Instrument Transformer Theory and Testing

Steve Hudson, PE
Engineering Manager

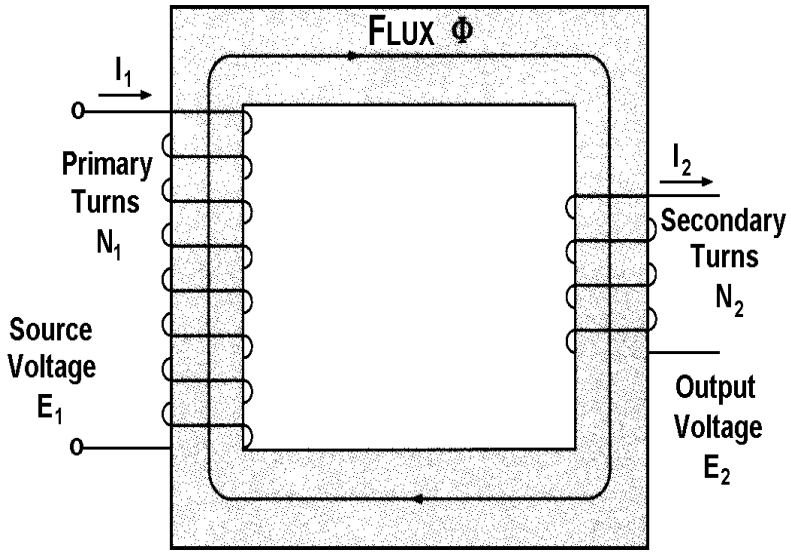
10737 Lexington Drive
Knoxville, TN 37932
Phone: (865) 966-5856

www.powermetrix.com

POWERMETRIX

What is a Transformer?

- A TRANSFORMER is a device used to change the voltage levels of electricity to facilitate the transfer of electricity from generating stations to customers. A step-up transformer increases the voltage while a step-down transformer decreases it.
  www.duquesnelight.com/understandingelectricityupdate/electricterms.html



POWERMETRIX

Basic Transformer Theory

- Vp = primary voltage
- Ip = primary current
- Np = primary turns
- Pp = primary power
- Vs = secondary voltage
- Is = secondary current
- Ns = secondary turns
- Ps = secondary power

$$Vs = \frac{Ns}{Np} Vp$$

$$Is = \frac{Np}{Ns} Ip$$

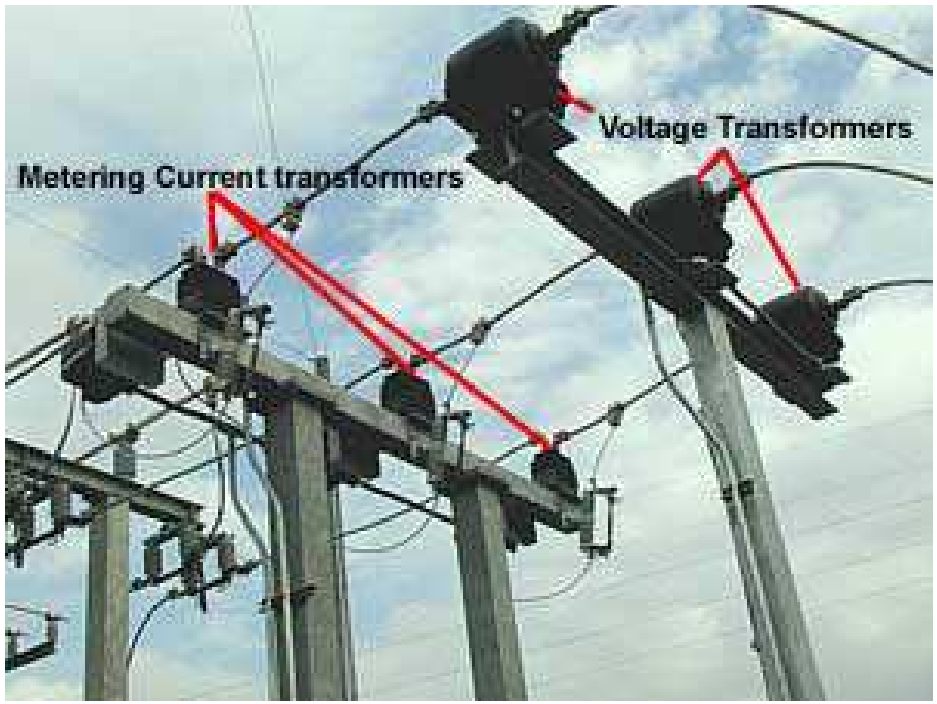
$$Pp = Vp \bullet Ip = Ps = Vs \bullet Is$$

This is true for an IDEAL transformer!

