Fundamentals of Electrical Power Measurement

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Presentation: IEEE / UTC Aerospace
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Barry is currently responsible for Yokogawa’s digital oscilloscope measurement applications support, including application notes and seminars.

Barry graduated from the Georgia Institute of Technology with a degree in electrical engineering, and he enjoys amateur radio, fly fishing, gardening, and travel with his family.
Fundamentals of Electrical Power Measurements

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Overview – Part I of III

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 – Part II of III

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
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
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
PART I
ELECTRICAL POWER MEASUREMENTS
First, Some Basics: OHM’S LAW

\[ P = \text{Power} \]
\[ I = \text{Current} \]
\[ V = \text{Voltage} \]
\[ R = \text{Resistance} \]

- \( P = \frac{V}{R} \) (Watts)
- \( I = \sqrt{\frac{V}{R}} \) (Amps)
- \( V = I \times R \) (Volts)
- \( R = \frac{V}{I} \) (Ohms)

Equations:

- Power: \( P = V \times I \)
- Current: \( I = \frac{V}{R} \)
- Voltage: \( V = I \times R \)
- Resistance: \( R = \frac{V}{I} \)

Symbols:

- \( P \): Power
- \( I \): Current
- \( V \): Voltage
- \( R \): Resistance
# Average and RMS Values

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

(multiplication factors)

<table>
<thead>
<tr>
<th>Known Value</th>
<th>Average</th>
<th>RMS</th>
<th>Peak</th>
<th>Peak-to-Peak</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>1.0</td>
<td>1.11</td>
<td>1.57</td>
<td>3.14</td>
</tr>
<tr>
<td>RMS</td>
<td>0.9</td>
<td>1.0</td>
<td>1.414</td>
<td>2.828</td>
</tr>
<tr>
<td>Peak</td>
<td>0.637</td>
<td>0.707</td>
<td>1.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Peak-to-Peak</td>
<td>0.32</td>
<td>0.3535</td>
<td>0.5</td>
<td>1.0</td>
</tr>
</tbody>
</table>
Average and RMS Values

\[\begin{align*}
U_{rms1} & = 120.000 \text{ V} \\
U_{mn1} & = 119.999 \text{ V} \\
F1 & = 108.107 \text{ V Avg} \\
U_{+pk1} & = 169.99 \text{ V}
\end{align*}\]
What’s A Watt?

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

DC Source: \( W = V \times A \)

AC Source: \( W = V \times A \times PF \)
AC Power Measurement

- **Active Power:**
  
  \[ P = V_{\text{rms}} \times A_{\text{rms}} \times \text{PF} \]
  
  Also sometimes referred to as True Power or Real Power

- **Apparent Power:**
  
  \[ S = V_{\text{rms}} \times A_{\text{rms}} \]
Measurement of AC Power

Watts: \[ P = V_{rms} \times A_{rms} \times PF = Urms1 \times Irms1 \times \lambda1 \]
Volt-Amps: \[ S = V_{rms} \times A_{rms} = Urms1 \times Irms1 \]
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.
Yokogawa Digital Power Analyzers and Digital Power Scopes use the following method to calculate power:

\[ P_{\text{avg}} = \frac{1}{T} \int_{0}^{T} v(t) * I(t) \, dt \]

Using digitizing techniques, the instantaneous voltage is multiplied by the instantaneous current and then integrated over some time period.
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.

\[ P_{\text{total}} = \frac{1}{T} \int_0^T v(t) \times I(t) \, dt \]

\[ U_{\text{RMS}} = \sqrt{\frac{1}{T} \int_0^T v(t)^2 \, dt} \]

\[ I_{\text{RMS}} = \sqrt{\frac{1}{T} \int_0^T i(t)^2 \, dt} \]
Single Phase Power Measurement

**AC Source**

\[ V(t) \]

\[ I(t) \]

**Wattmeter**

\[ A \] \[ \pm \] \[ W \]

