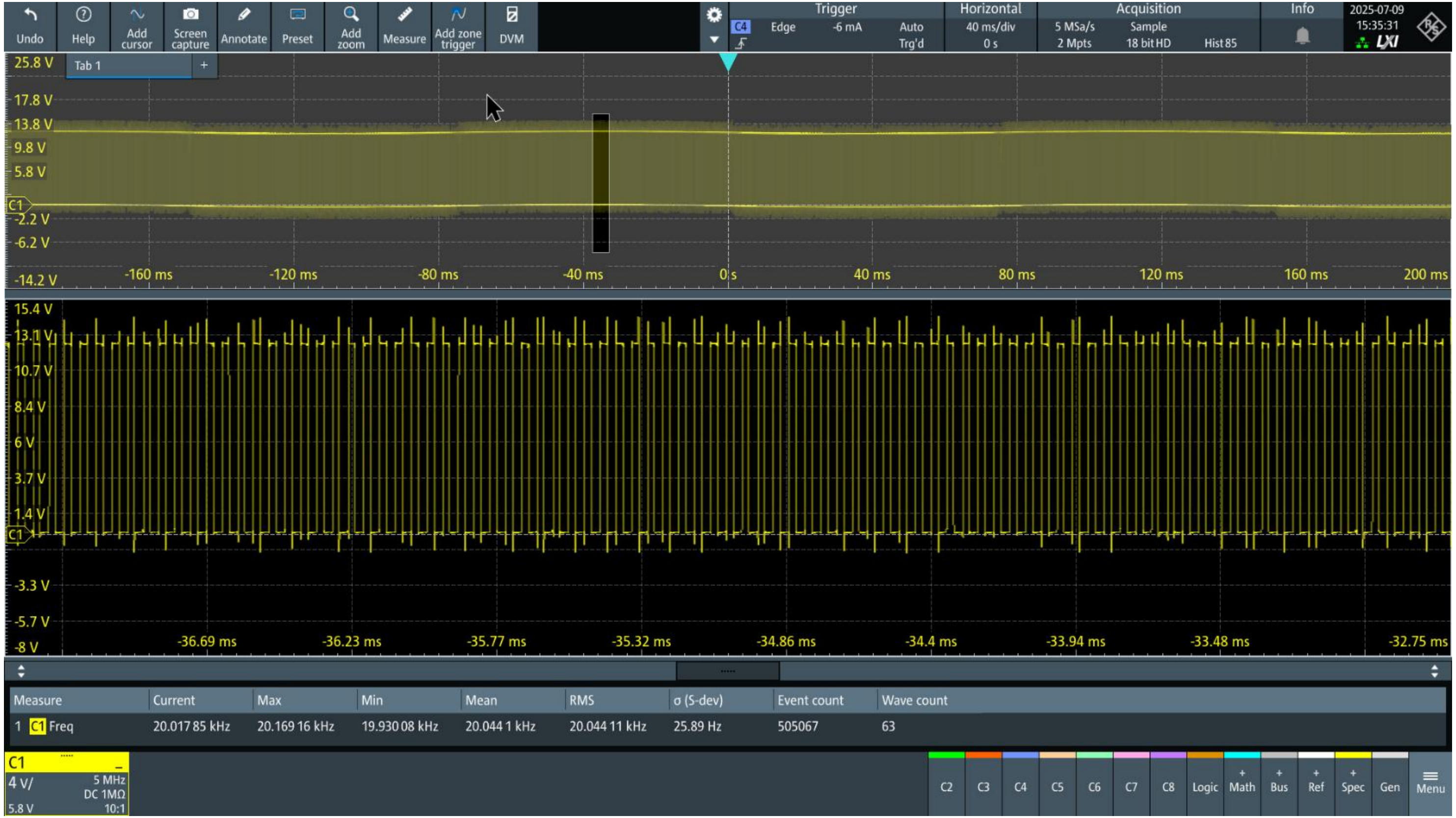
- Carrier Frequency
- % Duty Cycle change
- Motor Speed (RPM)
- V rms
- I rms
- VA
- P



WHAT MEASUREMENTS CAN WE MAKE?