POWERMETRIX

What is an Instrument Transformer?

Instrument Transformers convert signal levels from dangerous (high voltage) or inconvenient (high current, or current at high voltage) to levels appropriate for metering.



There are two fundamental types:

CT’s (Current Transformers)

PT’s (Potential Transformers)

POWERMETRIX

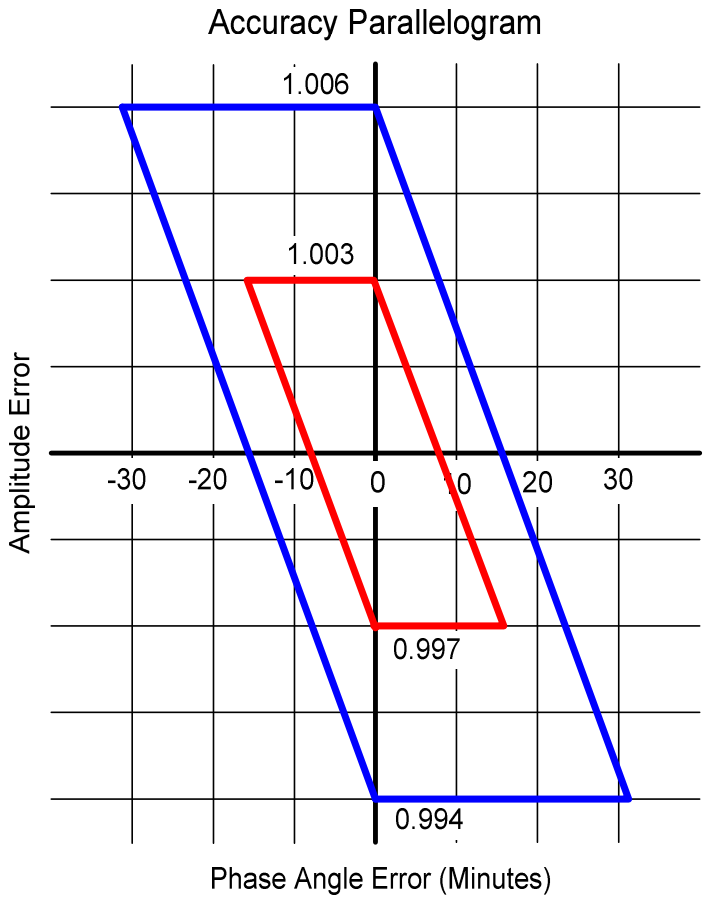
Potential Transformers (PT's)

- PT's step down high voltages to the voltage needed by the meter (usually 120V occasionally 67V).
- They come in many shapes and sizes for different applications
- They work exactly as you would expect them to: Vo=Vi•(Ns/Np).
- They come in various power ratings expressed in VA.
- They come in various accuracy classes, however the 0.3% accuracy class is generally used in North America.

POWERMETRIX

Potential Transformers (PT's)

- PTs are available in Accuracy Classes
  - 1.2 Pecent
  - 0.6 Percent
  - 0.3 Percent
- Burdens are expressed in VA
  - W 12.5 VA
  - X 25.0 VA
  - M 35.0 VA
  - Y 75.0 VA
  - Z 200.0 VA
  - ZZ 400.0 VA



POWERMETRIX

Potential Transformers (PT's)

- 600V Type
  - 240/416 2:1
  - 288/500 2.4:1
  - 300/520 2.5:1
  - 480/480 4:1
  - 600/600 5:1
- 5K Type
  - 2400/4160 20:1
  - 4200/7280 35:1
  - 4800/8320 40:1
- Medium Voltage
  - 7200/12470 60:1
  - 8400/14560 70:1
  - 12000/20800 100:1
  - 14400/24940 120:1
  - 18000/18000 150:1
  - 24000/24000 200:1
  - 27600/27600 240:1
  - 34500/34500 300:1
- High Voltage
  - Operate quite differently
  - May have no direct connection to transformer