**Load**

One - phase two - wire

**Single Wattmeter Method**
Measurement of Power

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>U_rms1</td>
<td>120.02</td>
</tr>
<tr>
<td>I_rms1</td>
<td>1.0003</td>
</tr>
<tr>
<td>P1</td>
<td>96.02</td>
</tr>
<tr>
<td>λ1</td>
<td>0.7998</td>
</tr>
</tbody>
</table>

- U_rms1: 120.06 VA
- I_rms1: 72.07 var
- P1: 60.017 Hz
- λ1: 1.420

Graph showing waveforms for voltages and currents.
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
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 $E = I \times R$
  - 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

\[ P_T = W_1 + W_2 \]
**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

**U_{rms5:** 111.86 V | **U_{rms4:** 223.25 V

**I_{rms5:** 20.796 A | **S_{5:** 4.8462 kVA

**U_{rms6:** 111.44 V | **S_{6:** 2.326 kVA

**I_{rms6:** 22.613 A

**P_{5:** 2.326 kW | **\phi_{5:** 1.0000

**P_{6:** 2.496 kW | **\phi_{6:** 0.9905

**P_{PE** 4.8221 kW | **\phi_{PE:** 0.9950

**f_{U5:** 59.995 Hz

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Measurement Results  Single-Phase Three-Wire System
Measurement Results  
Single-Phase Three-Wire System
Blondel Theorem

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
Blondel was born in France. He was employed as an engineer by the Lighthouses and Beacons Service until he retired in 1927 as its general first class inspector. He became a professor of electrotechnology at the School of Bridges and Highways and the School of Mines. Very early in his career he suffered immobility due to a paralysis of his legs, which confined him to his room for 27 years, but he never stopped working.

In 1893 André Blondel sought to solve the problem of integral synchronization. He determined the conditions under which the curve traced by a high-speed recording instrument would follow as closely as possible the actual variations of the physical phenomenon being studied.

This led him to invent the bifilar and soft iron oscillographs. These instruments won the grand prize at the St. Louis Exposition in 1904. They remained the best way to record high-speed electrical phenomena for more than 40 years when they were replaced by the cathode ray oscilloscope.

He published *Empirical Theory of Synchronous Generators* which contained the basic theory of the two armature reactions (direct and transverse). It was used extensively to explain the properties of salient-pole AC machines.

In 1909, assisted by M. Mähl, he worked on one of the first long distance schemes for the transmission of AC power. The project created a (then) large 300,000 hp hydroelectric power plant at Genissiat on the River Rhone, and transmitted electrical power to Paris more than 350 km away using polyphase AC current at 120 kV.
Three - Phase Systems

- $V_{cn}$
- $V_{bc}$
- $V_{bn}$
- $V_{ca}$
- $V_{ab}$
- $V_{an}$

120°
Three - Phase Systems

Phase Voltages Measured Line to Neutral
Three-Phase Systems

\[ V_{an} \]
\[ V_{bn} \]
\[ V_{cn} \]
\[ V_{ab} \]
\[ V_{bc} \]
\[ V_{ca} \]

Four-Wire Three-Phase System

\[ V_{l-n} = 120 / 277 \text{ Volts} \]
\[ V_{l-l} = \sqrt{3} \times V_{l-n} \]
\[ V_{l-l} = 208 / 480 \text{ Volts} \]
Measurement of Power

AC Source

\[ P_T = \sum W_a + W_b + W_c \]

Three Wattmeter Method

Four - Wire
Three - Phase Load
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

