Fundamentals of Electrical Power Measurement

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QUALITY ■ INNOVATION ■ FORESIGHT

Fundamentals
of
Electrical Power Measurements

Host

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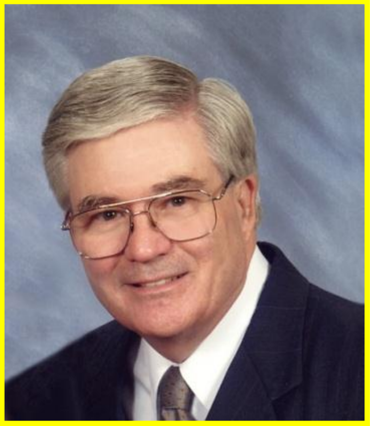
Presenter



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YOKOGAWA

Providing Solutions
and
Education
for
Electrical Power Measurements

Overview - What We Plan To Do

- **Part I: Electrical Power Measurements**
- **Review Some Basics**
- **Power Measurements Using a Precision Power Analyzer**
  - **Single-Phase Power Measurements**
  - **Current Sensors**
  - **Three-Phase Power Measurements**
  - **2 & 3 Wattmeter Method**

Overview - What We Plan To Do

- **Part II: Power Factor Measurement**
  - **Displacement Power Factor**
  - **True Power Factor**
  - **Power Factor Measurements in Single-Phase & Three-Phase Circuits**
  - **Practical Power Factor Measurement Applications**

Overview - What We Plan to Do

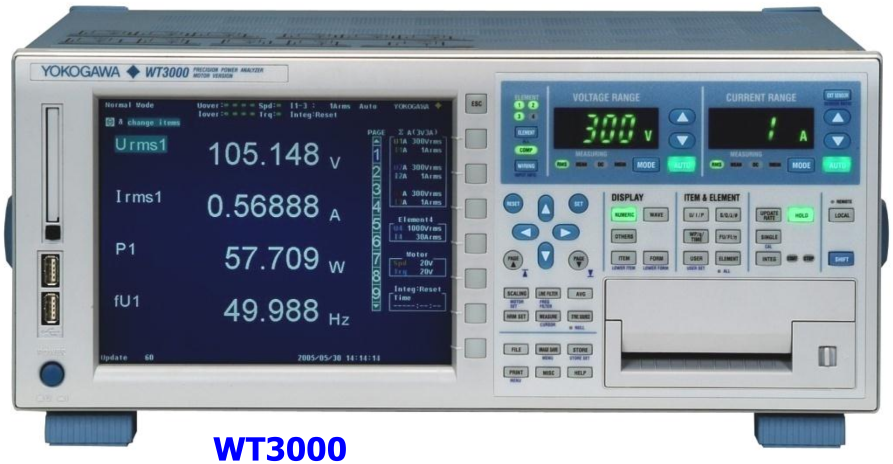
- **Part III: Power Measurements using a Digital Oscilloscope**
  - **How to properly use a Digital Oscilloscope to make Electrical Power Measurements**
  - **Some "Do's" and "Don'ts"**
  - **Measurement Examples**
  - **Comparison of a DSO and a Power Analyzer**

- **Answer your questions concerning Electrical Power Measurements**

Yokogawa Corporate History

1930 Vintage
Standard AC Voltmeter
0.2% Accuracy Class

- Founded in 1915.
- First to produce and sell electric meters in Japan.
- North American operation established in 1957
- World wide sales in excess of $4.3 Billion
- 84 companies world wide
- Over 19,000 employees worldwide
- Operations in 33 Countries

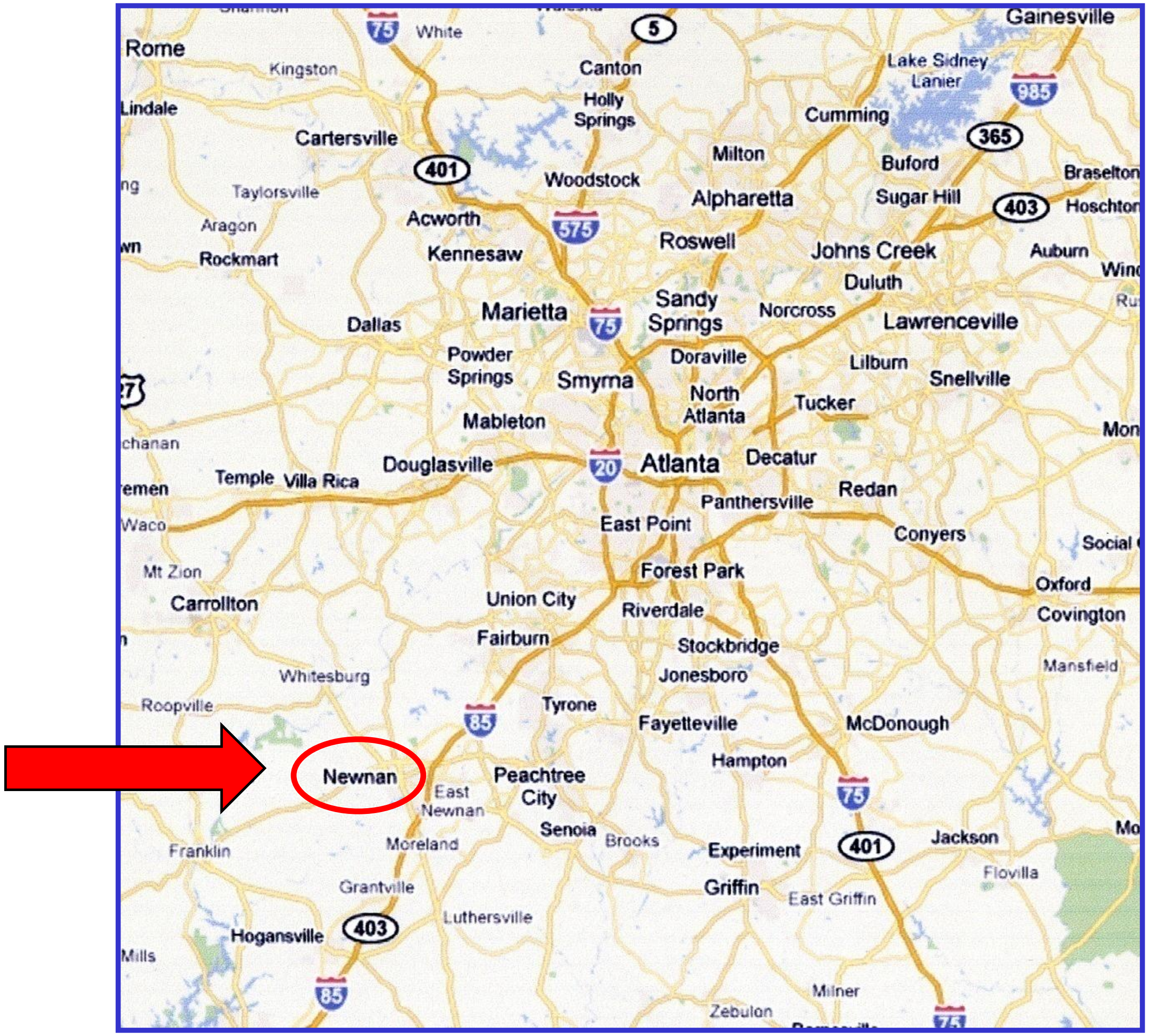


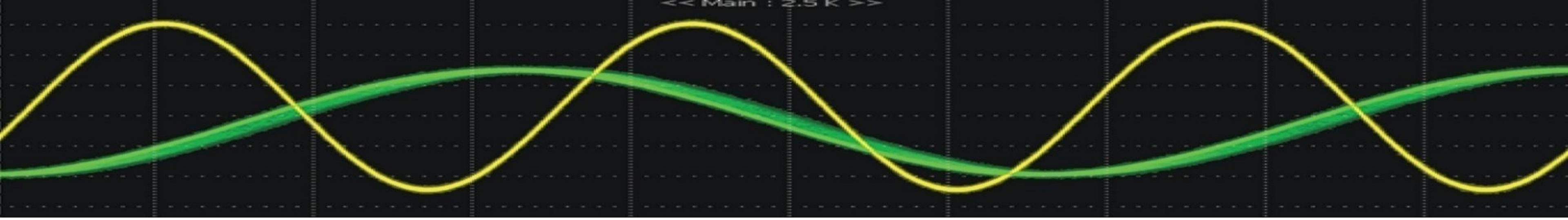
WT3000
Precision Power Analyzer

Yokogawa Corporation of America

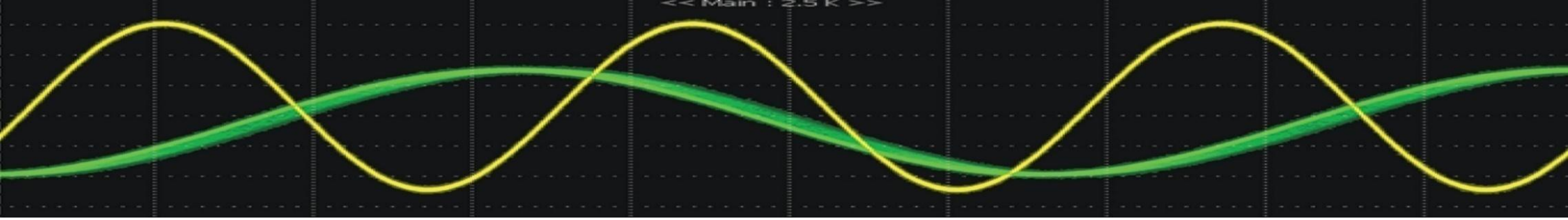
Yokogawa Corporation of America
Newnan, GA

Yokogawa Corporation of America



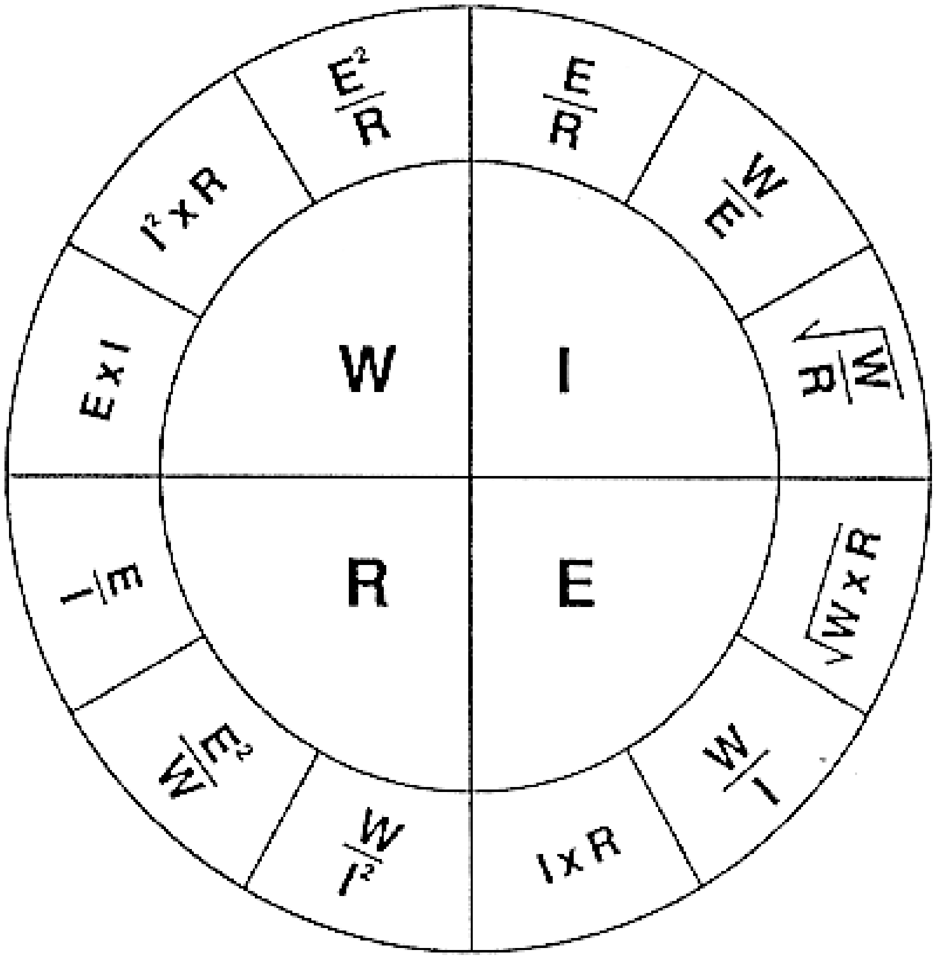


PART I
ELECTRICAL POWER MEASUREMENTS



First let’s Review some Basics

Review OHM'S LAW



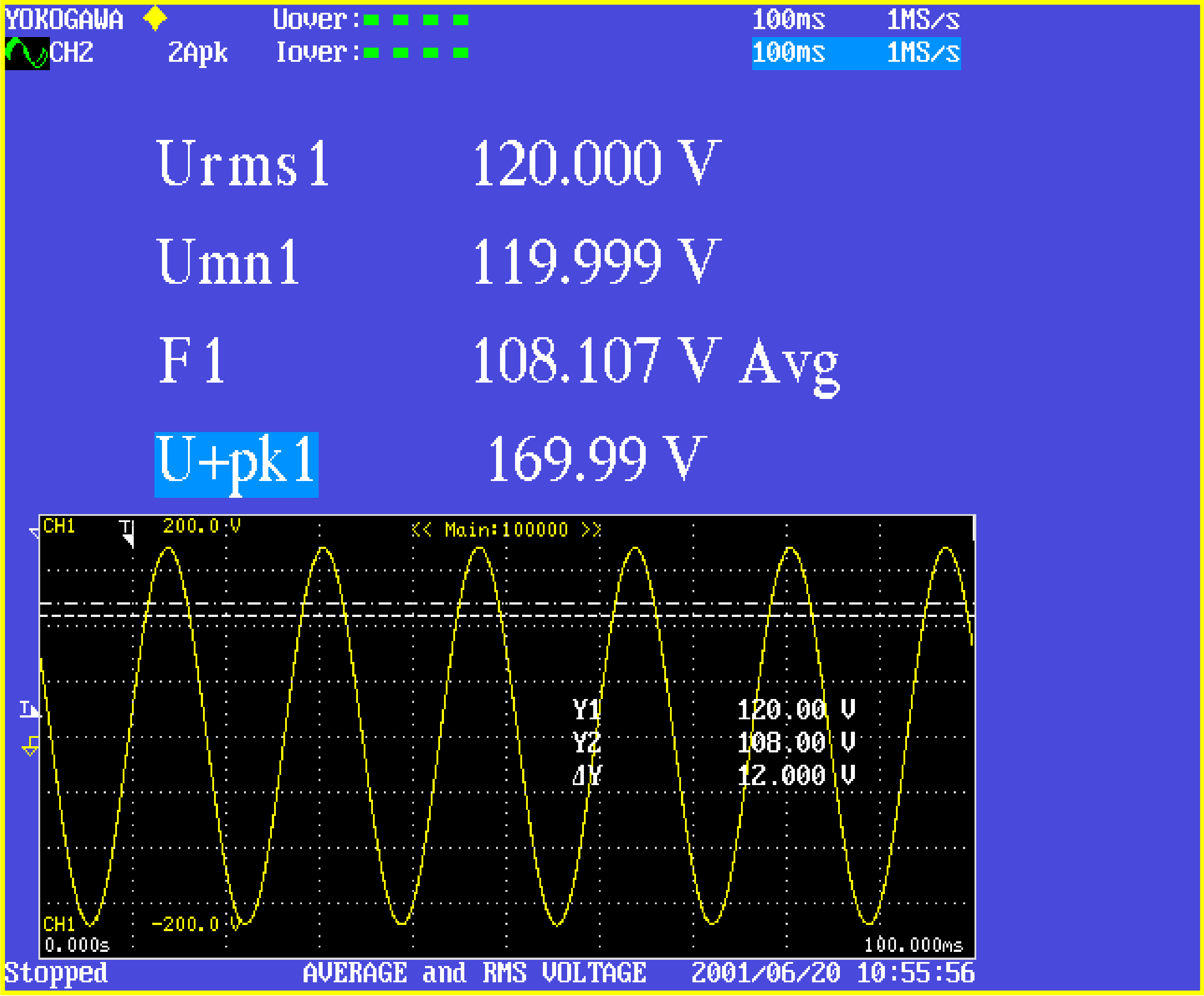
Average and RMS Values

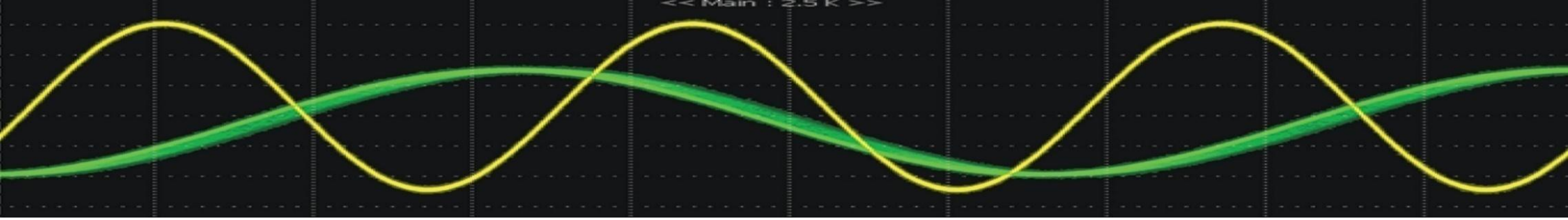
Average, RMS, Peak-to-Peak Value Conversion for Sinusoidal Wave

(multiplication factor to find)

Known Value	Average	RMS	Peak	Peak-to-Peak
Average	1.0	1.11	1.57	3.14
RMS	0.9	1.0	1.414	2.828
Peak	0.637	0.707	1.0	2.0
Peak-to-Peak	0.32	0.3535	0.5	1.0

Average and RMS Values





Electrical Power Measurements

What's A Watt ?

A unit of Power equal to one Joule of Energy per Second

DC Source: $\underline{W = V \times A}$

AC Source: $\underline{W = V \times A \times PF}$

Measurement of Power

AC Power Measurement

- **Active Power:**

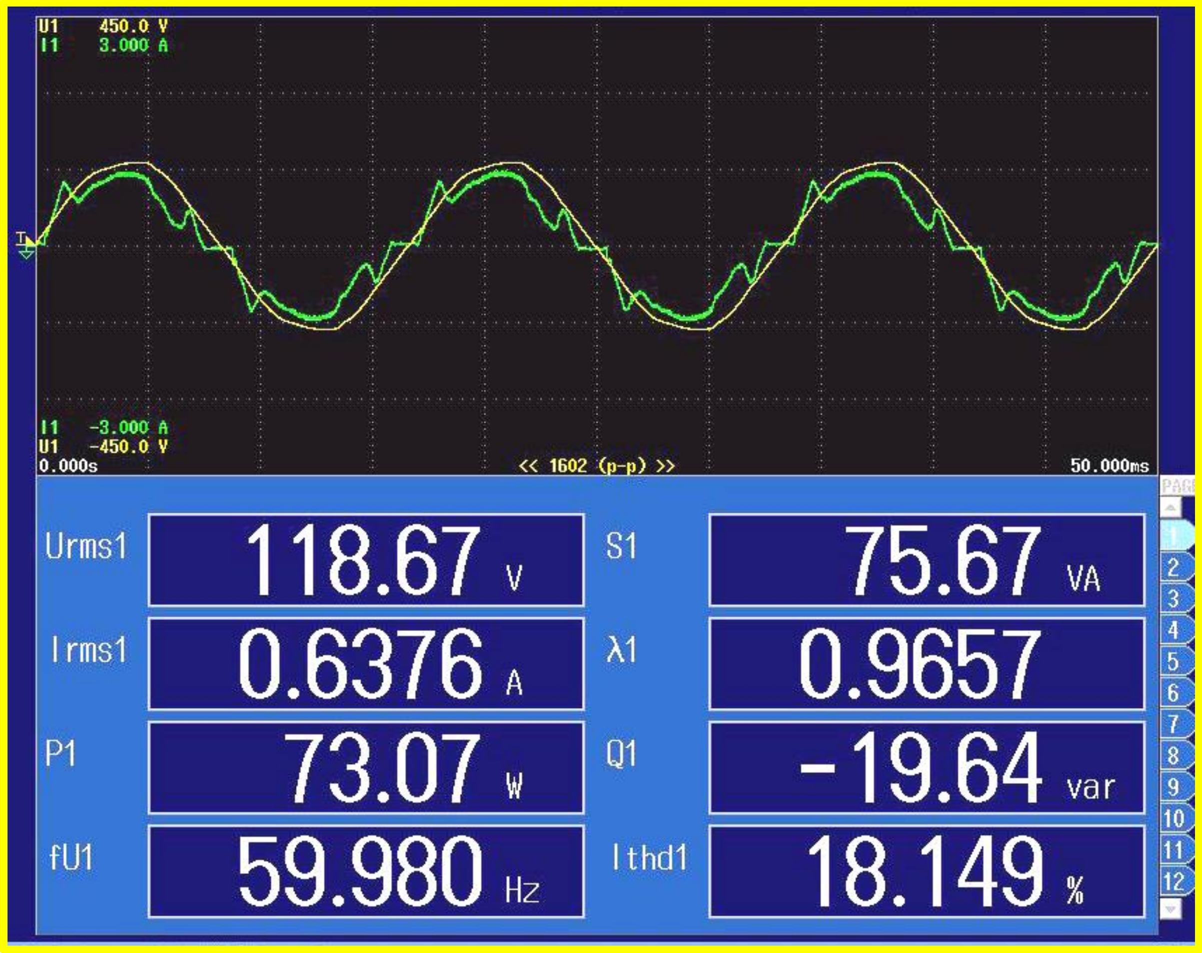
  Watts $P = V_{rms} \times A_{rms} \times PF$

