Electric Motor And Variable Speed Drive Testing

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Providing Solutions and Education for Electrical Power Measurements
Questions

If you have any questions for one of these Webinar Topics, please send them to the below e-mail. I will try to answer them during the Webinar or directly afterwards.

» webinarwednesdays@us.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 B
- 84 companies world wide
- Over 20,000 employees worldwide
- Operations in 33 Countries

1930 Vintage
Standard AC Voltmeter
0.2% Accuracy Class

WT3000E
Precision Power Analyzer
Harmonic Analysis

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Todays Topic

Electric Motor and Variable Speed Drive Testing
Objective

◆ Provide you with a Three Step Process for a Complete Electrical Test of an AC Motor & Variable Speed Drive System

DC or Single Phase or Three Phase AC Input

Inverter

Motor

Load

Speed and Torque Meter

Motor & Drive Testing
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Overview – What We Plan To Do

- Basic Power Measurements -
  - Review of Electrical Power Measurements
  - Review of Mechanical Power Measurements
  - Instrument Considerations & Current Sensors
- 3-Phase AC Motor Power Measurements
  - Three Phase Three Wire Measurements
- Mechanical Power Measurements
  - Speed and Torque Sensors
  - Motor Efficiency Measurements
Overview – What We Plan To Do

- PWM Motor Drive Measurements
  - Input & Output Electrical Measurements
  - Drive Power Loss & Efficiency
  - Other Typical Drive Measurements

- Motor and Drive System Measurements
  - Putting it All Together
  - Total System Measurements & Efficiency
  - IEEE Std 112 Testing

- Answer YOUR Power and Motor Measurement Questions
PART 1
BASIC ELECTRICAL POWER MEASUREMENTS
Review OHM’S LAW
# Average and RMS Values

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

*(multiplication factor to find)*

<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

\[
\begin{align*}
U_{rms1} & = 120.000 \text{ V} \\
U_{mn1} & = 119.999 \text{ V} \\
F_1 & = 108.107 \text{ V Avg} \\
U_{+pk1} & = 169.99 \text{ V}
\end{align*}
\]
Measurement of Power

What’s A Watt?

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

DC Source: \[ W = V \times A \]

AC Source: \[ W = V \times A \times PF \]
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 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:

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

- Using digitizing techniques, the **INSTANTANEOUS VOLTAGE** is multiplied by the **INSTANTANEOUS CURRENT** and then **INTEGRATED** over some time period.
Measurement of AC Power

Watts: $P = V_{rms} \times A_{rms} \times PF = Urms1 \times Irms1 \times \lambda1$

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

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True RMS Measurements

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

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

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

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.
Electrical Power Measurements

Total Power is Calculated as:

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

* OR More Precisely *

\[ P_{\text{total}} = V_0 \times I_0 + \sum_{\text{min}}^{\text{max}} V_n \times I_n \times \cos \theta_n \]
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
Electrical Power Measurements

Three - Phase Three - Wire System With Two Meters

AC Source

Three - Wire
Three - Phase
Load

Two Wattmeter Method

\[ P_T = \sum W_a + W_b \]
Electrical Power Measurements

Advantages of Two-Wattmeter System

- Simple installation and wiring configuration
- Accurate Power measurement on balanced or unbalanced system
- Lower cost installation requiring only two Current and Potential Transformers
- Good system for production testing
Electrical Power Measurements

Three-Phase Three-Wire System With Three Meters

*BEST* Method for Engineering and R&D Work

Three Watt Meter Method

AC Source

Three - Phase Three - Wire Load

\[ V_{ab} \]

\[ V_{bc} \]

\[ V_{ca} \]
Power Factor Measurement

For SINE WAVES ONLY

PF = \cos \theta

This is defined as the DISPLACEMENT Power Factor

For All Waveforms

PF = W/VA

This is defined as TRUE Power Factor
Power Factor on 3-Phase System

3-Phase 4-Wire System

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

\[ PF_{\text{Total}} = \frac{(W_1 + W_2 + W_3)}{(VA_1 + VA_2 + VA_3)} \]
Power Factor on 3-Phase 3-Wire System