Carrier (Switching) Frequency

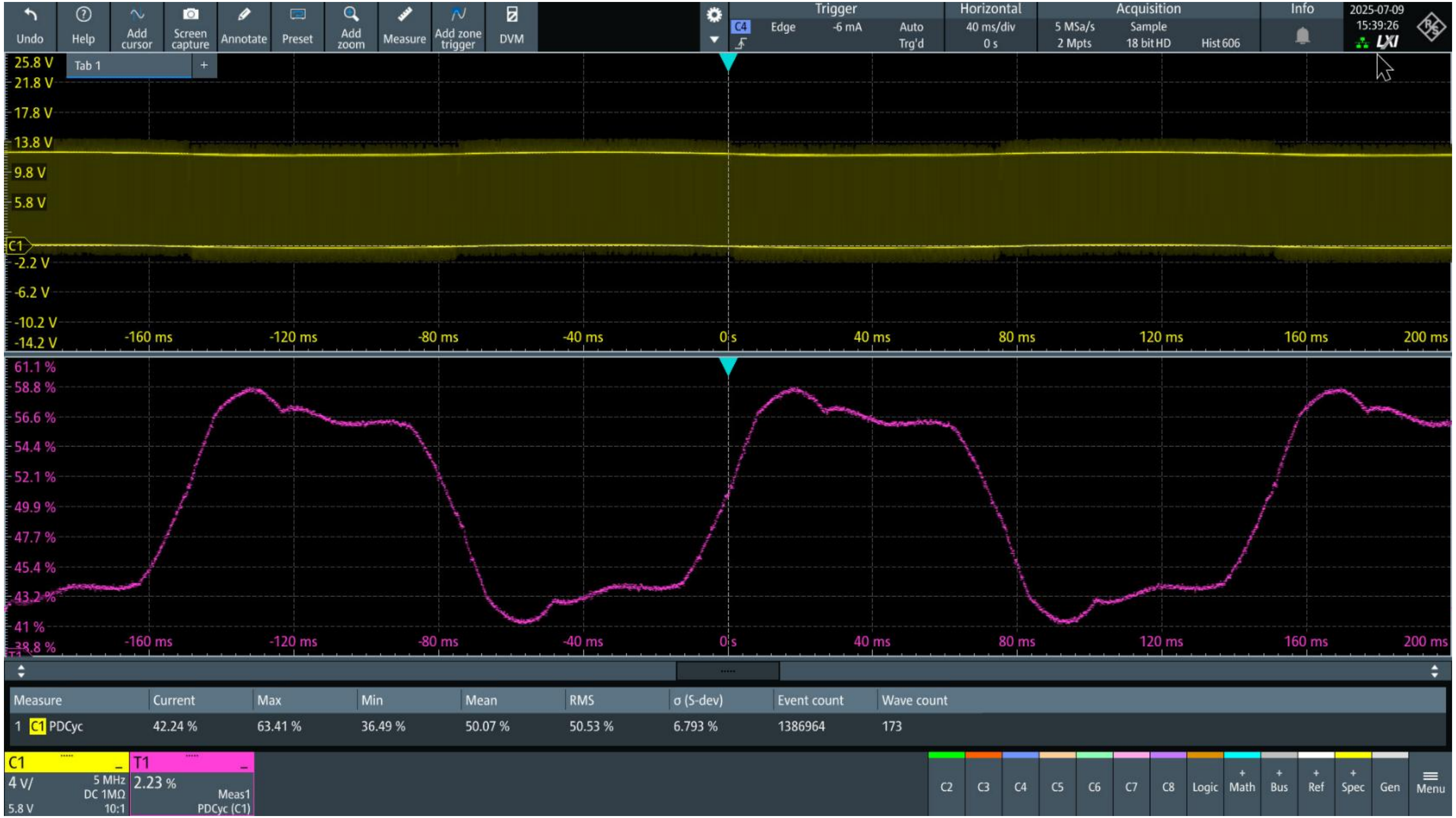
- Simple frequency measurement on CH1, zoomed in to show the square wave



WHAT MEASUREMENTS CAN WE MAKE?

% Duty Cycle change

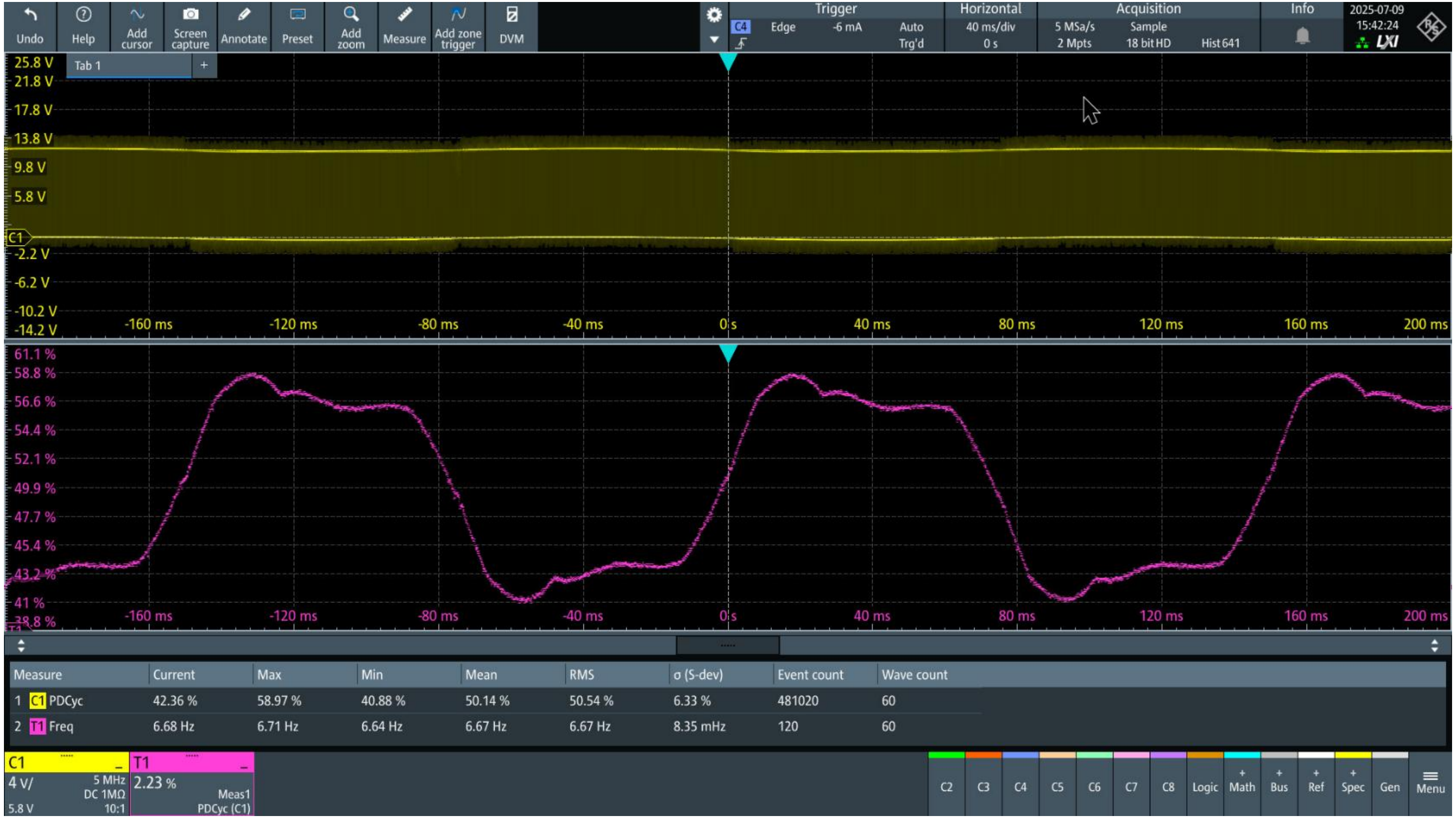
- Positive Duty Cycle Measurement
- Add a Track
- + and – values will be shown, but this can vary with the speed of the motor



WHAT MEASUREMENTS CAN WE MAKE?

