YOKOGAWA ◆ TEST & MEASUREMENT

Fundamentals of Electrical Power Measurement

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Precision Making

tmi.yokogawa.com

Yokogawa Corporate History

- 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

1930 Vintage
Standard AC Voltmeter
0.2% Accuracy Class

WT3000
Precision Power Analyzer

Location In United States

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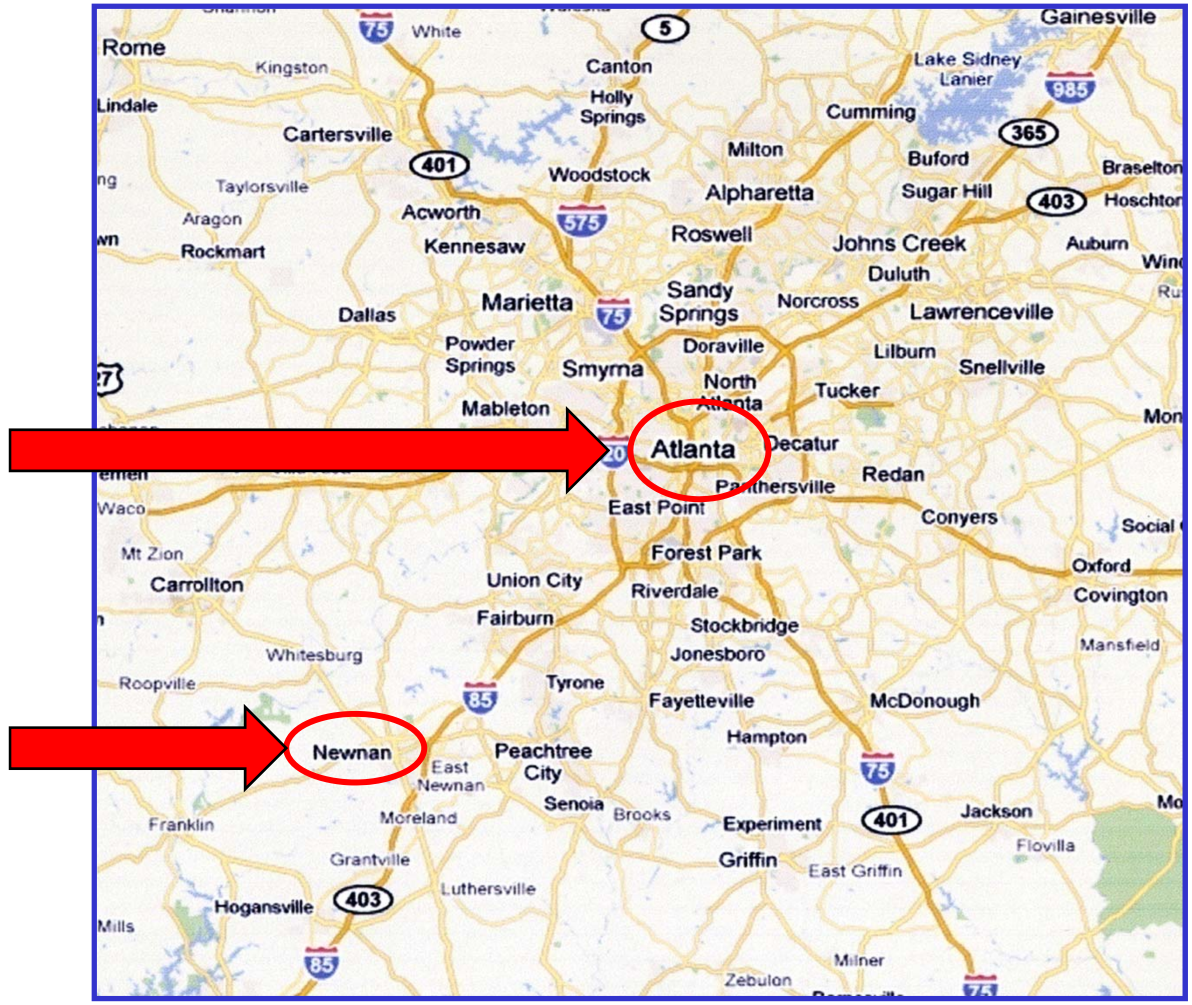
Yokogawa Corporation of America, Newnan, Georgia

Location In United States

Atlanta, Georgia

Newnan, Georgia



Overview

1. Electrical Power Measurement Theory
   - Review Some Basics
   - Power Measurements Using a Precision Power Analyzer
     - Single-Phase Power Measurements
     - Current Sensors
     - Three-Phase Power Measurements
     - 2 & 3 Wattmeter Method
   - Power Factor Measurement
   - Harmonic Measurements
   - Standby Power, Energy Star ®, IEC Testing
2. Power Analyzer Demonstration
3. Q & A and Hands-on

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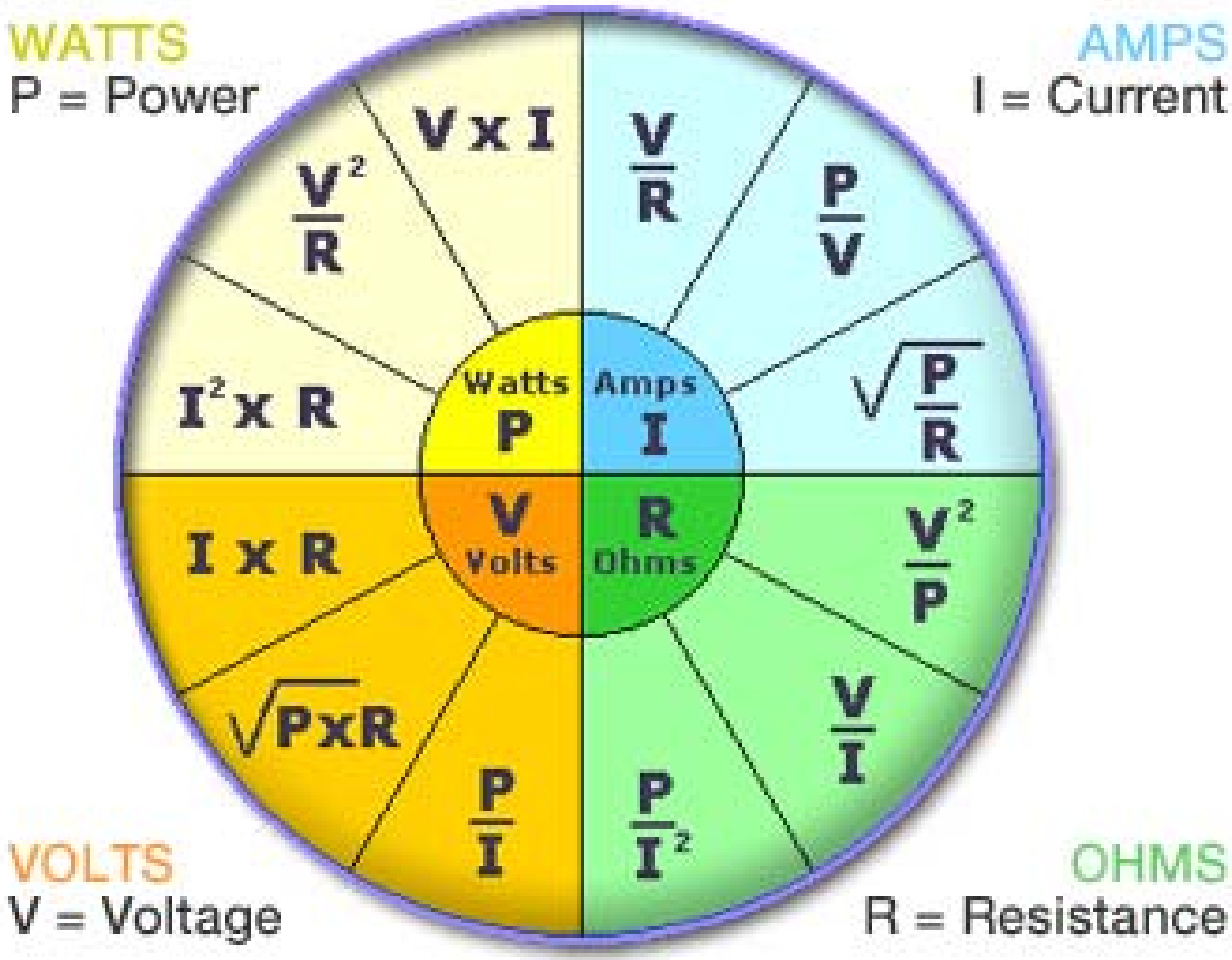
Electrical Power Measurement Theory

Review Ohm's Law



Measurement of Power

What's A Watt ?

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

DC Source: W = V x A

AC Source: W = V x A x PF

Measurement of Power

AC Power Measurement

Active Power:

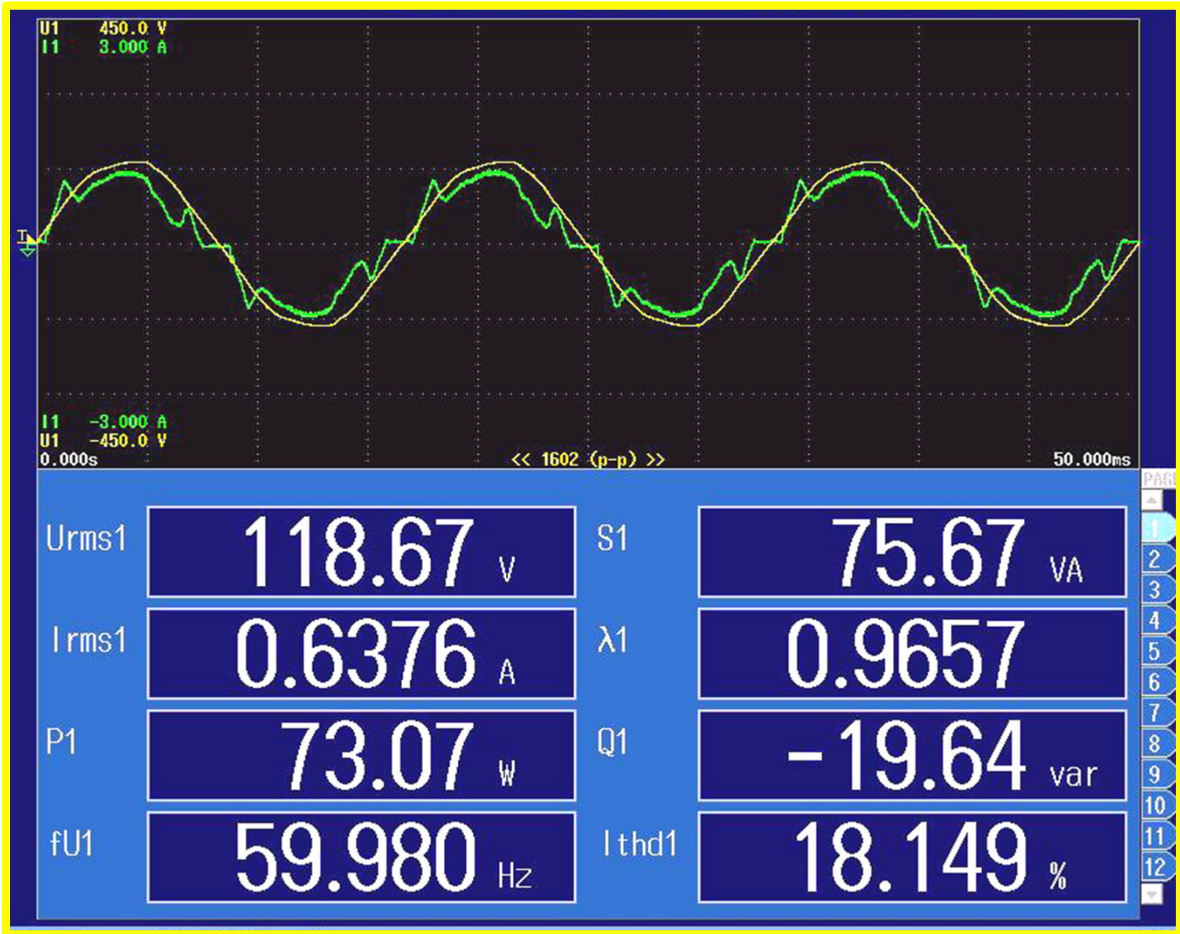
Watts P = Vrms x Arms x PF

Also sometimes referred to as True Power or Real Power

Apparent Power:

Volt-Amps S = Vrms x Arms

Measurement of Power



Watts P = Vrms x Arms x PF = Urms1 x Irms1 x λ1

Volt-Amps S = Vrms x Arms = Urms1 x Irms1

Measurement of Power

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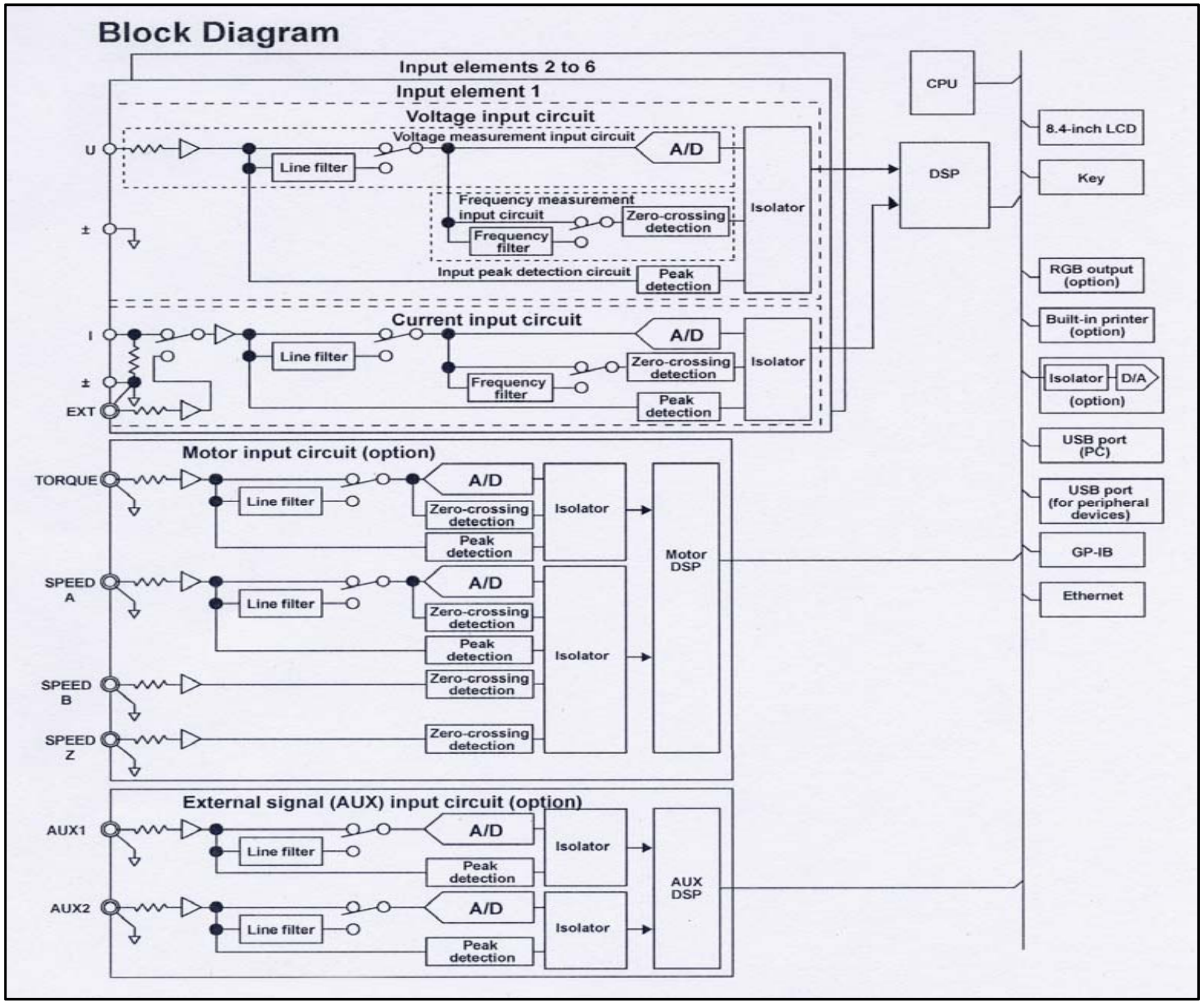
- Digital Power Analyzers are entirely electronic and use some form of **DIGITIZING TECHNIQUE** to convert analog signals to digital form.
- Higher end analyzers use **DIGITAL SIGNAL PROCESSING** techniques to determine values
- Digital Power Oscilloscopes use **SPECIAL FIRMWARE** to make true power 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

- Floating and Isolated Voltage and Current inputs

- Individual Analog to Digital Converters for each signal input.