Using 2 Wattmeter Method

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

\[
PF_{\text{Total}} = \frac{(W_1 + W_2)}{(\sqrt{3/2})(VA_1 + VA_2)}
\]

• 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.
Power Factor on 3-Phase 3-Wire System

Using 3 Wattmeter Method

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

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

- 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.
Power Factor on 3-Phase 3-Wire System

- With the Yokogawa Power Analyzers, on a 3-Phase 3-Wire System, use the 3V-3A wiring method. This method will give correct Total Power, Total Power Factor and VA Measurements on either Balanced or Unbalanced 3-Wire system.
PART 2

Basic MECHANICAL Power Measurements
Mechanical Power Measurements

- In an Electric Motor:
  \[ P_m = \text{Speed} \times \text{Torque} \]

- Mechanical Power is typically defined as Kilowatts or Horsepower

- 1 Watt = Joule/Sec
  \[ = \text{Newton-Meter}/\text{Sec} \]
Mechanical Power Measurements

\[ P_m = \frac{2 \times \pi \times \text{Rotating Speed}}{60} \times \text{Torque} \]

Rotating Speed = RPM
Torque = N-m
\( P_m = \text{Mechanical Power in Watts} \)
Mechanical Power Measurements

HP = Work done per unit of time.

1 HP = 33,000 lb-ft of work per minute.

\[
HP = \frac{RPM \times \text{Torque (lb-ft)}}{5,252}
\]

1 HP = 745.69987 W > 745.7 W > 746 W
Mechanical Power Measurements

AC Induction Motor Speed:

- **Actual Speed** – The Speed at which the Shaft rotates. Typically measured with a Tachometer.

- **Synchronous Speed** – The Speed of the Stator’s Magnetic Field Rotation. This is the motor’s theoretical speed since the rotor will always turn at a slightly slower rate.

\[
\text{Synchronous Speed} = \frac{120 \times \text{Frequency}}{\text{Number of Poles}}
\]
Mechanical Power Measurements

- Slip – The difference in the speed of the Rotor (RS) and the Synchronous Speed (SS).

\[
\% \text{ Slip} = \frac{\text{SS} - \text{RS}}{\text{SS}}
\]
Mechanical Power Measurements

Efficiency, in a Basic Simple form, can be calculated as the ratio of Output Power to Total Input power.

\[ \text{Eff} = \frac{\text{Output Power}}{\text{Input Power}} = \frac{P_m}{\text{Electrical Input Power}} \]
PART 3
Instrument Selection
## North American Motor Testing Standards

<table>
<thead>
<tr>
<th></th>
<th>IEEE 112 2004</th>
<th>NVLAP 150</th>
<th>CSA C390</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Input Power</strong></td>
<td>+/- 0.2% of FS</td>
<td>+/- 0.2% of FS</td>
<td>+/- 0.5% of Reading (includes CT &amp; PT errors)</td>
</tr>
<tr>
<td><strong>Voltage and Current</strong></td>
<td>+/- 0.2% of FS</td>
<td>+/- 0.2% of FS</td>
<td>+/- 0.5% of Reading (includes CT &amp; PT errors)</td>
</tr>
<tr>
<td><strong>CT’s and PT’s</strong></td>
<td>+/- 0.3% of FS (total ratio and phase)</td>
<td>+/- 0.3% of FS (total ratio and phase)</td>
<td></td>
</tr>
<tr>
<td><strong>Torque</strong></td>
<td>+/- 0.2% of FS</td>
<td>+/- 0.2% of FS</td>
<td>0.7% of Reading</td>
</tr>
<tr>
<td><strong>Supply Frequency</strong></td>
<td>+/- 0.2% of FS</td>
<td>+/- 0.2% of FS</td>
<td>+/- 0.5% of Reading</td>
</tr>
<tr>
<td><strong>Motor Speed (RPM)</strong></td>
<td>+/- 1 RPM</td>
<td>+/- 1 RPM</td>
<td>+/- 1 RPM</td>
</tr>
<tr>
<td><strong>Temperature</strong></td>
<td>+/- 0.2% of FS</td>
<td>+/- 0.2% of FS</td>
<td>+/- 1.5 deg. C</td>
</tr>
<tr>
<td><strong>Winding Resistance</strong></td>
<td>+/- 0.2% of FS</td>
<td>+/- 0.2% of FS</td>
<td>+/- 1% of Reading</td>
</tr>
</tbody>
</table>
Current Sensors