Motor Speed (RPM)

- Requires a frequency measurement to show electrical cycles. Could be the PDCyc measurement, Current Measurement, or even the output of the Hall Encoders
- 6.68 Hz in this setup.



WHAT MEASUREMENTS CAN WE MAKE?

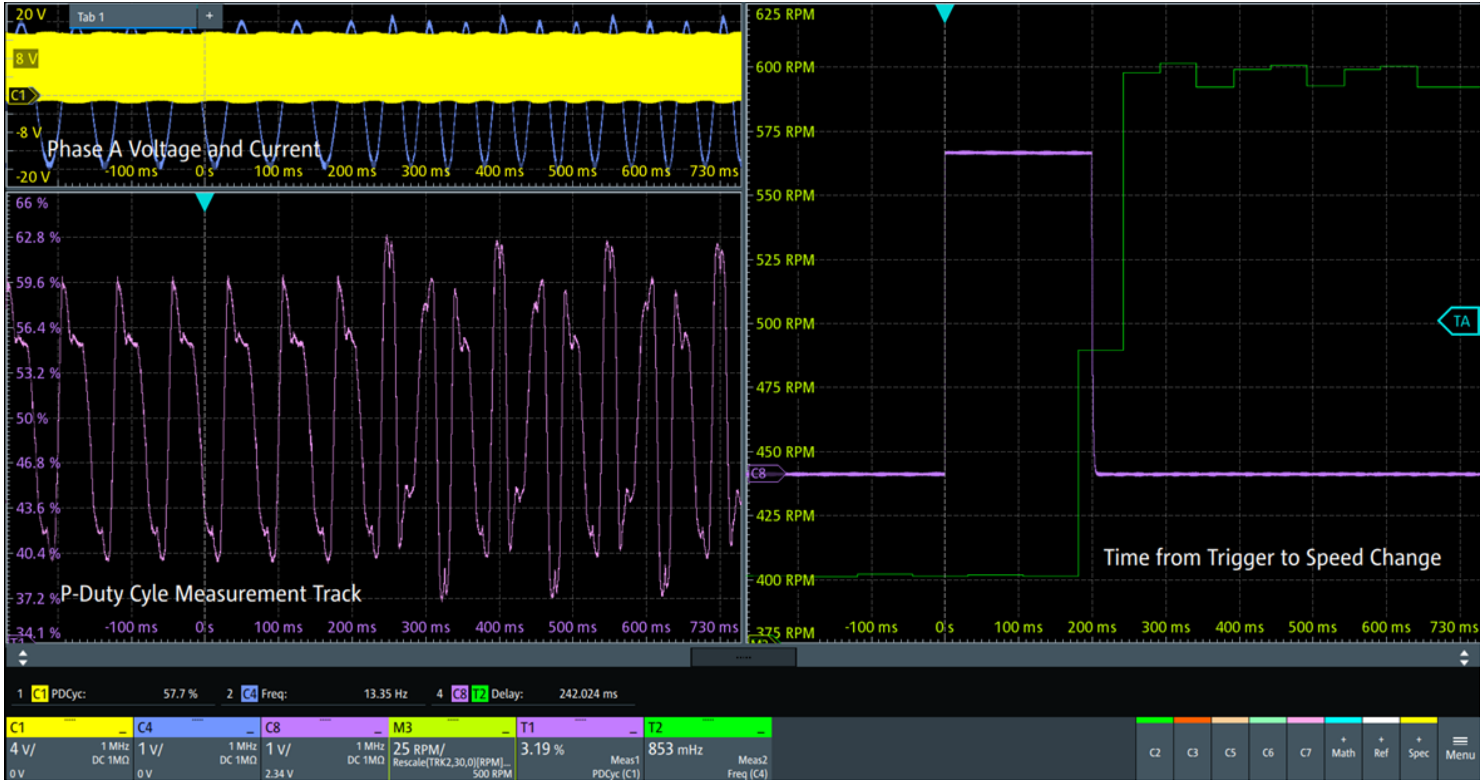
Motor Speed (RPM) – How do we get RPM from 6.68Hz?

- We know from the Motor specifications that there are 2 Polar Pairs. This means that there will be 2 electrical cycles per 1 mechanical revolution.
- RPM = Frequency / (# Polar Pairs) * 60s = 6.68 / 2 * 60 = 200 RPM.
- We could make a math trace using this formula taking the track of a frequency measurement to show speed over time. (e.g. Rescale of Track * 30)
- AC Induction motor's speed are impacted by slip, and gear ratios, making the calculation more complex.

WHAT MEASUREMENTS CAN WE MAKE?