  - **Also sometimes referred to as True Power or Real Power**

- **Apparent Power:**

  Volt-Amps $S = V_{rms} \times A_{rms}$

Measurement of AC Power



Watts $P = V_{rms} \times A_{rms} \times PF$ = Urms1 x Irms1 x λ1

Volt-Amps $S = V_{rms} \times A_{rms}$ = Urms1 x Irms1

Measurement of Power

- **Digital Power Analyzers are entirely electronic and use some form of DIGITIZING TECHNIQUE to convert analog signals to digital form.**
  - **higher end analyzers use DIGITAL SIGNAL PROCESSING techniques to determine values**
- **Digital Power Oscilloscopes use SPECIAL FIRMWARE to make true power measurements**
- **Digitizing instruments are somewhat RESTRICTED because it is a sampled data technique**
- **Many Power Analyzers and Power Scopes apply FFT algorithms for additional power and harmonic analysis**

Measurement of Power

- **Yokogawa Digital Power Analyzers and Digital Power Scopes use the following method to calculate power:**

  - $P_{avg} = 1/T \int_0^T v(t) * I\,(t)\,dt$

- **Using digitizing techniques, the <u>INSTANTANEOUS VOLTAGE</u> is multiplied by the <u>INSTANTANEOUS CURRENT</u> and then <u>INTEGRATED</u> over some time period.**

True RMS Measurements

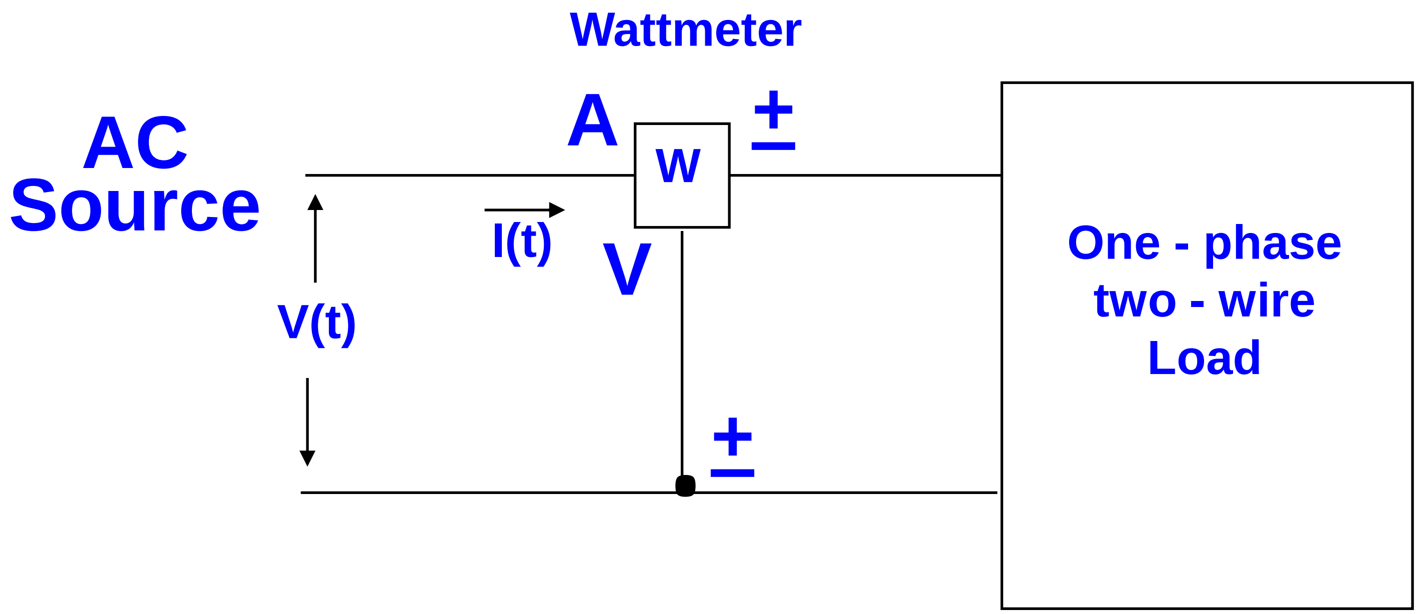
$$P_{total} = 1/T \int_0^T v(t) * I(t)\,dt$$

$$U_{RMS} = \sqrt{1/T \int_0^T v(t)^2\,dt}$$

$$I_{RMS} = \sqrt{1/T \int_0^T i(t)^2\,dt}$$

These calculation methods provide a True Power Measurement and True RMS Measurement on any type of waveform, including all the harmonic content, up to the bandwidth of the instrument.

Single Phase Power Measurement



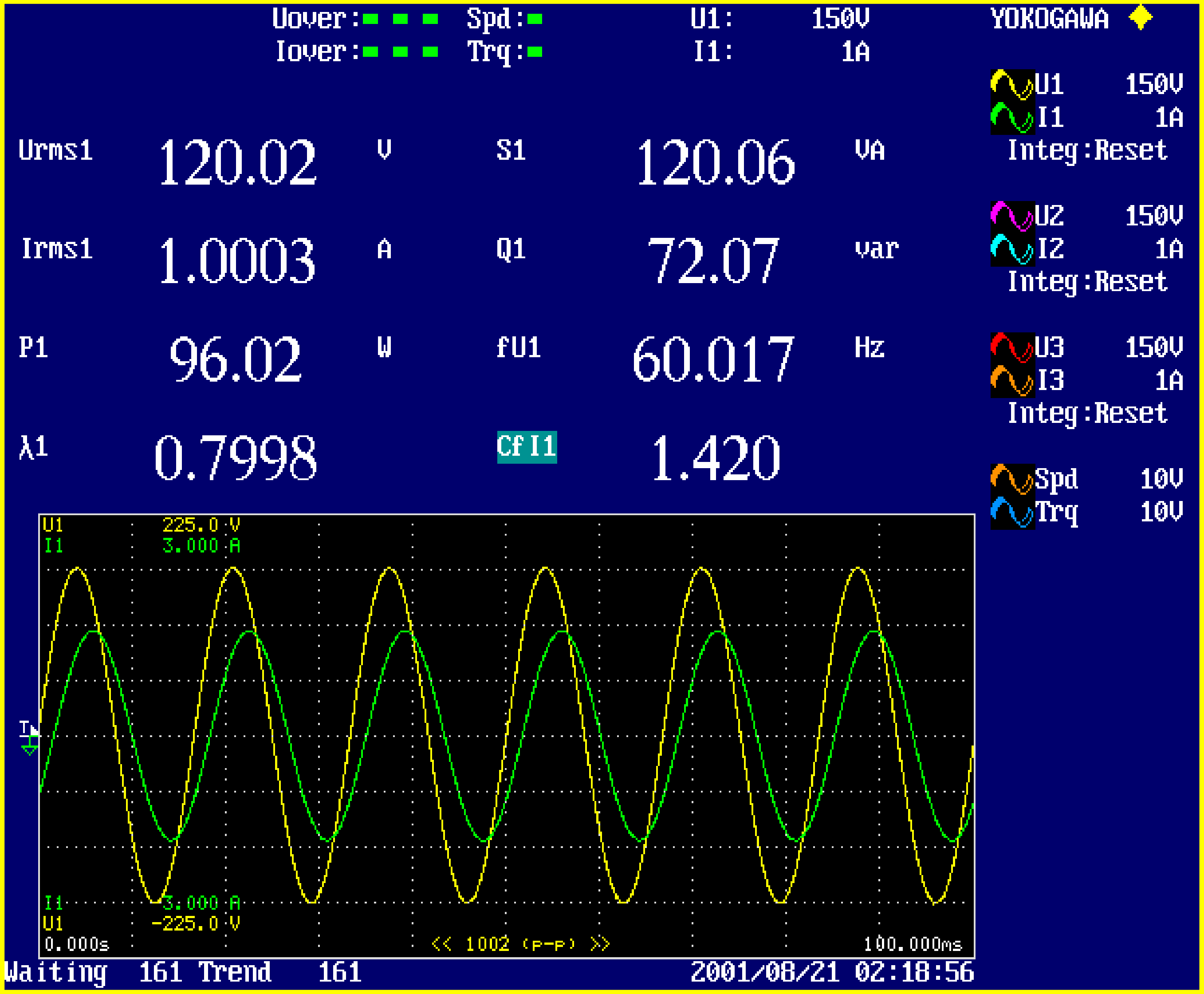
Single Wattmeter
Method

Single-Phase Two-Wire System

- The voltage and current detected by the **METER** are the voltage and current applied directly to the Load.

- The indication on the Meter is the **POWER** being dissipated by the load.

Measurement Results Single-Phase Two-Wire System



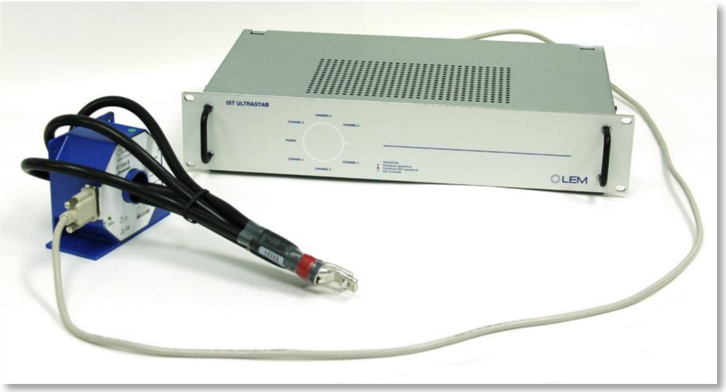
Current Sensors

AEMC

Yokogawa Scope Probes

Yokogawa CT's

Yokogawa/GMW-LEM/Danfysik CT System



Pearson Electronics

Ram Meter Shunts

Current Sensors

SELECTION CONSIDERATIONS

- Accuracy, CT Turns Ratio Accuracy
- Phase Shift
  - 1 or 2 Degrees Maximum: Cosine 2 Deg = 0.9994
- Frequency Range
  - DC to line frequency, sine waves: DC Shunts
  - DC & AC: Hall Effect or Active type CT
  - AC Approximately 30 Hz and higher: Various types of CT's

Current Sensors

SELECTION CONSIDERATIONS

- **Instrument Compatibility**
  - **Output: Millivolts/Amp, Milliamps/Amp; or Amps**
  - **Impedance and Load, Burden**
  - **Scope Probes - - *CAUTION!* Use on Scopes, NOT Power Analyzers**
- **Physical Requirements**
  - **Size**
  - **Connections: Clamp-On or Donut type**
  - **Distance from Load to Instrument**

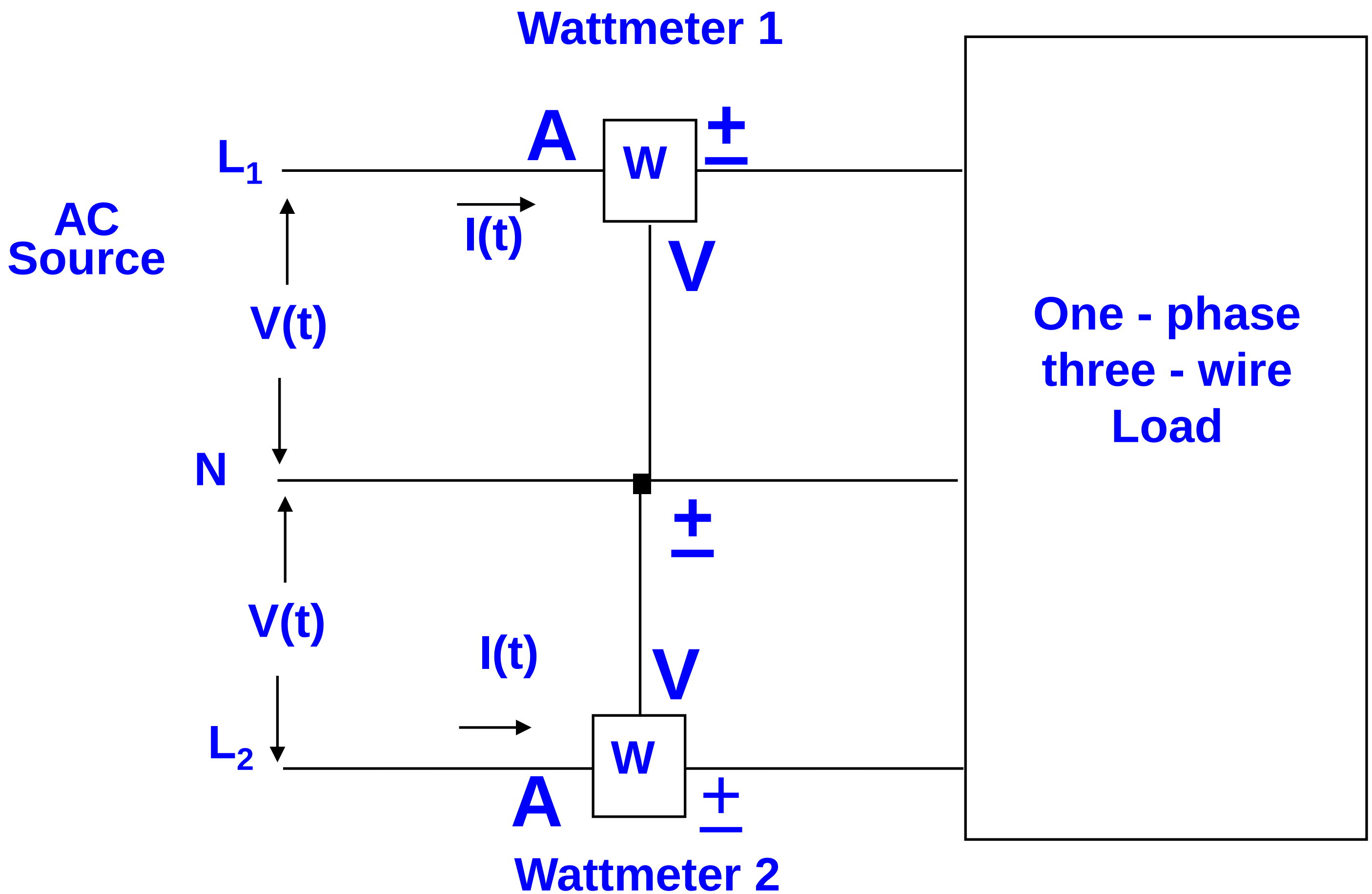
Current Sensors

A WORD OF CAUTION

➢ **NEVER Open Circuit the Secondary side of a Current Transformer while it is energized!**

- **This could cause serious damage to the CT and could possibly be harmful to equipment operators.**
- **A CT is a Current Source.**
    - **By Ohm's Law E = I x R**
    - **When R is very large, E becomes very high**
    - **The High Voltage generated inside the CT will cause a magnetic saturation of the core, winding damage, or other damage which could destroy the CT.**

Single-Phase Three-Wire Power Measurement



$$P_T = W1 + W2$$

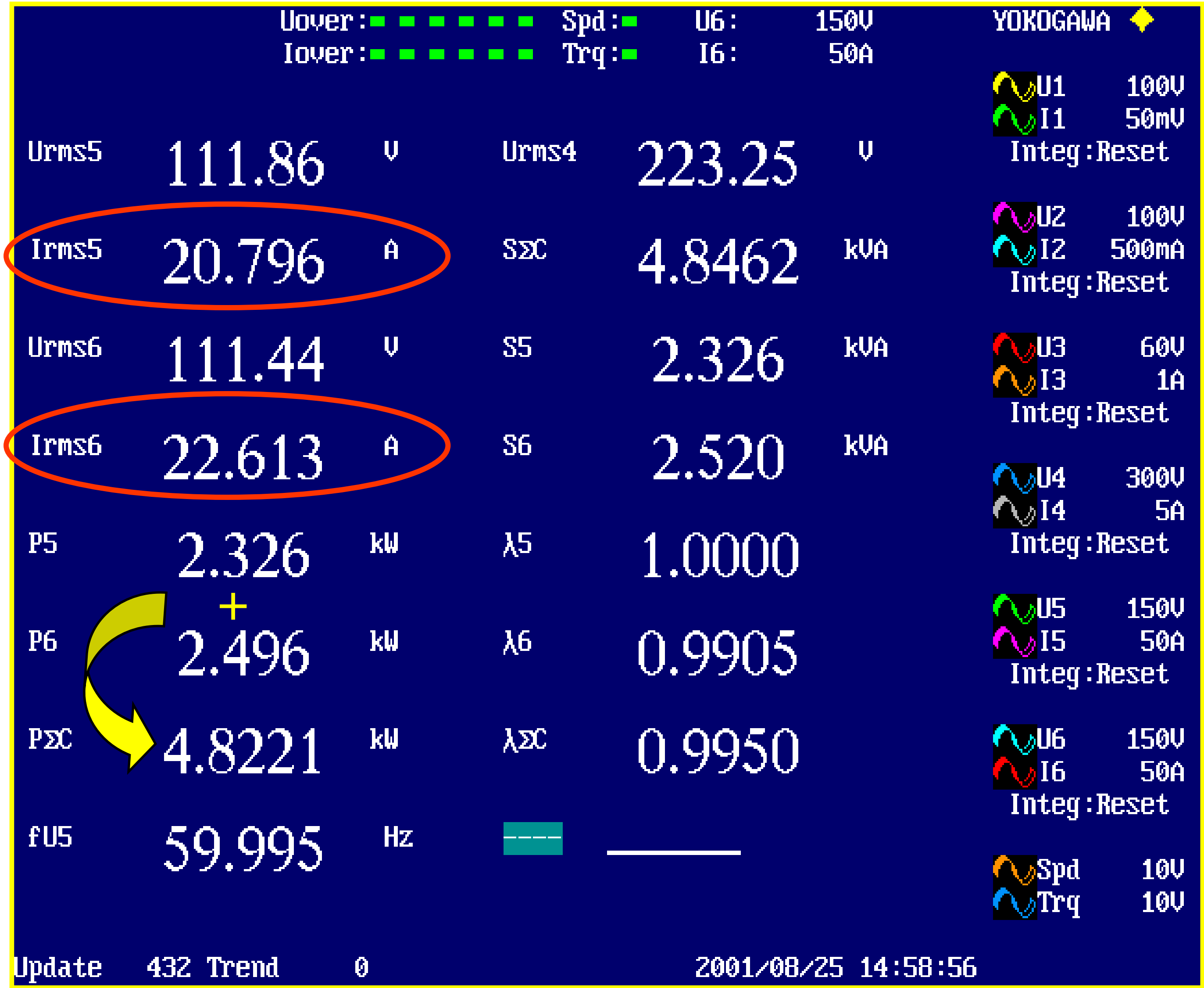
Two Wattmeter Method

Measurement of Power

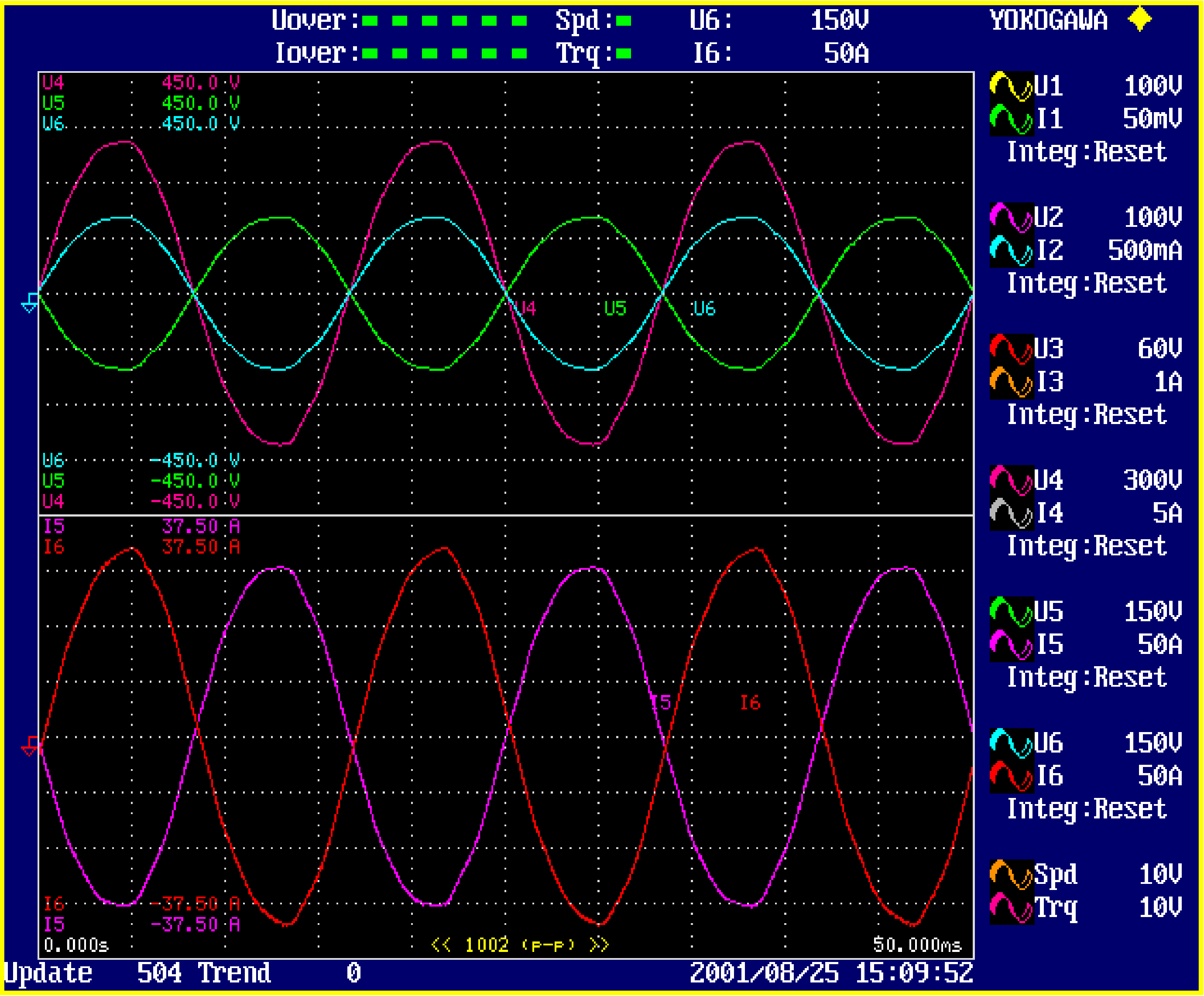
Single-Phase Three-Wire System
(Split Phase)