AEMC
0.3% - 0.5% AC
1.5% - 3% AC/DC

Yokogawa
Scope Probes 1% - 2%

Yokogawa CT’s 0.2%

Yokogawa/LEM (Danfysik)
CT System 0.05%

Ram Meter Shunts
Pearson Electronics

1%
0.1%
0.33%
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 Instrument 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. Check the Specs!

• 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.
PART 4

Electrical Power Measurements
On a
3 – Phase AC Motor
Motor System Measurements

Three Phase AC Input

Three Phase Power Analyzer

Motor

Load
Typical Power Measurements

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U_{rms1}$</td>
<td>120.127</td>
<td>V</td>
</tr>
<tr>
<td>$U_{rms2}$</td>
<td>120.341</td>
<td>V</td>
</tr>
<tr>
<td>$U_{rms3}$</td>
<td>120.016</td>
<td>V</td>
</tr>
<tr>
<td>$I_{rms1}$</td>
<td>415.795</td>
<td>mA</td>
</tr>
<tr>
<td>$I_{rms2}$</td>
<td>415.356</td>
<td>mA</td>
</tr>
<tr>
<td>$I_{rms3}$</td>
<td>415.708</td>
<td>mA</td>
</tr>
<tr>
<td>$\sum A$</td>
<td>77.775</td>
<td>W</td>
</tr>
<tr>
<td>$\lambda \Sigma A$</td>
<td>0.89912</td>
<td></td>
</tr>
</tbody>
</table>
Three-Phase Three-Wire “Delta” Connection

Note that the Voltage Waveforms are 60 Degrees apart. The Current Waveforms are 120 Degrees apart.
Total Power Calculated by Two Watt Meter Method

The Readings Are Not Phase Power
Typical 3P-3W Power Measurements

Voltage Waveforms Connected Line to Line

Phase Current Waveforms
Three-Phase Three-Wire System with Three Meters

The Phase Angle between the Voltage waveforms is 60 Degrees (NOT 120 Degrees) when the Power Analyzer is connected LINE-to-LINE.

The Phase Angle between the Current waveforms is 120 Degrees.

In this wiring configuration there is an additional 30 Degree Phase Shift between the Voltage and Current.
3P-3W Power Measurements Tip

- What if you need to measure the Phase Power and Phase Power Factor on your 3-Phase 3-Wire motor?

- Following is a technique that will allow you to measure the Phase Parameters on a 3-Phase 3-Wire motor.
3P-3W Power Measurements Tip

3-P 3-W System with “Floating Neutral”

Input Element 1
Input Element 2
Input Element 3

Floating Neutral
3P-3W Power Measurements Tip

Caution . . .

- This technique will work without problems on the input to an Induction Motor, Synchronous Motor or similar motor without a Variable Speed Drive.

- Use Caution when using on a Variable Speed Drive system. The High Frequency Distorted Waveforms and Harmonics can cause some inconsistent measurements.
3P-3W Power Measurements Tip

Caution . . .

- Use this technique **Only** on products with **Sinewave** type waveforms.

- **TIP** – On a PWM Drive, Turn on the 500 Hz Line Filter (Low Pass Filter). The readings displayed will be that of the Fundamental Frequency, **NOT** total.
3P-3W and 3P-4W Power Measurements

PWM Drive with 500 Hz Line Filter ON
### 3P-3W and 3P-4W Power Measurements

<table>
<thead>
<tr>
<th>Component</th>
<th>3P-3W</th>
<th>3P-4W F-N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urms1</td>
<td>95.40</td>
<td>55.06</td>
</tr>
<tr>
<td>Urms2</td>
<td>95.60</td>
<td>55.20</td>
</tr>
<tr>
<td>Urms3</td>
<td>95.44</td>
<td>55.15</td>
</tr>
<tr>
<td>Irms1</td>
<td>0.2981</td>
<td>0.2984</td>
</tr>
<tr>
<td>Irms2</td>
<td>0.2986</td>
<td>0.2986</td>
</tr>
<tr>
<td>Irms3</td>
<td>0.3011</td>
<td>0.3011</td>
</tr>
<tr>
<td>P3W</td>
<td>40.87</td>
<td>40.89</td>
</tr>
<tr>
<td>λΣW</td>
<td>0.8258</td>
<td>0.8259</td>
</tr>
</tbody>
</table>