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 **INSTANTANEOUS VOLTAGE** is multiplied by the **INSTANTANEOUS CURRENT** and then **INTEGRATED** over some time period.

Measurement of Power

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

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

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

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.

Power Measurement Accuracy

- Power Analyzers manufacturers often state their Power Accuracy as:
  - Voltage Accuracy + Current Accuracy
- Accuracy of Yokogawa Power Analyzers is based on Actual Watt Measurements.
- Power Accuracy is stated as:
  - **X % of Watt Reading + Y % of Watt Range**

Measurement of Power

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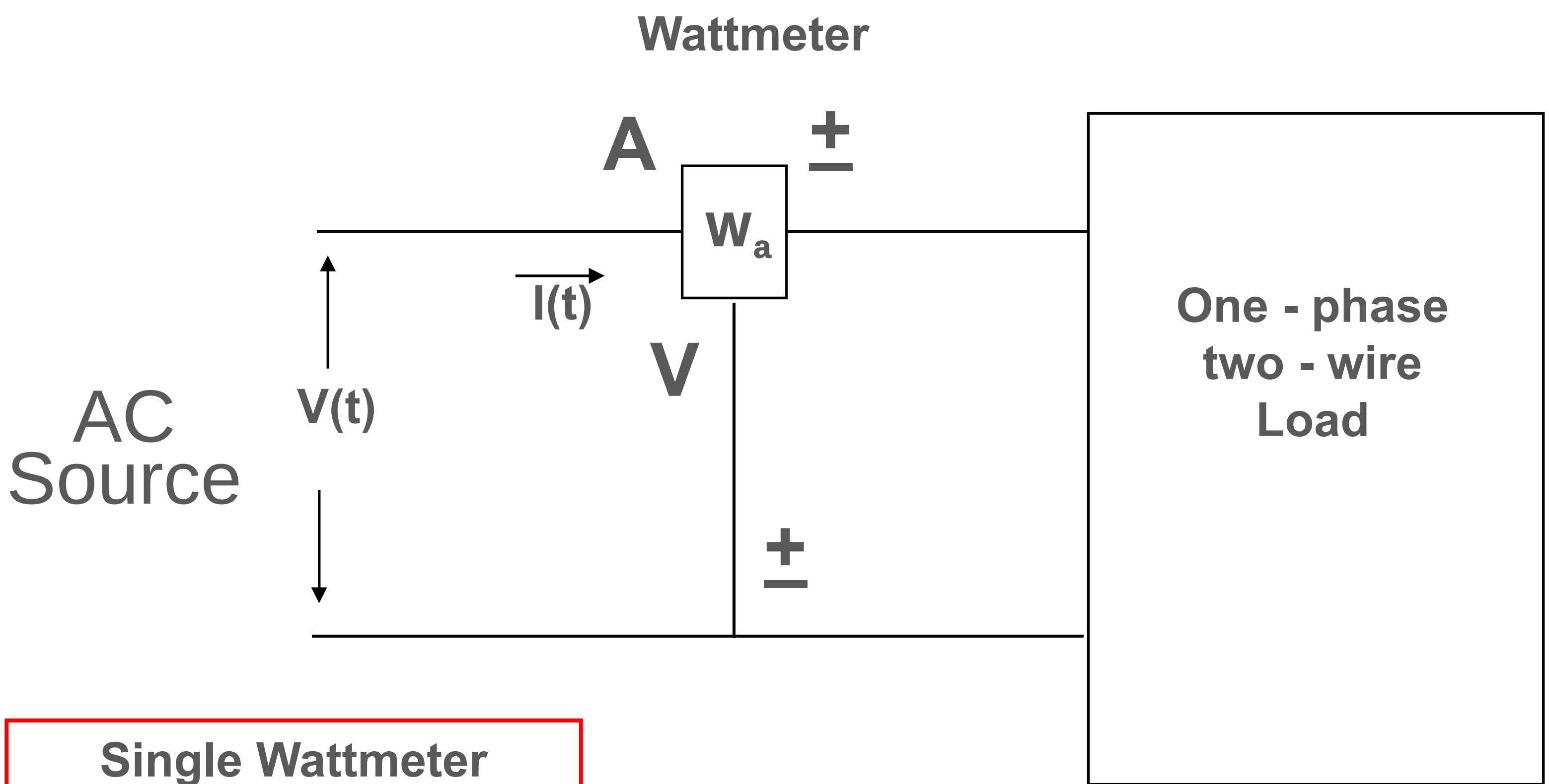
Single Phase



Single Wattmeter Method

Measurement of Power

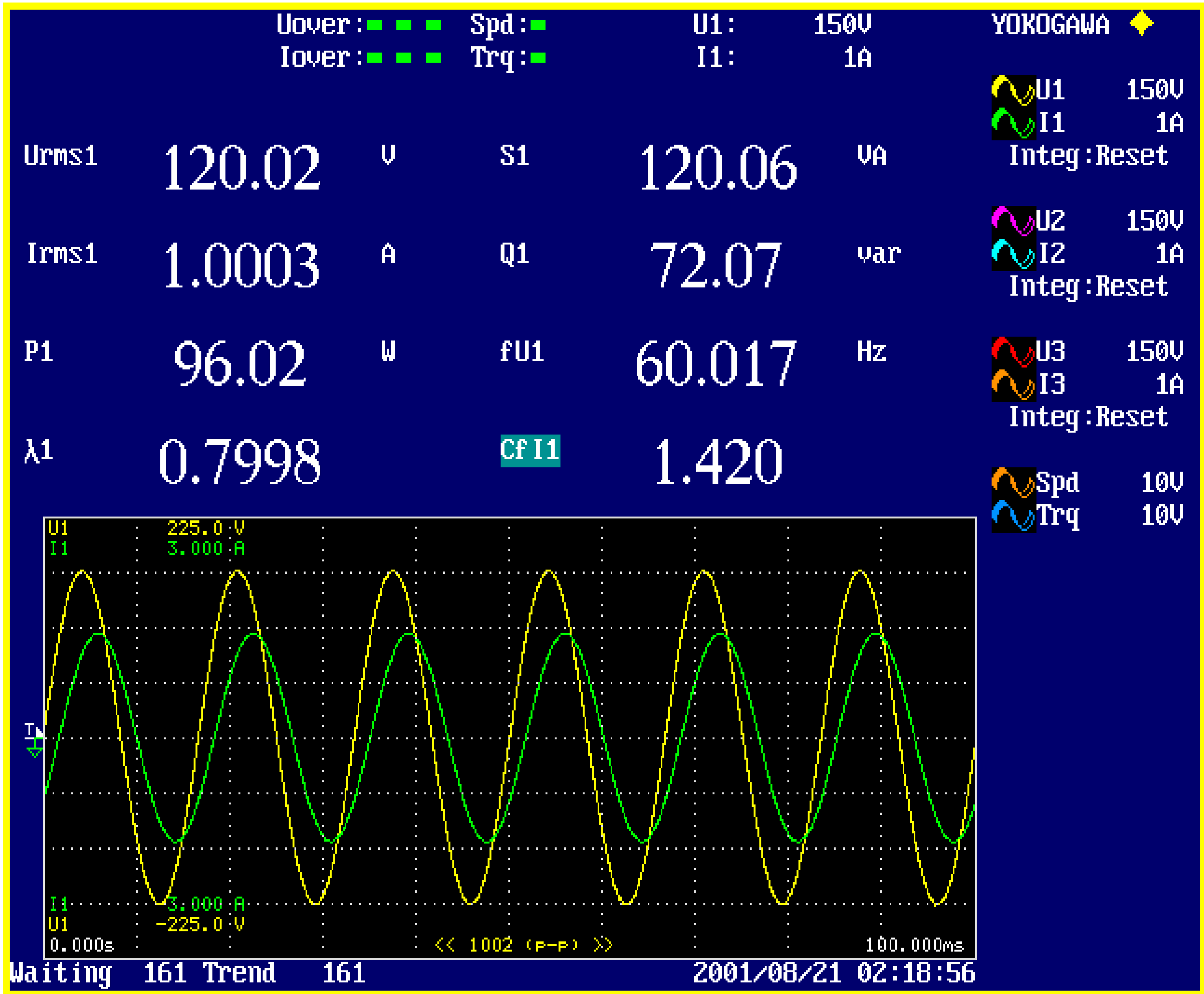
AC Power Measurement

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 of Power

Measurement Results of Single Phase Two Wire Meter method



Current Sensors

AEMC

Yokogawa Scope Probes

Yokogawa/GMW-LEM/Danfysik CT System

Pearson Electronics

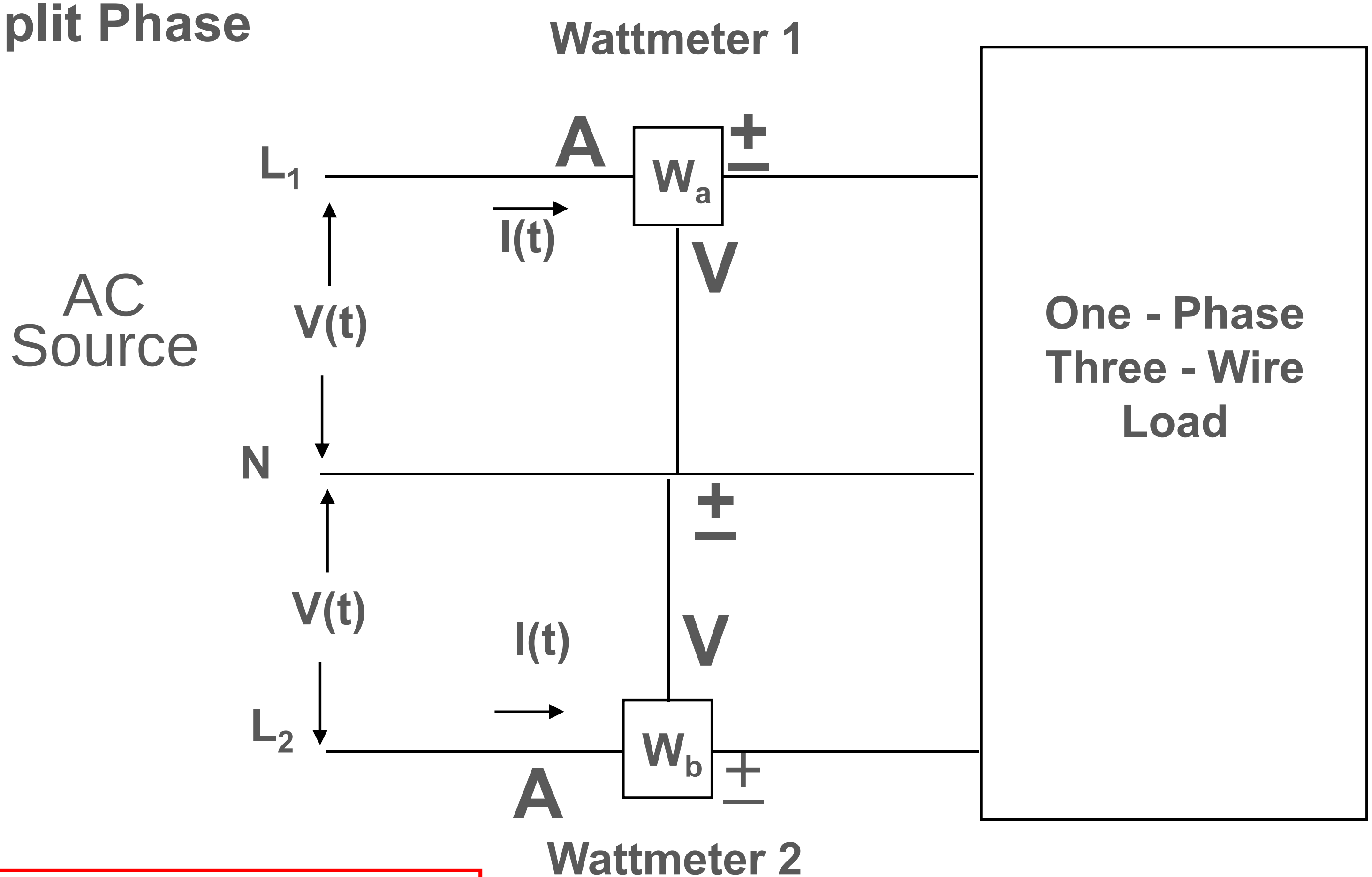
A WORD OF CAUTION

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.