POWERMETRIX

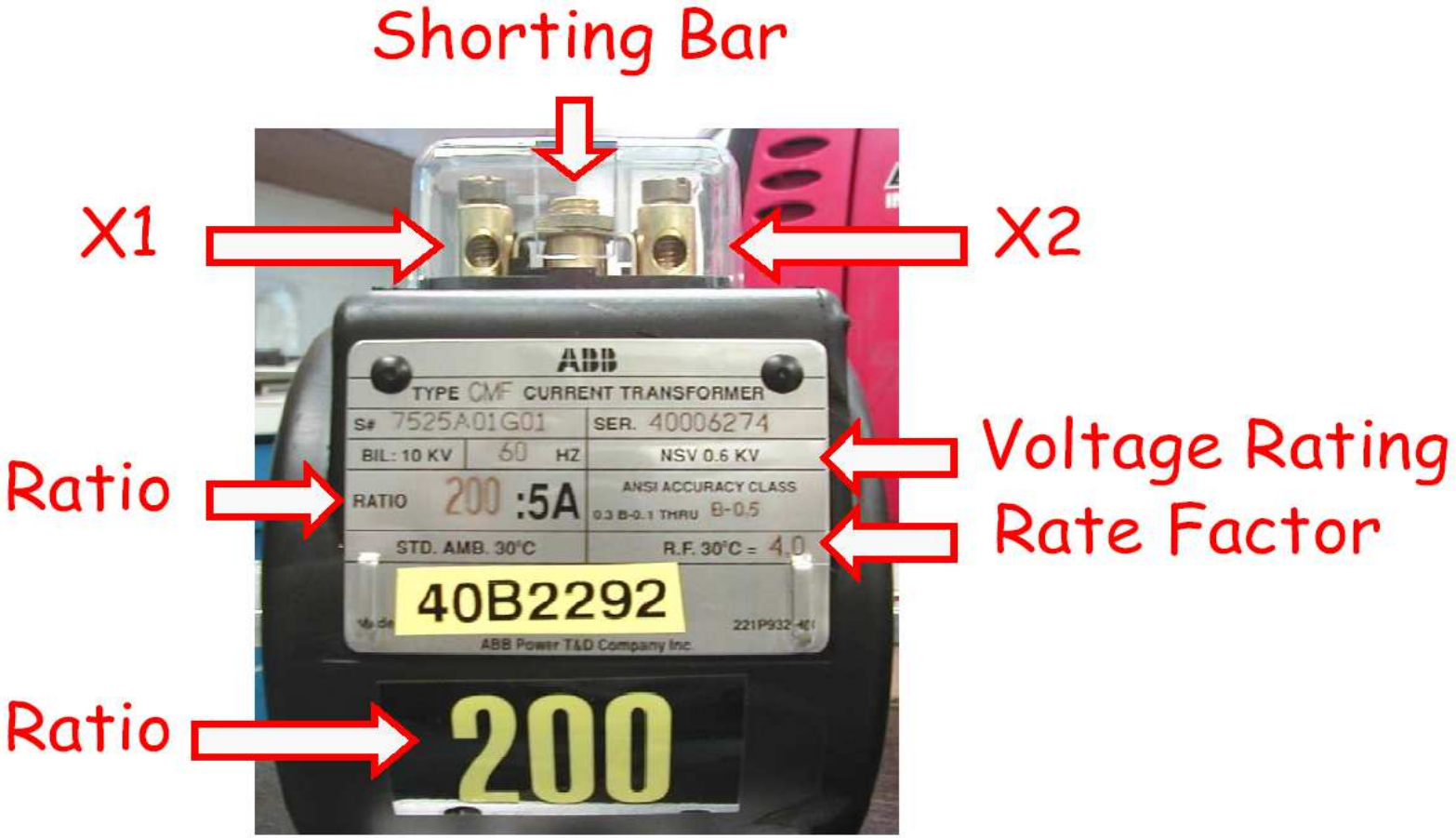
Current Transformers (CT's)

- CT's allow the measurement of high currents at potentially high voltages.
- They come in many shapes and sizes for different applications
- They are potentially extremely dangerous.