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

\[
55.20 \times \sqrt{3} = 95.60
\]

\[
P_{3P3W} = P_{3P4W}
\]
### 3P-3W and 3P-4W “Delta” Measurements

<table>
<thead>
<tr>
<th>Normal Mode</th>
<th>Uover:</th>
<th>Spd:</th>
<th>I1-3: 500mArms</th>
<th>Iover:</th>
<th>Trq:</th>
<th>Integ: Reset</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urms1</td>
<td>119.877</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Urms2</td>
<td>120.099</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Urms3</td>
<td>119.210</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \Delta F_1 ) [UrA]</td>
<td>69.513</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>( \Delta F_2 ) [UsA]</td>
<td>69.604</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>( \Delta F_3 ) [UtA]</td>
<td>69.170</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>PΣA</td>
<td>65.967</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>λΣA</td>
<td>0.87350</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Irms1</td>
<td>363.712 mA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Irms2</td>
<td>364.872 mA</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Irms3</td>
<td>363.927 mA</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>( \Delta F_4 ) [InA]</td>
<td>0.569 mA</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>SΣA</td>
<td>75.520 VA</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>QΣA</td>
<td>38.946 var</td>
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</table>

**Neutral Current**

V L-L

V L-N

---

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## Delta Measurements

<table>
<thead>
<tr>
<th></th>
<th>Voltage [V]</th>
<th>Power [W]</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-L</td>
<td>135.33</td>
<td>78.18</td>
</tr>
<tr>
<td>L-L</td>
<td>135.30</td>
<td>78.17</td>
</tr>
<tr>
<td>L-L</td>
<td>135.48</td>
<td>78.10</td>
</tr>
</tbody>
</table>

## Phase Power Measurement

<table>
<thead>
<tr>
<th></th>
<th>Voltage [V]</th>
<th>Power [W]</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-N</td>
<td>78.18</td>
<td>6.80</td>
</tr>
<tr>
<td>L-N</td>
<td>78.17</td>
<td>6.84</td>
</tr>
<tr>
<td>L-N</td>
<td>78.10</td>
<td>6.85</td>
</tr>
</tbody>
</table>

\[
P_{3P3W} = P_{3P4W}
\]
PART 5

Mechanical Power Measurements
On an AC Motor
Mechanical Power Measurement

Three Phase AC Input

Motor

Load

In-Line Speed & Torque Sensor

Three Phase Power Analyzer

Speed and Torque Meter
Speed & Torque Sensors

- Various Manufacturers
  - Honeywell Sensotech - Lebow
  - S. Himmelstein and Company
  - Magtrol Inc
  - HBM
  - Others

- Various Types and Sizes of Sensors

- Contact the Sensor Manufacturer for Selection and Application Assistance
Speed & Torque Sensors

S. Himmelstein and Company
2490 Pembroke Avenue
Hoffman Estates, IL 60169
www.himmelstein.com

Digital Torquemeters

Mechanical Power Instrument
Speed & Torque Sensors

Honeywell Sensotec Sensors and Lebow Products
www.honeywell.com/sensing
Speed & Torque Sensors
Magtrol Inc
70 Gardenville Parkway
Buffalo, NY 14224
www.magtrol.com
Mechanical Power Measurements

System #1

- Speed Sensor
- Torque Sensor

Sensor Manufacturers Measurement Instrument

PC

Application Software

Use the Sensor Manufacturers Measurement System
Mechanical Power Test System

NovaTorque Test Fixture with Magtrol Speed/Torque Transducer, Brake and Dynamometer Controller
Mechanical Power Test System