- **The voltage and current detected by the METERS are the voltage and current applied directly to the Load.**
- **The indication on EACH METER is the power being delivered by the LINE to which the meter is connected.**
- **The total power dissipated by the load is the ALGEBRAIC SUM of the two indications.**

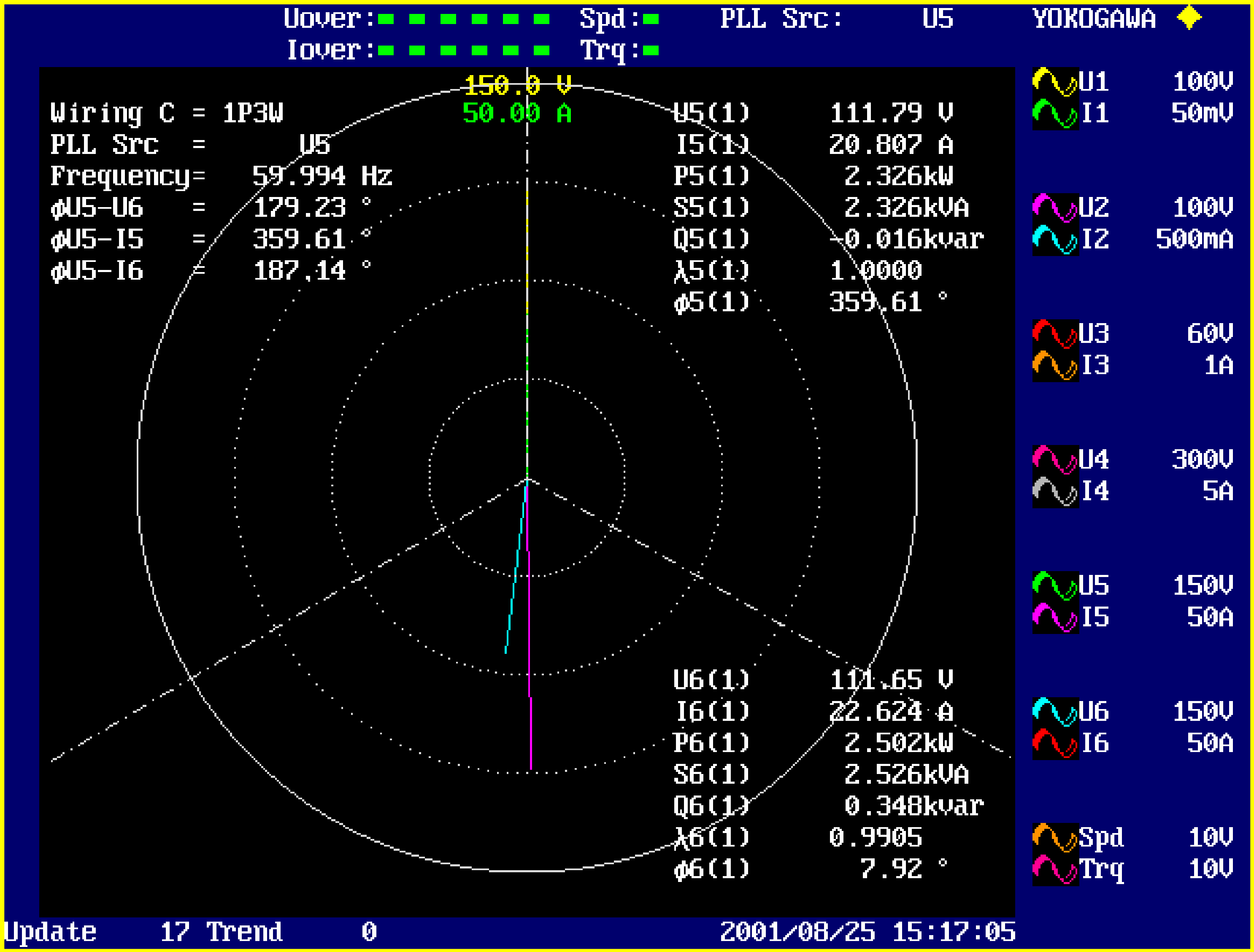
Measurement Results　Single-Phase Three-Wire System



Measurement Results　Single-Phase Three-Wire System



Measurement Results　Single-Phase Three-Wire System

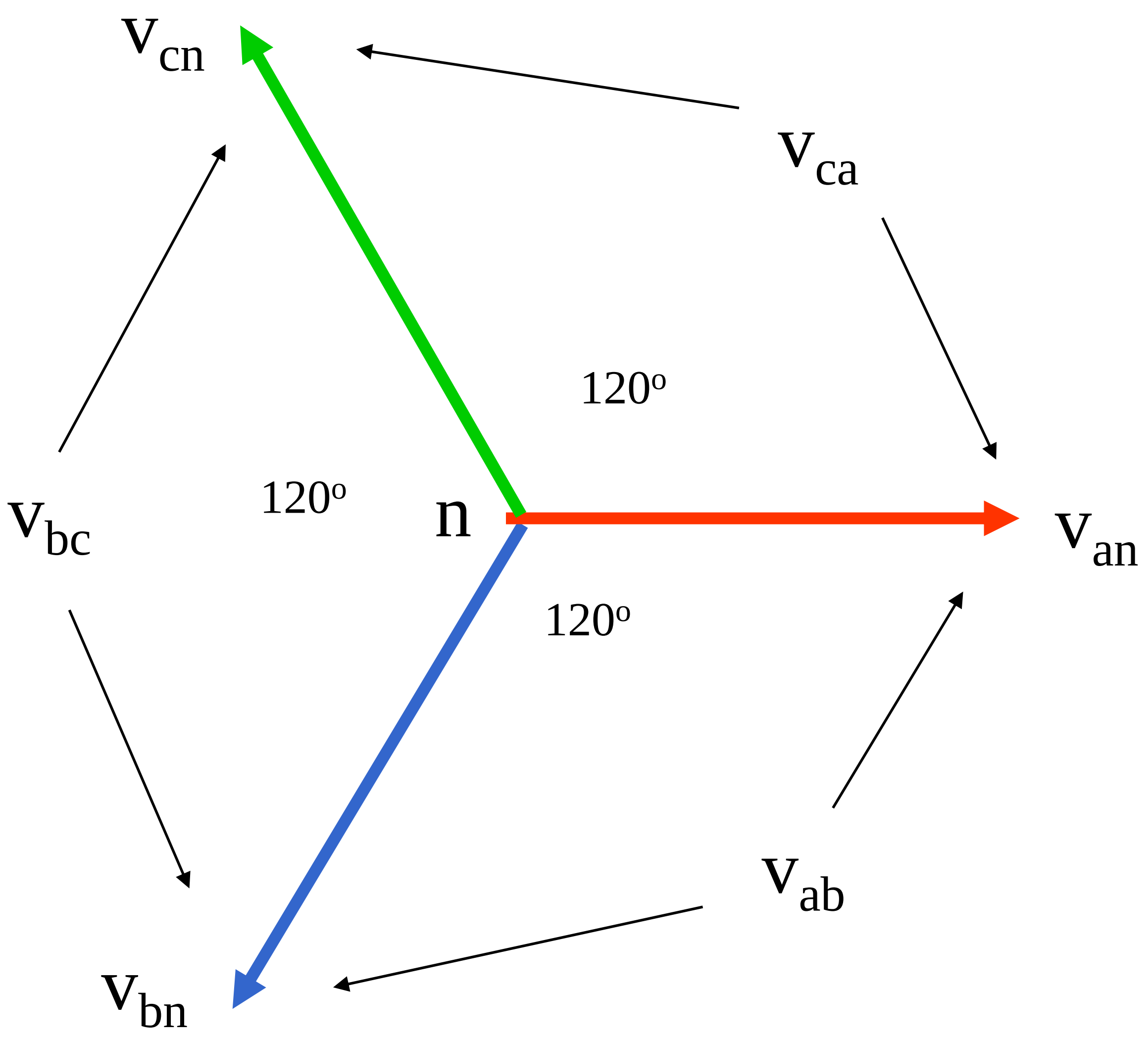


Blondel Transformation

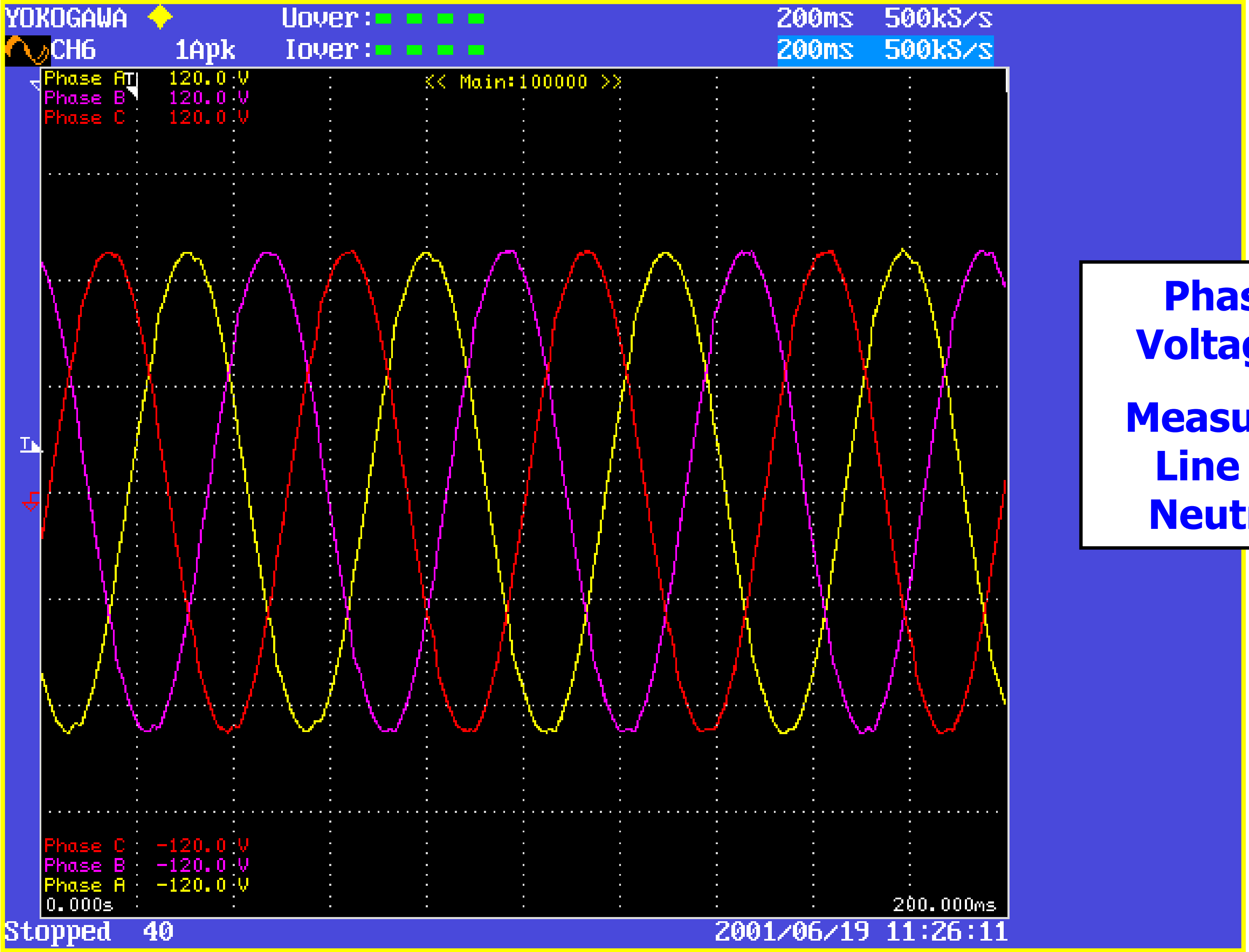
Blondel theory states that total power is measured with ONE LESS wattmeter than the number of WIRES.

1-P 2-W	**1 Wattmeter**
1-P 3-W	**2 Wattmeters**
3-P 3-W	**2 Wattmeters**
3-P 4-W	**3 Wattmeters**

Three - Phase Systems



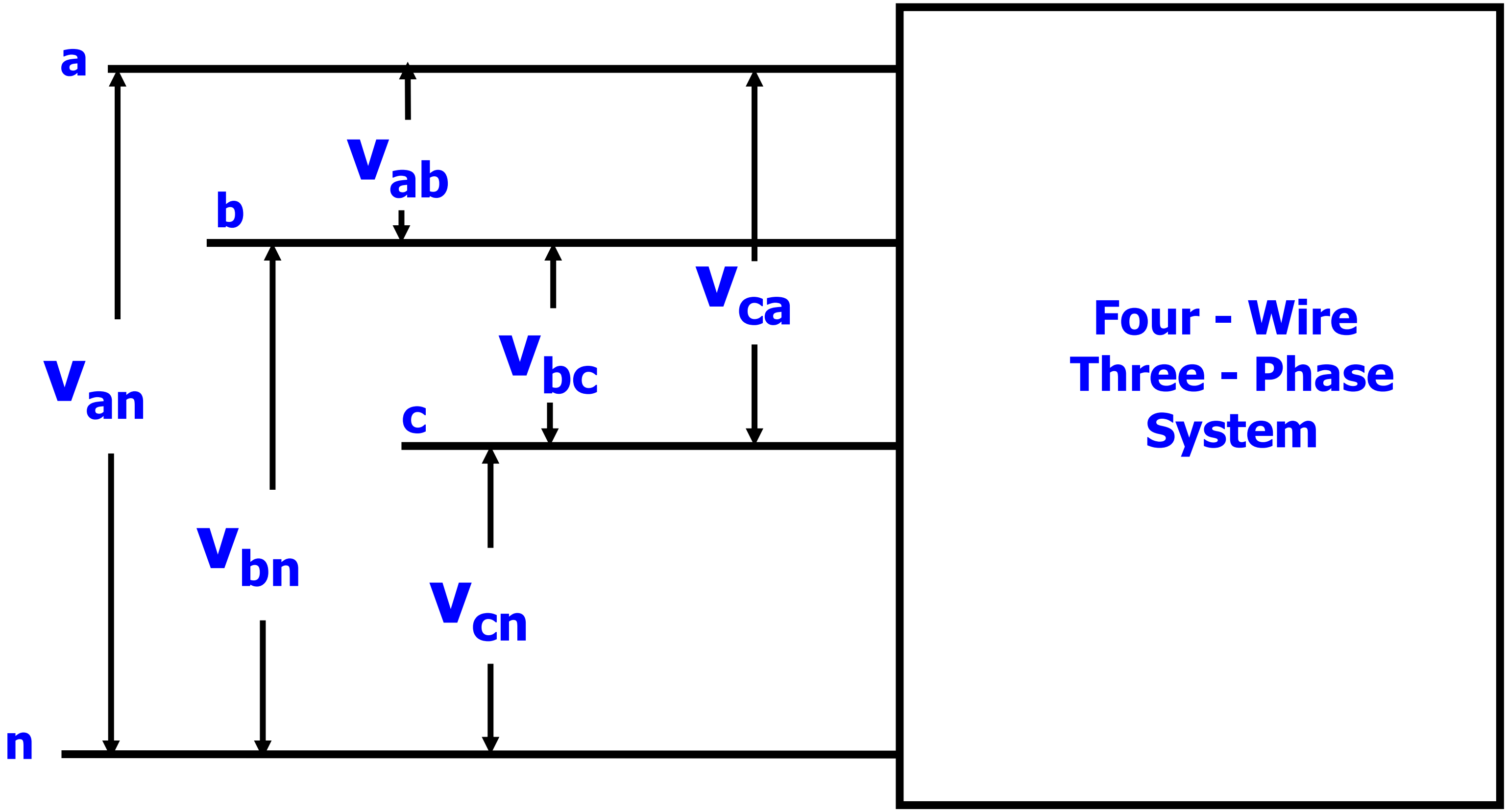
Three - Phase Systems



Phase Voltages

Measured Line to Neutral

Three - Phase Systems

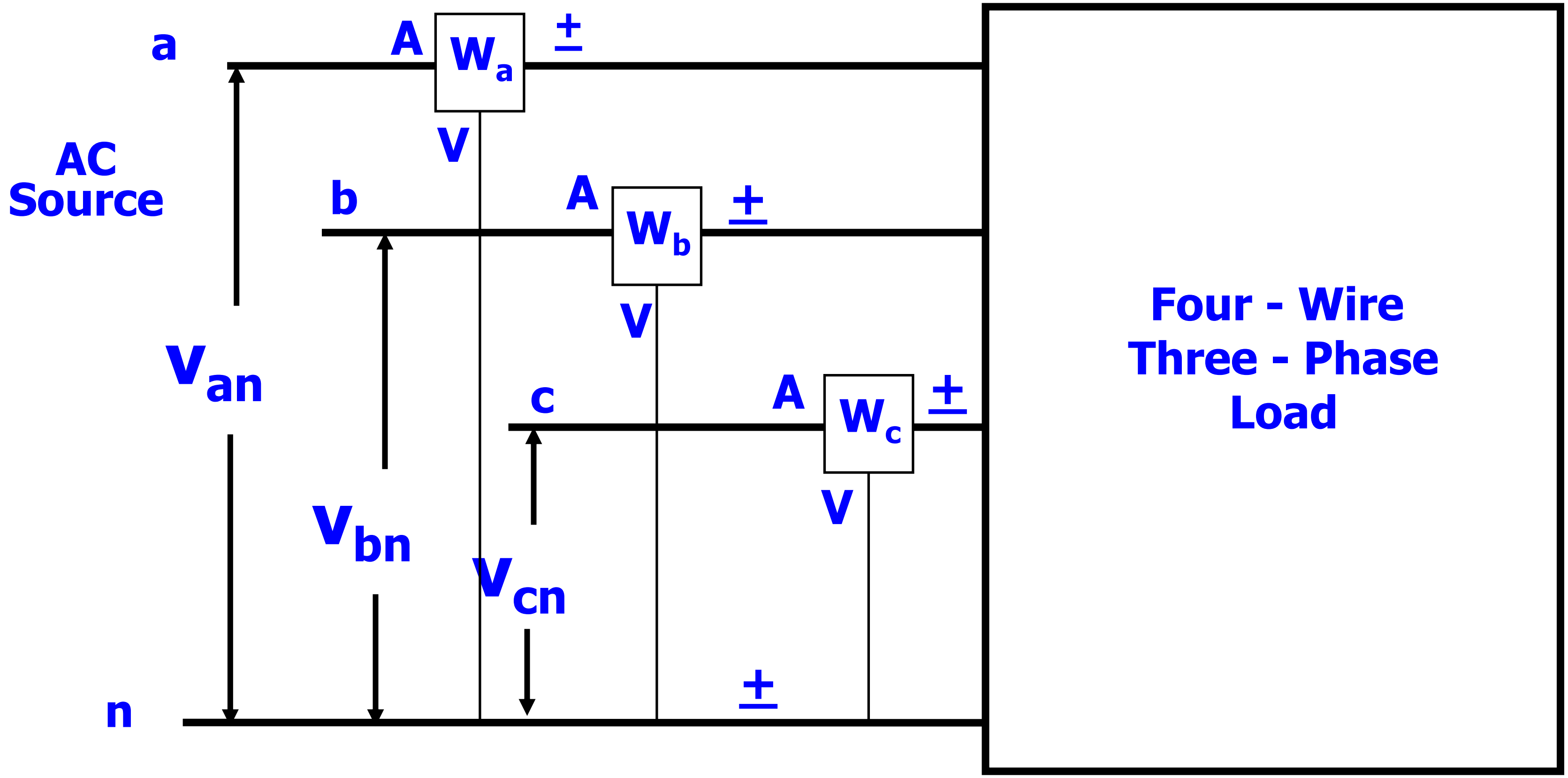


$V_{l\text{-}n}$ = 120 / 277 Volts

$V_{l\text{-}l}$ = 208 / 480 Volts

$$V_{l\text{-}l} = \sqrt{3} \ * \ V_{l\text{-}n}$$

Measurement of Power



Three Wattmeter Method

$$P_T = \sum W_a + W_b + W_c$$

Measurement of Power

Three-Phase Four-Wire System

- **The three meters use the FOURTH wire as the common voltage REFERENCE.**
- **Each meter indicates the PHASE power.**
- **The TOTAL POWER for the three phases is the ALGEBRAIC SUM of the three meters.**
- **In essence, each meter measures a SINGLE PHASE of the three phase system.**