Measurement of Power

Split Phase



Two Wattmeter Method

$$P_T = W1 + W2$$

Measurement of Power

AC Power Measurement

Single-Phase Three-Wire System
(Split Phase)

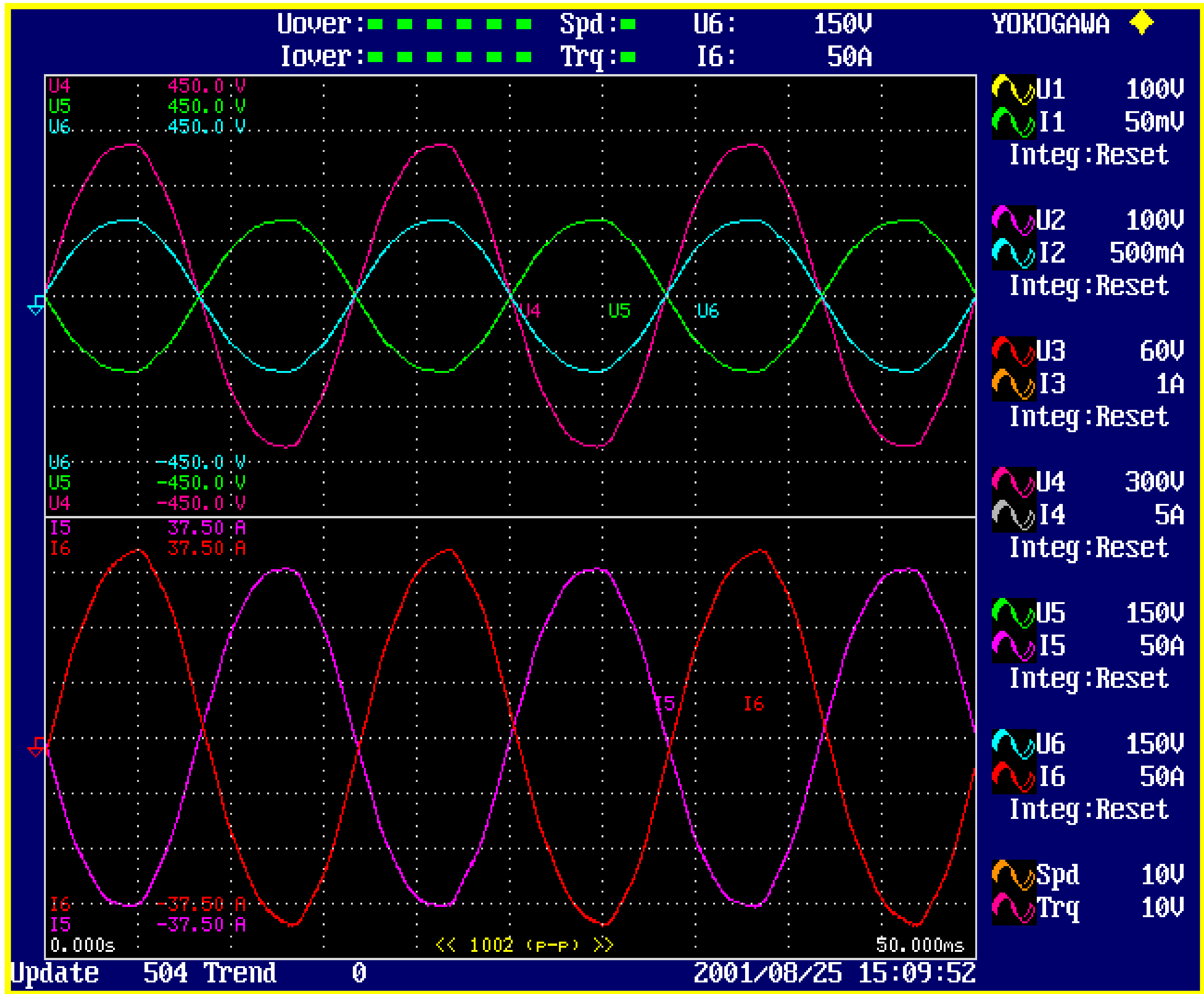
- The voltage and current detected by the **METERS** are the voltage and current applied directly to the Load.
- The indication on **EACH METER** is the power being delivered by the **LINE** to which the meter is connected.
- The total power dissipated by the load is the **ALGEBRAIC SUM** of the two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

Measurement of Power

Measurement Results of Single Phase Three Wire Meter method

Measurement of Power

Measurement Results of Single Phase Three Wire Meter method



Measurement of Power

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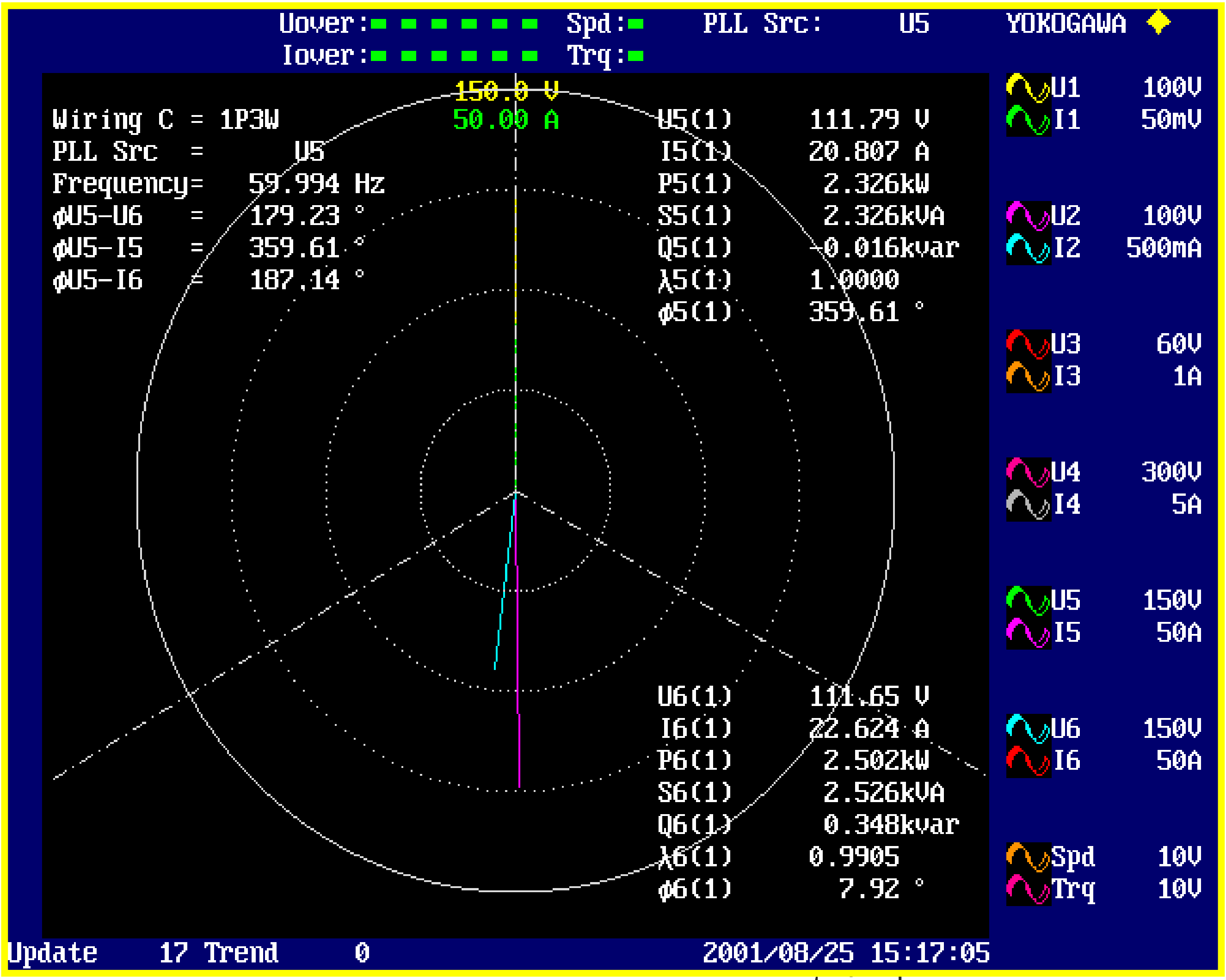
Measurement Results of Single Phase Three Wire Meter method



Blondel Transformation

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Blondel's 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

3-Phase 4-Wire System

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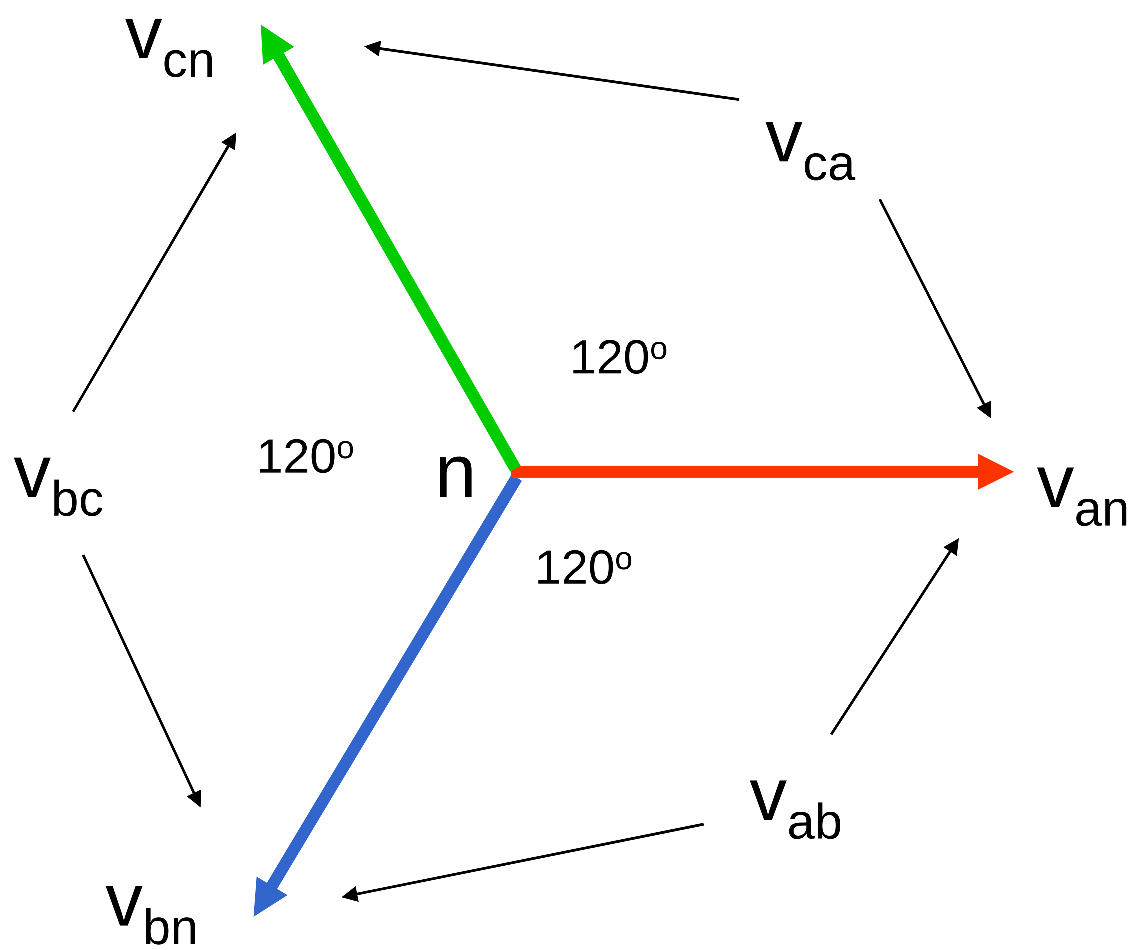
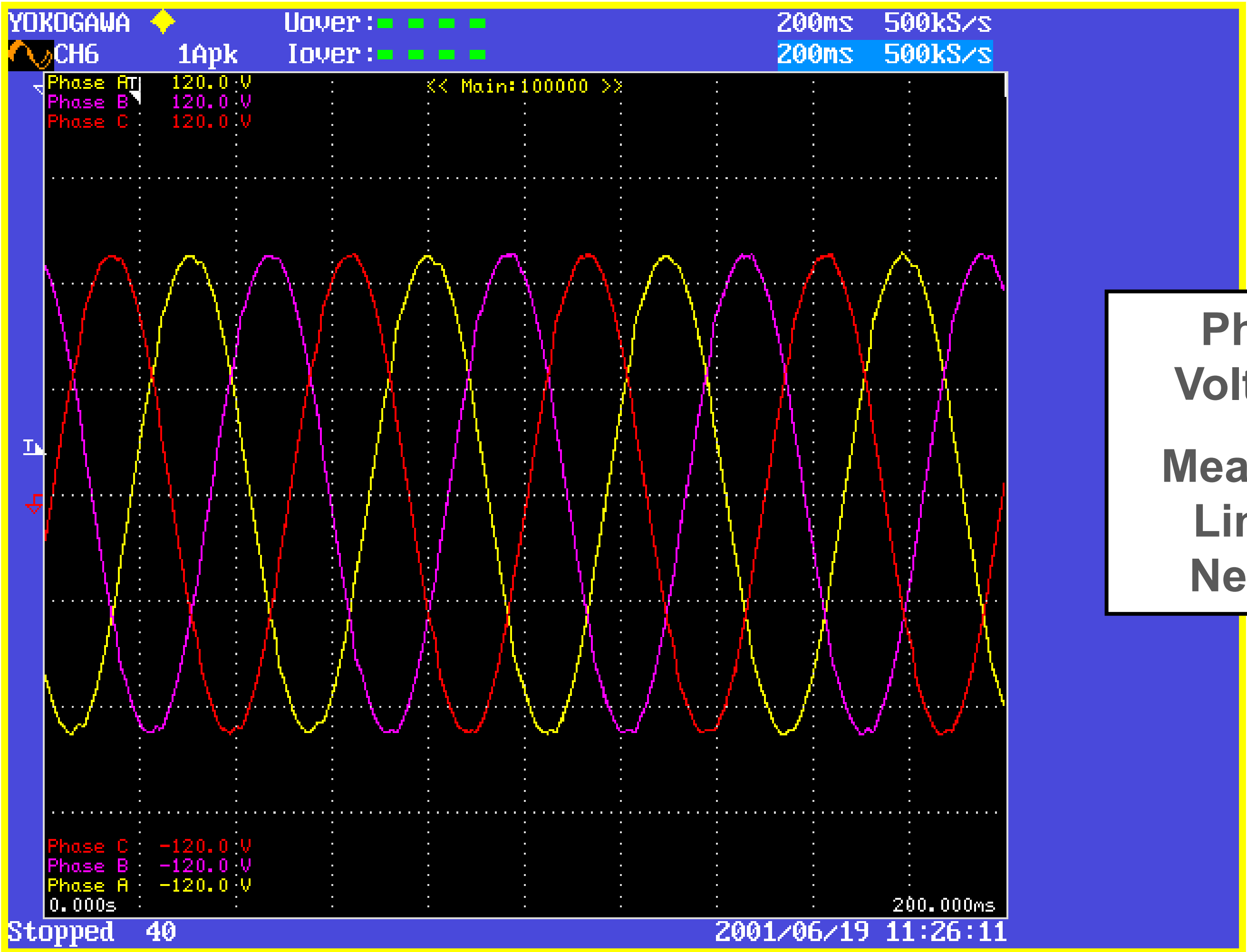