Advantages of System #1

- **Sensor Manufacturers Measurement Instrument**
  - Matched System to Sensors
  - Provides Proper Signal Conditioning
  - Readout for Torque, Speed & Power
  - Communication Output – RS232 & GPIB
  - Analog Output Signals – For other Readout Instruments

- **Application Software**

- **Contact the Sensor Manufacturer for Selection and Application Assistance**
Use the Power Analyzer for Mechanical Power Measurements
Mechanical Power Test System
Advantages of System #2

- Sensor Manufacturers Signal Conditioning
  - Matched System to Sensors
  - Provides Proper Signal Conditioning
  - Pulse and/or Analog Output Signal
  - Conditioned Speed & Torque Signals Provided for Power Analyzer

- Power Analyzer Calculates the Electrical and Mechanical Power parameters
  - Electrical and Mechanical Measurements made Simultaneously
  - Efficiency Calculations

- Custom or Generic Application Software
Power Analyzer Setup Menu

Motor Set

- Scaling: 505.0000
- Unit: rpm
- Sense Type: Analog
- Auto Range: ON
- Range: 2V
- Line Filter: OFF
- Sync Source: None
- Pulse Range Upper: 10000.0000
- Pulse Range Lower: 0.0000
- Pulse Rated Upper: 50.0000
- Pulse Rated Lower: -50.0000
- Pulse N: 60

Speed
- Rated Freq: 5000Hz

Torque
- Rated Freq: 5000Hz

Pm

Sync Speed
- Pole: 2
- Source: I1

Pulses/Revolution
### Speed and Torque Measurements

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urms1</td>
<td>92.854</td>
</tr>
<tr>
<td>Urms2</td>
<td>93.434</td>
</tr>
<tr>
<td>Urms3</td>
<td>92.437</td>
</tr>
<tr>
<td>Irms1</td>
<td>229.623 mA</td>
</tr>
<tr>
<td>Irms2</td>
<td>187.226 mA</td>
</tr>
<tr>
<td>Irms3</td>
<td>200.420 mA</td>
</tr>
<tr>
<td>ΡΣΑ</td>
<td>21.252 W</td>
</tr>
<tr>
<td>ΛΣΑ</td>
<td>0.64195</td>
</tr>
<tr>
<td>Urms4</td>
<td>119.882 V</td>
</tr>
<tr>
<td>Irms4</td>
<td>0.53418 A</td>
</tr>
<tr>
<td>λ4</td>
<td>0.50774</td>
</tr>
<tr>
<td>η1</td>
<td>65.362 %</td>
</tr>
<tr>
<td>Speed</td>
<td>3.60034 krpm</td>
</tr>
<tr>
<td>Torque</td>
<td>5.2620 Nm</td>
</tr>
</tbody>
</table>

*Update: 32, 2007/10/01 09:22:54*
PART 6
PWM Drive Measurements
With an AC Motor
PWM Drive Measurements

DC or Single Phase or Three Phase AC Input

Inverter

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WT1800 Six-Phase Power Analyzer
PWM Drive Measurements

Yokogawa Variable Speed Drive Trainer

Variable Speed Drive
Single Phase input
Three Phase Output
PWM Drive Measurements

PWM Voltage Waveform
PWM Drive Measurement Issues

- **High Frequency Switching on the Voltage Signal**
  - Voltage Driving Waveform is very Distorted
  - Very High Voltage Harmonic Content
  - Variable Frequency from 0 Hz up . . . .

- **Current Signal contains a High Noise Level**
  - Special Current Sensors required for Variable Frequency measurements from 0 Hz up . . . .
  - Distorted Waveform with low level Harmonic Content.

- **Accurate Power Measurements require Wide Bandwidth Power Analyzer**
Harmonic Spectrum of PWM Drive

Voltage Harmonic Content in Excess of 500 Orders - - Approximately 30 kHz
PWM Motor Drive Measurement Issues

- Inverter Voltage is Typically Measured Two Ways
  - True RMS Measurement to include total harmonic content
  - Amplitude of the Fundamental Wave that contributes to the Motor Torque
  - Variable Frequency Fundamental from 0 Hz up . . . .