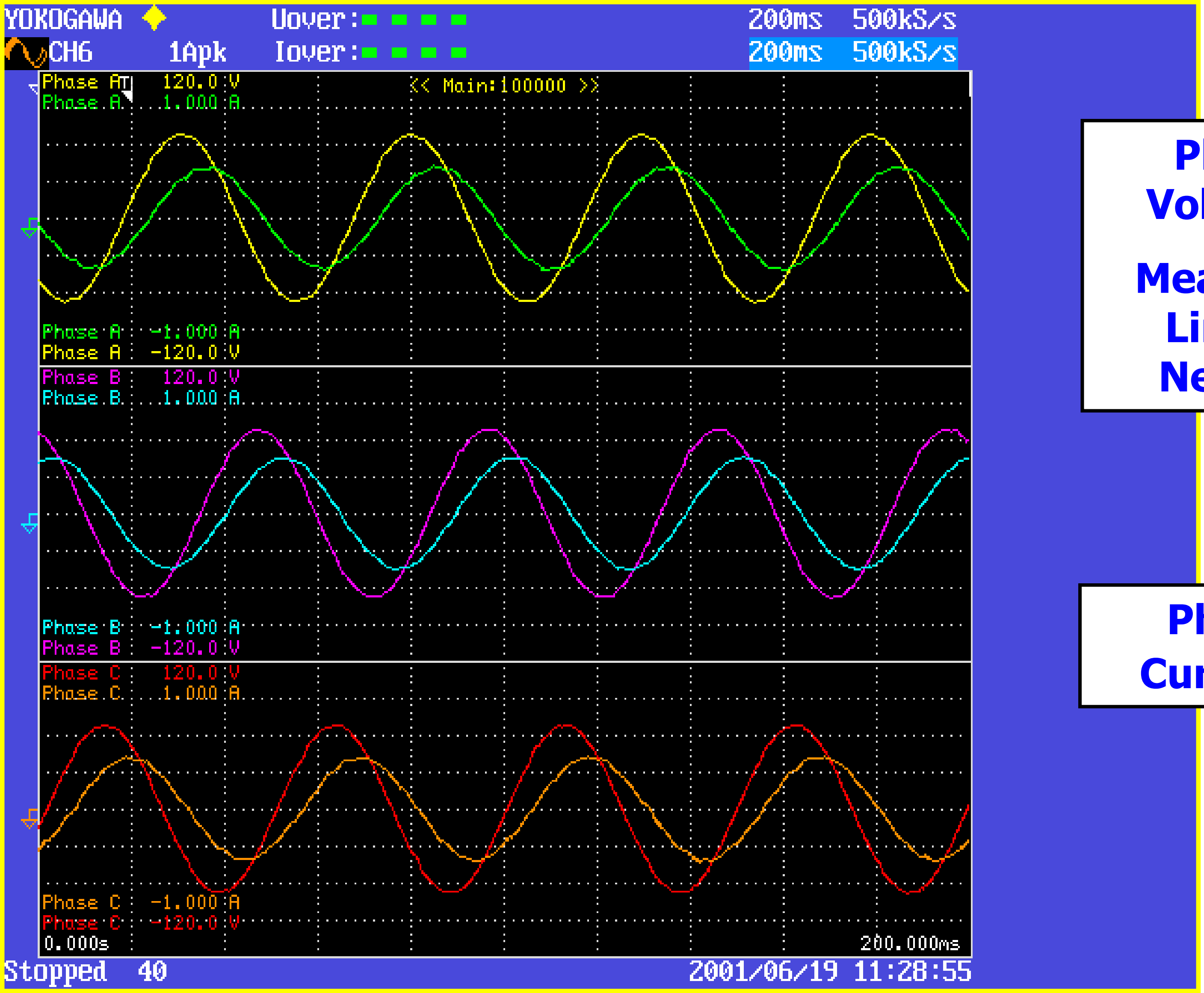
Measurement Results Three-Phase Four-Wire System

Phase Power

Phase Power Factor

Phase Current & Voltage

Measurement Results Three-Phase Four-Wire System

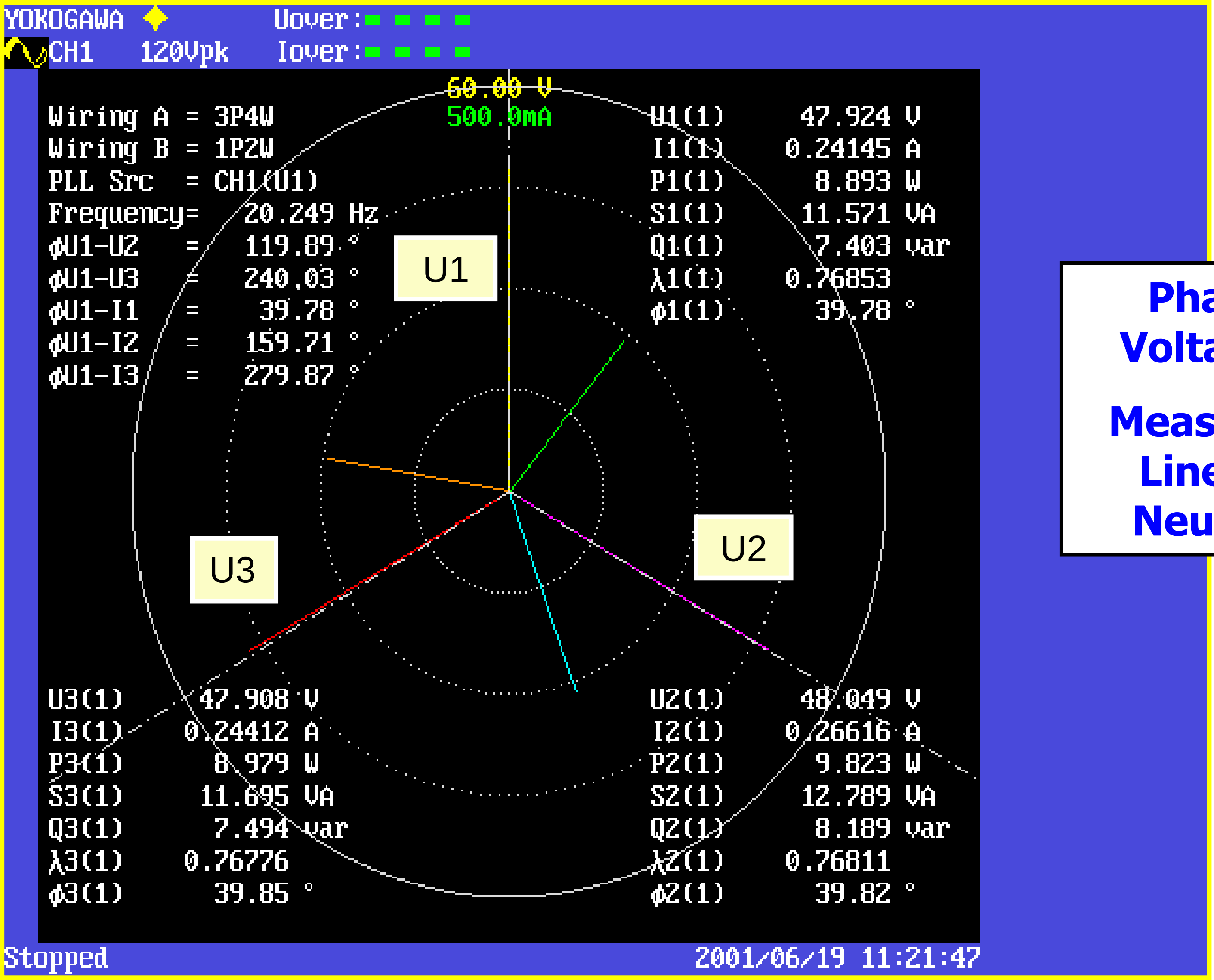


Phase Voltages

Measured Line to Neutral

Phase Currents

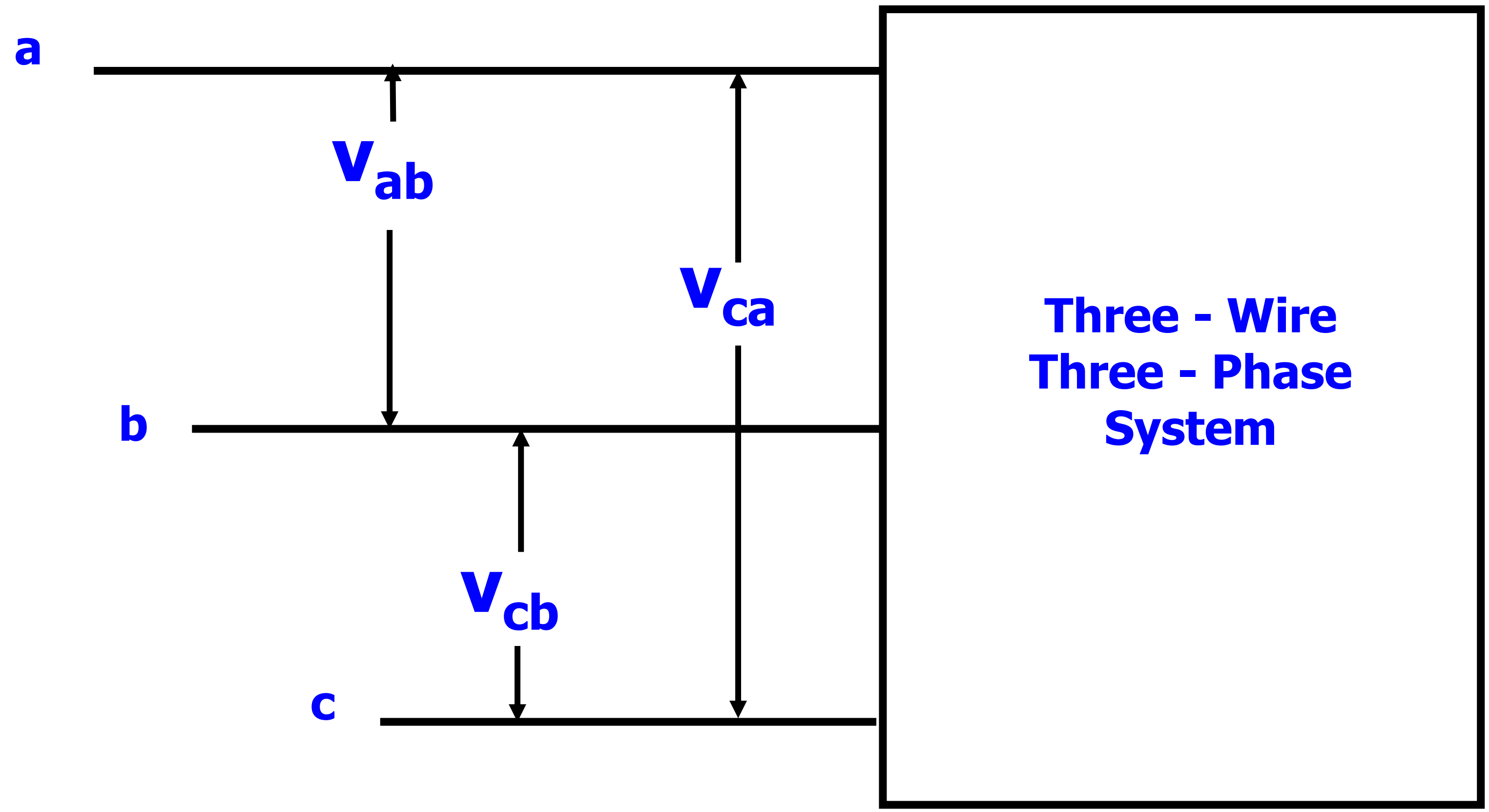
Three-Phase Four–Wire Vector Diagram



Phase Voltages

Measured Line to Neutral

Three-Phase Three-Wire Systems

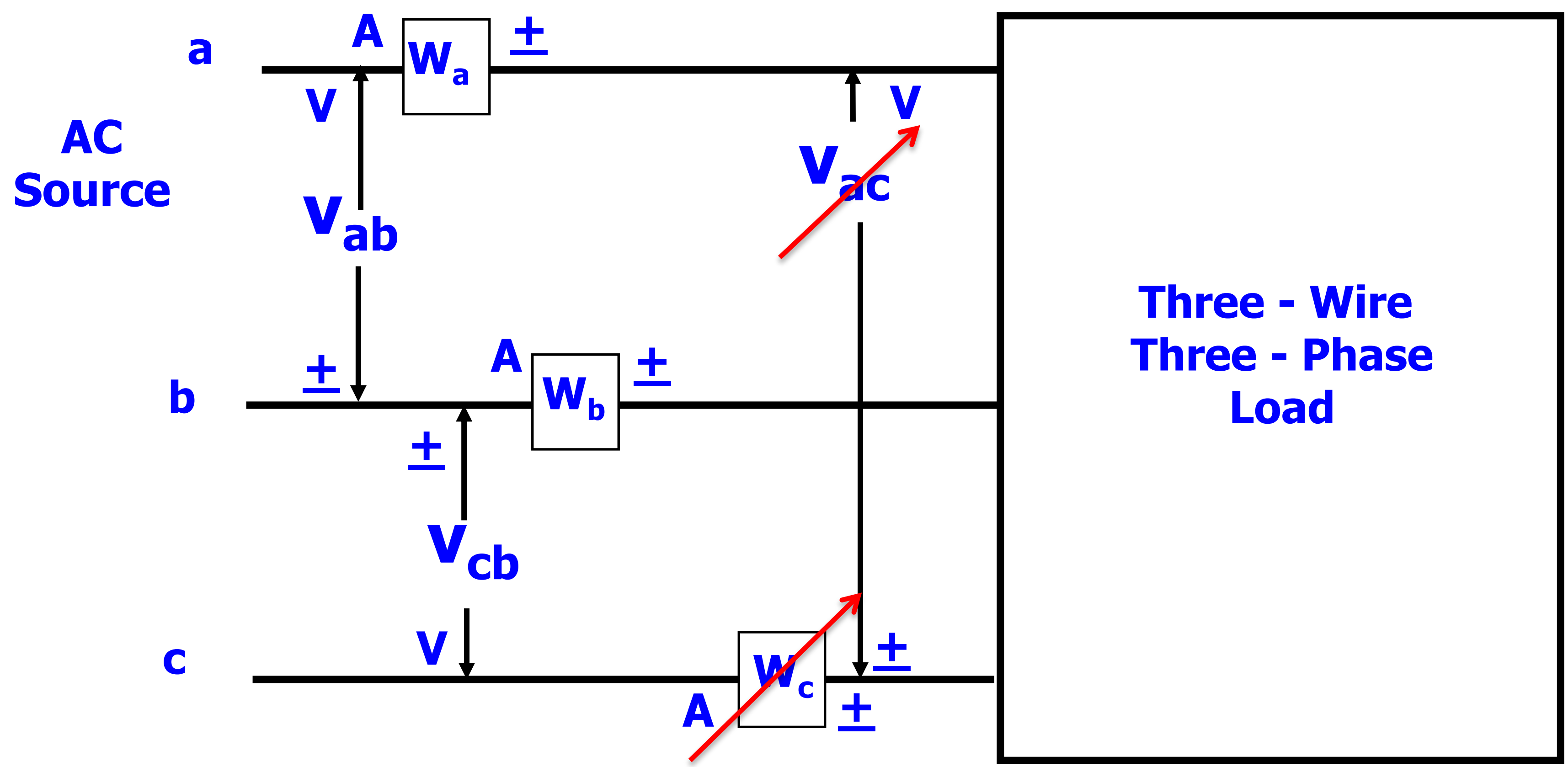


Remember

Blondel's Transformation

. . . total power is measured with ONE LESS wattmeter than the number of WIRES.

Three - Phase Three - Wire System With Two Meters



Two Wattmeter Method

$$P_T = \sum W_a + W_b$$

Measurement of Power

Three-Phase Three-Wire System

The wattmeters used for this connection each measure the <u>PHASE CURRENTS</u>

The measured voltages are the <u>LINE-TO-LINE</u> values, <u>NOT</u> Phase Voltage.

Thus the indications on each of the meters <u>IS NOT</u> the power delivered by the <u>PHASE</u> of the measured current.

This configuration is a very <u>NON-INTUITIVE</u> connection!

Three-Phase Three-Wire System

The method yields the Total Power as the Sum of the <u>TWO METERS</u> in Phase 1 and 2. Note that <u>NONE</u> of the meters is indicating the correct <u>PHASE POWER</u>.

Electrical Power Measurements

- The Two Wattmeter technique tends to cause less confusion than the three meter technique since there is no expectation that a meter will give an accurate phase indication.

- However, with the Yokogawa Power Analyzers, on a 3-Phase 3-Wire System, use the 3V-3A wiring method. This method will give all three Voltages and Currents, and correct Total Power, Total Power Factor and VA Measurements on either Balanced or Unbalanced 3-Wire system.

Three-Phase Three-Wire System With Three Meters

The method yields the Total Power as the Sum of the TWO METERS in Phase 1 and 2. Note that NONE of the meters is indicating the correct PHASE POWER.

Delta Measurements

3P3W (3V3A) Connection $P_{3P3W} = P_{3P4W}$

L-L Voltage

L-N Voltage

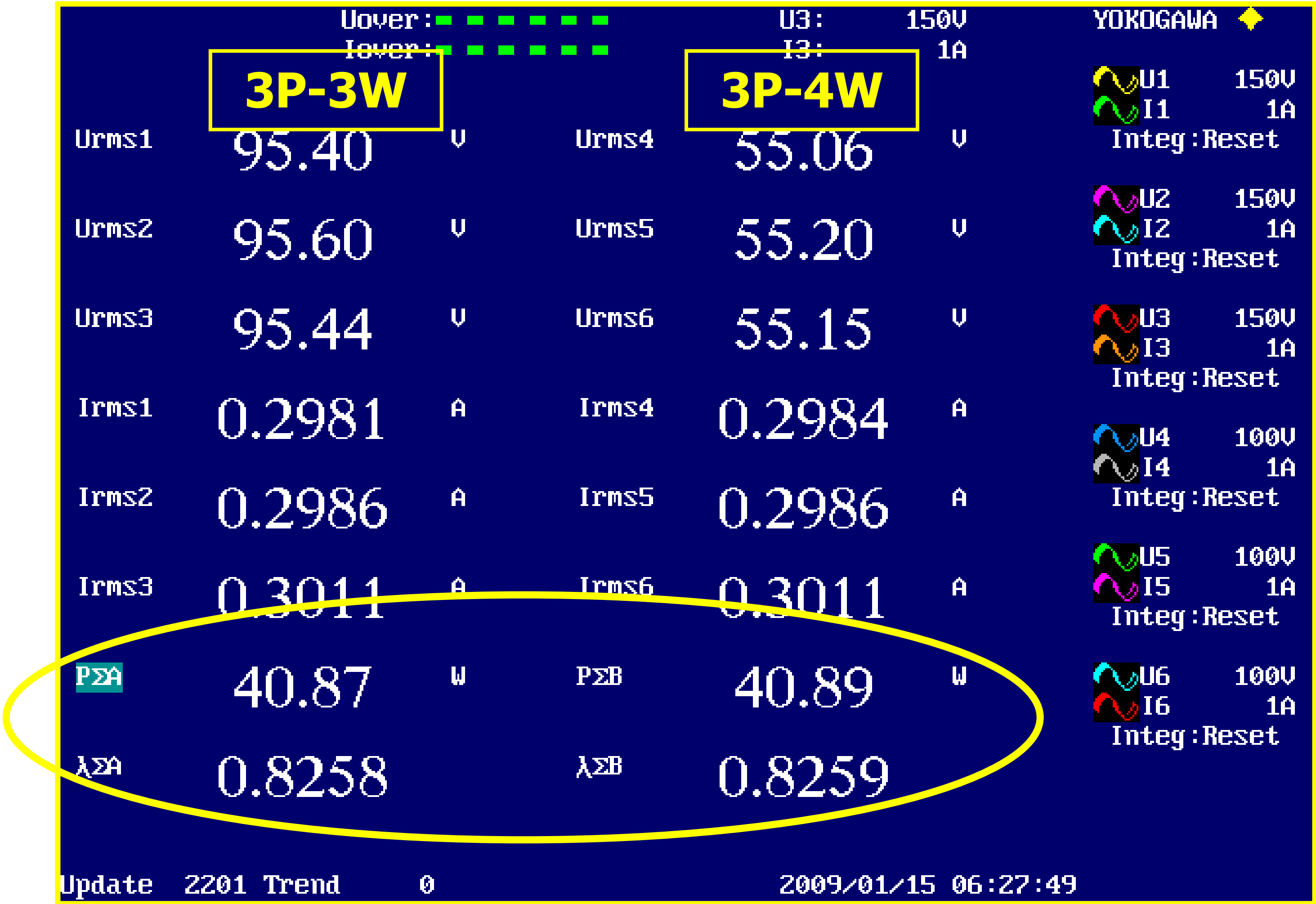
Phase Power

Neutral Current

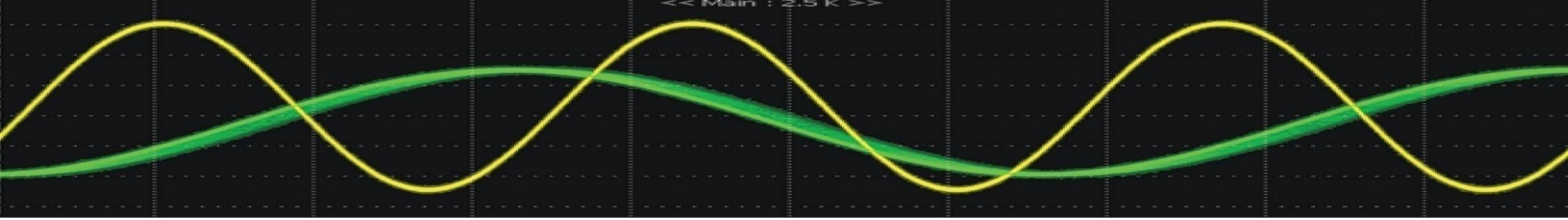
Phase Power Measurement Solution on 3P3W (3V3A) Connection

3P-3W and 3P-4W Power Measurements

$P_{3P3W} = P_{3P4W}$



$U_{L\text{-}N} \times \sqrt{3} = U_{L\text{-}L}$ $\quad 55.20 \times \sqrt{3} = 95.60$