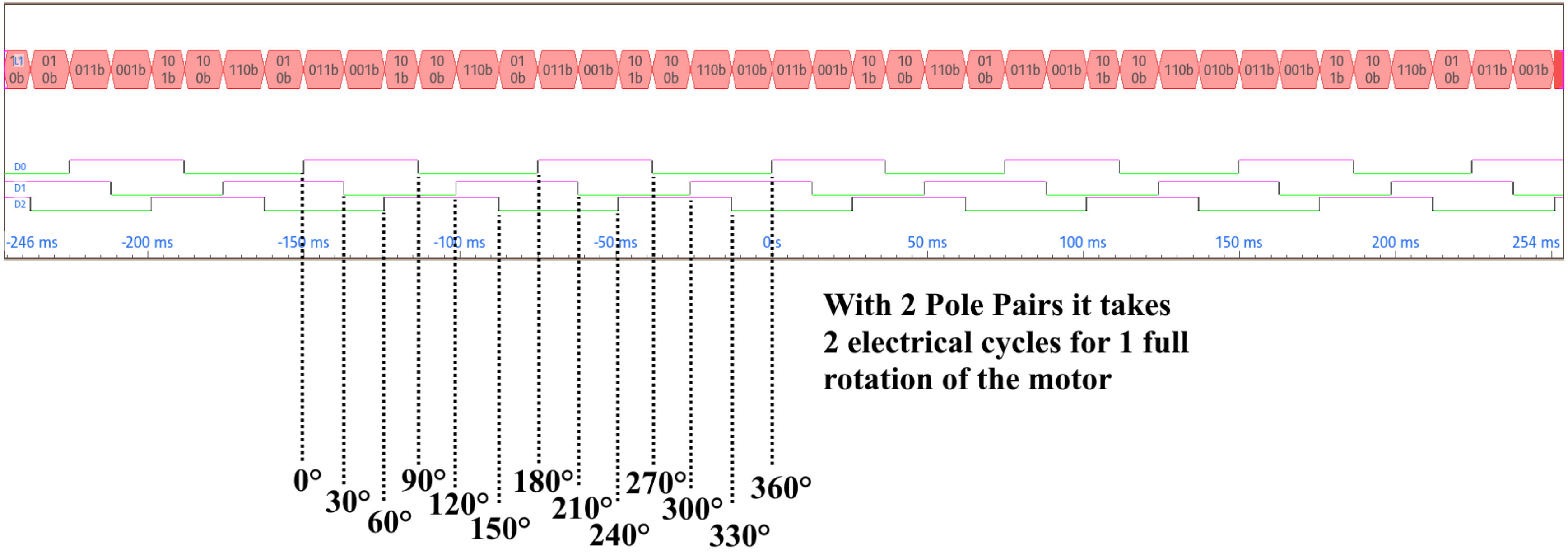
Time to Change Speed

- Using a rescale of the track of the frequency measurement of the track of the Pduty Cycle measurement of Phase A, we can plot the RPM of the motor
- Trigger on the Speed Change button, and measure delay until RPMs change



WHAT MEASUREMENTS CAN WE MAKE?

Motor Speed (RPM) –Hall Encoder



With 2 Pole Pairs it takes 2 electrical cycles for 1 full rotation of the motor

WHAT MEASUREMENTS CAN WE MAKE?

V and I rms

- To Accurately measure V rms or I rms, we need either a Cycle RMS measurement, or to capture enough cycles that a partial cycle in the measurement does not skew the results. Both have challenges.

Cycle RMS:

- Set up measurement Gate to cover 1 electrical cycle (can eyeball based on PDCyc track, of current measurement)
- Try to set up your total acquisition time to be an even multiple of an electrical cycle

Long Duration RMS measurement:

- This would take a large amount of data to do so well on an Oscilloscope, but we have a built in DVM that makes this easy. We can set its measurement period to a maximum of 1 second.

WHAT MEASUREMENTS CAN WE MAKE?

V rms

- Both the gated RMS and the DC RMS with the Measurement time set to 1s agree
- 8.65V-ish

WHAT MEASUREMENTS CAN WE MAKE?

I rms

- Easier to measure, since its cycle is correct. Could use a Cycle RMS measurement, or any of the other two method
- 2.76 A

Measure	Current	Max	Min	Mean	RMS	σ (S-dev)	Event count	Wave count
1 C1 PDCyc	41.93 %	58.89 %	40.78 %	50.13 %	50.54 %	6.42 %	8017	1
2 T1 Freq	6.68 Hz	6.68 Hz	6.68 Hz	6.68 Hz	6.68 Hz	4.81 mHz	2	1
3 C1 G1 RMS	8.65 V	8.65 V	8.65 V	8.65 V	8.65 V	0 V	1	1
4 C4 CRMS	2.75 A	2.76 A	2.75 A	2.76 A	2.76 A	1.92 mA	2	1
5 C4 G1 RMS	2.76 A	2.76 A	2.76 A	2.76 A	2.76 A	0 A	1	1

WHAT MEASUREMENTS CAN WE MAKE?

Apparent Power in VA

- Apparent Power is the power required to drive the circuit
- Vrms * Irms

Scope Measurements:

- 8.65V * 2.76A = 23.874VA

DVM measurements

- 8.64V * 2.72A =
- 23.5VA

DVM is continuously running, so not including the waveform in acq memory

WHAT MEASUREMENTS CAN WE MAKE?

Active Power in W

- Active Power gets used up in the circuit
- Cycle Mean of the Power Waveform (V*I)

Same Cycle challenges as with Voltage. Use the Gates and a Mean Measurement

1.562W

DERIVED POWER MEASUREMENTS

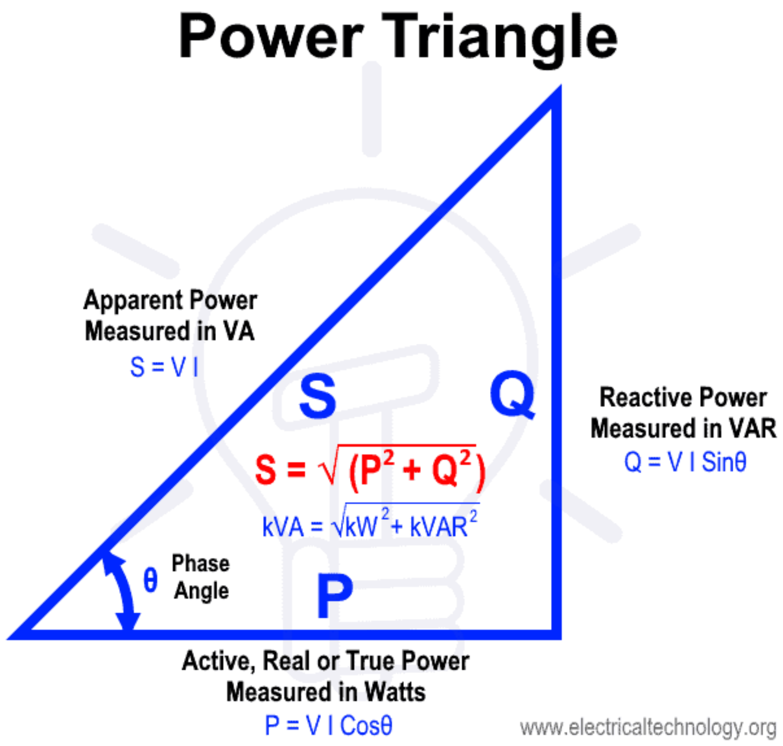
With a known Active and Apparent power, we can calculate the rest of the Power Triangle