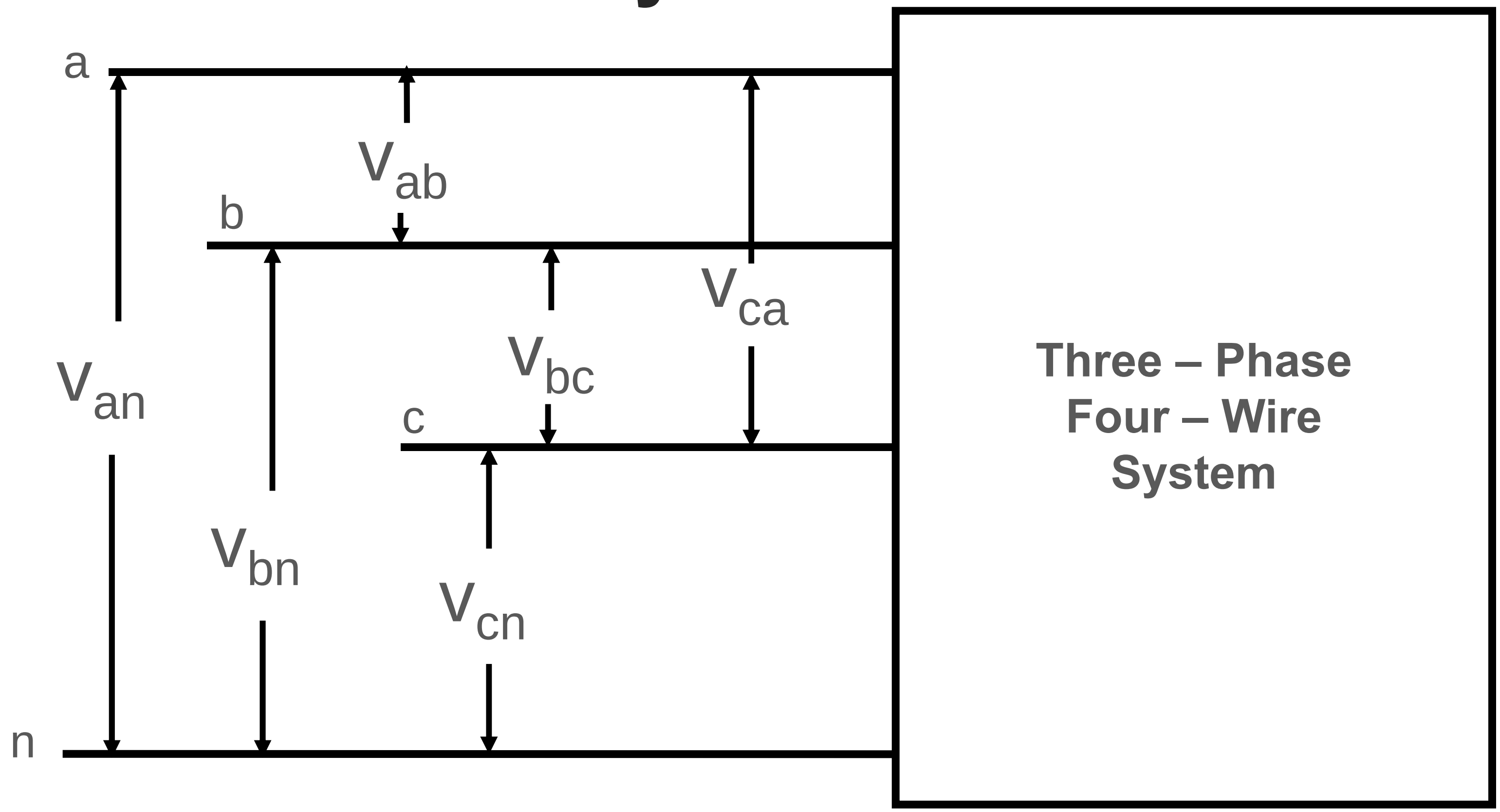
3-Phase 4-Wire System



Phase Voltages

Measured Line to Neutral

3-Phase 4-Wire System



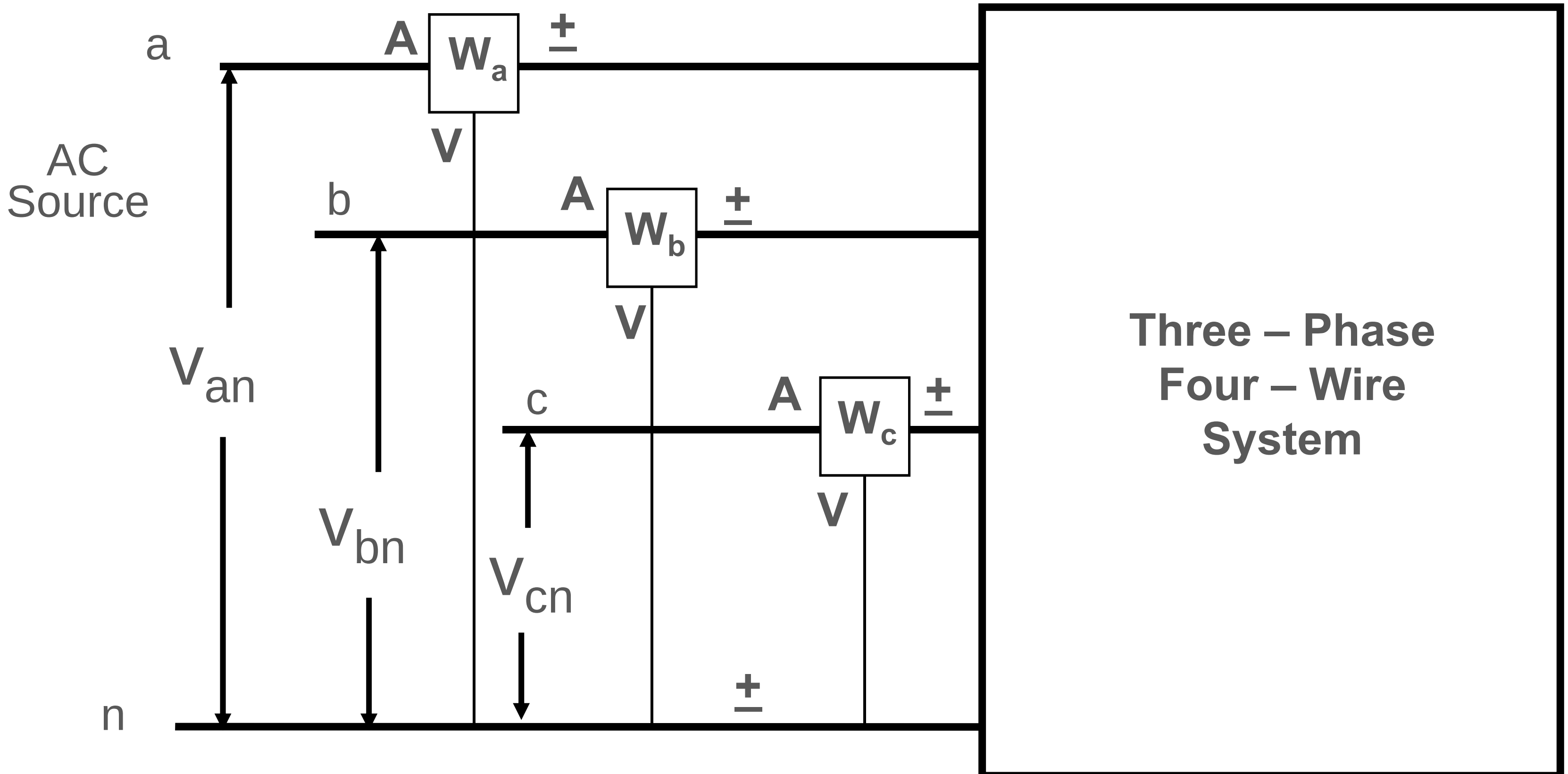
$V_{l\text{-}n}$ = 120 / 277 Volts

⇕ ⇕

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

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

3-Phase 4-Wire System



Three Wattmeter Method

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

Measurement of Power

AC Power Measurement

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.

3-Phase 4-Wire System

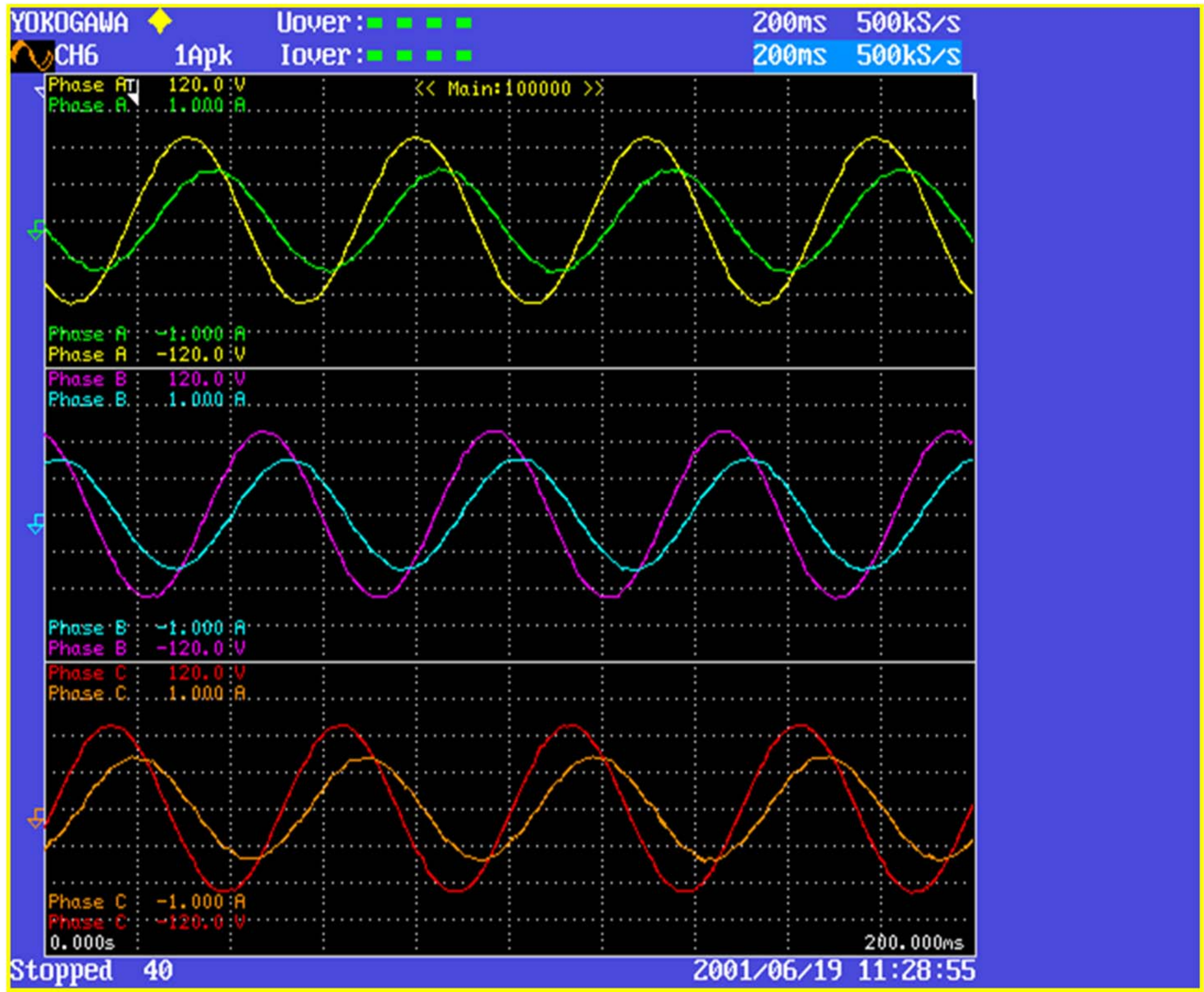
Measurement Results of 3-Phase 4-Wire System

- Phase Voltage & Current
- Phase Power
- Phase Power Factor

3-Phase 4-Wire System

Measurement Results of 3-Phase 4-Wire System

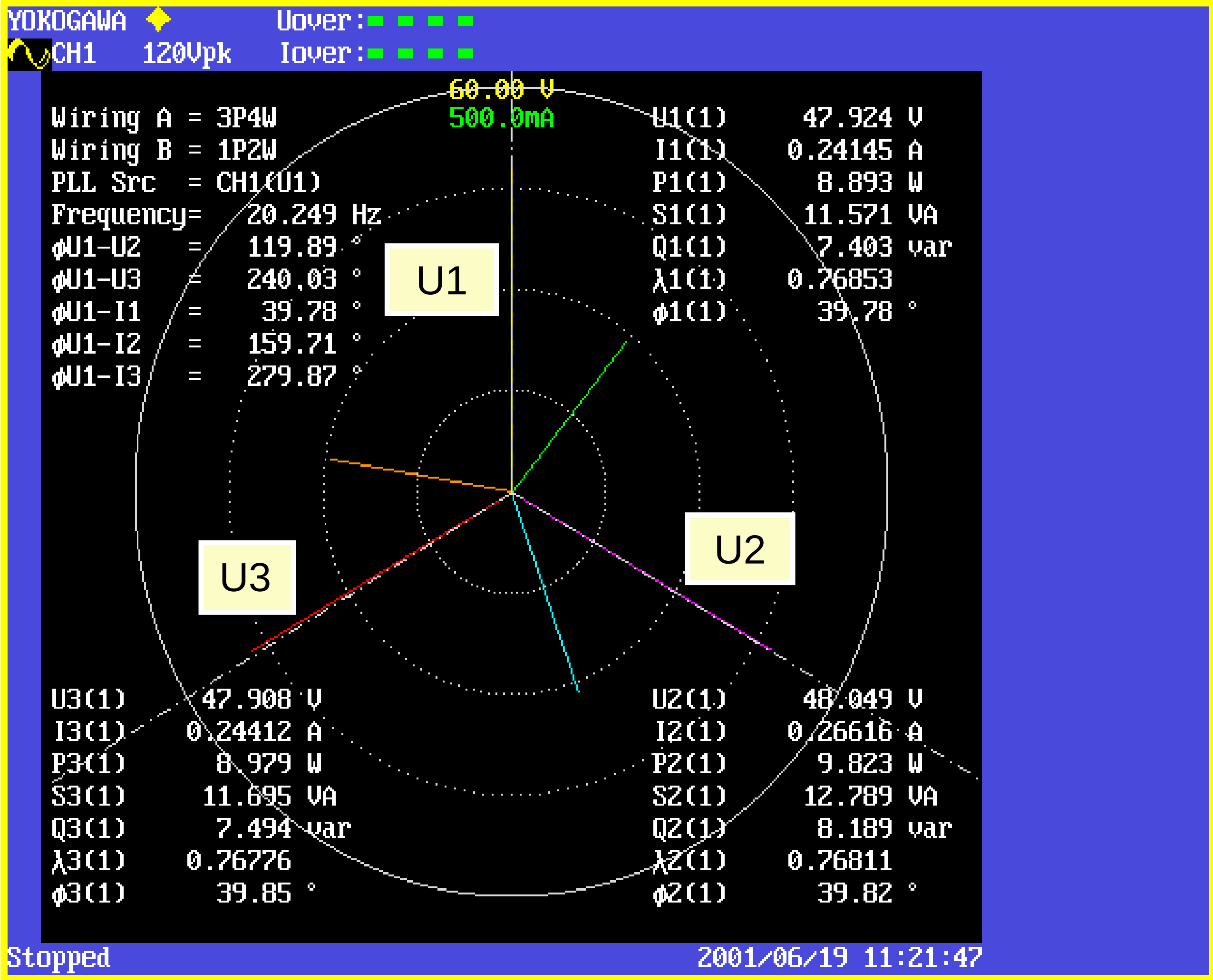
- Phase Voltage - Measured Line to Neutral
- Phase Currents