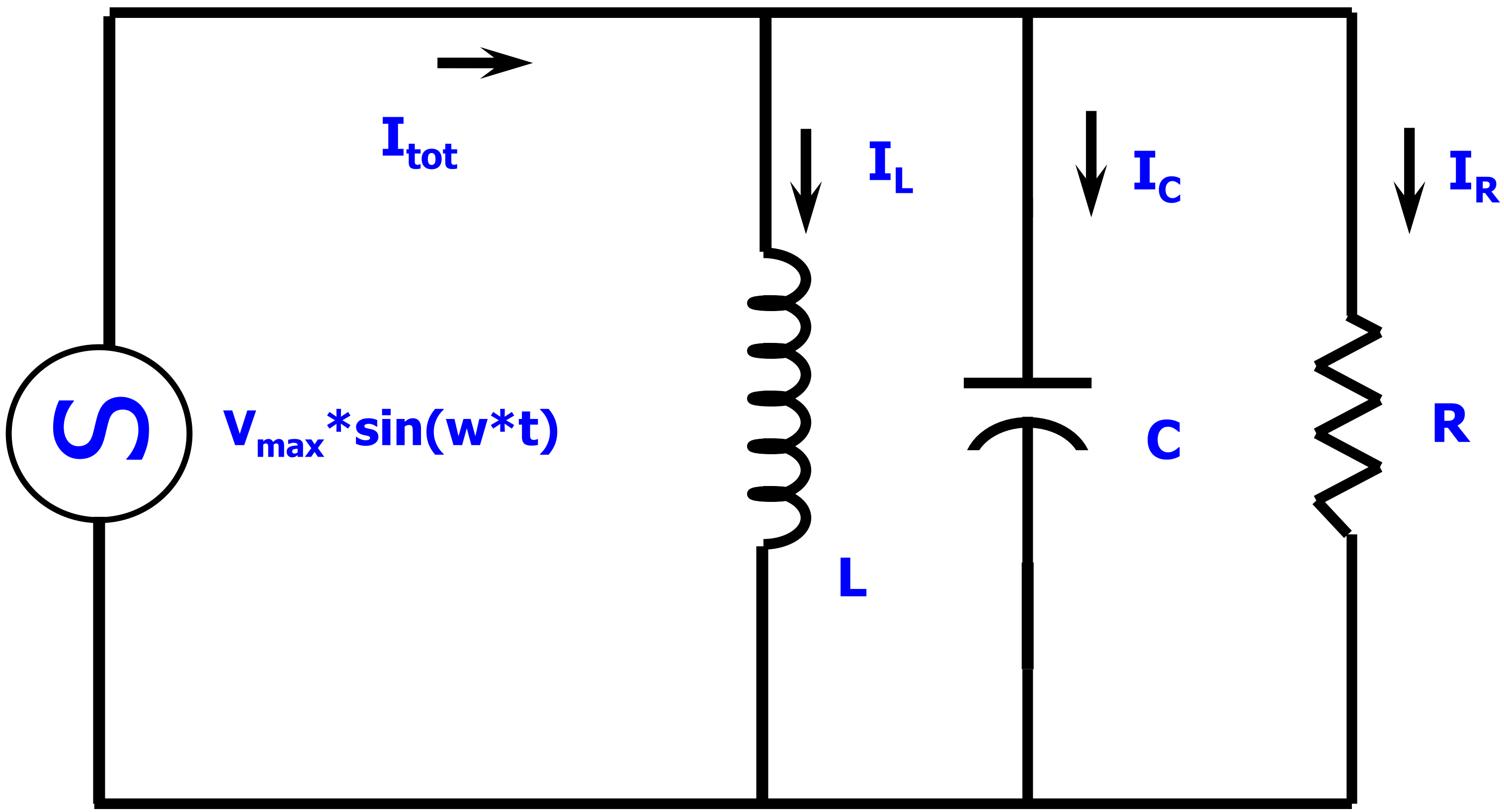


PART II
POWER FACTOR MEASUREMENTS

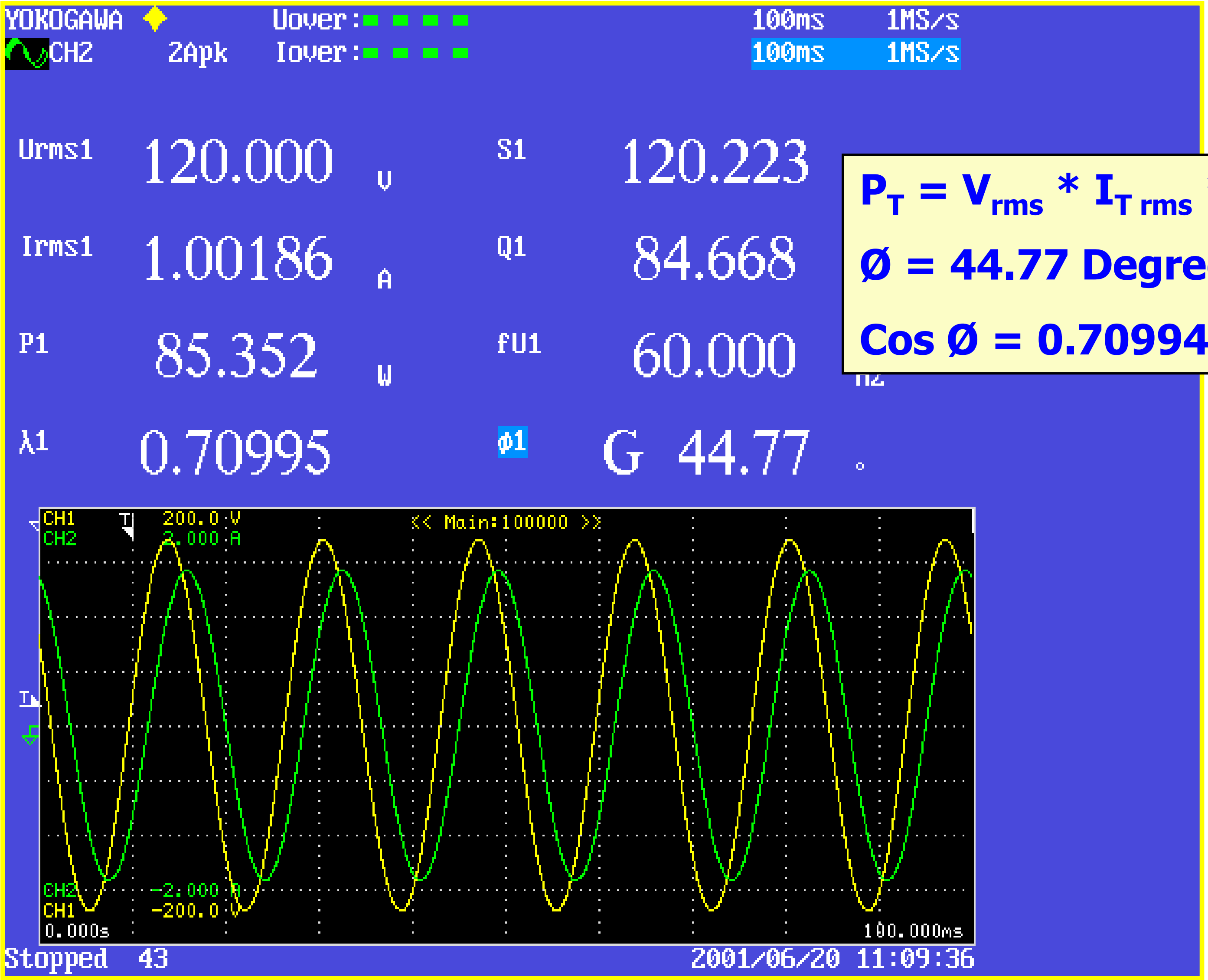
Power Factor Measurement

If Power Factor is the Cosine of the Angle between Voltage and Current, then how do we measure Power Factor on a Three Phase Circuit?

R - L - C Circuit



Current LAGS Voltage in an Inductor

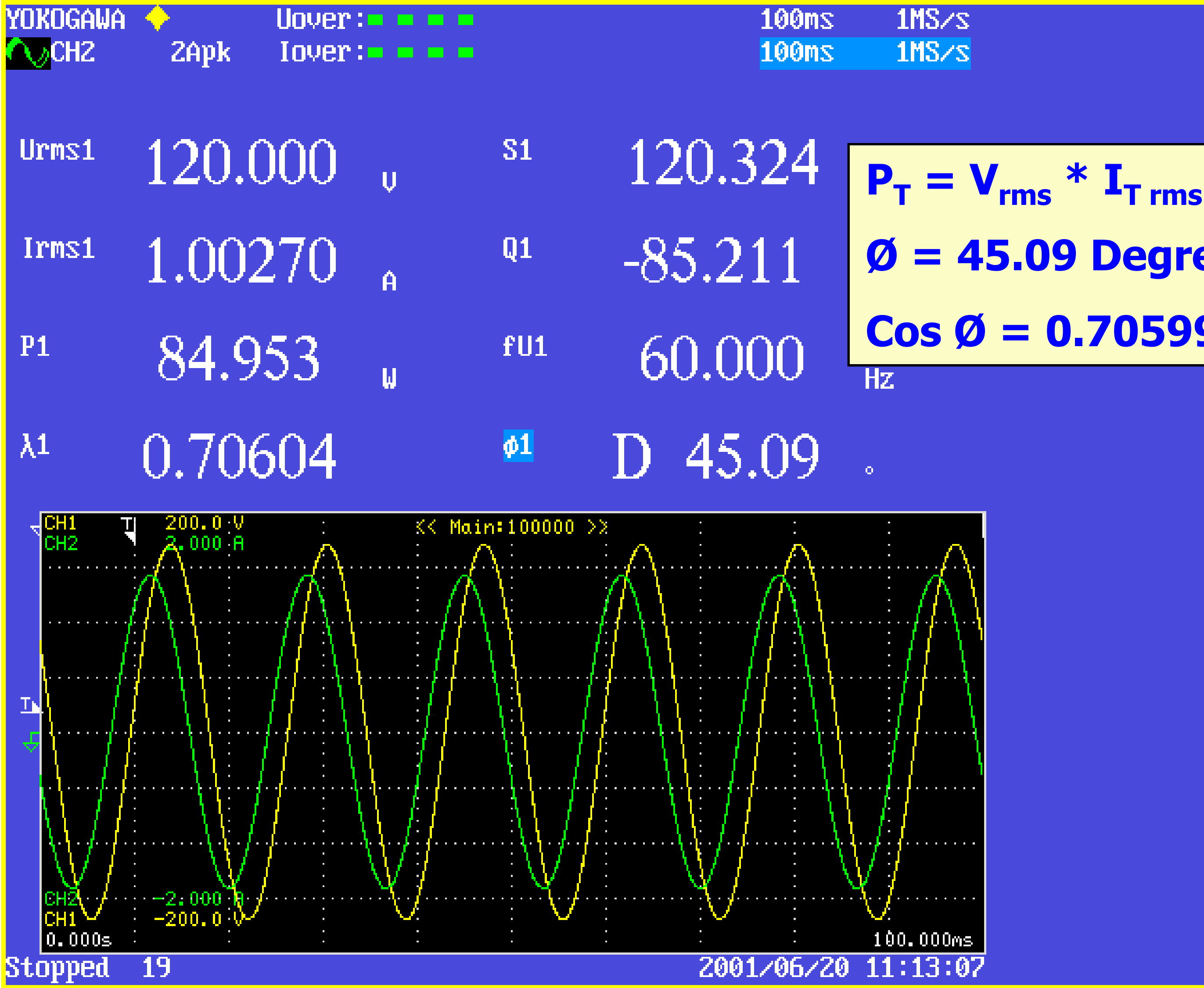


$P_T = V_{rms} * I_{T\ rms} * \mathrm{Cos}\ Ø$

$Ø$ = 44.77 Degrees

Cos $Ø$ = 0.70994

Current LEADS Voltage in a Capacitor

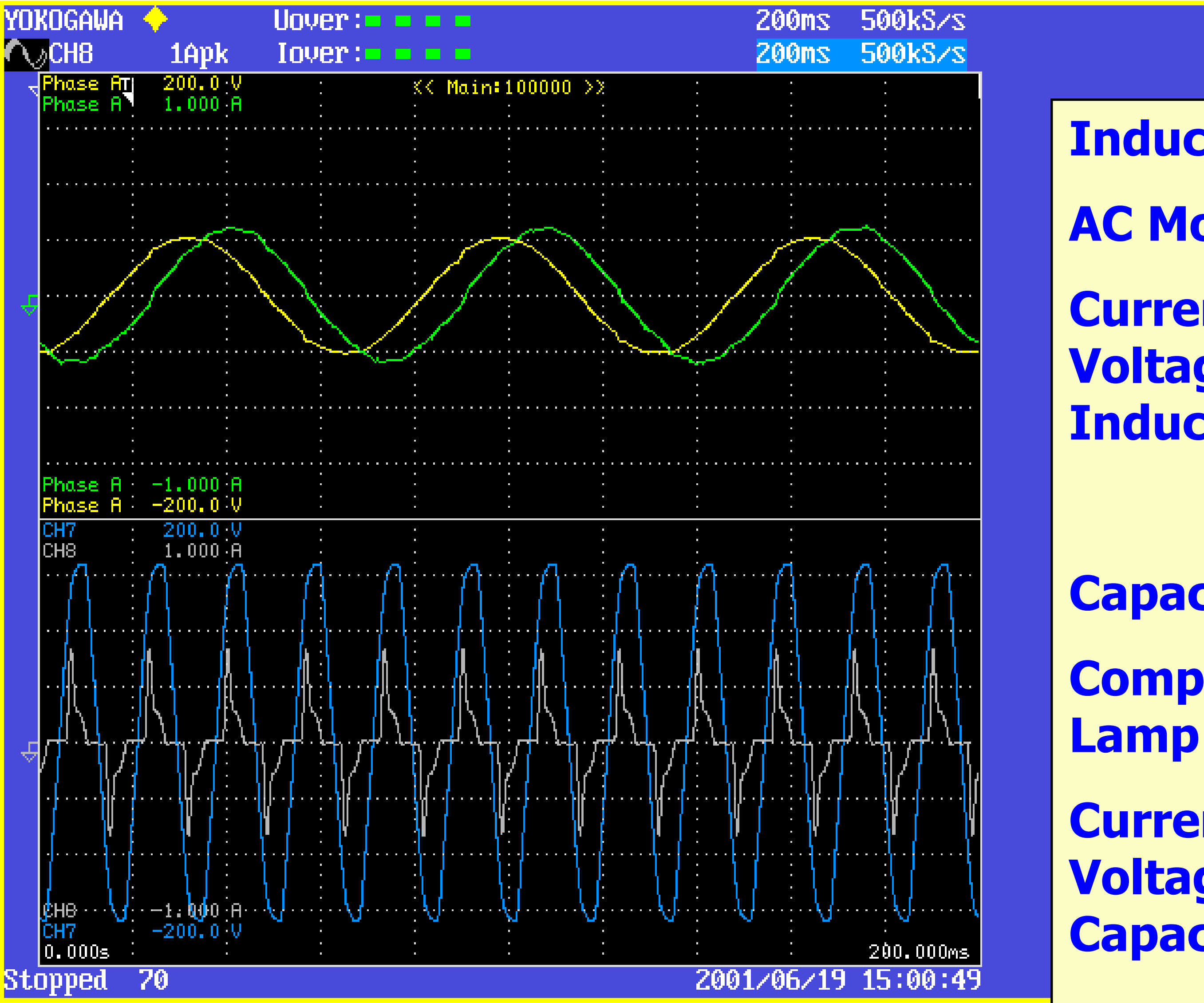


$P_T = V_{rms} * I_{T\ rms} * \cos Ø$

Ø = 45.09 Degrees

Cos Ø = 0.70599

Real World Examples



Inductive Load

AC Motor

Current LAGS Voltage in an Inductor

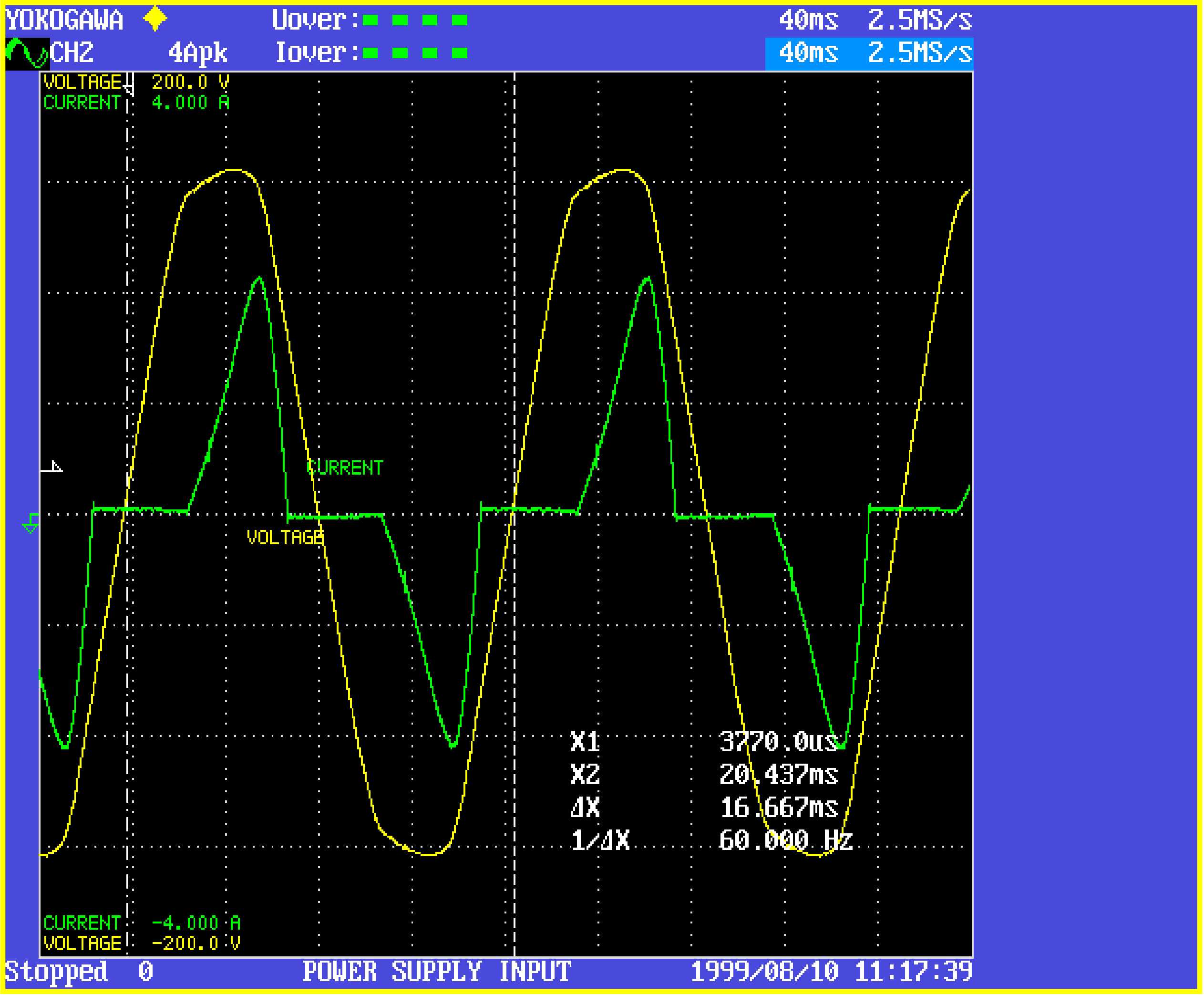
Capacitive Load

Compact Florescent Lamp

Current LEADS Voltage in a Capacitor

Power Factor Measurement

- **PF = COS Ø**
- **Where is the Zero Crossing for the Current Waveform?**
- **How do we accurately measure Ø between these two waveforms?**