<table>
<thead>
<tr>
<th>Phase</th>
<th>Power</th>
<th>Factor</th>
<th>Current &amp; Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>22.07</td>
<td>0.8714</td>
<td></td>
</tr>
<tr>
<td>P2</td>
<td>22.21</td>
<td>0.8721</td>
<td></td>
</tr>
<tr>
<td>P3</td>
<td>22.09</td>
<td>0.8708</td>
<td></td>
</tr>
<tr>
<td>P2A</td>
<td>66.37</td>
<td>0.3637</td>
<td></td>
</tr>
<tr>
<td>S2A</td>
<td>76.17</td>
<td>0.3648</td>
<td></td>
</tr>
<tr>
<td>Λ2A</td>
<td>0.8714</td>
<td>0.3644</td>
<td></td>
</tr>
<tr>
<td>Urms1</td>
<td>69.65</td>
<td>69.81</td>
<td></td>
</tr>
<tr>
<td>fU1</td>
<td>30.434</td>
<td>69.61</td>
<td></td>
</tr>
</tbody>
</table>

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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

Wiring A = 3P4W
Wiring B = 1P2W
PLL Src = CH1(U1)
Frequency = 20.249 Hz
φU1-U2 = 119.89°
φU1-U3 = 240.03°
φU1-I1 = 39.78°
φU1-I2 = 159.71°
φU1-I3 = 279.87°

U1(1) = 47.924 V
I1(1) = 0.24145 A
P1(1) = 8.893 W
S1(1) = 11.571 VA
Q1(1) = 7.403 var
λ1(1) = 0.76853
φ1(1) = 39.78°

U2(1) = 48.049 V
I2(1) = 0.26616 A
P2(1) = 9.823 W
S2(1) = 12.789 VA
Q2(1) = 8.189 var
λ2(1) = 0.76811
φ2(1) = 39.82°

U3(1) = 47.908 V
I3(1) = 0.24412 A
P3(1) = 8.979 W
S3(1) = 11.695 VA
Q3(1) = 7.494 var
λ3(1) = 0.76776
φ3(1) = 39.85°
Three-Phase Three-Wire Systems

\[ V_{ab} \]
\[ V_{ca} \]
\[ V_{cb} \]

Three-Wire
Three-Phase
System
Remember Blondel’s Theory

. . . total power is measured with **ONE LESS** wattmeter than the number of **WIRES**.
Measurement of Power  3P-3W System

Three - Phase Three - Wire System With Two Meters

AC Source

\[ P_T = \sum W_a + W_b \]
Measurement of Power

Three-Phase Three-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!
Three-Phase Three-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**.
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

\[ P_{3P3W} = P_{3P4W} \]

<table>
<thead>
<tr>
<th>3P-3W</th>
<th>3P-4W</th>
</tr>
</thead>
<tbody>
<tr>
<td>(U_{rms1})</td>
<td>95.40</td>
</tr>
<tr>
<td>(U_{rms2})</td>
<td>95.60</td>
</tr>
<tr>
<td>(U_{rms3})</td>
<td>95.44</td>
</tr>
<tr>
<td>(I_{rms1})</td>
<td>0.2981</td>
</tr>
<tr>
<td>(I_{rms2})</td>
<td>0.2986</td>
</tr>
<tr>
<td>(I_{rms3})</td>
<td>0.3011</td>
</tr>
</tbody>
</table>

\[ U_{L-N} \times \sqrt{3} = U_{L-L} \]

\[ 55.20 \times \sqrt{3} = 95.60 \]
PART II
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 Three Phase Circuit?
R - L - C Circuit

\[ V_{\text{max}} \times \sin(\omega t) \]

- **I_{\text{tot}}**
- **I_{L}**
- **I_{C}**
- **I_{R}**
Current **LAGS** Voltage in an Inductor

\[
PT = V_{\text{rms}} \times I_{\text{rms}} \times \cos \phi
\]

\[
\phi = 44.77\text{ Degrees}
\]

\[
\cos \phi = 0.70994
\]
Current **LEADS** Voltage in a Capacitor

\[ P_T = V_{rms} \times I_{T \, rms} \times \cos \phi \]

\[ \phi = 45.09 \text{ Degrees} \]

\[ \cos \phi = 0.70599 \]
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**

\[ PF = \cos \phi \]