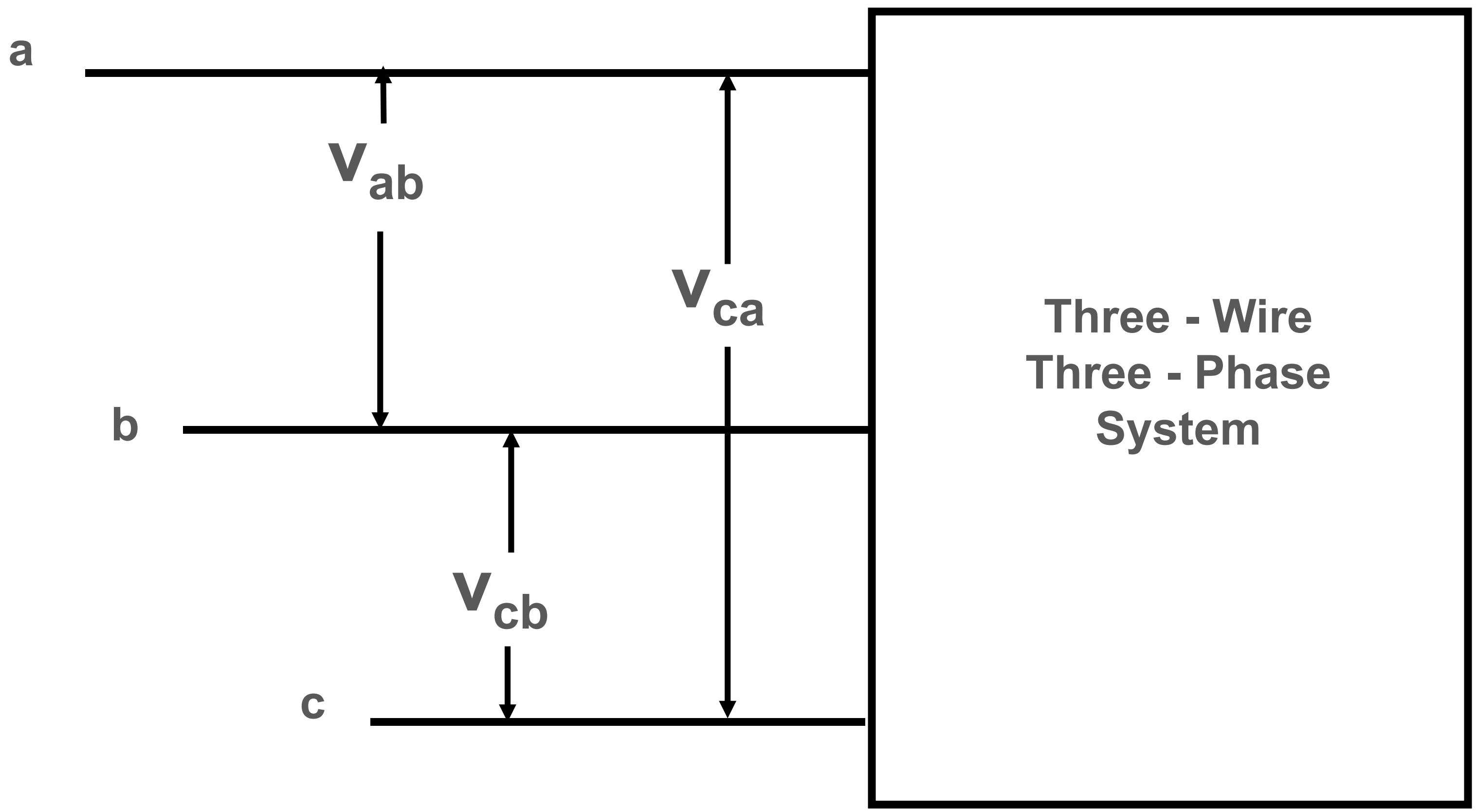
3-Phase 4-Wire System

Measurement Results of 3-Phase 4-Wire System

- Phase Voltage - Measured Line to Neutral



3-Phase 3-Wire System



3-Phase 3-Wire System

Remember

Blondel's Transformation

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

3-Phase 3-Wire System

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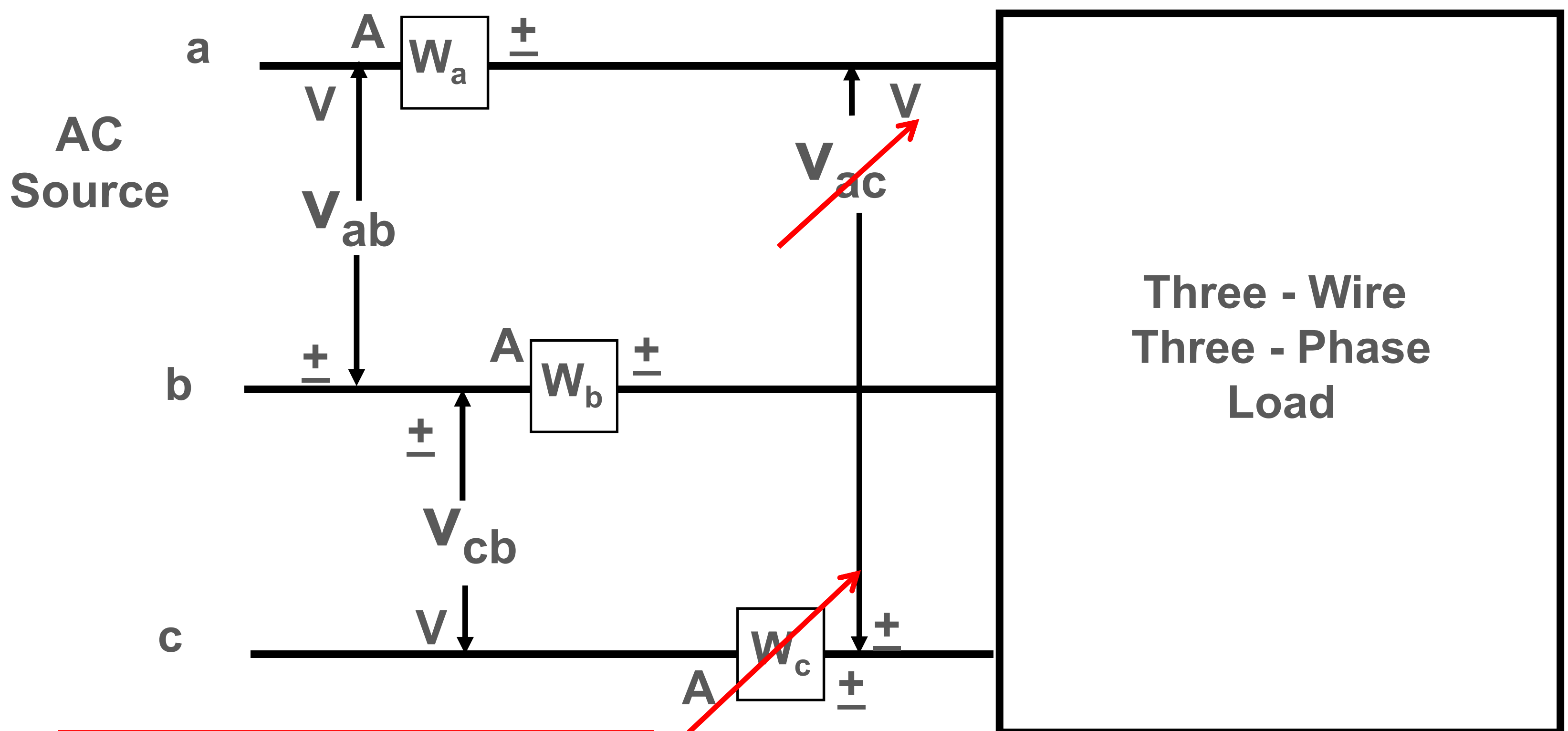
Measuring With Two Meters



Two Wattmeter Method

$$P_T = \sum W_a + W_b$$

3-Phase 3-Wire System

- The wattmeters used for this connection each measure the **PHASE CURRENTS**
- The measured voltages are the **LINE-TO-LINE** values, **NOT** Phase Voltage.
- Thus the indications on each of the meters **IS NOT** the power delivered by the **PHASE** of the measured current.
- This configuration is a very **NON-INTUITIVE** connection!

3-Phase 3-Wire System

- 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.**

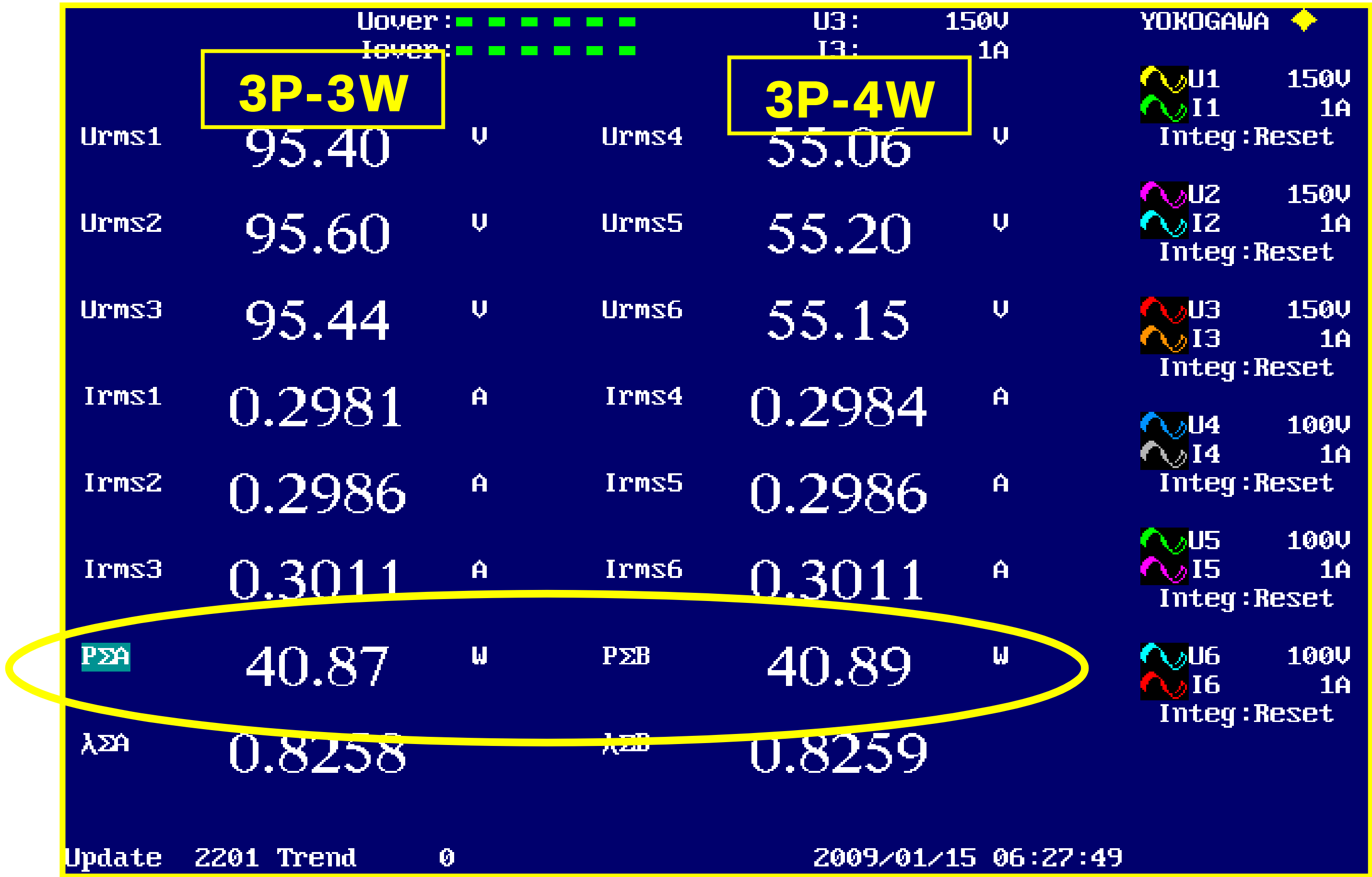
Measurement of Power

3-Phase 3-Wire System

- 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.

Total P_{3P3W} = Total P_{3P4W}



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

Measurement of Power

- All the power measurement techniques illustrated thus far have had one thing in common - The meters used to determine the total power have had a **COMMON CONNECTION** between them.

- In the four - wire system the common point was the **NEUTRAL WIRE**.

- In the three - wire system the common point is one of the **PHASE CONNECTIONS**.

- The bottom line is for a **THREE-WIRE** system we need only **TWO METERS** to determine the total three - phase power.