Power Factor Measurement

For SINE WAVES *ONLY*

PF = Cos Ø

This is defined as the DISPLACEMENT Power Factor

--

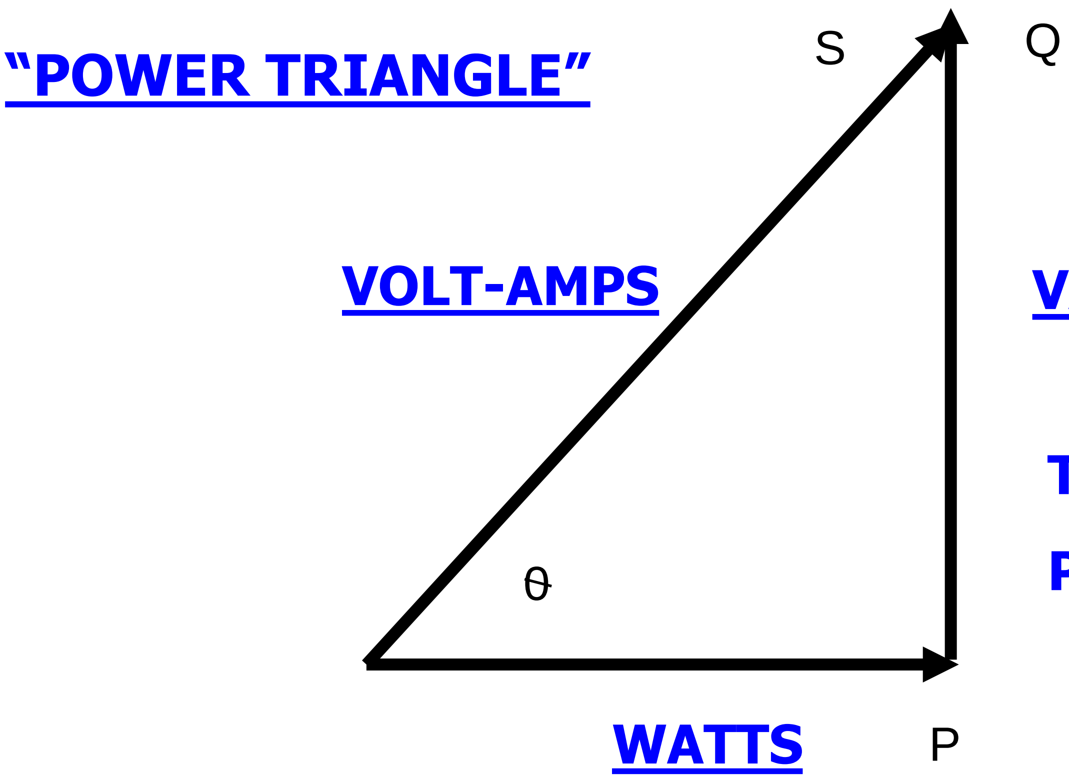
For All Waveforms

PF = W/VA

This is defined as TRUE Power Factor

Phasor Form of Power

Phasor Diagram of Power for R - L Circuit



TRUE POWER FACTOR

PF = W / VA

Power Factor Measurement

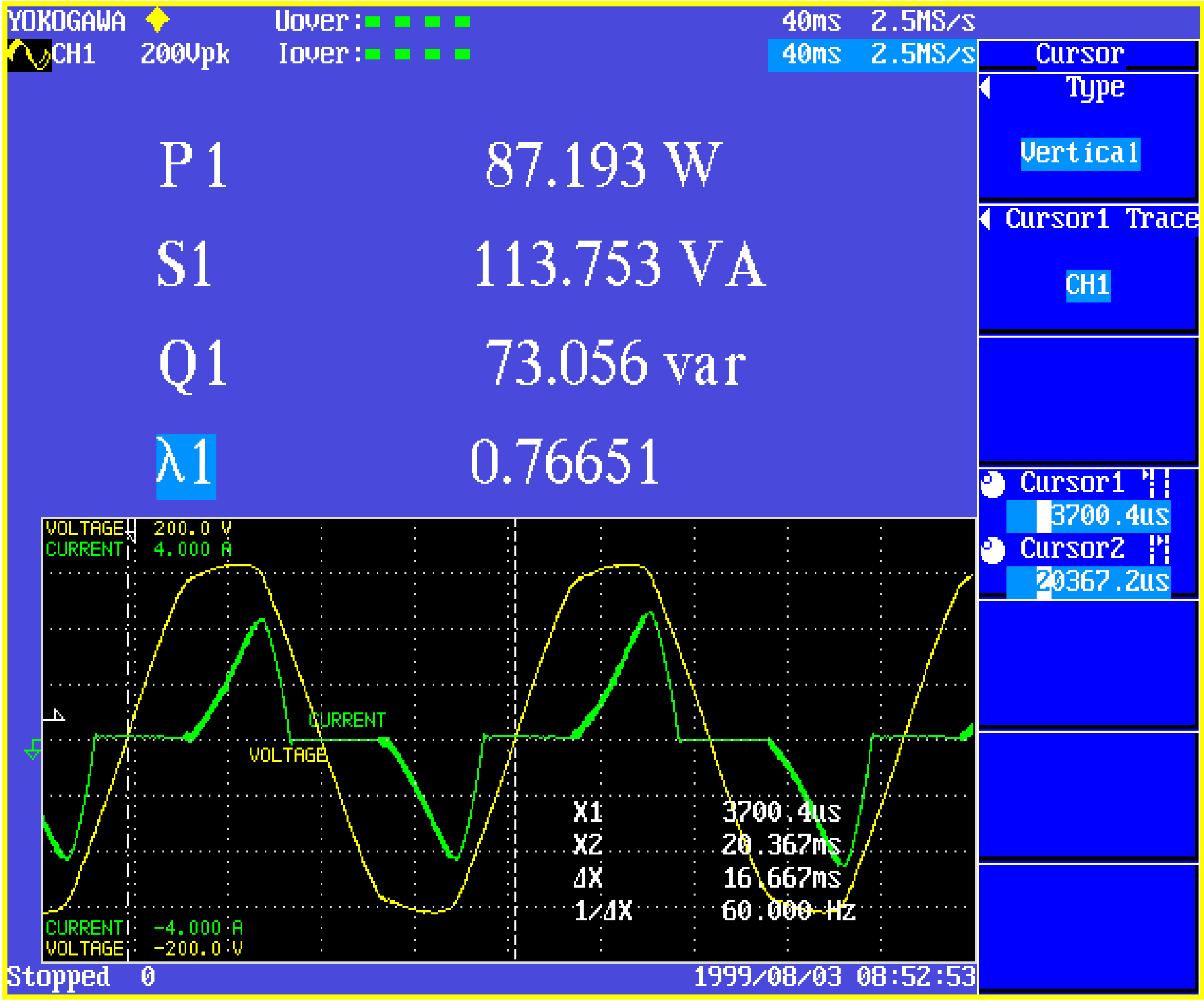
True Power Factor

PF = W / VA

PF = 87.193/113.753

PF = 0.76651

Power Supply Input



Power Factor Measurement

Displacement Power Factor

PF = Cos Ø Between Fundamental Waveforms

PF = Cos 21.06

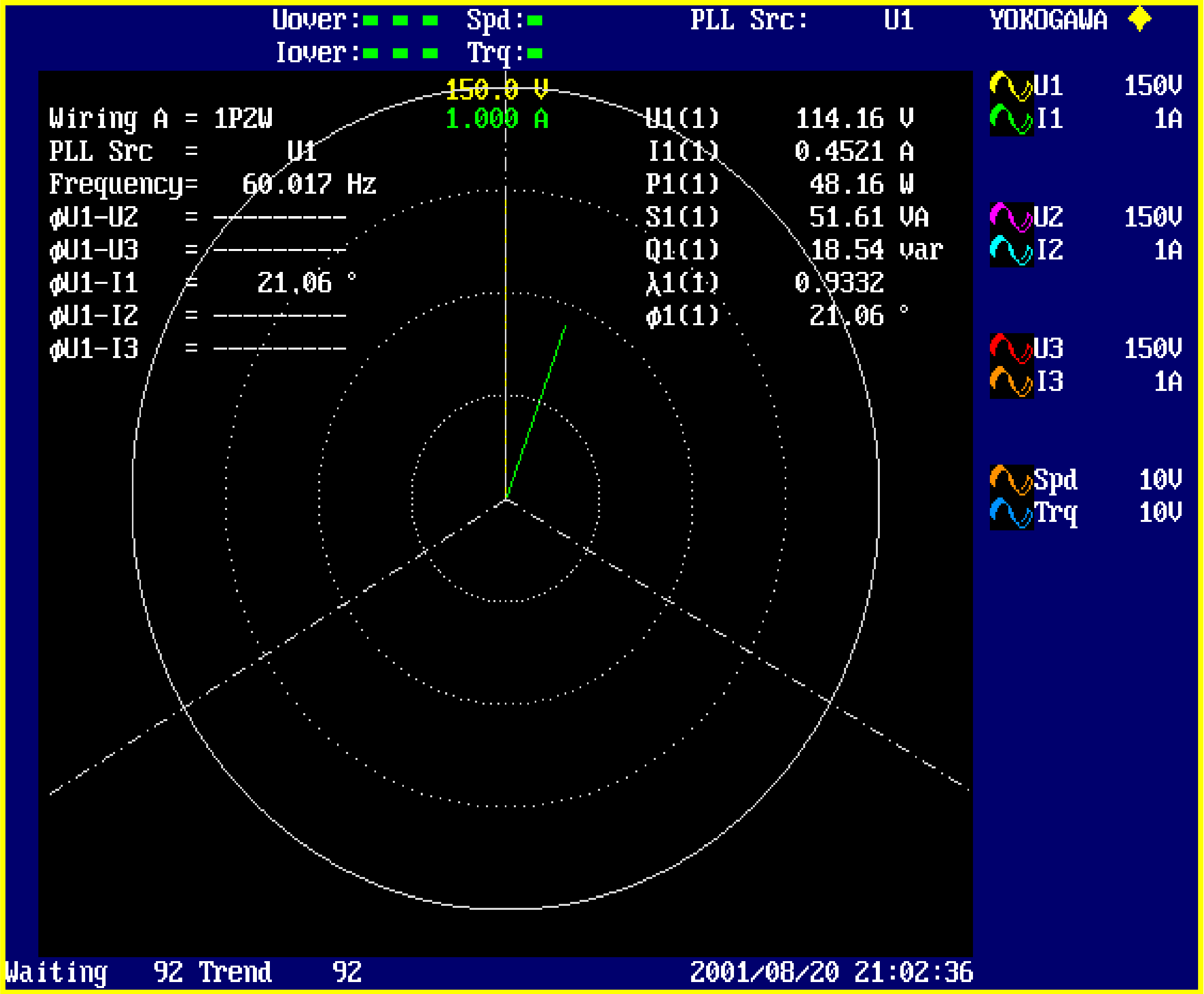
PF = 0.9332

PF = P1 / S1

PF = 48.16 / 51.61

PF = 0.9332

Power Supply Input



Current LAGS Voltage by 21.06 Degrees

Power Factor on 3-Phase System

3-Phase 4-Wire System

$$PF_{Total} = \sum W \,/\, \sum VA$$

$$PF_{Total} = (W_1 + W_2 + W_3) \,/\, (VA_1 + VA_2 + VA_3)$$

Power Factor on 3-Phase 3-Wire System

Using 2 Wattmeter Method

$$PF_{Total} = \sum W / \sum VA$$

$$PF_{Total} = (W_1 + W_2) / (\sqrt{3}/2)(VA_1 + VA_2)$$

- **If the load is Unbalanced, that is the Phase Currents are different, this method could result in an error in calculating total Power Factor since only two VA measurements are used in the calculation.**

Power Factor on 3-Phase 3-Wire System

Using 3 Wattmeter Method

$$PF_{Total} = \sum W \,/\, \sum VA$$

$$PF_{Total} = (\, W_1 + W_2 \,) \,/\, (\sqrt{3}/3)(\, VA_1 + VA_2 + VA_3 \,)$$

- **This method will give correct Power Factor calculation on either Balanced or Unbalanced 3-Wire system. Note that all three VA measurements are used in the calculation. This calculation is performed in the Yokogawa Power Analyzers when using the 3V-3A wiring method.**

3-Phase 3-Wire Power Factor Measurement

3V 3A

Measurement Method

- $\sum P = P1 + P2$
- $\sum PF = \sum P / \sum VA$
- $\sum PF = 49.466 / 93.060$
- $\sum PF = 0.53155$

- How is $\sum$ VA calculated?

POWER MEASUREMENT APPLICATIONS

Standby Power

Energy Star®

&

IEC62301 Testing

Overview

- International Standard IEC62301
- Household Electrical Appliances – Measurement of Standby Power
- Hardware and Software Measurement Solution

Scope

- **This International Standard specifies methods of measurement of electrical power consumption in Standby Mode. It is applicable to mains powered electrical household appliances.**

- **The objective of this standard is to provide a standard method of test to determine the power consumption of a range of appliances and equipment in standby mode.**

Terms and Definitions

- **The Standard also references Twenty Five (25) IEC Standards for various Household electrical appliances.**

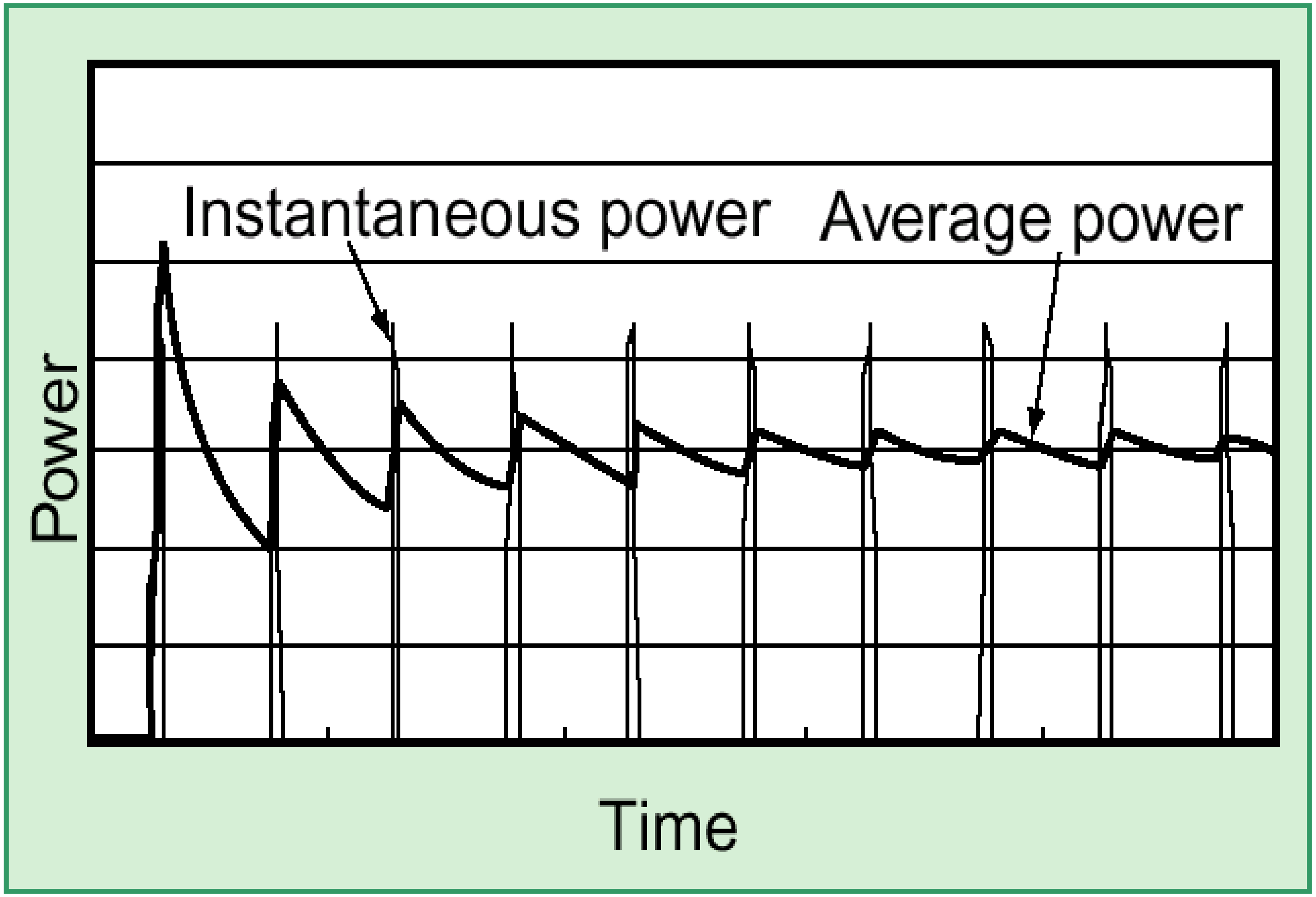
- **These standards define the various test parameters with the limits for items such as THD, Power and other items for the appropriate product.**

- **In the US and North America, the Energy Star® standard is typically used for the testing limits.**

Appliance Type

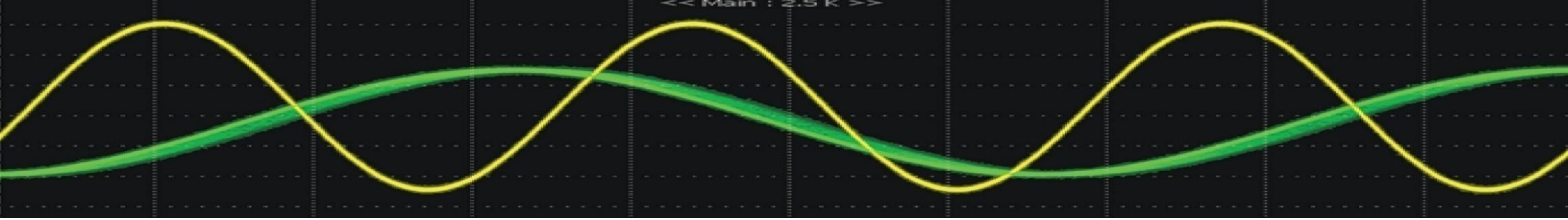
Pulse Power Mode

Example: Laser Printer or Copy Machine with Heaters



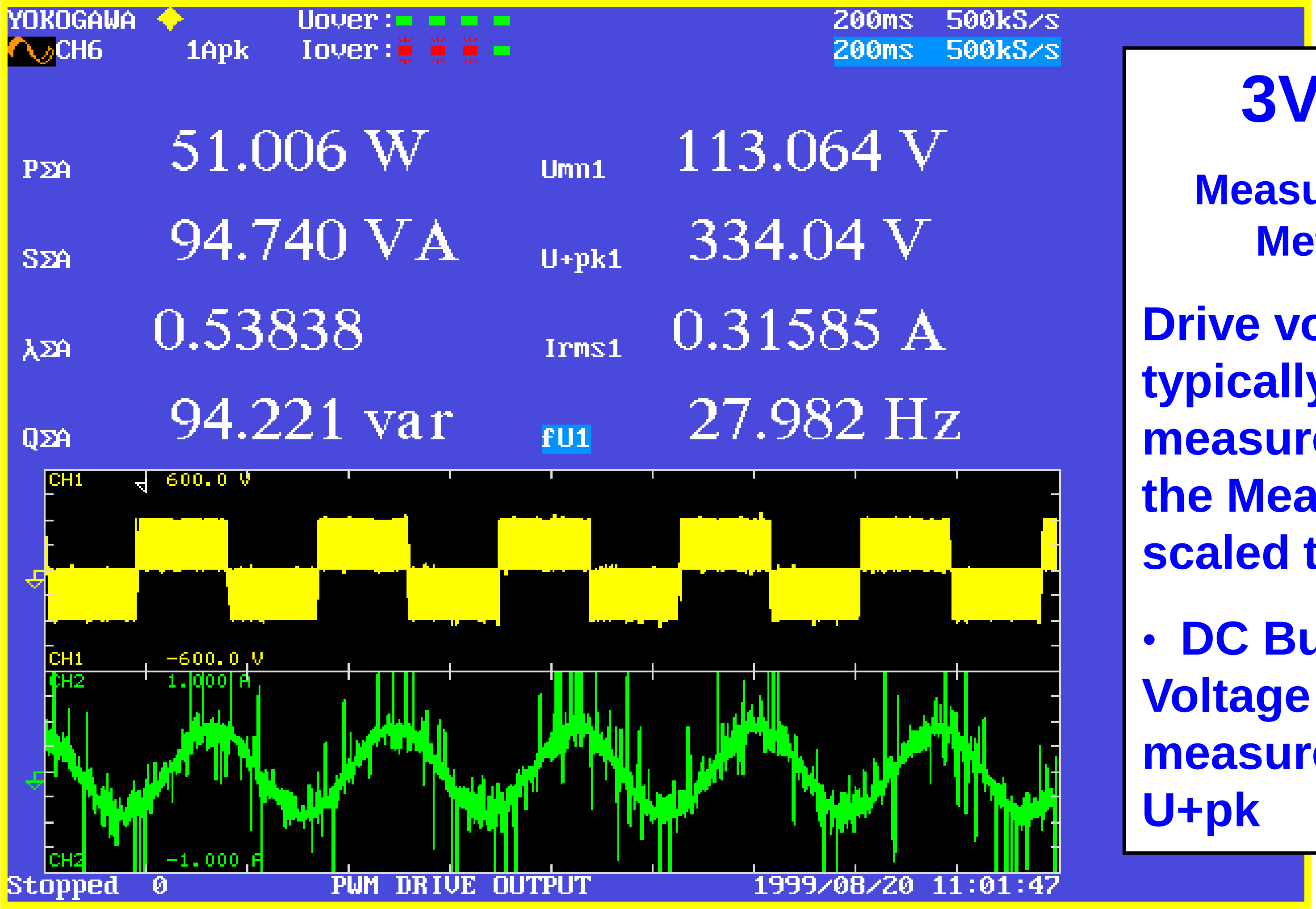
Terms and Definitions

- **Yokogawa's Standby Power Measurement:**
  - **Energy divided by Time > Watt-Hour/Time.**
  - **This is the Average Active Power measurement mode.**
  - **This is the preferred method as it works on both steady and fluctuating power sources and is the most accurate method.**
  - **Yokogawa pioneered this method with the Model WT200 introduced in 2000.**



OTHER APPLICATIONS

3-P 3-W PWM Motor Drive Power Measurement



3V 3A

Measurement Method

Drive voltage is typically measured using the Mean value scaled to rms.