$S = 23.874VA$, $P = 1.562W$

$Q = \sqrt{S^2 - P^2} = \sqrt{23.874^2 - 1.562^2} = 23.82$ VAR

Power Factor = $P / S = 1.562 / 23.874 = 0.065\ \lambda$

Phase Angle = $\cos^{-1} \lambda = \cos^{-1} 0.065 = 86.24$ degrees



DOES OUR PA SOFTWARE AGREE?

That Pesky Cycle Issues creeps in again

The PA (Power Analyzer) software grabs the cycle from our carrier frequency on Ch1. The Mean and RMS measurements are closer, using all 8K events. Setting the Fund. Frequency manually doesn't change how the cycles are sliced and calculated.

Solution –
Trick* the PA software, swap sources for I and V

DOES OUR PA SOFTWARE AGREE?

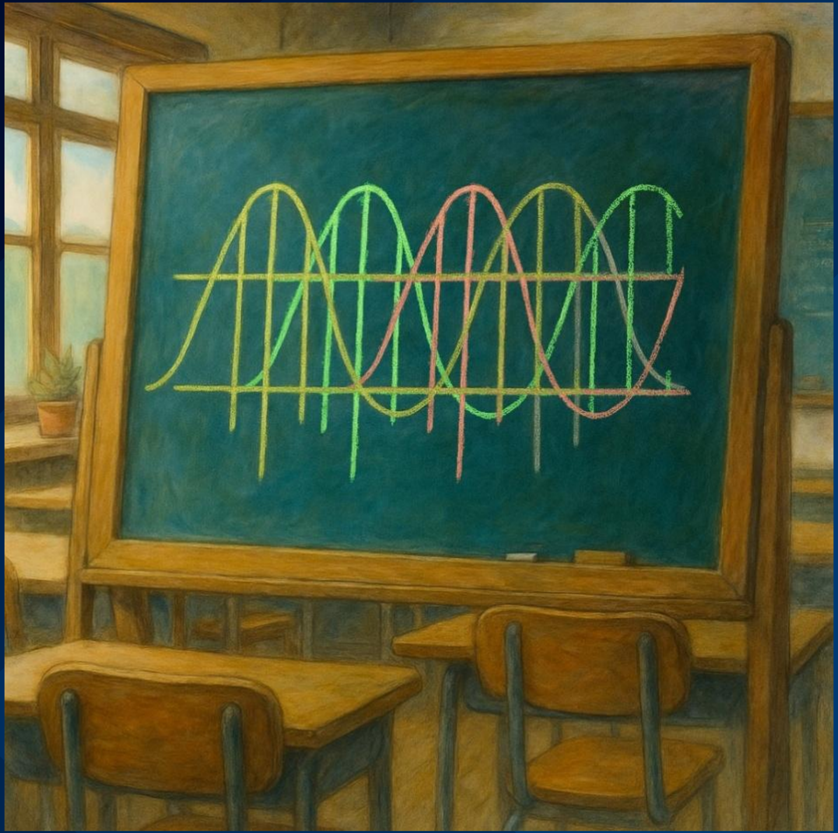
Compare to Calculated Results

V rms = 8.65V
I rms = 2.76 A
P = 1.562W
S = 23.874VA
Q = 23.82 VAR
PF = 0.065 λ
Phase = 86.24 degrees

	Measure	Current	Max	Min	Mean	RMS	σ (S-dev)	Event count	Wave count
1	C4 Freq	6.68 Hz	6.68 Hz	6.66 Hz	6.67 Hz	6.67 Hz	15.7 mHz	2	1
2	C4 CRMS	2.76 A	2.76 A	2.75 A	2.75 A	2.75 A	3.88 mA	2	1
3	C4 CCrest	1.5	1.5	1.5	1.5	1.5	2.27 m	2	1
4	C4 CMax	4.14 A	4.14 A	4.13 A	4.14 A	4.14 A	12.09 mA	2	1
5	C1 CRMS	8.64 V	8.64 V	8.64 V	8.64 V	8.64 V	3.29 mV	2	1
6	C1 CCrest	1.65	1.65	1.65	1.65	1.65	1.27 m	2	1
7	C1 CMax	14.26 V	14.28 V	14.26 V	14.27 V	14.27 V	16.41 mV	2	1
8	P1 Apparent	23.81 VA	23.81 VA	23.77 VA	23.79 VA	23.79 VA	24.46 mVA	2	1
9	P1 Factor	66 m	67 m	66 m	67 m	67 m	68 µ	2	1
10	P1 Active	1.58 W	1.58 W	1.58 W	1.58 W	1.58 W	14.12 µW	2	1
11	P1 Reactive	23.76 VAR	23.76 VAR	23.72 VAR	23.74 VAR	23.74 VAR	24.51 mVAR	2	1
12	P1 Phase	86.19 °	86.19 °	86.18 °	86.19 °	86.19 °	3.89 m°	2	1

What Measurements Can We Make?

3 Phases



PHASE TO PHASE MEASUREMENTS

Compare the Phases of the Duty Cycle Tracks to the Current waveforms

We expect these to be 120 degrees apart for a balanced system. They are very close.

WHAT ABOUT TOTAL POWER OF ALL 3 PHASES

Three Wattmeter Method

The total power (P, S, Q) of the system is the Sum of all 3 together. If the system is balanced, we can assume it is 3x of any individual leg measurement.