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Power Factor Measurements

Power Factor Measurements

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

Real World Example - PF

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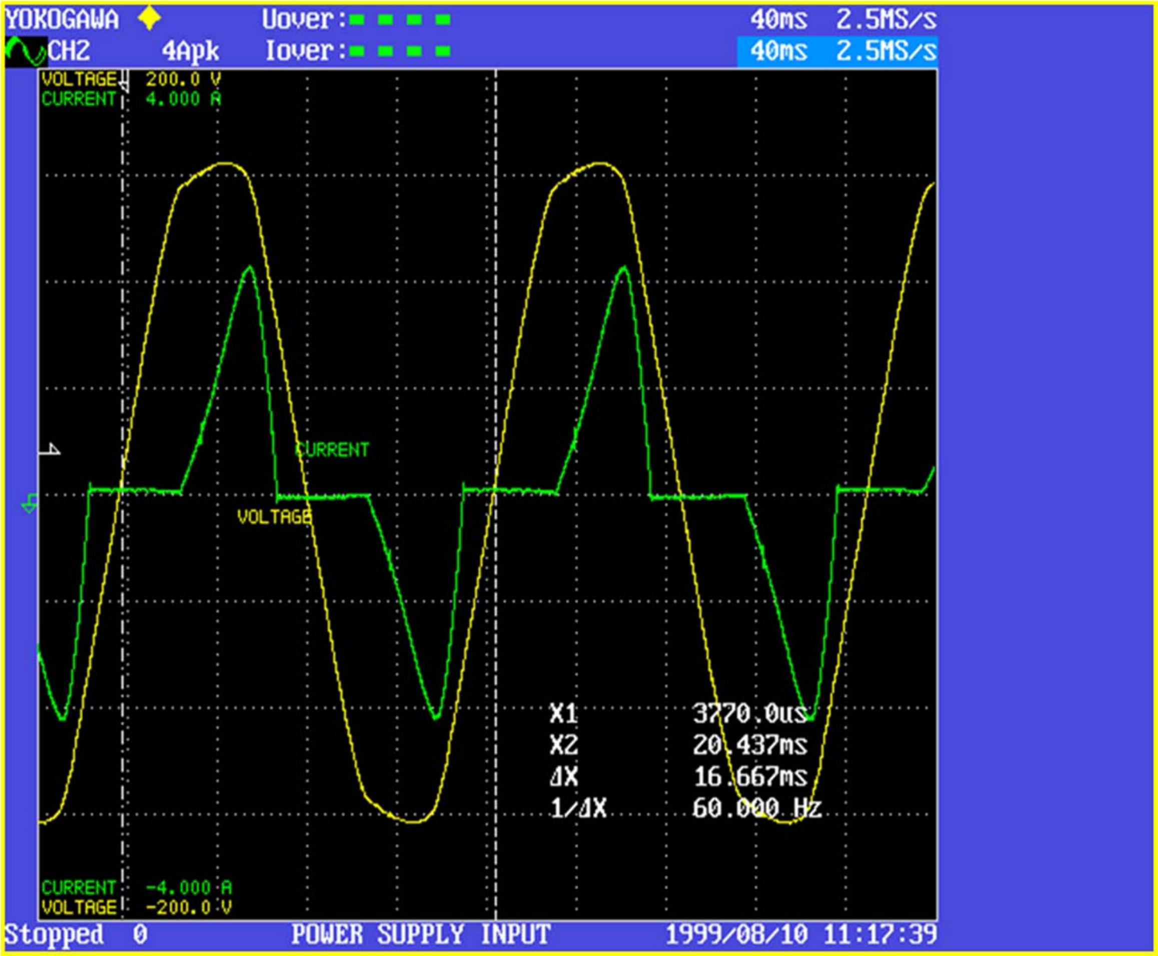
- PF = COS Ø
- Where is the Zero Crossing for the Current Waveform?
- How do we accurately measure Ø between these two waveforms?



Power Factor Measurements

For SINE WAVES ONLY

PF = Cos Ø

This is defined as the DISPLACEMENT Power Factor

For All Waveforms

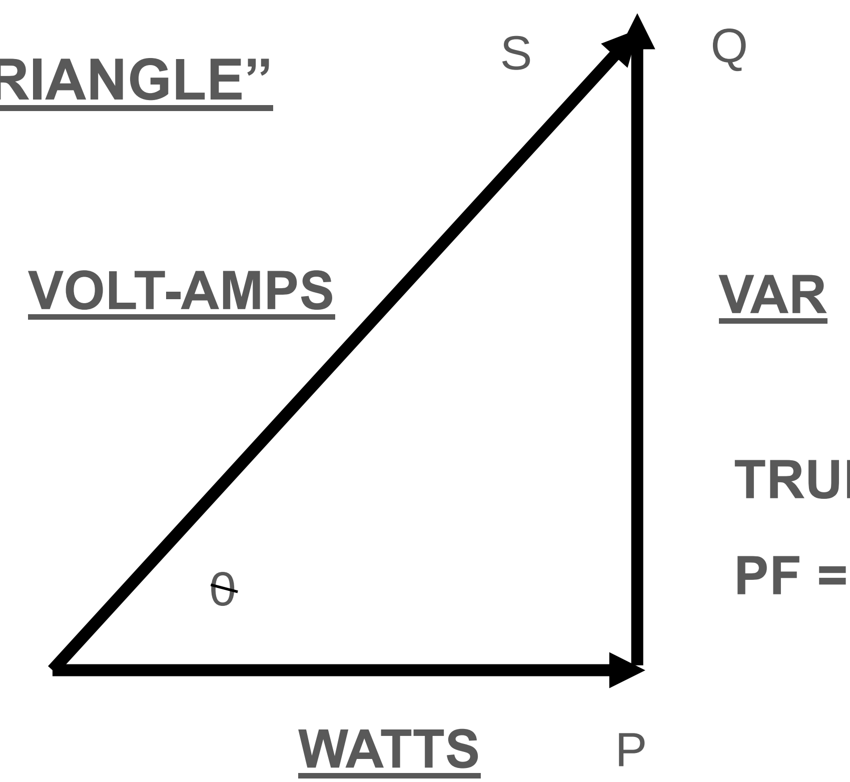
PF = W/VA

This is defined as TRUE Power Factor

Power Factor Measurements

Phasor Diagram of Power for R - L Circuit

"POWER TRIANGLE"



TRUE POWER FACTOR

PF = W / VA

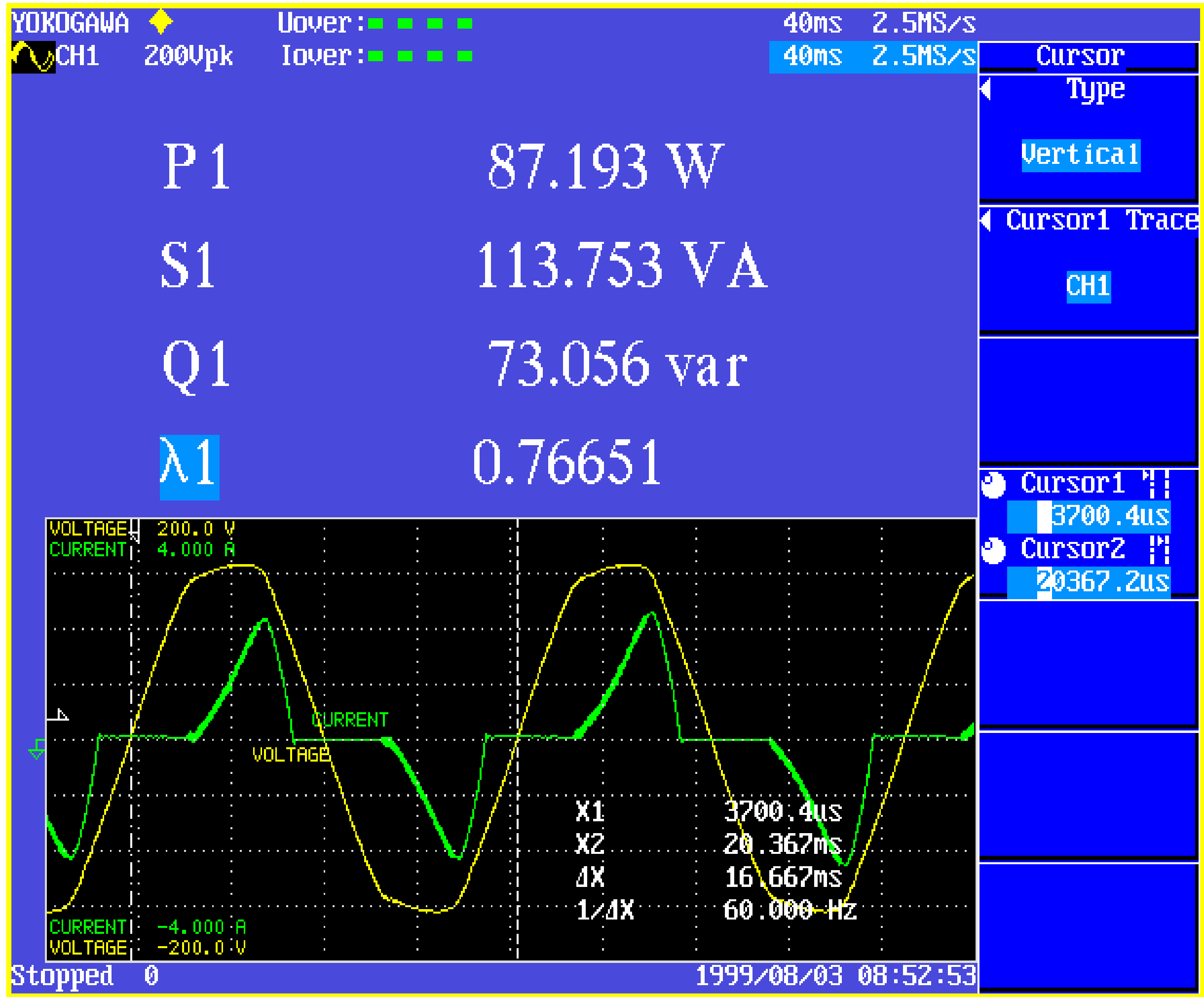
Power Factor Measurements

Power Supply Input

PF = W / VA

PF = 87.193/113.753

PF = 0.76651



Power Factor Measurements

3-Phase 4-Wire System

Using 3 wattmeter method

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

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

Power Factor Measurements

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 Measurements

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.

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Harmonic Measurements

Why Are We Concerned with Harmonics on the Power System?

Harmonics Measurements

Concerns

- Cause excess heat in electrical equipment
- Cause inefficient operation – wasted power, higher electric operating costs
- Cause damage to electrical equipment
- Some examples:
  - Transformers can be less efficient
  - Circuit Breakers & GFI's can trip
  - Electric Motors can be less efficient
  - Overheating in Neutral Conductors

Harmonics Measurements

Distorted AC Wave Shapes

There are many causes of distortion on AC systems:

- non-linear magnetic circuits
- rectifiers
- capacitors interacting with inductances
- switching power electronic loads
- phase-controlled rectifiers
- ac voltage controllers
- inverters
- electronic ballasts

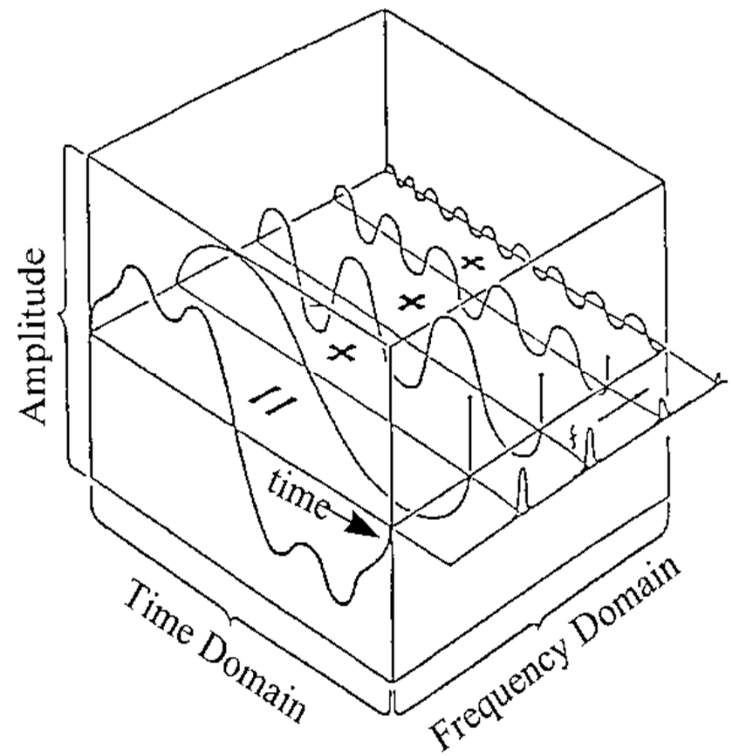
Harmonics Measurements

Distorted AC Wave Shapes

Elements of a distorted or non-sinusoidal waveform consist of Sine Waves of various:

- **Amplitudes**
- **Frequencies**
- **Phase**

Because of the Phase differences in some of the harmonics, negative or reverse power can actually be produced.



Harmonics Measurements

Distorted AC Wave Shapes

- Harmonics are usually specified as **Orders**

  180 Hz = 3rd Order for a 60 Hz Fundamental Signal

  (60 Hz x 3 = 180 Hz)
- Harmonics are also referred to as **Even**-order and **Odd**-order.
- In some complex waveforms, there can be Inter-Harmonics, or non-integer orders.

Harmonics Measurements

Distorted AC Wave Shapes

Total Power of the Distorted Waveshape is Calculated as:

$$P_{total} = V_0 \times I_0 + V_1 \times I_1 \times \cos\theta_1 + V_2 \times I_2 \times \cos\theta_2 + V_3 \times I_3 \times \cos\theta_3 + \ldots + V_n \times I_n \times \cos\theta_n$$

*** OR More Precisely ***

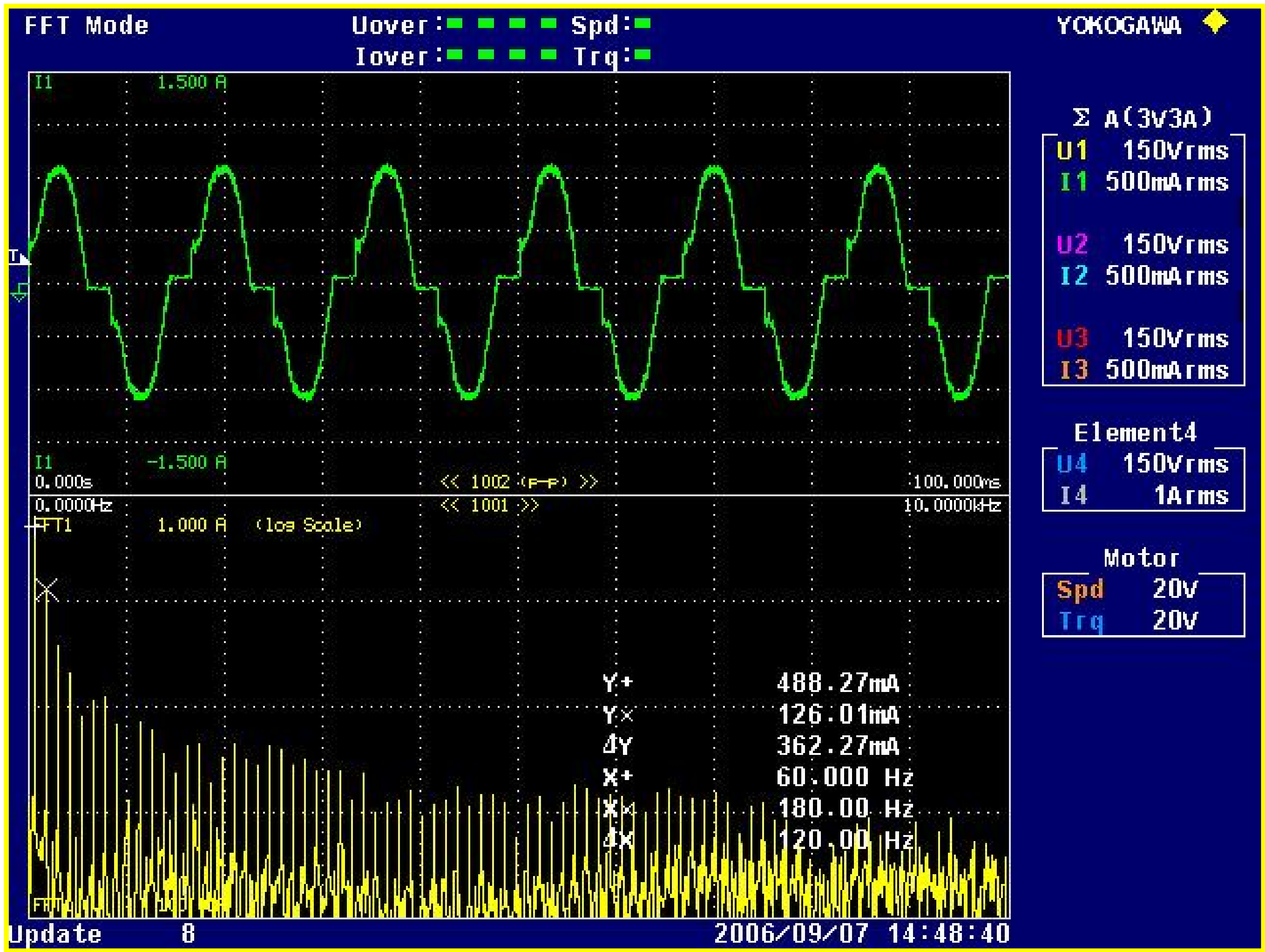
$$P_{total} = V_0 \times I_0 + \sum_{min}^{max} V_n \times I_n \times \cos\theta_n$$

Harmonics Measurements

- The Yokogawa Digital Power Analyzers and Power Scopes use the **FFT** algorithm.
- FFT Analysis must be performed on a periodic waveform with a true integer number of cycles.
- Yokogawa Power Analyzers use a **Phase Lock Loop (PLL)** circuit to sync on the fundamental frequency and adjust the sample rate to obtain a true integer number of cycles.