This is defined as the **DISPLACEMENT** Power Factor

For All Waveforms

\[ PF = \frac{W}{VA} \]

This is defined as **TRUE** Power Factor
Phasor Form of Power

Phasor Diagram of Power for R - L Circuit

"POWER TRIANGLE"

VOLT-AMPS

VAR

TRUE POWER FACTOR

PF = W / VA

WATTS

\[ S = \sqrt{P^2 + Q^2} \]
Power Factor Measurement

**True Power Factor**

\[
PF = \frac{W}{VA}
\]

\[
PF = \frac{87.193}{113.753}
\]

\[
PF = 0.76651
\]

**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
3-Phase 4-Wire System

$$\text{PF}_{\text{Total}} = \frac{\sum W}{\sum VA}$$

$$\text{PF}_{\text{Total}} = \frac{(W_1 + W_2 + W_3)}{(VA_1 + VA_2 + VA_3)}$$
Using 2 Wattmeter Method

$$PF_{\text{Total}} = \frac{\sum W}{\sum VA}$$  
$$PF_{\text{Total}} = \frac{(W_1 + W_2)}{(\sqrt{3}/2)(VA_1 + VA_2)}$$

• 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.
Using 3 Wattmeter Method

\[
PF_{\text{Total}} = \frac{\sum W}{\sum VA}
\]

\[
PF_{\text{Total}} = \frac{(W_1 + W_2)}{(\sqrt{3}/3)(VA_1 + VA_2 + VA_3)}
\]

- 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**

- \( \Sigma P = P_1 + P_2 \)
- \( \Sigma PF = \frac{\Sigma P}{\Sigma VA} \)
- \( \Sigma PF = \frac{49.466}{93.060} \)
- \( \Sigma PF = 0.53155 \)

- How is \( \Sigma VA \) calculated?

<table>
<thead>
<tr>
<th>( P_1 )</th>
<th>( P_2 )</th>
<th>( P_{Total} )</th>
<th>( \lambda_1 )</th>
<th>( \lambda_2 )</th>
<th>( \lambda_3 )</th>
<th>( S_1 )</th>
<th>( S_2 )</th>
<th>( S_3 )</th>
<th>( S_{Total} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.477 W</td>
<td>33.989 W</td>
<td>49.466 W</td>
<td>0.28578</td>
<td>0.64245</td>
<td>-0.35395</td>
<td>54.157 VA</td>
<td>52.905 VA</td>
<td>54.122 VA</td>
<td>93.060 VA</td>
</tr>
</tbody>
</table>

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Power Measurement Applications

POWER MEASUREMENT APPLICATIONS
Standby Power & Energy Star

Standby Power

Energy Star®

&

IEC62301 Testing
(Household Appliances)
Overview

◆ International Standard IEC62301

◆ Household Electrical Appliances – Measurement of Standby Power

◆ Hardware and Software Measurement Solution
IEC62301 specifies methods of measurement of electrical power consumption in Standby Mode.

IEC62301 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.
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
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.
3-P 3-W PWM Motor Drive Power Measurement

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

Power Analyzer Setup Menu

\[ \eta_1 = \frac{P_{\Sigma A}}{P_4} \times 100\% \]

\[ \eta_2 = 1 \]

\[ \eta_3 = \frac{1}{1} \times 100\% \]

\[ \eta_4 = \frac{1}{1} \times 100\% \]

S\Sigma A

32.248 \, \text{VA}

\lambda^3

0.70811

Q\Sigma A

22.831 \, \text{var}

\\]

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## Device Efficiency & Power Loss

### Input Power

<table>
<thead>
<tr>
<th>Input Voltage (Urms)</th>
<th>150.685 V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current (Irms)</td>
<td>0.27227 A</td>
</tr>
<tr>
<td>Power (P)</td>
<td>54.987 W</td>
</tr>
</tbody>
</table>