- Inverter Current is Typically Measured One Way
  - True RMS Currents are measured because all harmonic currents are responsible for temperature rise in the motor
PWM Motor Drive Voltage Measurements

How Do We Measure the Amplitude of the Fundamental Wave?

- Apply a Low Pass Filter
  - This will give a RMS Voltage of the Fundamental with the proper filter applied
  - Proper filter must be available in the instrument based on the Inverter Fundamental Frequency
  - It will also filter the Current and Power Measurements
  - Filtering is not a desirable method
How Do We Measure the Amplitude of the Fundamental Wave?

Rectified MEAN Measurement Method

- This will give a RMS Voltage of the Fundamental without filtering
- This method uses a Mean-Value Voltage Detection, scaled to RMS
- The measured voltage will be very close to the RMS value of the fundamental wave
- This has been an accepted method for many years
## Average and RMS Values

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

*(multiplication factor to find)*

<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>
PWM Motor Drive Voltage Measurements

How Do We Measure the Amplitude of the Fundamental Wave?

- Harmonic Analysis to Determine True Fundamental Voltage
  - The Harmonic Analysis function uses a Fast Fourier Transform, FFT, to determine the amplitude of each harmonic component
  - This will give an accurate RMS Voltage measurement of the Fundamental Wave
  - New Power Analyzers can make the True RMS Measurements simultaneously with the Harmonic measurements
PWM Motor Drive Voltage Measurements

- \( U_{rms1} \): 119.905 V
- \( I_{rms1} \): 3.75943 A
- \( P1 \): 0.34118 kW
- \( U_{rms2} \): 219.147 V
- \( F2 \): 194.342 V
- \( U_{rms3} \): 194.669 V
- \( U2(1) \): 193.820 V
- \( fU2 \): 59.987 Hz

RMS
Mean
Filter
Fundamental
PWM Motor Drive Efficiency Measurements

- Drive 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
PWM Motor Drive Efficiency Measurements

Power Analyzer Setup Menu

Drive Efficiency
Output P
Input P

\[
\eta_1 = \frac{P_{\text{out}}}{P_{\text{in}}} \times 100[\%]
\]

\[
\eta_2 = \frac{P_{\text{out}}}{P_{\text{in}}} \times 100[\%]
\]

\[
\eta_3 = \frac{P_{\text{out}}}{P_{\text{in}}} \times 100[\%]
\]

\[
\eta_4 = \frac{P_{\text{out}}}{P_{\text{in}}} \times 100[\%]
\]
PWM Motor Drive Power Loss

■ In Addition to Drive Efficiency, Drive Power Loss is often a requested Measurement

■ Several Yokogawa Power Analyzers offer a Function to Obtain this Measurement

■ A “User Defined Math” function permits writing and equation for this measurement

■ Power Loss = Input Power – Output Power
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 $U_{+pk}$
PWM Motor Drive Power Loss

Input Power

Drive Efficiency

Drive Loss

Output Power
PWM Motor Drive Volts-Per-Hertz Measurement

- PWM Drives Should maintain a Constant Volts- Per-Hz Ratio to the Motor
- Verify that the V/Hz Ratio is maintained over the Speed Range of the Drive
- V/Hz can be calculated using the RMS or Fundamental Voltage Value
- The “User Defined Math” function permits writing an equation for this measurement
Volts-Per-Hertz Math Function

RMS

Fundamental
PWM Motor Drive Volts-Per-Hertz Measurement

RMS V/Hz

Fundamental V/Hz
DC Bus Voltage Measurement

- The DC Bus Voltage needs to be measured to check for Over and Under Voltage conditions
- The measurements can be taken inside the Drive on the terminals to the Capacitor bank
- If not accessible, use the Power Analyzer Waveform Display with Cursor Measurement
DC Bus Voltage Measurement

- $U_{rms1} = 150.108\, \text{V}$
- $U_1(1) = 83.655\, \text{V}$
- $I_{rms1} = 265.896\, \text{mA}$
- $f_{U1} = 20.485\, \text{Hz}$

DC Bus Voltage Using Cursor Measurement
Power Analyzer Setup for PWM Drive Measurements

- **Setup Mode:**
  - WT1600 & PZ4000, WT1800 & PX8000 - Normal Mode
  - WT3000 - RMS Mode

- **Wiring Configuration:** 3V-3A (3 Voltage, 3 Current connection on 3-Phase 3-Wire system.)