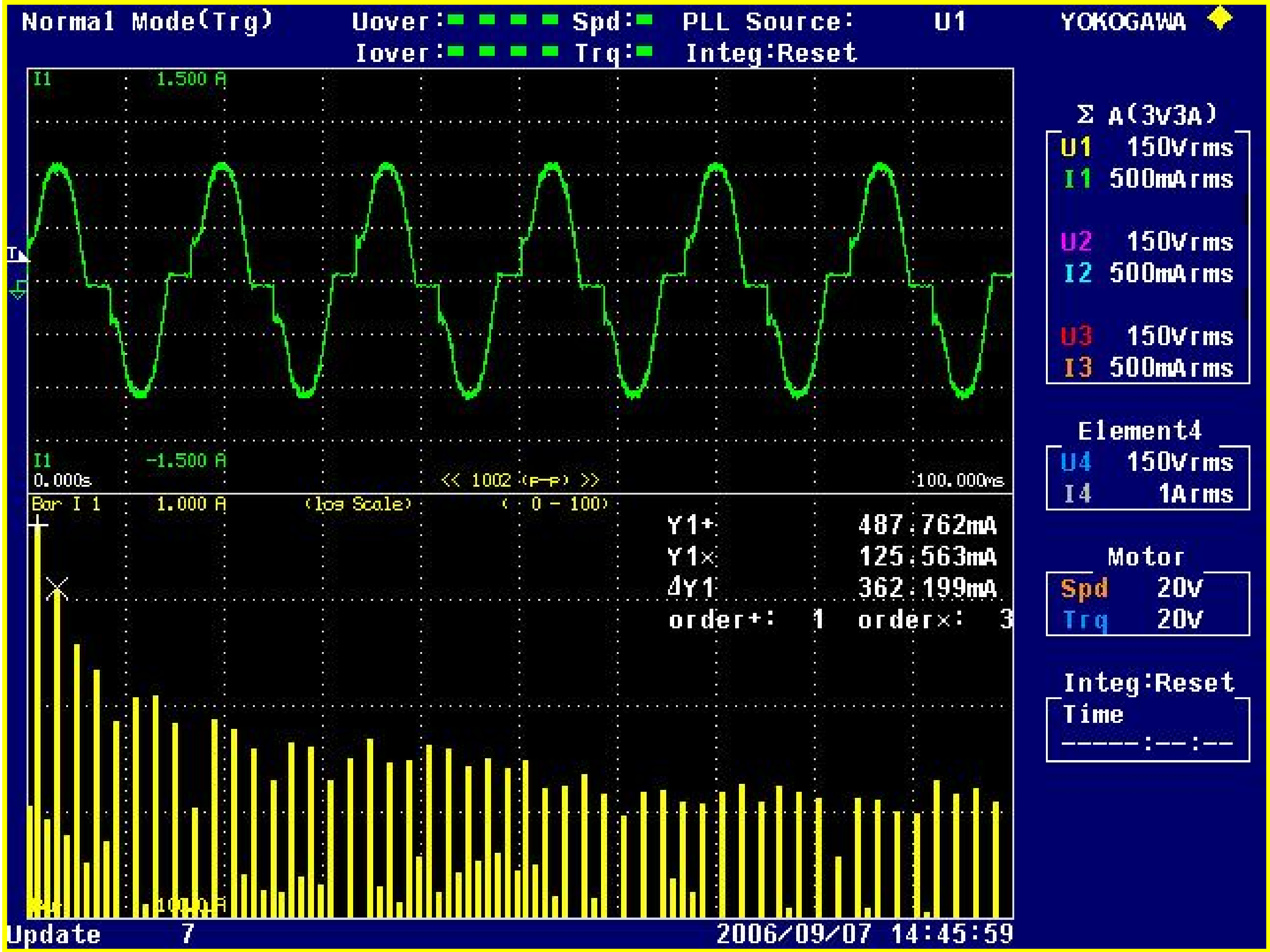
Harmonics Measurements

Simple MATH FFT Analysis Function



Harmonics Measurements

Harmonic Analysis Function on a Power Analyzer



Harmonics Measurements

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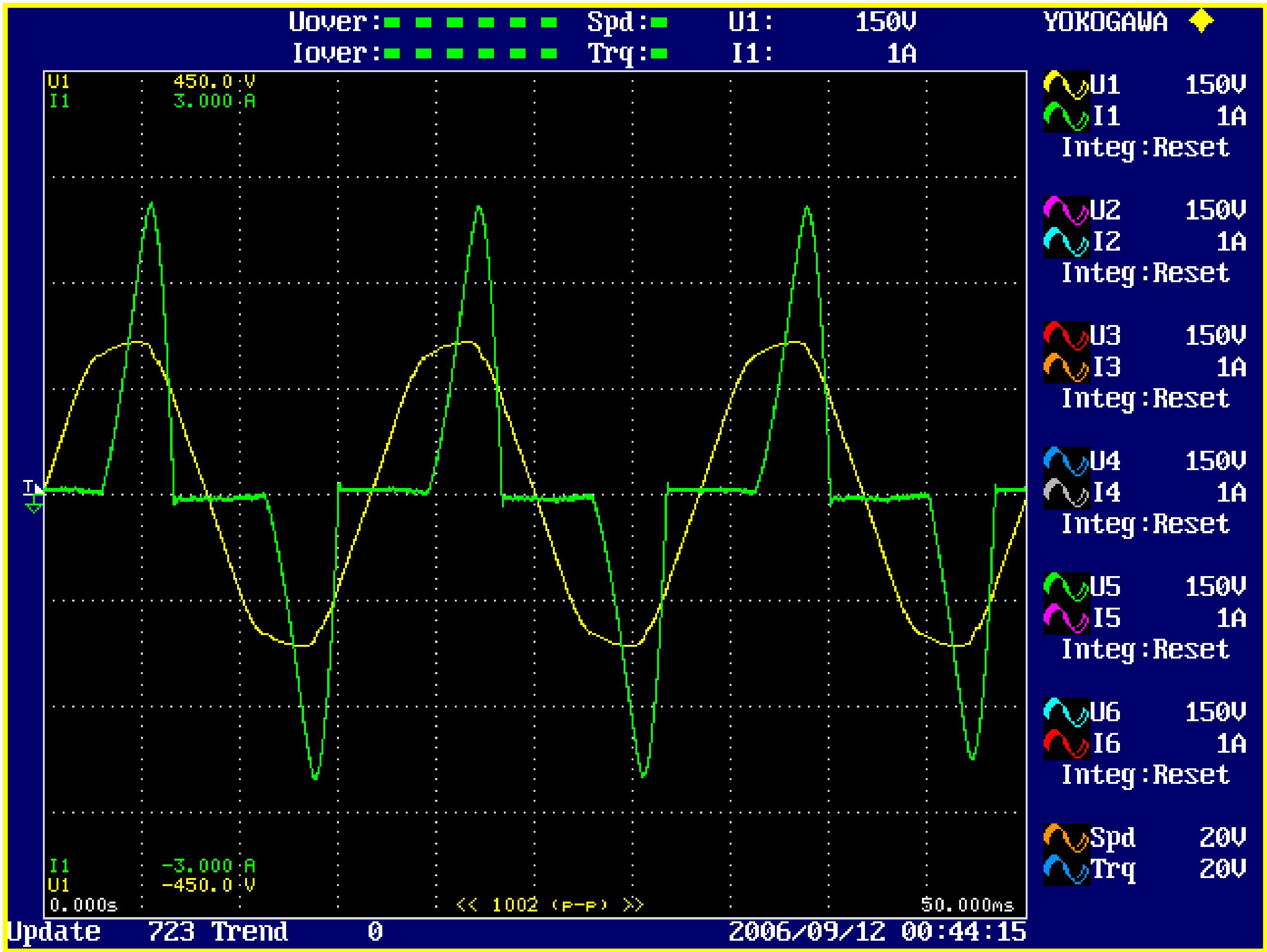
Harmonic Measurement Application



Harmonics Measurements

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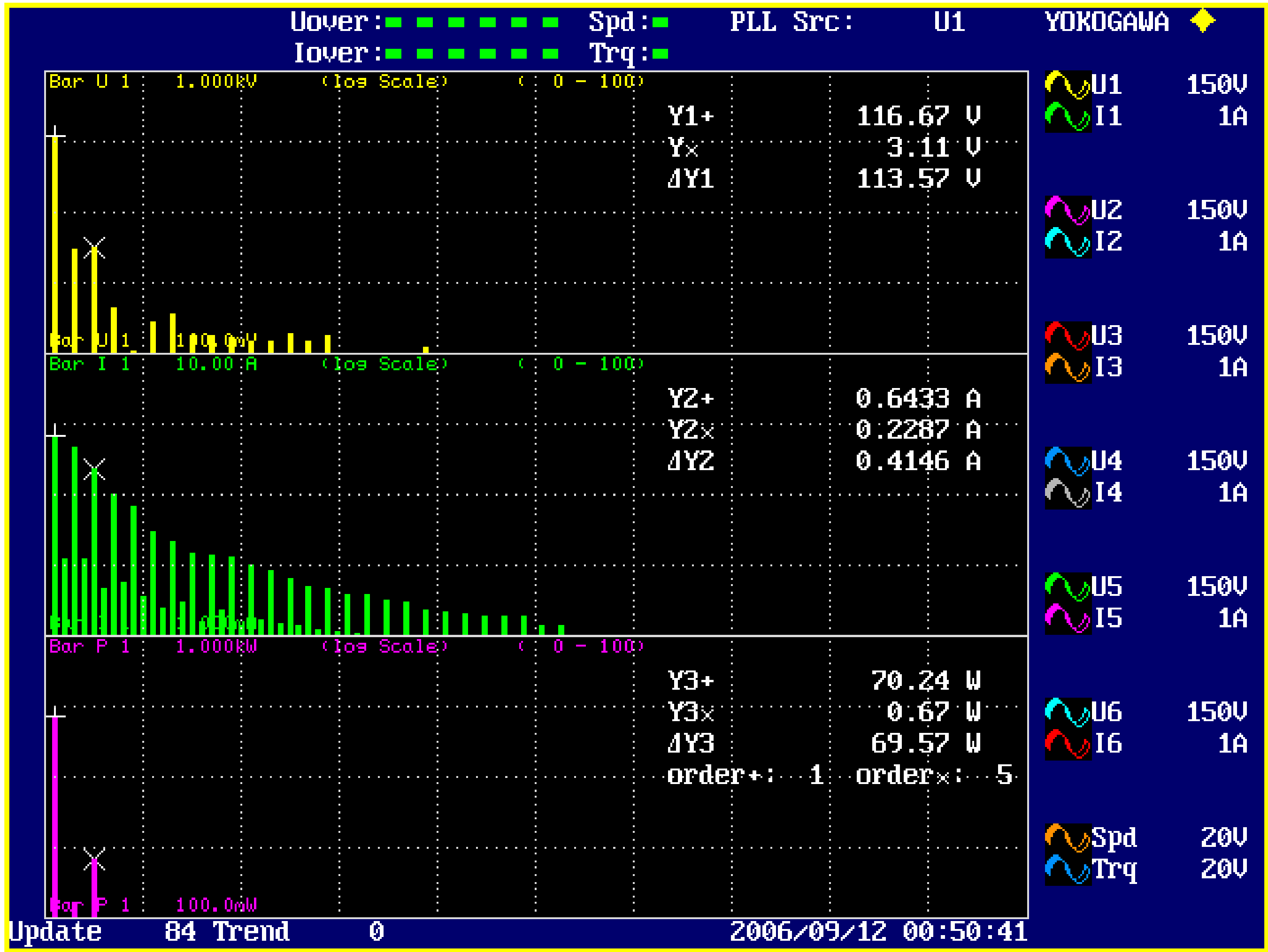
Typical Harmonic Display