They can kill you!

POWERMETRIX

Current Transformers (CT's)



POWERMETRIX

Current Transformers (CT's)
Basic Theory

- Basic formula: Is = Ip•(Np/Ns) = Ip/Ns
- Open Circuit Voltage: $V = \sqrt{3.5 \bullet Z_b \bullet I_p / N_s}$
- Where:
  - Zb = Burden Impedance
  - Ip = Primary Current
  - Ns = Number of Secondary Turns (Ratio to 1)

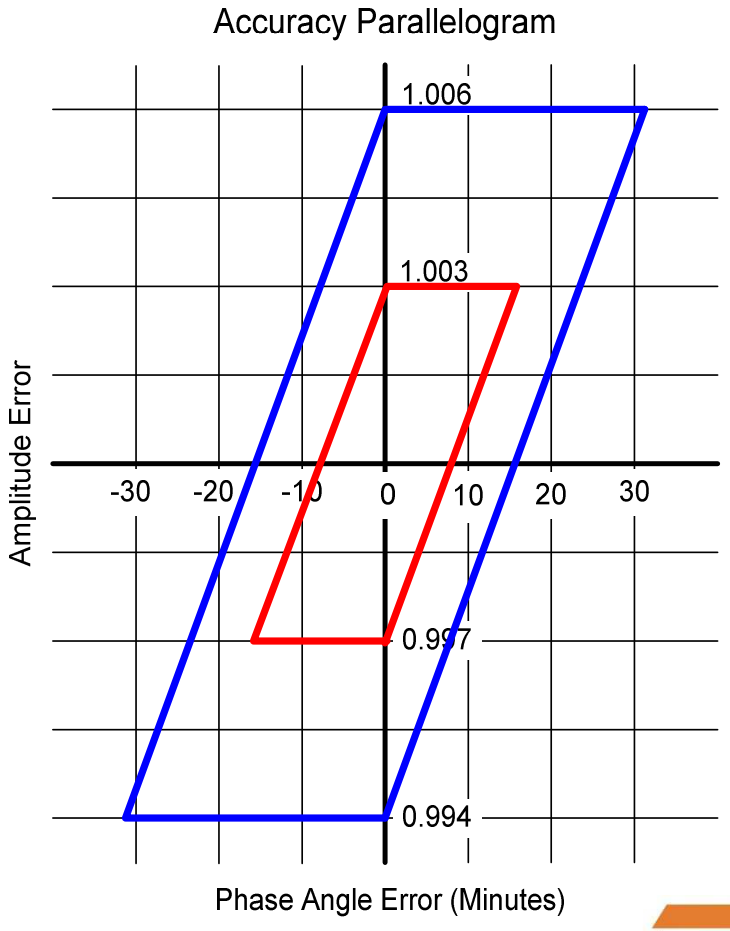
$$V = \sqrt{3.5 \bullet 10^5 \bullet 1000/200} = 1320V$$

Tests have shown values ranging from 500 to 11,000 volts.

POWERMETRIX

CT – Accuracy Class/Burden

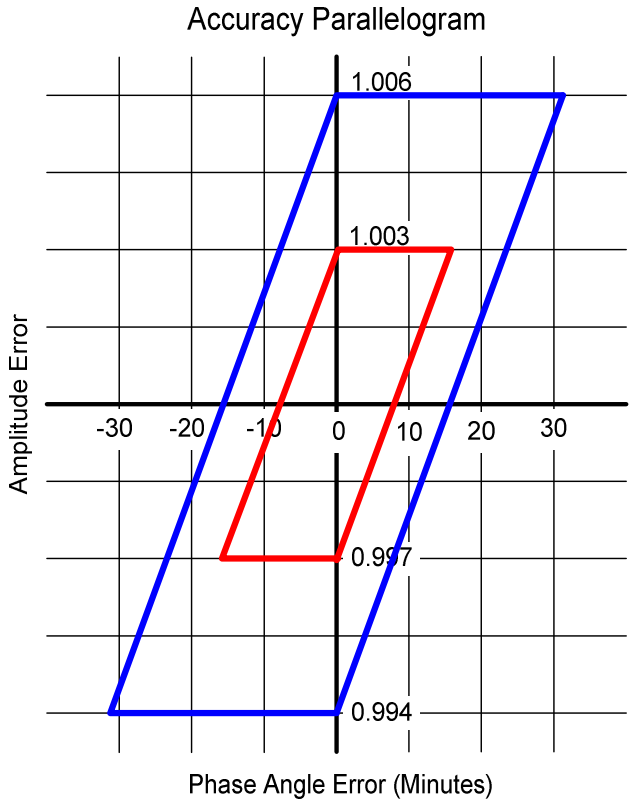
- Most CTs used in North America are 0.3 (0.3 percent) Class devices.
- When an accuracy class is specified the maximum burden for which the device meets the class accuracy is also specified.