- **DC Bus Voltage is measured as U+pk**

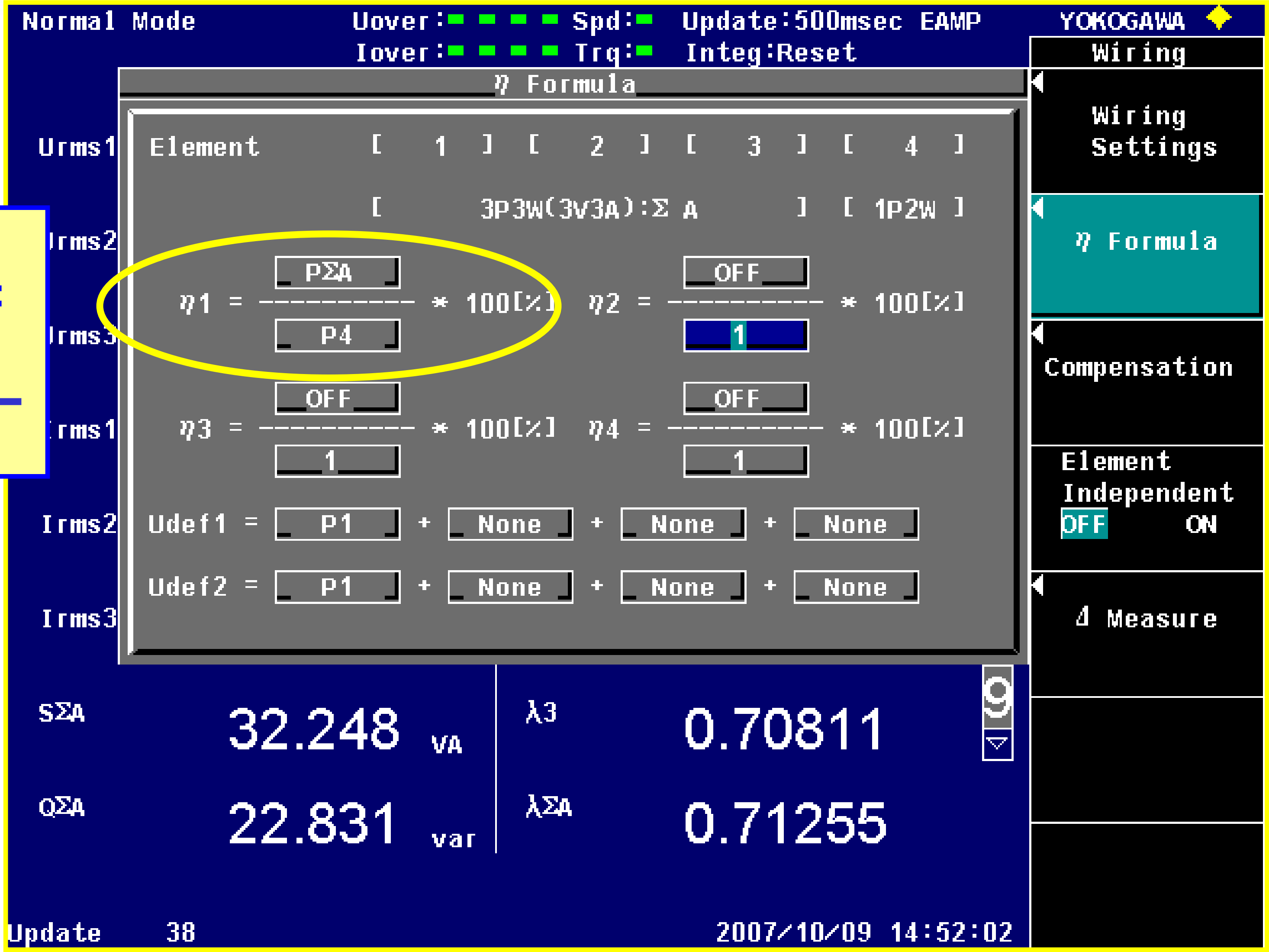
Device Efficiency Measurement

- **Device Efficiency is Calculated as Output Power Divided by Input Power**
  - **Usually expressed as a percentage**
- **Use Two Power Meters to Measure the Input and Output Power**
  - **Calculate the Efficiency from the readings of the two Power Meters**
  - **Problem – Input and Output Readings may not be made Simultaneously. Possible error due to Time Skew**
- **Use a Multi-Element Power Analyzer to Measure Input and Output Power**
  - **Calculate the Efficiency in a Single Power Analyzer**
  - **Eliminates any Error due to Time Skew of Measurements**

Device Efficiency Measurements

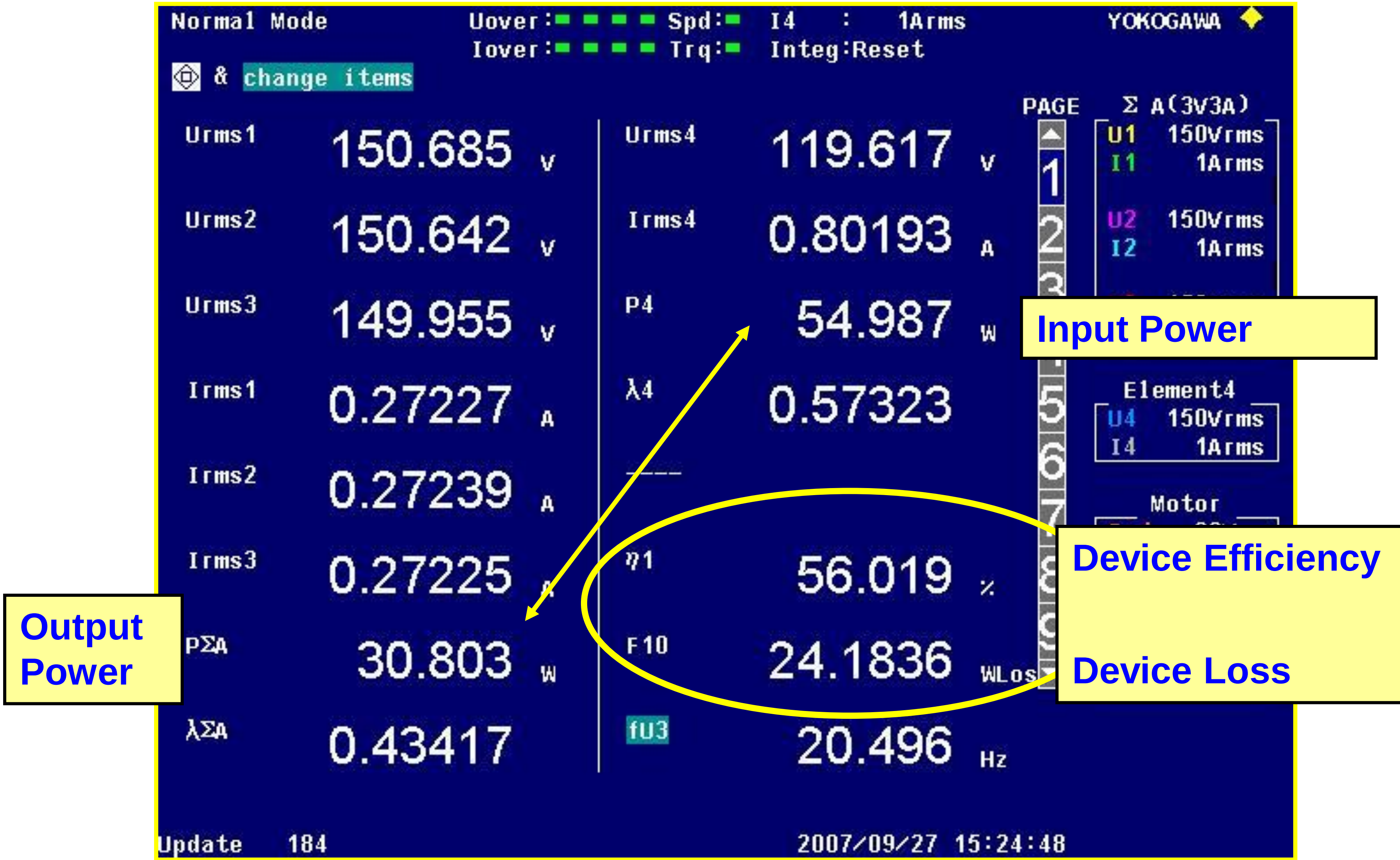
Device Efficiency:

Output P / Input P



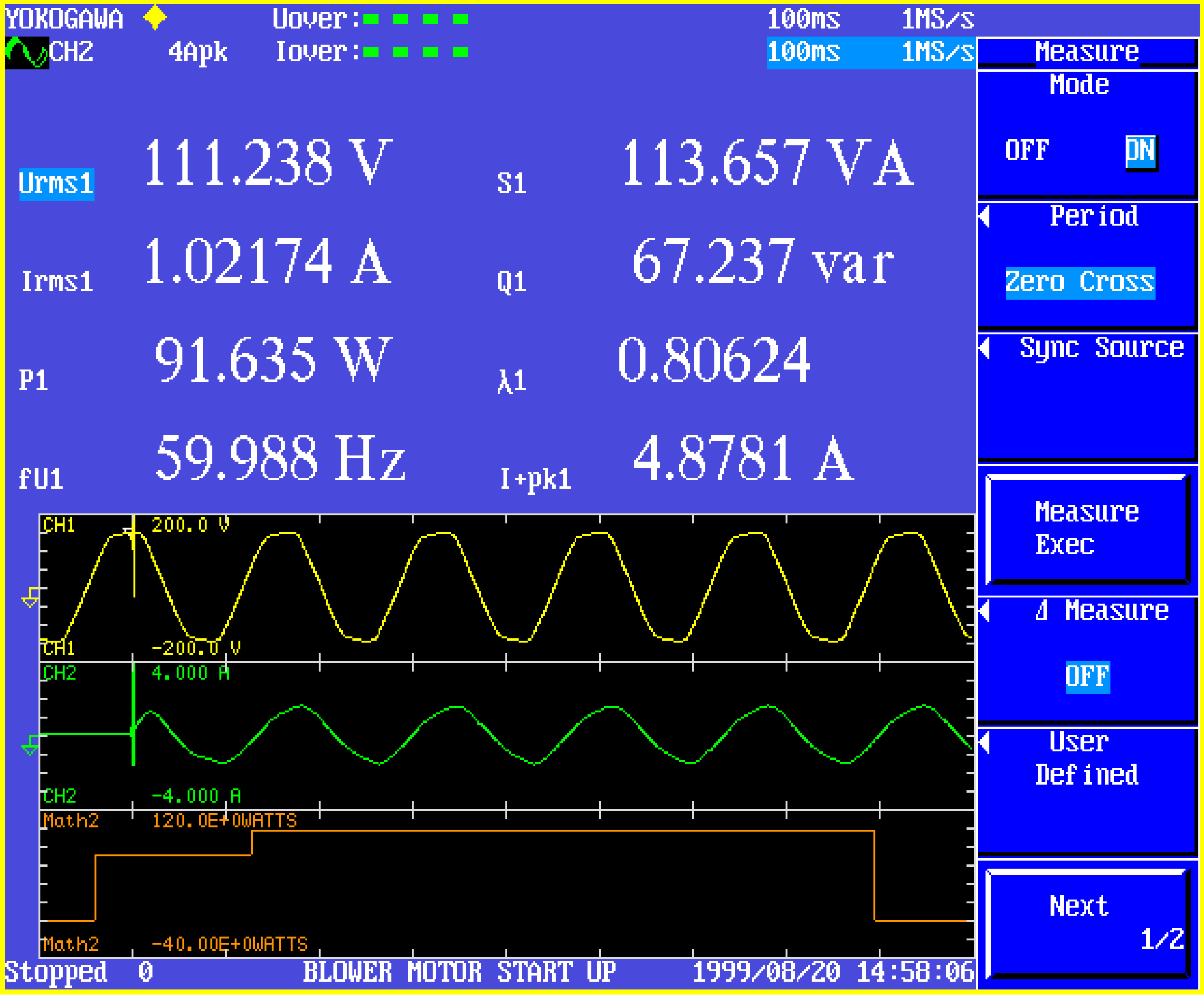
Power Analyzer Setup Menu

Device Efficiency & Power Loss



Power Measurement Application

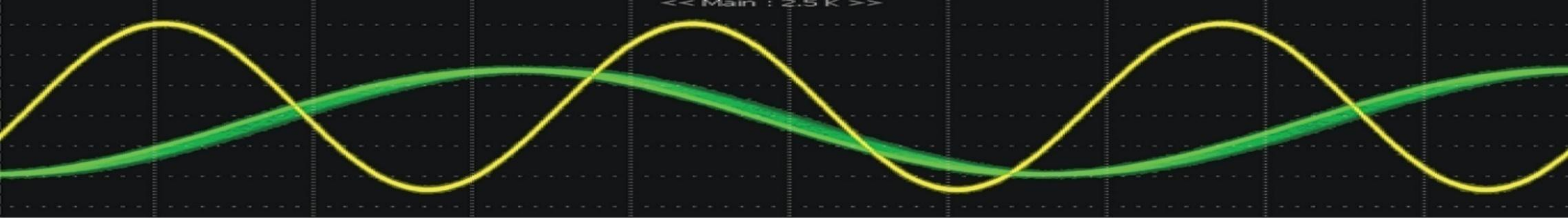
Device Start Up Analysis



Device Voltage

Device Current

Cycle-by-Cycle Start Up Power



PART III

BASIC POWER MEASUREMENTS using a DIGITAL OSCILLOSCOPE

Power Analysis with a DSO

Why use a Digital Oscilloscope for Electrical Power Measurements?

- We have a "Comfort Level" using an Oscilloscope
- Dedicated Probes & Ease of Connections
- Power Analysis Math Capabilities
- High-frequency Bandwidth
- Waveform Display & Analysis
- Harmonic Analysis to IEC Standards

Measurement of Power

- **Special Note:**

When using an oscilloscope, AC Power is not just connecting a voltage probe to Ch1 and a current probe to Ch2 and then multiplying Ch1 x Ch2.

This will give an AC measurement of VA, not AC Watts.

Measurement of Power

Remember - AC Power Measurement

- **Active Power:**

  Watts $P = V_{rms} \times A_{rms} \times PF$

  - Also sometimes referred to as True Power or Real Power

- **Apparent Power:**

  Volt-Amps $S = V_{rms} \times A_{rms}$

Measurement of Power

- **Yokogawa Digital Power Scopes use the following method to calculate power:**

  - $P_{avg} = 1/T \int_0^T v(t) * I(t)\, dt$

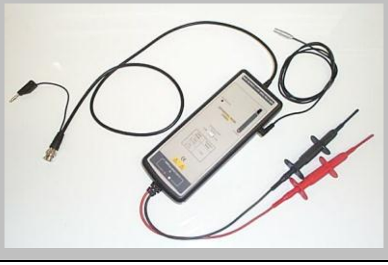
- **Taking advantage of digitizing techniques, the INSTANTANEOUS VOLTAGE is multiplied by the INSTANTANEOUS CURRENT and then INTEGRATED over some time period.**

Power Analyzer vs. DSO

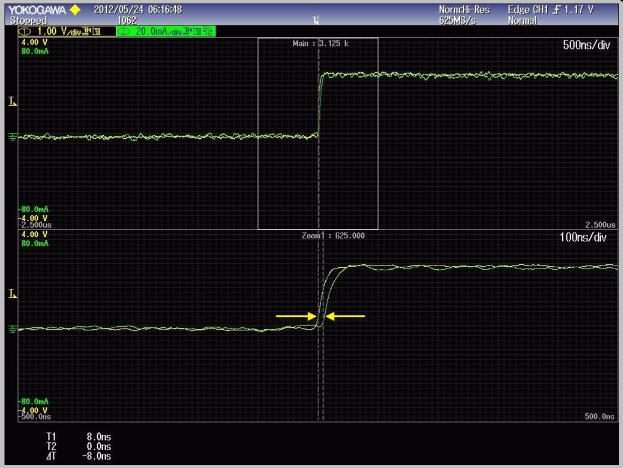
Function	Power Analyzer	DSO
Bandwidth	DC – 2MHz	DC – 500 MHz Power DC –50 MHz
Accuracy	0.1 to 0.02%	1.5% at input terminals, at DC
	Calibrated Traceable Measurement System	Power approx 3.5% Based on Probes DC Accuracy
Ranges	Direct connection High Voltage & High Currents	Probes for high frequency & small currents
Digitizers	Typical 16-Bit 65,536 levels	Typical 8-Bit 256 Levels

Measurement Challenge: SKEW

Current clamp
e.g. 30 A, 100 MHz
model 701932

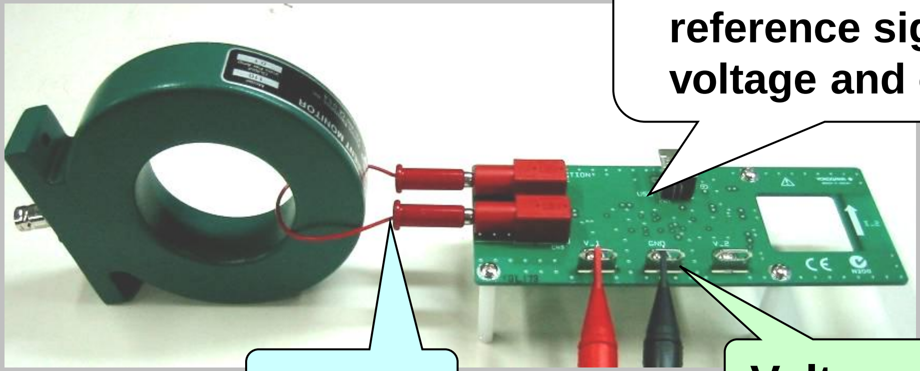


Differential probe
e.g. 1400 V, 100 MHz
model 700924



Skew = Propagation Delay Difference

Deskew Source - model 701936



Synchronous reference signal for voltage and current

Current

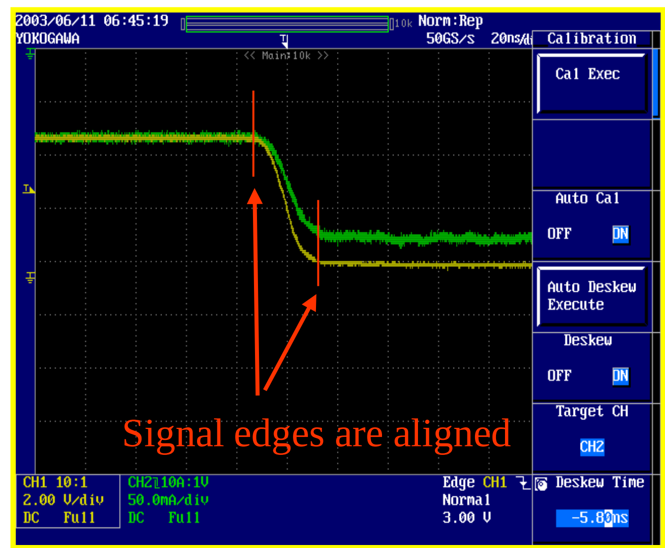
Voltage

Auto Deskew function

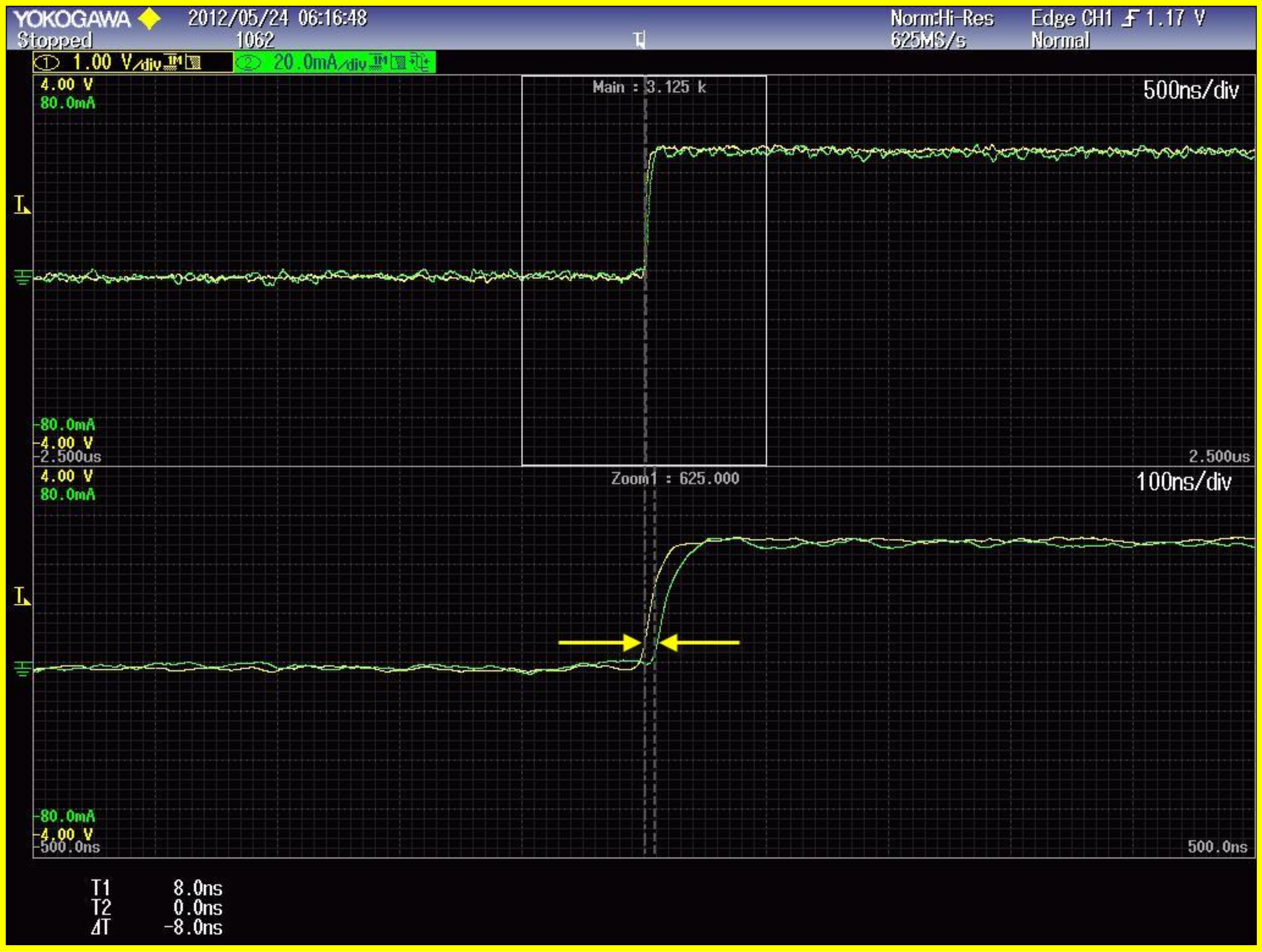
Successful de-skew!

Deskew Calibration

- **Signal source used for adjusting the skew between a voltage probe and a current probe.**
  - **- Many different kinds of probes can be used for power measurements. Each probe has a <u>different signal path length.</u>**
  - **- Signal source generates time-coincident voltage and current signals. This allows you to adjust for skew between voltage and current probes.**



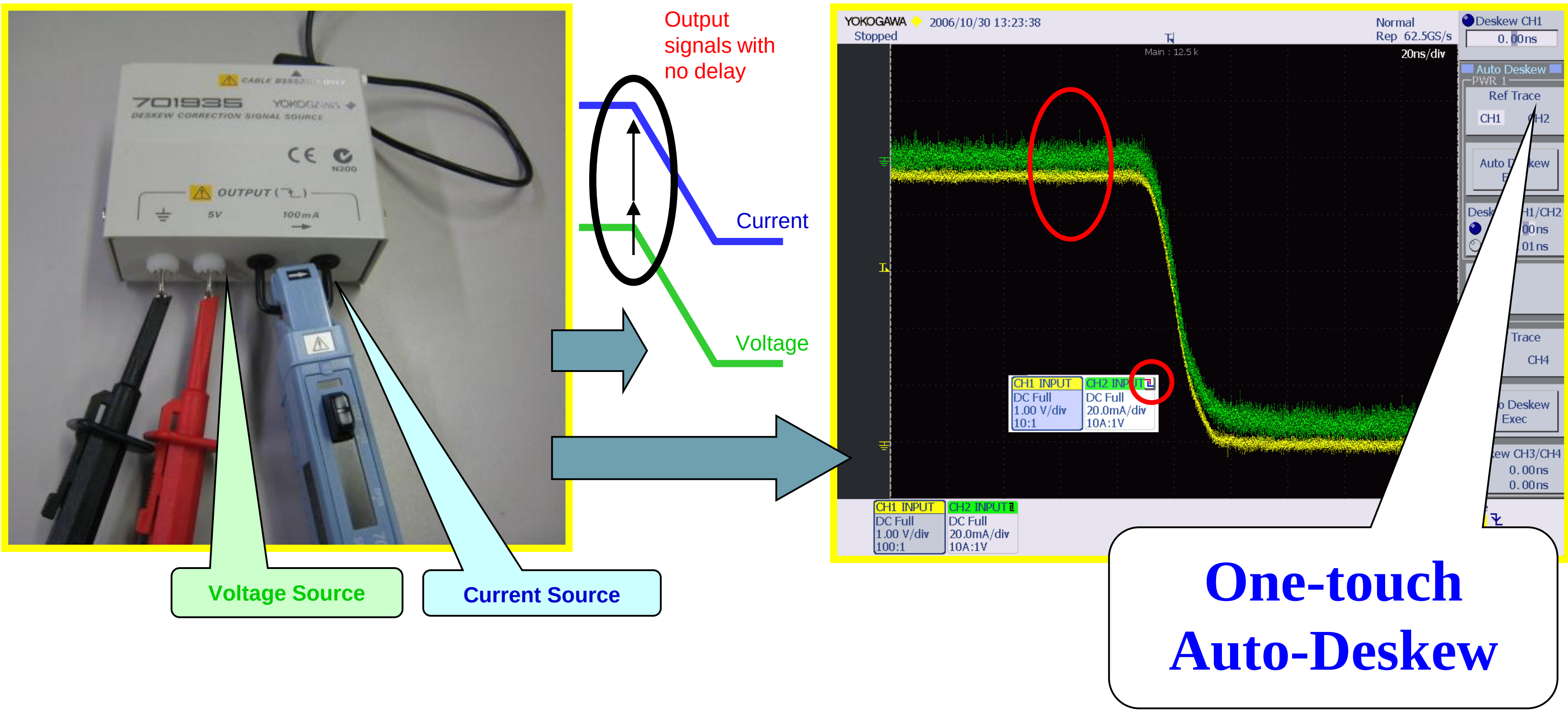
BEFORE DE-SKEW



AFTER DE-SKEW

Yokogawa Solution: Auto De-skew

To correctly measure the analysis parameters such as power, impedance, power factor, watt hour, and ampere hour from the voltage and current under analysis, the voltage and current signals must be applied to the Vertical Input channels of the Oscilloscope while preserving the phase relationship which exists between U & I in the DUT.