Voltage

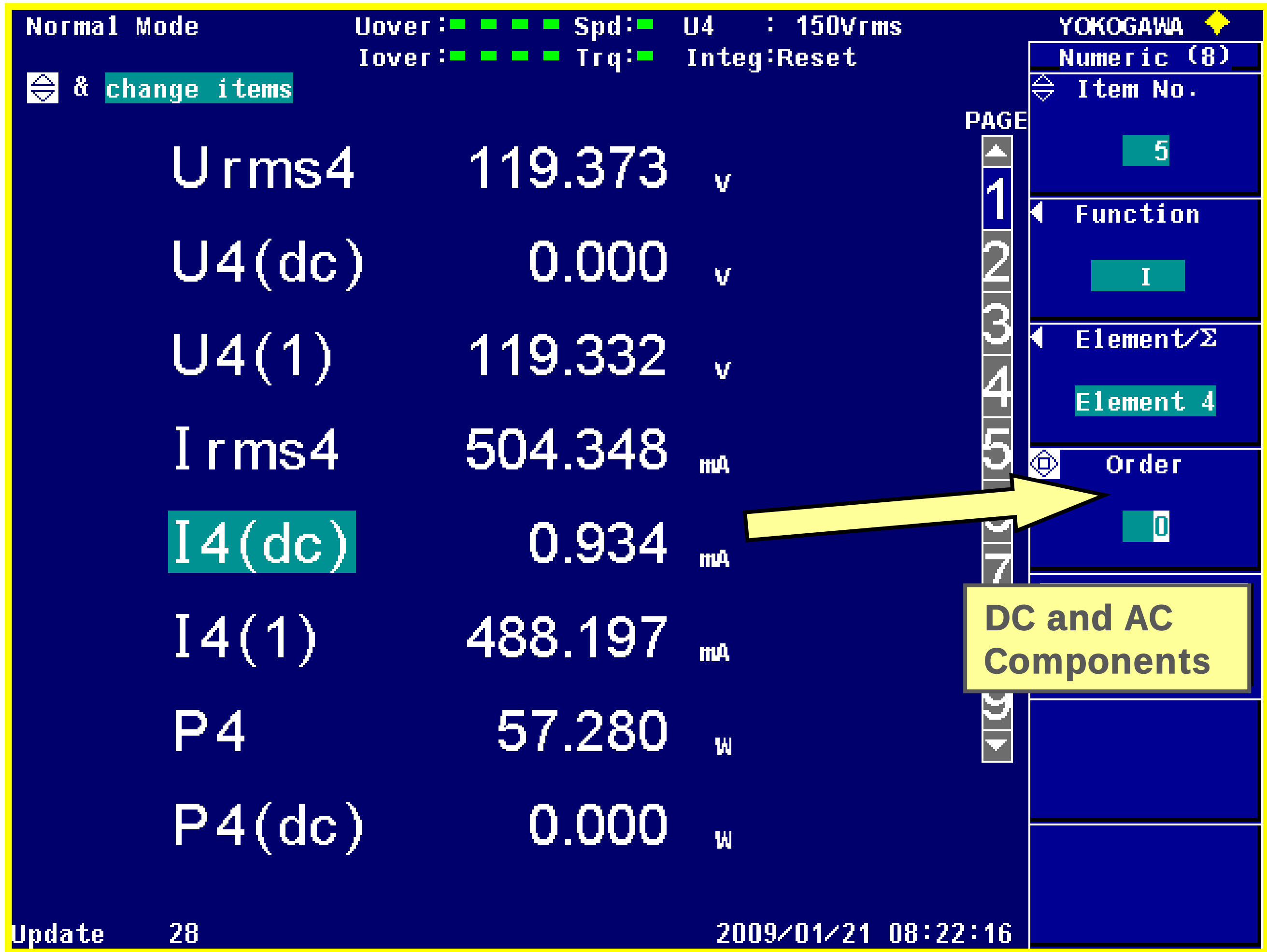
Current

Power



Harmonics Measurements

Numeric Harmonic Data



Harmonics Measurements

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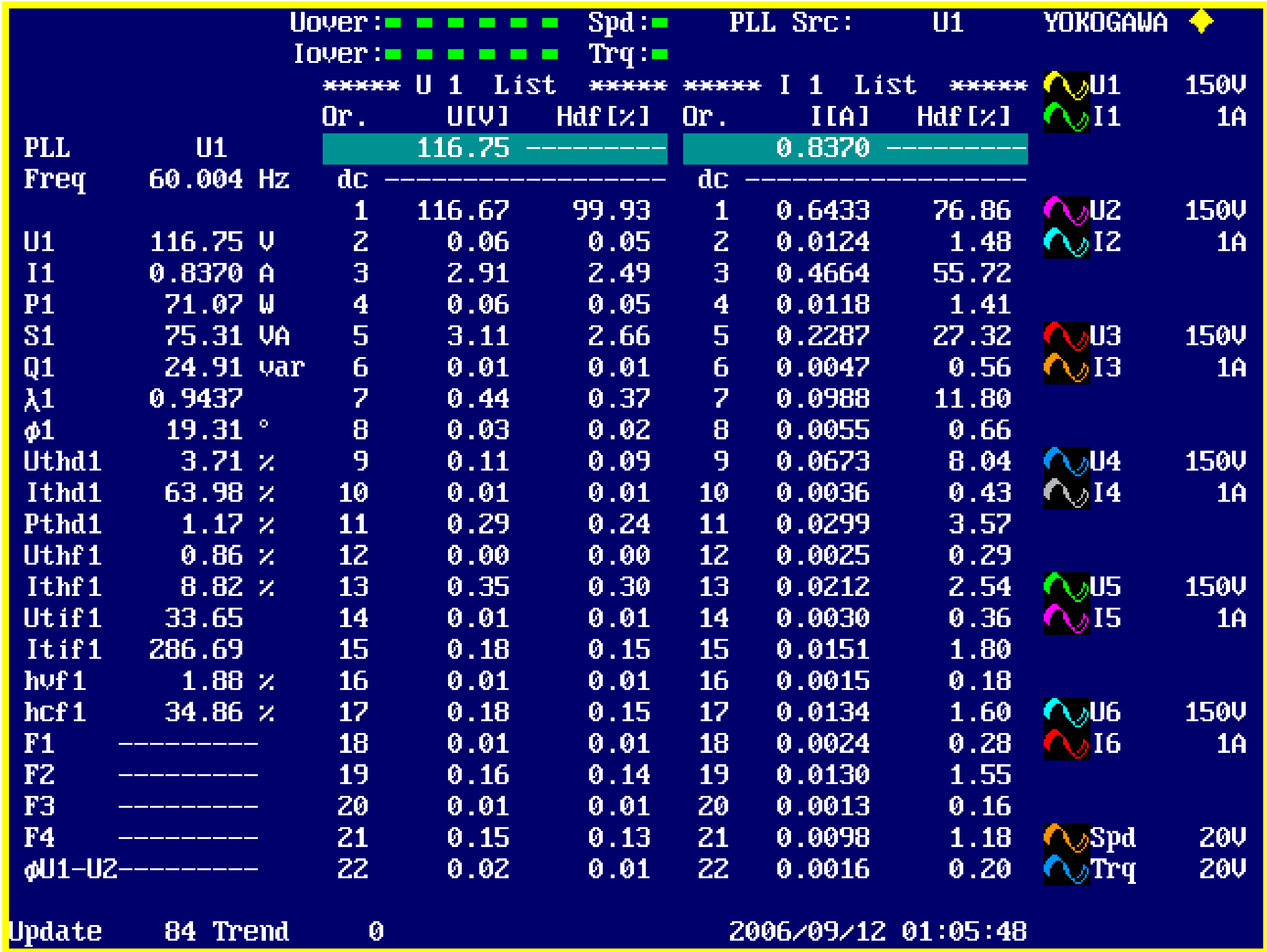
Dual Data Display

Voltage
Current

&

Harmonic Distortion Factor

% Total



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Harmonics Measurements

- How do we measure Harmonics in the Yokogawa Power Analyzers?

Fast Fourier Transform > FFT

- What is the PLL and what is it used for?

Yokogawa Power Analyzers use a **Phase Lock Loop (PLL)** circuit to sync on the fundamental frequency and adjust the sample rate to obtain a true integer number of cycles for the FFT Analysis.

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Standby Power Energy Star® IEC Testing

Standby Power

- ## What is Standby Power?
  - **Standby power is the energy consumed by appliances when they are not performing their main function. The power consumption is because of standby functions like built-in clock, memory and displays for settings and other information.**
  - This is not to be confused with the related issue of “off mode” power, which occurs when the product is connected to the main power supply and is switched off. In this mode the equipment does not offer any functionality.

IEC Standard

- The **International Electro-technical Commission (IEC):** Preparing international standards to measure and reduce standby power.
- 2nd edition of **IEC62301 (Household electrical appliance – Measurement of standby power)**.
- **The European standard EN50564:2011** is based on IEC62301 Ed.2.0 with few modifications.
- Objective: To provide a method of test to determine the power consumption of a range of appliances and equipment in Standby mode.

IEC Standard

- Second Edition of IEC62301 standard defines the Power Accuracy and Resolution as follows:
- Power Measurement Accuracy:
  - 1 W or greater: 2% of Reading
  - Less than 1 W: 0.02W uncertainty
- Power Measurement Resolution:
  - 10 W or less: 0.01 W
  - 10 to 100 W: 0.1 W
  - Greater than 100 W: 1 W
- The Measuring Instrument must have a minimum Current Range of 10 mA.

Sampling Methods & Stability Check (IEC & EN)

- **Sampling Method:** Where the power value is stable, record the instrument power reading
- **Averaging Method:** Where the power value is not stable, average the instrument power readings over a specified period
- **Direct Meter Reading Method:** By recording the energy consumption over a specified period and divide by time.

- **Stability**
  - **When the power difference between the two comparison periods divided by the time difference of the mid-points of the comparison period has slope that follows the stability criteria**

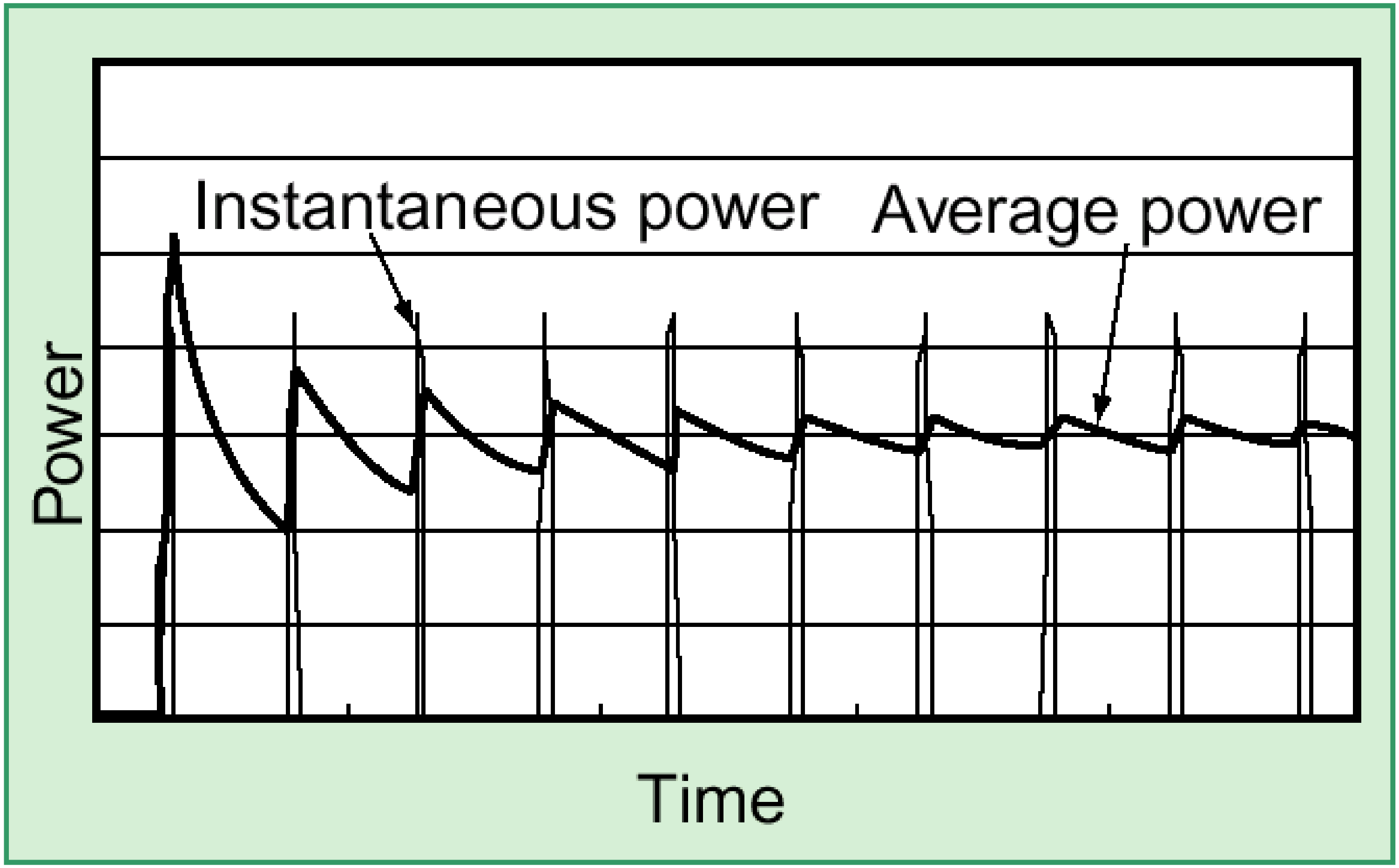
- **Stability Algorithm**
  - **Linear Regression**
  - **Cumulative Average**
  - **Comparing two average periods reading**

Yokogawa's Standby Power Measurement

- We use the third method, Energy divided by Time > **Watt-Hour/Time**.
- The WT Series Power Analyzers measure a True Average Power over a user selected time period.
- 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.

Yokogawa's Standby Power Measurement

Pulse Power Mode



Yokogawa's Solutions

The World Leader in Electrical Power Measurements

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Power Analyzer Demonstration

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For
Your Time

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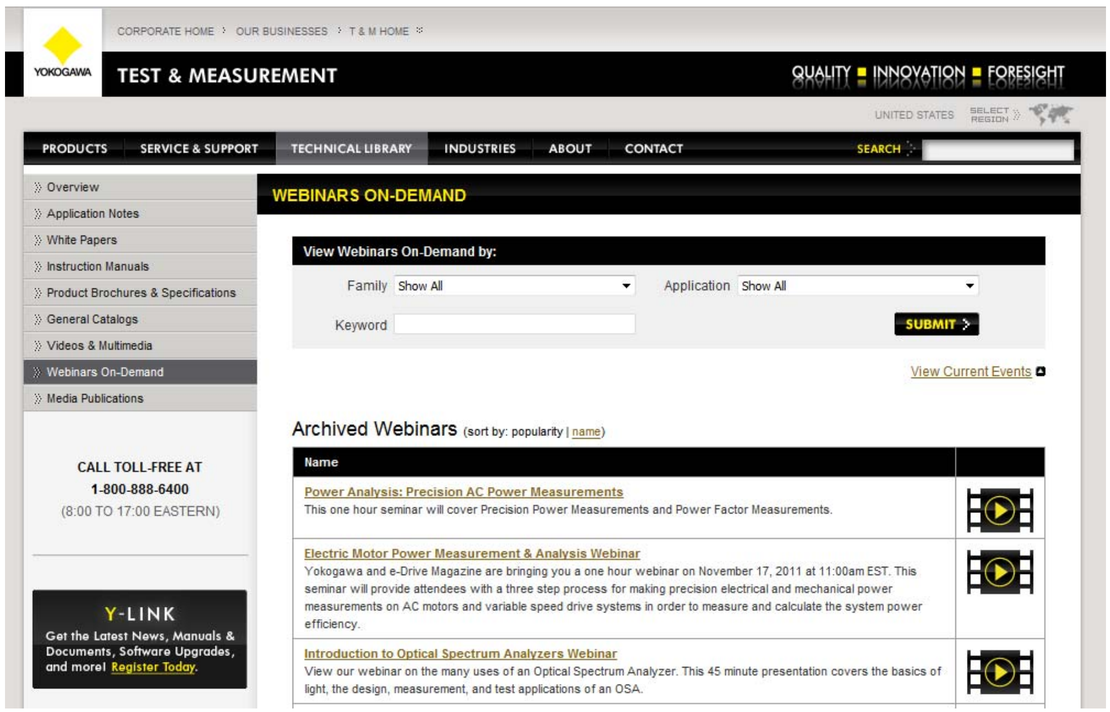

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Q & A