POWERMETRIX

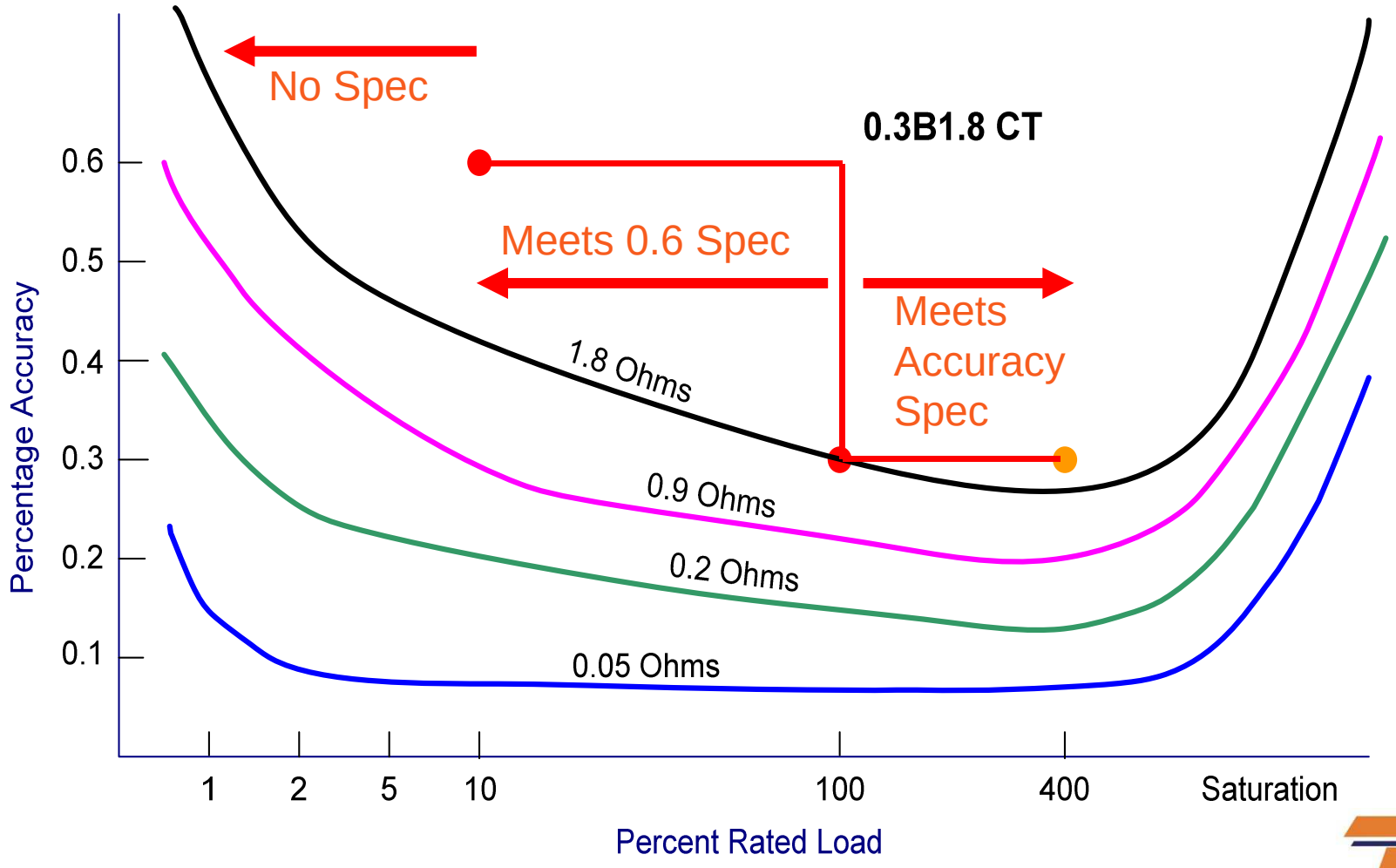
CT – Class 0.3

- Metering error shall be less than 0.3% when the CT is used at FULL RATED LOAD and with rated burden.
- Metering error shall be less than 0.6% when the CT is used between 10% and 100% of full rated load.
- Error is a combination of amplitude and phase error.