Two Wattmeter Method

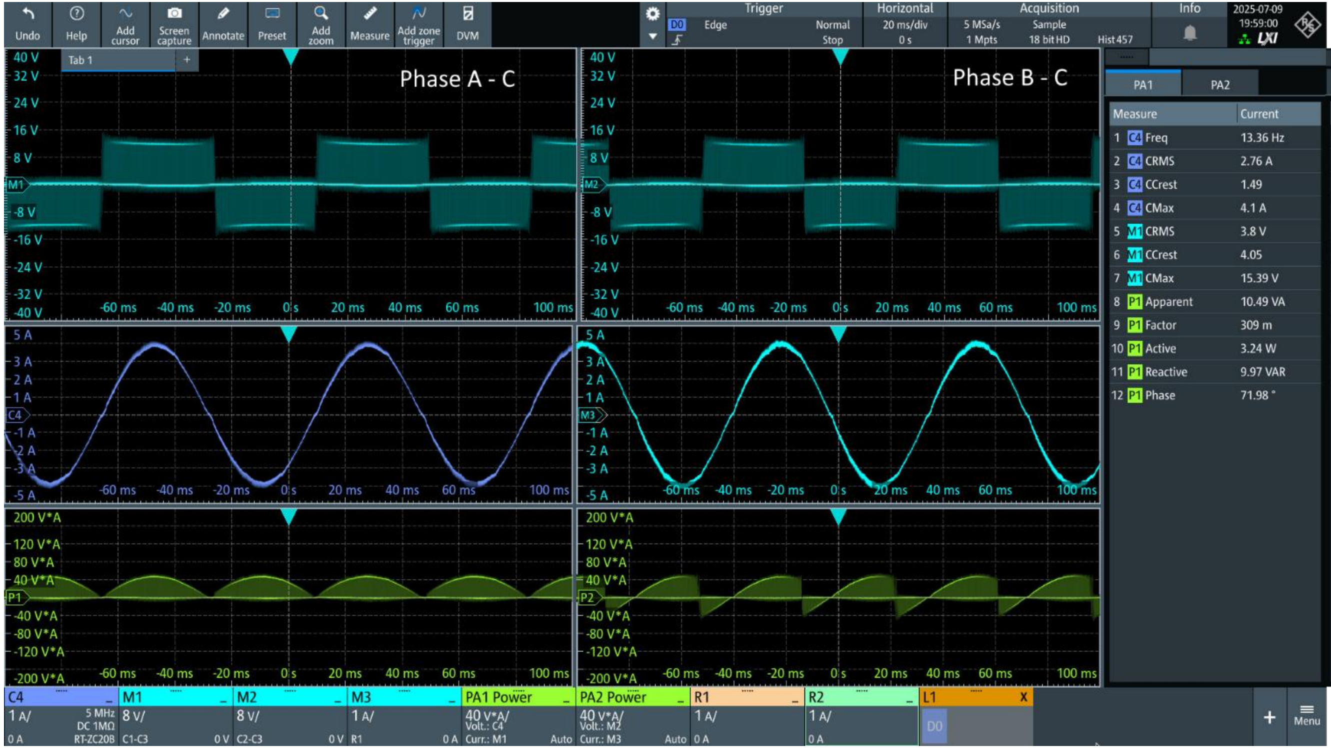
In many systems, the voltages cannot be measured for each phase from line-to-neutral. Instead we have to measure them line-to-line.

Let's test it out!

THREE WATTMETER METHOD

P total = 4.25W S total = 71.39VA Q total = 71.27VAR

TWO WATTMETER METHOD



Measure	Current
1 C4 Freq	13.36 Hz
2 C4 CRMS	2.76 A
3 C4 CCrest	1.49
4 C4 CMax	4.1 A
5 M1 CRMS	3.8 V
6 M1 CCrest	4.05
7 M1 CMax	15.39 V
8 P1 Apparent	10.49 VA
9 P1 Factor	309 m
10 P1 Active	3.24 W
11 P1 Reactive	9.97 VAR
12 P1 Phase	71.98 °

Measure	Current
1 M3 Freq	13.38 Hz
2 M3 CRMS	2.79 A
3 M3 CCrest	1.49
4 M3 CMax	4.16 A
5 M2 CRMS	3.78 V
6 M2 CCrest	3.89
7 M2 CMax	14.71 V
8 P2 Apparent	10.56 VA
9 P2 Factor	149 m
10 P2 Active	1.57 W
11 P2 Reactive	10.44 VAR
12 P2 Phase	81.43 °

P total = 4.8W S total = 21.05VA Q total = 20.41VAR

RESULTS COMPARED

P total = 4.25W	S total = 71.39VA	Q total = 71.27VAR	3 Wattmeter Method
P total = 4.8W	S total = 21.05VA	Q total = 20.41VAR	2 Wattmeter Method

P is close (ish), but S and Q are very far off? What's going on?

Answer – Apparent power is heavily impact by the DC offset of the signals and the harmonic content of the carrier. This also impacts the viewed values of Q, but does not have as large of an impact on P.

RESULTS COMPARED

In our Power Analyzers we handle this with a dual path A/D converter, one for narrow band and one for wideband.

Our Oscilloscope by default is Wideband, but it has tools that allow us to get a narrow band measurement.