- **Filters:**
  - Line Filter OFF (Low Pass Filter)
  - Zero Cross Filter ON (Frequency Filter)

- **Voltage Measurement (Fundamental Voltage):**
  - WT1600 & PZ4000 - Umn  Mean Voltage
  - WT3000, WT1800 & PX8000 - Normal Harmonics U_ (1) Order 1 for Fundamental.
PWM Drive Measurements

UrmsΣA: 192.13 V
Irms1: 0.4192 A
Irms2: 0.4188 A
Irms3: 0.4213 A
U1 (1): 138.36 V
λ1: 0.7204
PΣA: 0.0905 kW
fU1: 35.087 Hz
PART 7
The Total System
Custom Motor Dyno System

Automation Engineering, Fort Wayne, Indiana
www.autoeng.com
Motor Test System

Three Step Measurement Process
Motor & Drive System

1. Inverter
2. Motor
3. Load

DC or Single Phase or Three Phase AC Input

Motor Test System

Motor & Drive Testing
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Precision Making
Motor Test System with Power Analyzer

Accurate Measurements of PWM Variable Speed Drive

1. Input & Output Power
   - Calculate Drive Efficiency and Power Loss
   - Measure Other Drive Performance Functions

2. Accurate Measurements of Motor Input Power
   - Measure Electrical Performance of the Motor
   - Kilowatts, Horsepower, Power Factor,

3. Accurate Measurements of Motor Mechanical Power
   - Measure Motor Speed and Torque
   - Calculate Mechanical Power
   - Develop Speed Torque Curves
Motor Test System with Power Analyzer

- Use the Power Analyzer for All Electrical and Mechanical Power Measurements
  - All Measurements will be made Simultaneously
  - No Time Skew Error between Electrical & Mechanical Measurements
  - Accurate Efficiency Calculations
  - Single Software Solution
Motor Test System with Power Analyzer

Drive Efficiency

Total System Efficiency

“Method A” Motor Efficiency
IEEE Std 112 Requirements

IEEE Standard Test Procedure for Polyphase Induction Motors and Generators

- The Standard provides instructions for conducting and reporting generally accepted tests for polyphase induction motors and generators
- Procedures are defined for all parameters such as:
  - Temperature
  - Resistance Electrical
  - Stator $I^2R$ Loss
  - Rotor $I^2R$ Loss
  - No-Load Test
  - Efficiency Test Methods
- Eleven different Test Methods are outlined and in IEEE Std 112 for the determination of Motor Efficiency!
IEEE Std 112 Efficiency Test Methods

Test Method A – Input-Output

- The Efficiency is calculated as the Ratio of measured Output Power to the measured Input Power, after Temperature and Dynamometer corrections if applicable.

- Tests are to be done at Rated Load by means of a mechanical brake or dynamometer.

- This method should be limited to motors with Full Load Ratings of 1 kW or less.

\[
\text{Eff} = \frac{\text{Output Power}}{\text{Input Power}} = \frac{P_m}{\text{Electrical Input Power}}
\]
IEEE Std 112 Efficiency Test Methods

- Test Method B – Input-Output with Loss Segregation

- In Method B, Input and Output Power are measured and various losses are separated out.

- Most of these losses just produce heat which must be dissipated by the motor assembly. These losses are Energy which is not available to perform work.

- This method is the recognized testing standard for the US Motor industry for motors with Full Load Ratings of 1 to 300 kW.

- Typical Losses:
  - Friction & Windage
  - Core Loss
  - Stator I²R Loss
  - Rotor I²R Loss
  - Stray-load Loss
  - Apparent total Loss

- All these calculation methods and procedures are outlined and defined in the Standard
IEEE Std 112 Efficiency Test Methods

With several Accepted methods for determining Efficiency, which should I use?