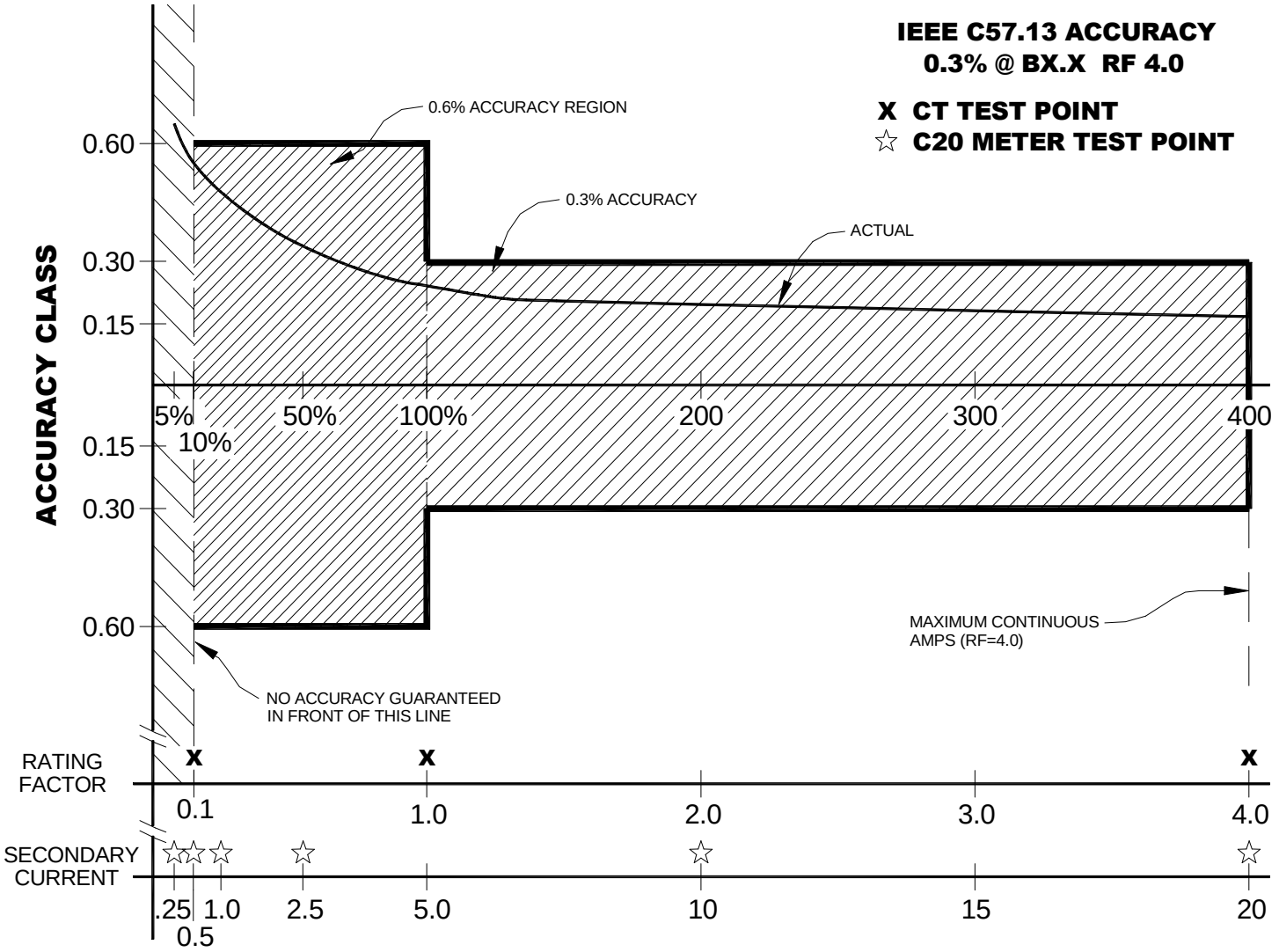
POWERMETRIX

CT – Accuracy – Burden - Load



POWERMETRIX