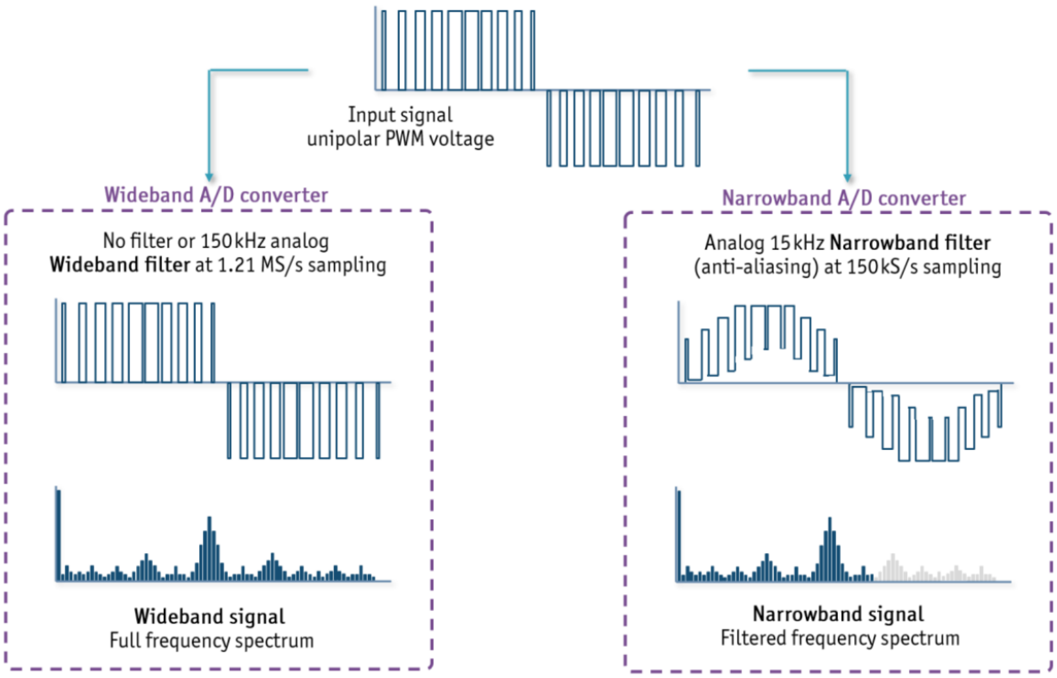


Figure 4: Schematic representation of the LMG600 series DualPath signal processing