### Output Power

<table>
<thead>
<tr>
<th>Output Voltage (Urms)</th>
<th>119.617 V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current (Irms)</td>
<td>0.80193 A</td>
</tr>
<tr>
<td>Power (P)</td>
<td>56.019 W</td>
</tr>
</tbody>
</table>

### Efficiency

| Efficiency (η) | 56.019 % |

### Loss

<table>
<thead>
<tr>
<th>Loss (F10)</th>
<th>24.1836</th>
</tr>
</thead>
</table>

### Device Efficiency & Power Loss

- **Input Power** calculated as the product of voltage and current:
  \[ P_{input} = U_{input} \times I_{input} \]

- **Output Power** calculated as the product of voltage and current:
  \[ P_{output} = U_{output} \times I_{output} \]

- **Efficiency** calculated as:
  \[ \eta = \frac{P_{output}}{P_{input}} \]

- **Device Loss** calculated as the difference between input and output power:
  \[ F_{10} = P_{input} - P_{output} \]
Power Measurement Application

Device Start Up Analysis

Device Voltage

Device Current

Cycle-by-Cycle Start Up Power

- \( U_{\text{rms1}} \): 111.238 V
- \( I_{\text{rms1}} \): 1.02174 A
- \( P_1 \): 91.635 W
- \( f_{U1} \): 59.988 Hz

- \( S_1 \): 113.657 VA
- \( Q_1 \): 67.237 var
- \( \lambda_1 \): 0.80624
- \( I_{pk1} \): 4.8781 A
PART III
BASIC POWER MEASUREMENTS using a DIGITAL OSCILLOSCOPE
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
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:**
  
  \[ P = V_{\text{rms}} \times A_{\text{rms}} \times \text{PF} \]

  - Also sometimes referred to as True Power or Real Power

- **Apparent Power:**
  
  \[ S = V_{\text{rms}} \times A_{\text{rms}} \]
Measurement of Power

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

\[ P_{\text{avg}} = \frac{1}{T} \int_{0}^{T} v(t) * I(t) \, dt \]

- 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

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

**Auto Deskew function**

Successful de-skew!
Signal edges are aligned

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 different signal path length.
  - Signal source generates time-coincident voltage and current signals. This allows you to adjust for skew between voltage and current probes.
BEFORE DE-SKEW

[Image of an oscilloscope graph showing before and after de-skew results]
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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U_{rms4}$</td>
<td>118.28 V</td>
</tr>
<tr>
<td>$I_{rms4}$</td>
<td>1.3323 A</td>
</tr>
<tr>
<td>$P_4$</td>
<td>97.54 W</td>
</tr>
<tr>
<td>$\lambda_4$</td>
<td>0.6190</td>
</tr>
</tbody>
</table>

Update: 151 (500msec)
Power Supply Input with DSO
## Power Supply Input Summary

<table>
<thead>
<tr>
<th>Measurement Item</th>
<th>Power Analyzer</th>
<th>Power DSO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage RMS</td>
<td>118.28 V</td>
<td>117.27 V</td>
</tr>
<tr>
<td>Current RMS</td>
<td>1.3323 A</td>
<td>1.3321 A</td>
</tr>
<tr>
<td>Watts</td>
<td>97.54 W</td>
<td>96.49 W</td>
</tr>
<tr>
<td>Power Factor</td>
<td>0.619</td>
<td>0.617</td>
</tr>
</tbody>
</table>
Switching Loss