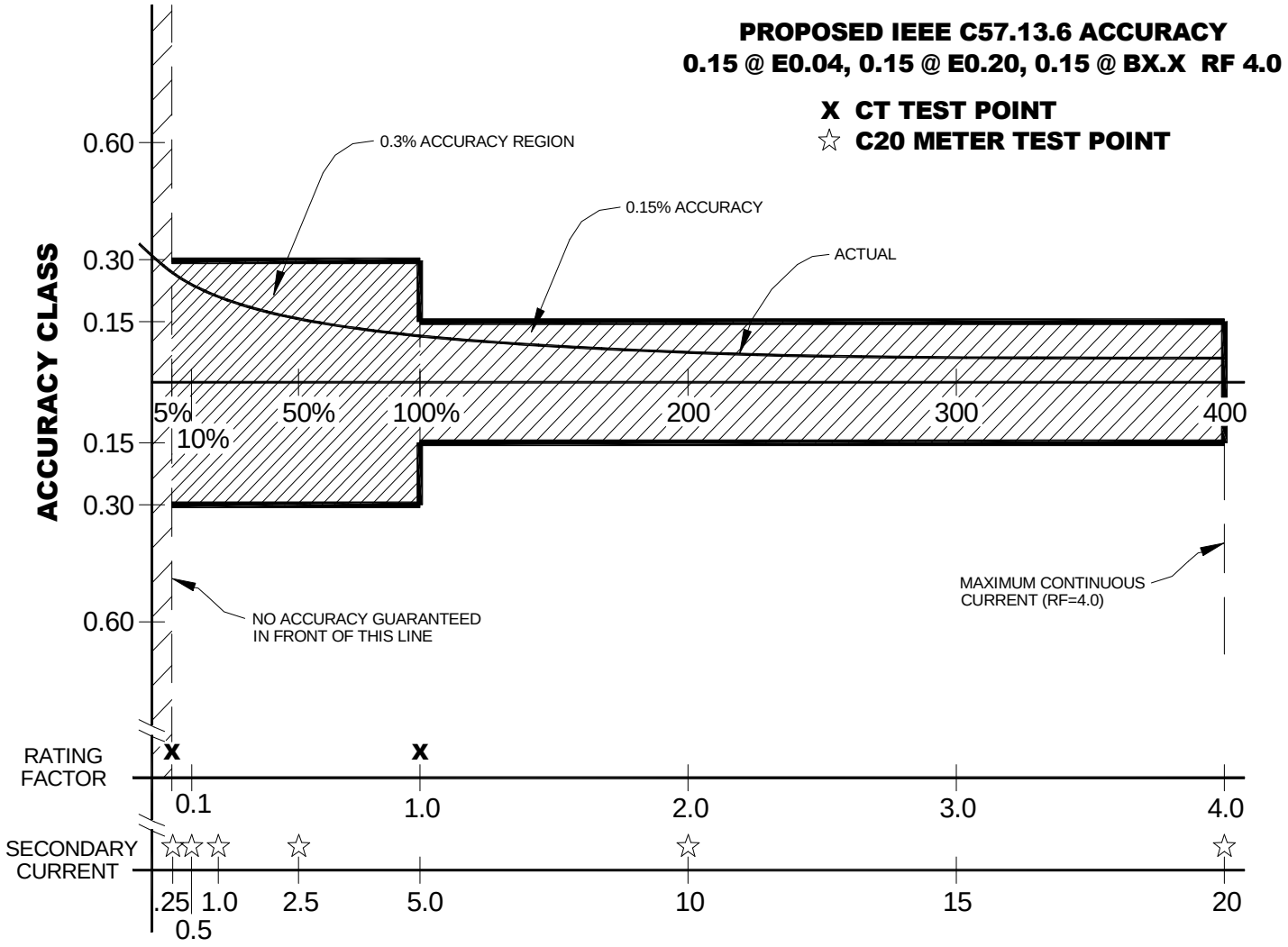
Accuracy Class 0.3



Slide Courtesy Kent Jones, GE

POWERMETRIX