RESULTS COMPARED

Wideband spectrum of the Voltage for Phase A

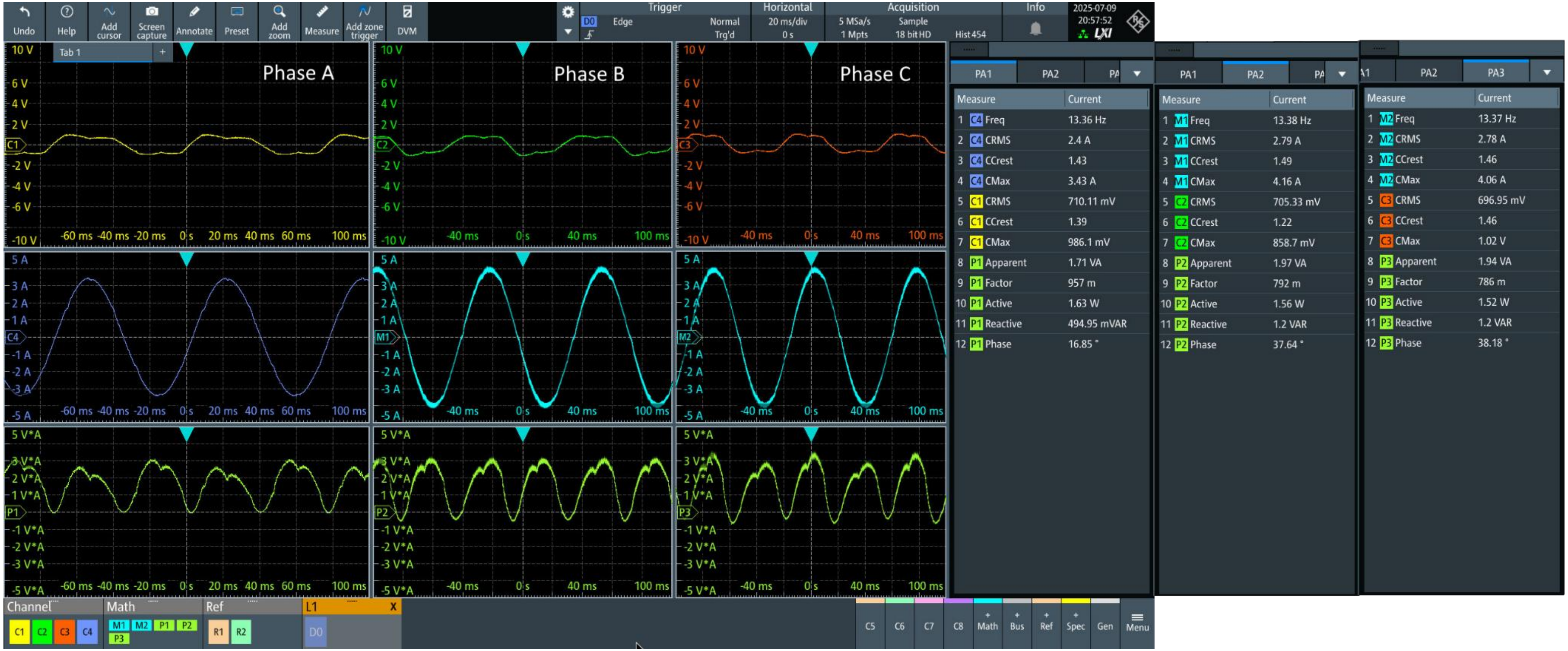
RESULTS COMPARED

Narrowband spectrum of the Voltage for Phase A

AC Coupling to remove DC component

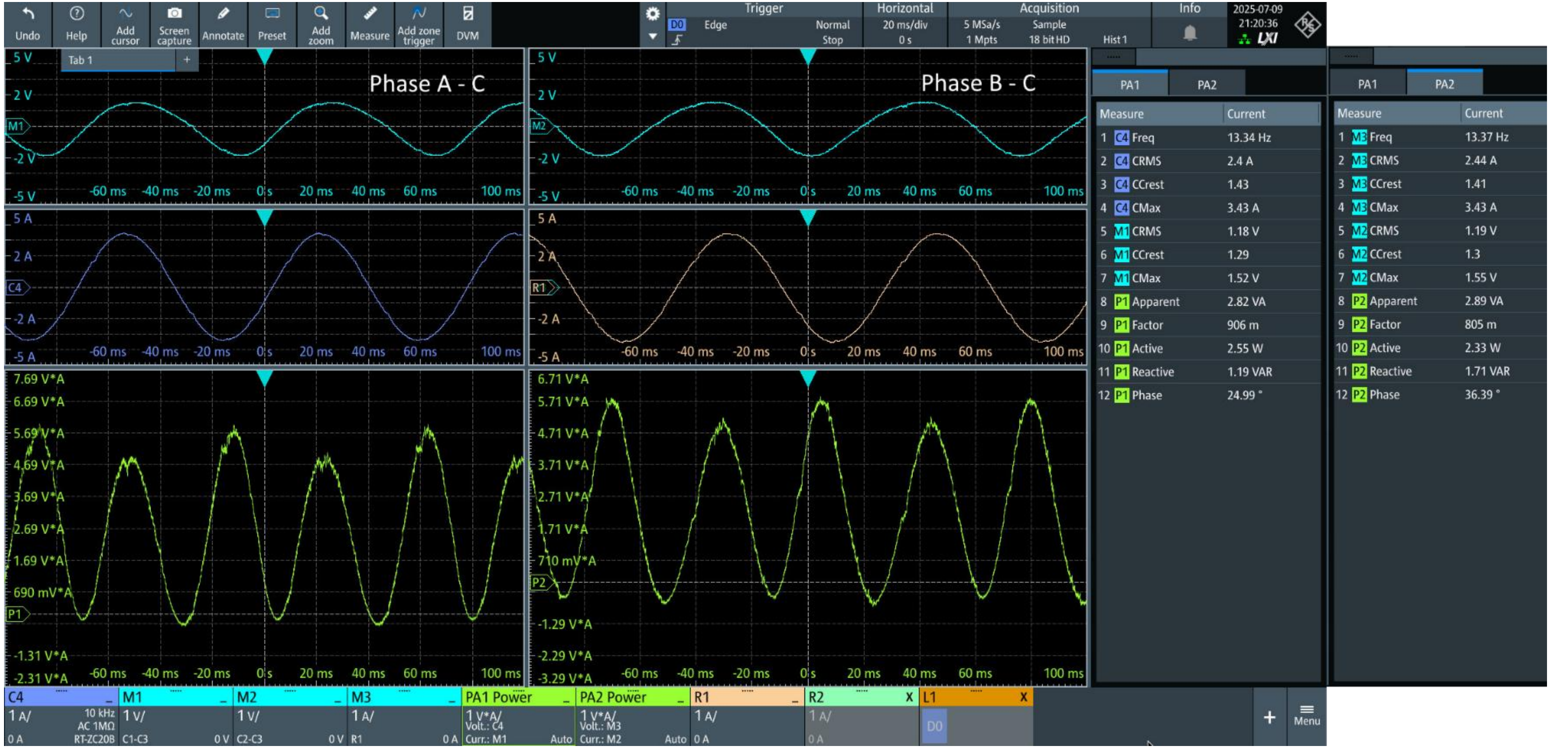
HD Mode Filter set to 1KHz BW

THREE WATTMETER METHOD



P total = 4.71W S total = 5.62VA Q total = 2.89VAR

TWO WATTMETER METHOD



P total = 4.58W S total = 5.71VA Q total = 2.9VAR

RESULTS COMPARED AGAIN

P total = 4.71W	S total = 5.62VA	Q total = 2.89VAR	3 Wattmeter Method
P total = 4.58W	S total = 5.71VA	Q total = 2.9VAR	2 Wattmeter Method

These results are much closer!

RESULTS COMPARED WITH VARIOUS METHODS

In these measurements, LPF was with an FIR custom math filter, instead of using the HD mode filter

		Non-Filtered Waveforms	AC Coupled	Filtered Waveforms	AC Coupled and Filterd Waveforms	Units
Two Wattmeter Method	VArms	8.5	5.98	5.47	0.542	V
	VBrms	8.62	6.11	5.49	0.508	V
	VCrms	8.55	6.04	5.49	0.542	V
	IArms	2.74	2.73	2.75	2.74	A
	IBrms	2.77	2.78	2.78	2.79	A
	ICrms	2.77	2.78	2.78	2.79	A
	VArms * IArms	23.4	16.36	15.03	1.49	VA
	VBrms * IBrms	23.95	16.98	15.25	1.42	VA
	VCrms * ICrms	23.7	16.83	15.25	1.51	VA
	Total	71.05	50.17	45.53	4.42	VA
	Reactive (A)	23.47	16.49	15	0.655	VAR
	Reactive (B)	23.98	17.04	15.2	0.682	VAR
	Reactive (C)	23.89	17.68	15.22	0.917	VAR
	Total	71.34	51.21	45.42	2.254	VAR
	Mean (VArms * IArms)	1.7	1.52	1.44	1.34	W
	Mean (VBrms * IBrms)	1.59	1.43	1.39	1.25	W
	Mean (VCrms * ICrms)	1.25	1.36	1.11	1.2	W
	Total	4.54	4.31	3.94	3.79	W
Two Wattmeter Method	V(A_C)rms	3.64	3.55	0.96	0.92	V
	V(B_C)rms	3.51	3.52	0.88	0.869	V
	V(A_C)rms * IArms	9.98	9.81	2.65	2.53	VA
	V(B_C)rms * IArms	9.75	9.77	2.43	2.42	VA
	Total	19.73	19.58	5.08	4.95	VA
	Reactive (A-C)	9.73	9.71	0.803	0.562	VAR
	Reactive (B-C)	9.77	9.81	1.96	2.05	VAR
	Total	19.5	19.52	2.763	2.612	VAR
	mean (V(A-C)rms * IArms)	2.85	2.8	2.52	2.47	W
	mean (V(B-C)rms * IBrms)	1.71	1.47	1.51	1.29	W
	Total	4.56	4.27	4.03	3.76	W

Note: R&S will be launching 3-phase and motor analysis software for the MXO Oscilloscopes over the next few firmware releasees

Part of that software features selecting a sync signal to correctly grab cycles even from PWM signals