Graph showing the voltage across the device (Vds) and the current through the device (Id) during the turn-off period. The graph highlights the turn-off loss, which is the energy dissipated during the transition from the on-state to the off-state.
**PWM Inverter Output with Power Analyzer**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U_{rms1}$</td>
<td>176.18 V</td>
</tr>
<tr>
<td>$I_{rms1}$</td>
<td>0.3830 A</td>
</tr>
<tr>
<td>$P_1$</td>
<td>44.75 W</td>
</tr>
<tr>
<td>$\lambda_1$</td>
<td>0.6632</td>
</tr>
</tbody>
</table>
PWM Inverter Output with Power DSO
<table>
<thead>
<tr>
<th>Measurement Item</th>
<th>Power Analyzer</th>
<th>Power DSO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage RMS</td>
<td>176.18 V</td>
<td>178.56 V</td>
</tr>
<tr>
<td>Current RMS</td>
<td>0.3830 A</td>
<td>0.3950 A</td>
</tr>
<tr>
<td>Watts</td>
<td>44.75 W</td>
<td>46.37 W</td>
</tr>
<tr>
<td>Power Factor</td>
<td>0.6632</td>
<td>0.6602</td>
</tr>
</tbody>
</table>
## DSO Power Calculation

<table>
<thead>
<tr>
<th>Name</th>
<th>Expression</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calc 1</td>
<td>S</td>
<td>RMS(C3) * RMS(C2)</td>
</tr>
<tr>
<td>Calc 2</td>
<td>P</td>
<td>(1/DeltaT(C3)) * IntegTY(M1)</td>
</tr>
<tr>
<td>Calc 3</td>
<td>Q</td>
<td>SQRT(P2(RMS(C3) * RMS(c2)) - P2((1/DeltaT(C3)) * IntegTY(M1))) / RMS(C3)</td>
</tr>
<tr>
<td>Calc 4</td>
<td>PF</td>
<td>((1/DeltaT(C3)) * IntegTY(M1)) / RMS(C3)</td>
</tr>
</tbody>
</table>
DSO Power Calculation

Line Measurements:
- 49.5 VA
- 42.1 W
- 25.9 VAR
- PF = 0.85

\[ S \ [VA] \quad Urms \cdot Irms \]

\[ P \ [W] \quad \frac{1}{T} \int_{0}^{T} u(t) \cdot i(t) dt \]

\[ Q \ [\text{var}] \quad \sqrt{S^2 - P^2} \]

\[ PF \quad \lambda \quad \frac{P}{S} \]
Six Cycles of a 100Hz 10Apeak current-burst from a 10Vpeak Voltage Supply
Calculated Power using DL850/G3 Power Function;
one-cycle delay graphically demonstrated
Power Function trigger is on rising-edge of ch1 at 0.0V zero-crossing
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 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 Scopes & ScopeCorders 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
Yokogawa’s Power Measuring Solutions

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
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
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
Invitation to Power Measurement Webinars

**Power Analysis: Precision AC Power Measurements** This one hour seminar will cover Precision Power Measurements and Power Factor Measurements.

**Power Measurement & Harmonic Analysis** This 1-hour seminar is packed with tips and techniques for making accurate power measurements on distorted waveforms like from a Power Supply, Electronic Ballast and Variable Speed PWM Motor Drive. We will also cover methods for making and analyzing the harmonic content of various power waveforms.

**Advances in Precision Electrical Power Measurement** This informative Webinar covers new measurement techniques and solutions for making precision power measurements to improve product performance and efficiency designs.

**Back to the Basics of Electrical Power Measurement** Target audience is Engineers and Technicians that need to make Power Measurements but may not be experts in the field or may need a refresher course.

**Power Analysis: Precision AC Power Measurements** This webinar will cover Precision Power Measurements and Power Factor Measurements.

**Digital Oscilloscope Power Analysis** In this 1-hour seminar you will be introduced to the many specialized power measurements necessary to evaluate switched-mode power supplies.

**Requirements and Easy Solutions for Standby Power Measurements** This 30-minute Webinar discusses the area of Standby Power Measurements.

**Power Measurement and Analysis** Power measurement requires much more than a simple measurement of voltage and current, requiring phase angle as well as harmonic distortion. Government regulations exist for both. (not yet online)

**Fundamentals of Electrical Power Measurements** This one hour webinar will provide attendees with Solutions and Education for making Electrical Power Measurements.
Join Us for Future Web Seminars

Visit our Web Site

Thank You & Contact Info

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