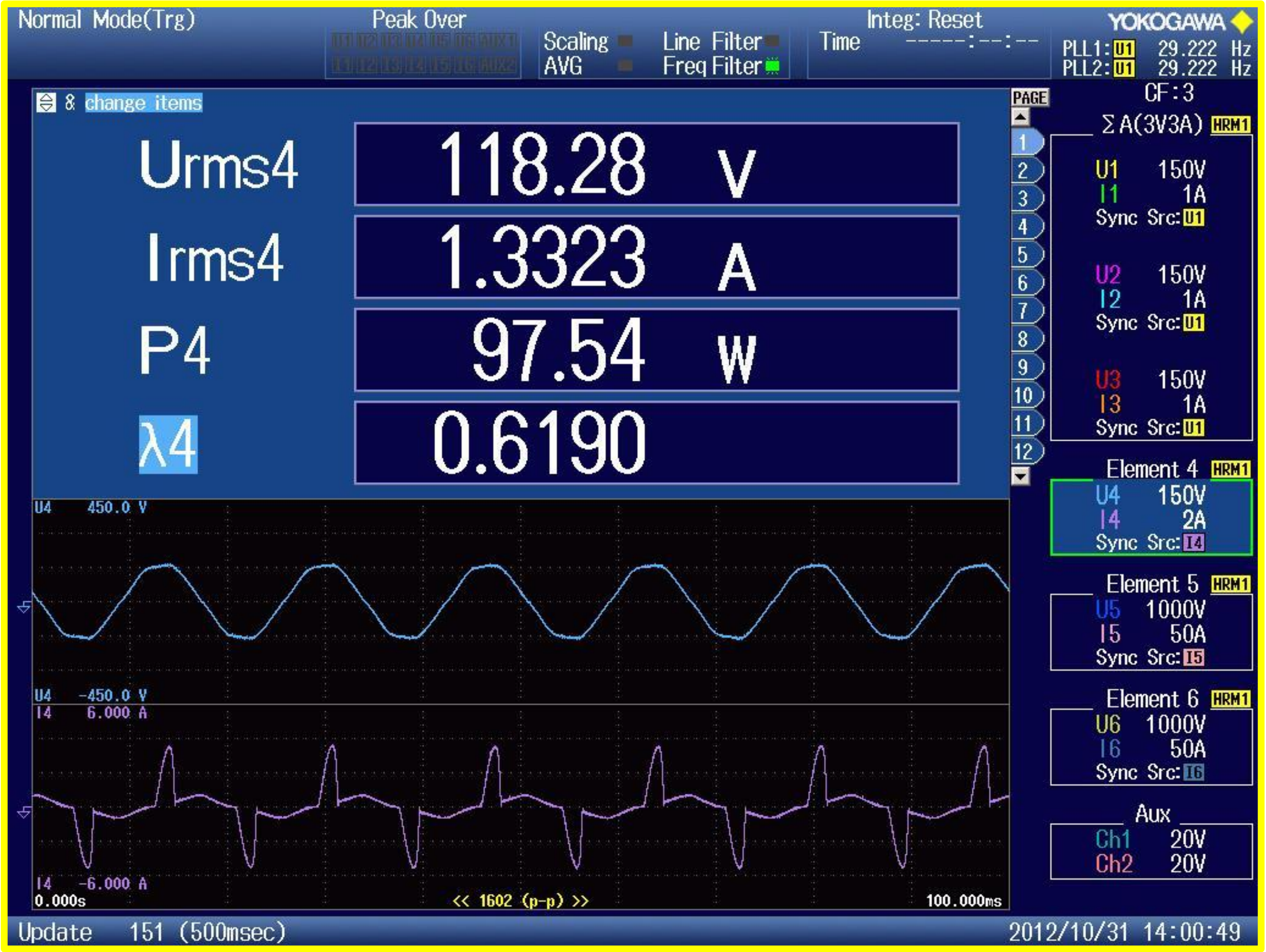


Deskew - The difference in the current probe and voltage probe signal propagation time (skew) is automatically corrected.

Typical Measurements

- Board Lever Power Measurements
- Switching Power Loss
- Device Power Consumption
- Switching Noise Level
- Harmonics
- Waveform Display & Analysis
- Inrush & Transients

Power Supply Input with Power Analyzer

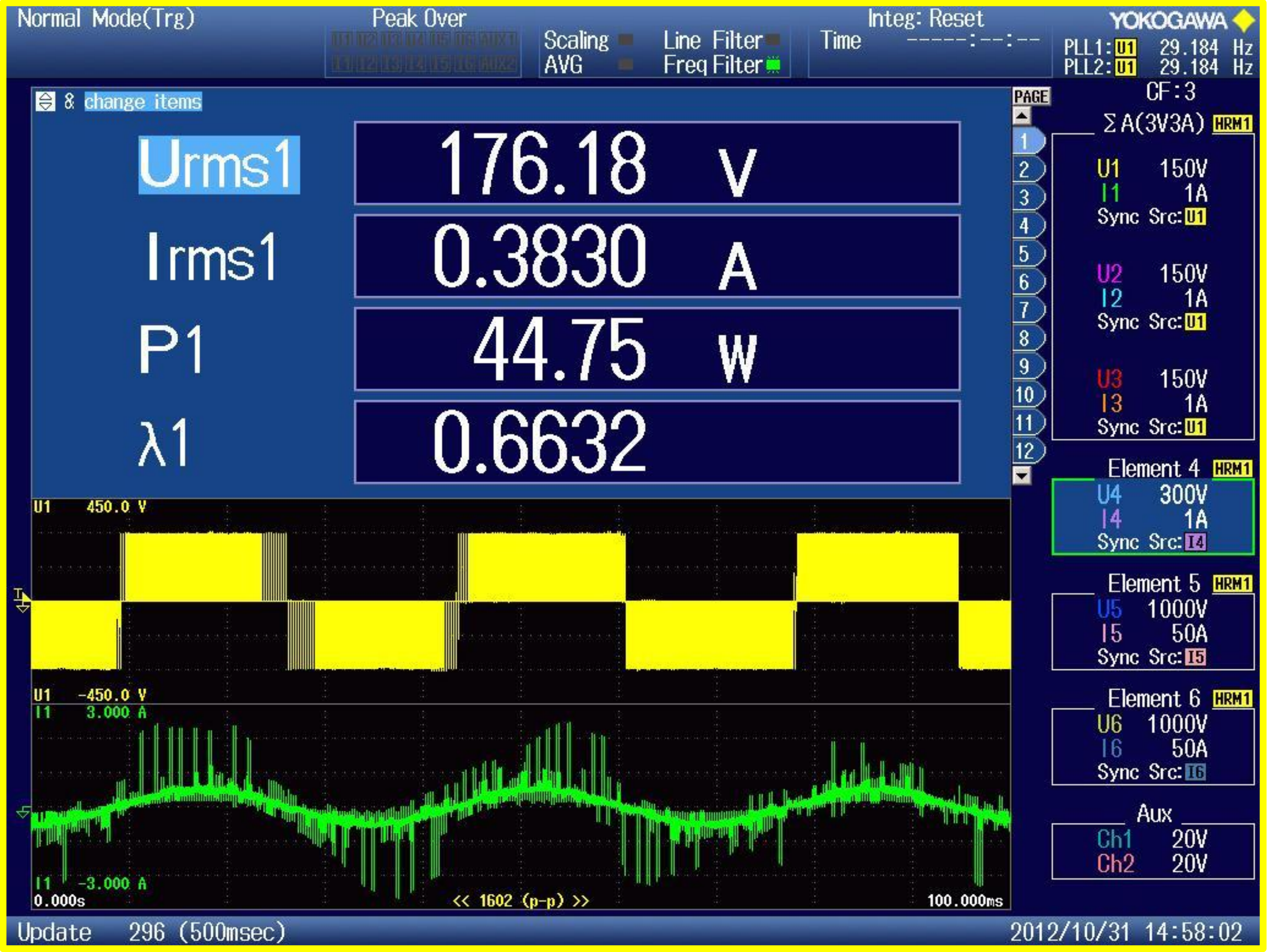


Power Supply Input with DSO

Power Supply Input Summary

Measurement Comparison		
Measurement Item	Power Analyzer	Power DSO
Voltage RMS	118.28 V	117.27 V
Current RMS	1.3323 A	1.3321 A
Watts	97.54 W	96.49 W
Power Factor	0.619	0.617

PWM Inverter Output with Power Analyzer



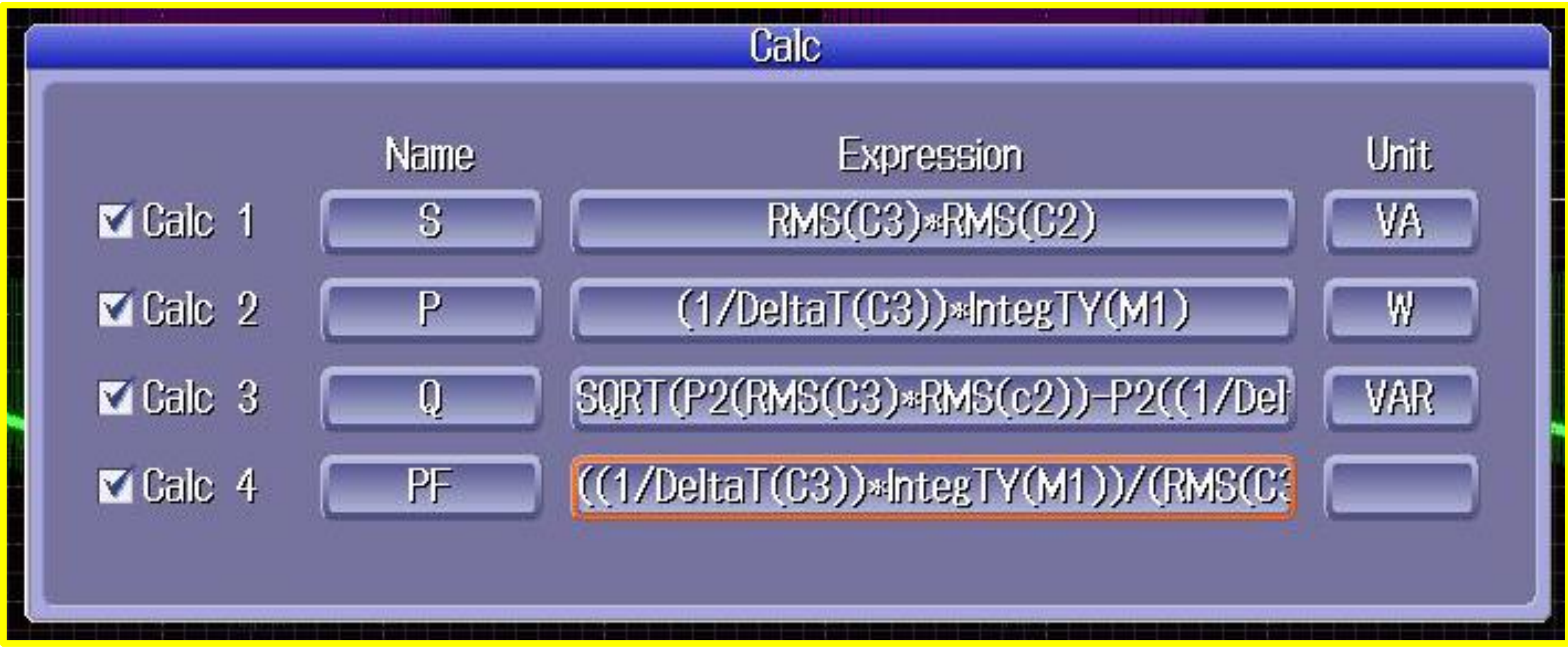
YOKOGAWA

PWM Inverter Output with Power DSO

PWM Inverter Output Summary

Measurement Comparison		
Measurement Item	Power Analyzer	Power DSO
Voltage RMS	176.18 V	178.56 V
Current RMS	0.3830 A	0.3950 A
Watts	44.75 W	46.37 W
Power Factor	0.6632	0.6602

DSO Power Calculation



What You Will Need

- **Power Measurements with a DSO**
  - Oscilloscope
  - Options – power analysis, probe power
  - Probes
    - Differential Voltage Probe
    - Current probe
    - High Voltage Probe
  - Other
    - Isolation line-transformer for non-isolated designs (safety).
    - Deskew Device




Yokogawa's Power Measuring Solutions

- **Yokogawa offers the Most Complete Line of Power Measurement Products to meet the customers Application and Budget.**

- **Product, Application and Software support provided from a network of Field Sales Reps, Factory Regional Sales Managers and Factory Support Engineers.**

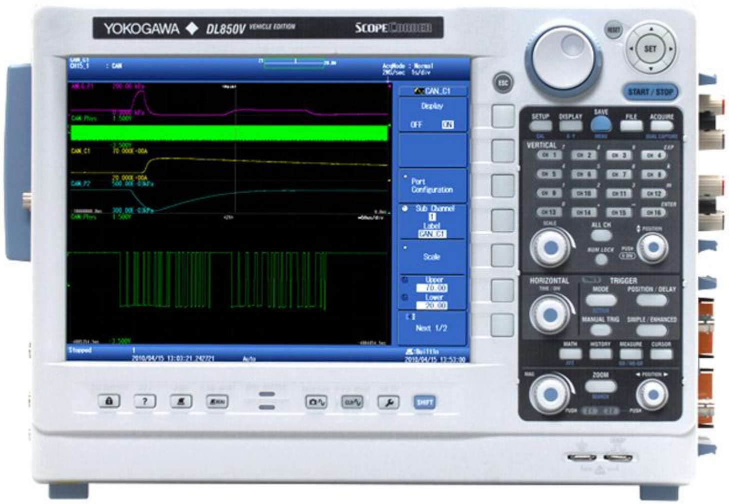
- **NIST Traceable Calibration provided by Factory Trained technicians in Newnan, GA.**

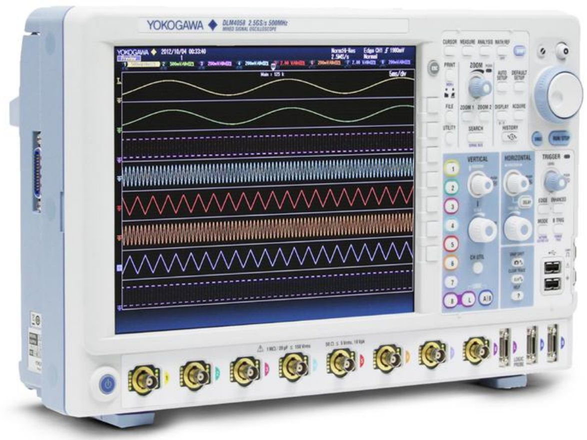
Yokogawa's Power Measuring Solutions

Precision Power Analyzers

Yokogawa's Power Measuring Solutions

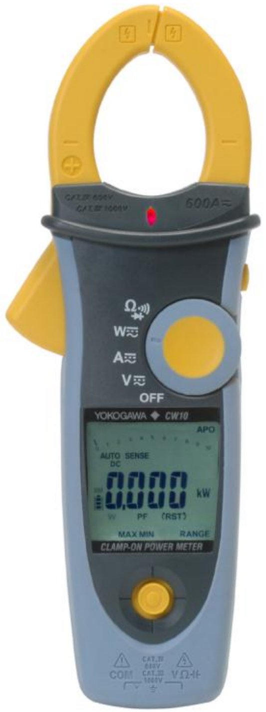
Digital Oscilloscopes with Power Analysis





Yokogawa's Power Measuring Solutions

Portable Power Test Instruments



Yokogawa's Power Measuring Solutions

Panel and Switchboard Analog Meters

Yokogawa's Power Measuring Solutions

Power Transducers

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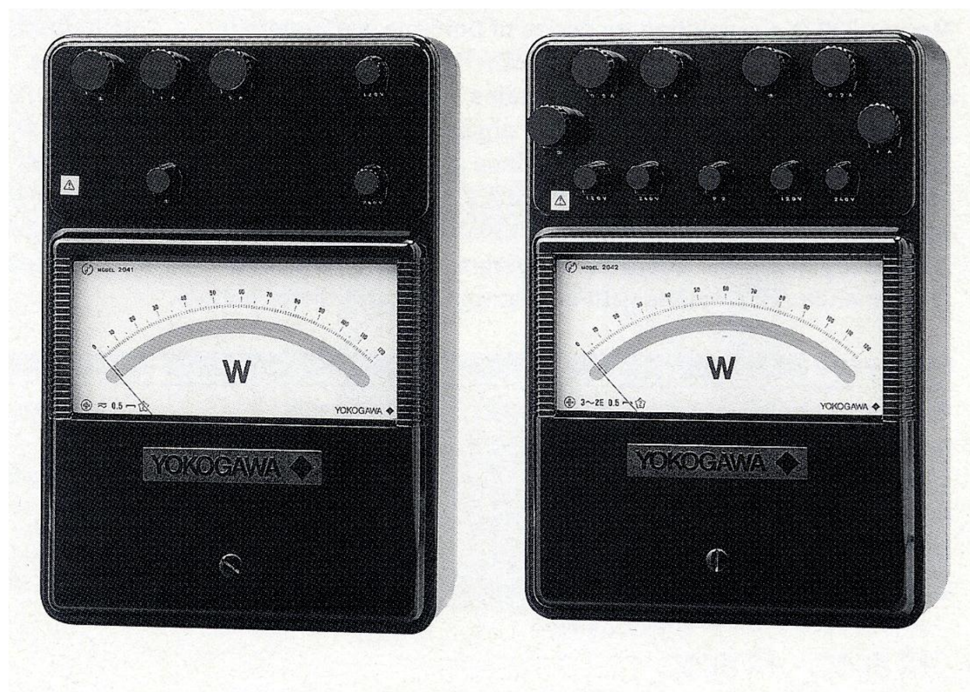
Multi Function Digital Meters

Yokogawa's Power Measuring Solutions

Portable Instruments



Overview - What We Hope You Learned

- **Helped You With a Better Understanding of Electrical Power Measurements**
- **Review of Some of the Basics**
- **Power Measurements Using a Precision Power Analyzer and Digital Oscilloscope**
  - **Single-Phase Power Measurements**
  - **Current Sensors**
  - **Three-Phase Power Measurements**
  - **2 & 3 Wattmeter Method**

Overview - What We Hope You Learned

- **Part II: Power Factor Measurements**
  - **Displacement Power Factor**
  - **True Power Factor**
  - **Power Factor Measurements in Single-Phase & Three-Phase Circuits**
  - **Practical Power Factor Measurement Applications**

Overview - What We Hope You Learned

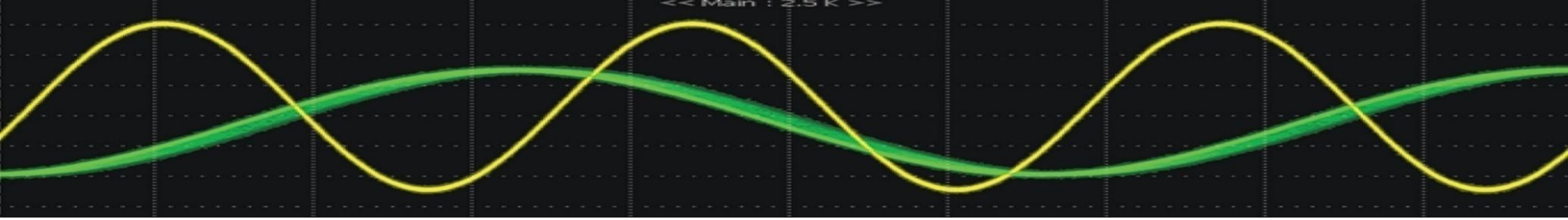
- **Part III: Power Measurements using a Digital Oscilloscope**
  - **How to properly use a Digital Oscilloscope to make Electrical Power Measurements**
  - **De Skew Operation**
  - **Measurement Examples on a Power Supply Input and a PWM Inverter Output**
  - **Measurement Comparison between the DSO and a Power Analyzer**

- **Answer your questions concerning Electrical Power Measurements**

Thank You

For

Attending



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