- For Electric Motor Manufacturers use Method A or Method B based on motor size.
- For Manufacturers of a Product using an Electric Motor, or Motor & Drive System, use Method B if you have a Dyno and Equipment to make all Loss Measurements.
- Otherwise, use Method A.
- Remember – Your Efficiency Calculations may be different than the Motor, Motor/Drive Manufacturers performance data.
- Key reasons for the differences might include –
  - Test Method
  - Test Load, Motor Speed, Other Test Conditions
### Electrical System Accuracy

<table>
<thead>
<tr>
<th>Voltage:</th>
<th>Reading</th>
<th>480</th>
<th>Conditions: 3P3W, Unity PF, 60 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range</td>
<td>600</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Watt:</td>
<td>Reading</td>
<td>554.517</td>
<td></td>
</tr>
<tr>
<td>Range</td>
<td>1,200.00</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Current:</th>
<th>Reading</th>
<th>0.667</th>
<th>CT 600:1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range</td>
<td>1</td>
<td>400</td>
<td>425</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>WT330</th>
<th>WT500</th>
<th>WT1800</th>
<th>WT3000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entry Level</td>
<td>Mid Range</td>
<td>High End</td>
<td>Precision</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Voltage Uncertainty (V)</th>
<th>1.08</th>
<th>1.08</th>
<th>0.78</th>
<th>0.228</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current Uncertainty (A)</td>
<td>0.001667</td>
<td>0.001667</td>
<td>0.001167</td>
<td>0.0003667</td>
</tr>
<tr>
<td>Watt Uncertainty (W)</td>
<td>1.754517</td>
<td>1.754517</td>
<td>1.154517</td>
<td>0.5909034</td>
</tr>
<tr>
<td>W % Reading Uncertainty</td>
<td>0.316%</td>
<td>0.316%</td>
<td>0.208%</td>
<td>0.107%</td>
</tr>
<tr>
<td>CT Uncertainty % Reading</td>
<td>0.02125%</td>
<td>0.02125%</td>
<td>0.02125%</td>
<td>0.02125%</td>
</tr>
<tr>
<td>System Uncertainty % Reading</td>
<td>0.319%</td>
<td>0.319%</td>
<td>0.212%</td>
<td>0.115%</td>
</tr>
</tbody>
</table>

CT Reading Uncertainty = (0.02% x Range) / Current Reading

System Uncertainty = Sq Root of Sum of Squares (CT Un x 2) + Watt Un

---

CT Model M1114AK-A

YCA/LEM ITZ600-SPR

Precision CT System

0.02% Of Full Scale

Motor & Drive Testing Workshop
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Conclusion
In Conclusion

- **We Provided you with a Three Step Process for a Complete Electrical Test of an AC Motor & Variable Speed Drive System**

---

**DC or Single Phase or Three Phase AC Input**

**Inverter**

**Motor**

**Load**

**Speed and Torque Meter**

---

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In Conclusion

- Reviewed Basic Power Measurements -
  - Including Electrical Power Measurements
  - Mechanical Power Measurements
  - Instrument Considerations & Current Sensors

- Step 1: 3-Phase AC Motor Measurements
  - Three Phase Three Wire Measurements

- Step 2: Mechanical Power Measurements
  - Speed and Torque Sensors
  - Motor Efficiency Measurements
In Conclusion

- **Step 3: PWM Motor Drive Measurements**
  - Input & Output Electrical Measurements
  - Drive Power Loss & Efficiency
  - Other Typical Drive Measurements

- Motor and Drive System Measurements
  - Put All Three Steps Together
  - Total System Measurements & Efficiency
  - Reviewed IEEE Std 112 Testing Methods

- Answered YOUR Power and Motor Measurement Questions
Conclusion

- Yokogawa offers the Most Complete Line of Power Analyzers to meet your Application and Budget.

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

- Guaranteed Measurement Accuracy over the Bandwidth of the Instrument. Available NIST Traceable and ISO17025 Calibration provided by Factory Trained technicians in Newnan, GA.

- All Yokogawa Power Analyzers are covered by a 3-Year Warranty.
Yokogawa’s Power Measuring Solutions

Precision Power Analyzers

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Yokogawa’s Power Measuring Solutions

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• Others

Make it a *FUN* Family project - OR
a *FUN* Family competition
Thank You For Attending
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