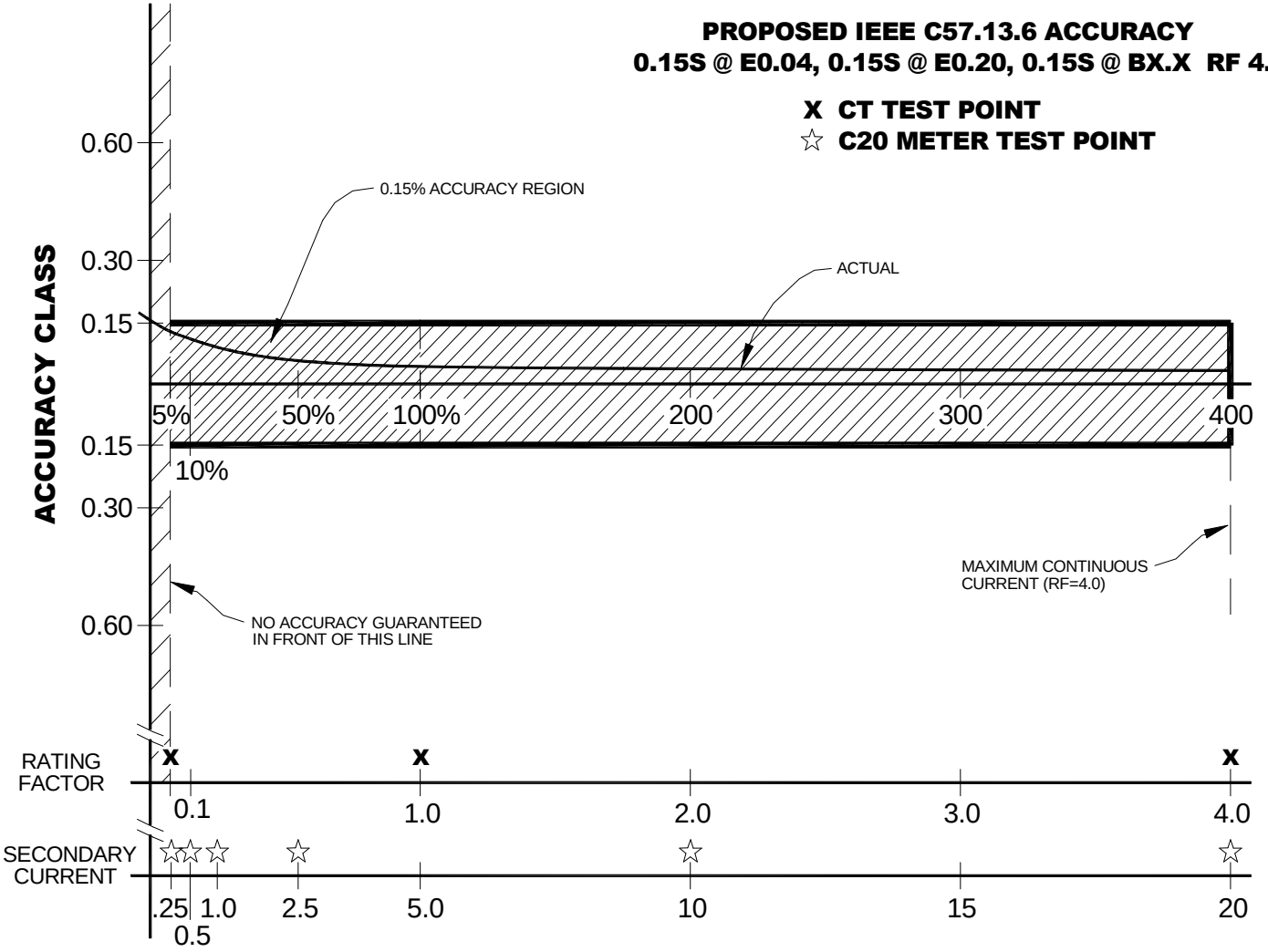
Accuracy Class 0.15



Slide Courtesy Kent Jones, GE

POWERMETRIX

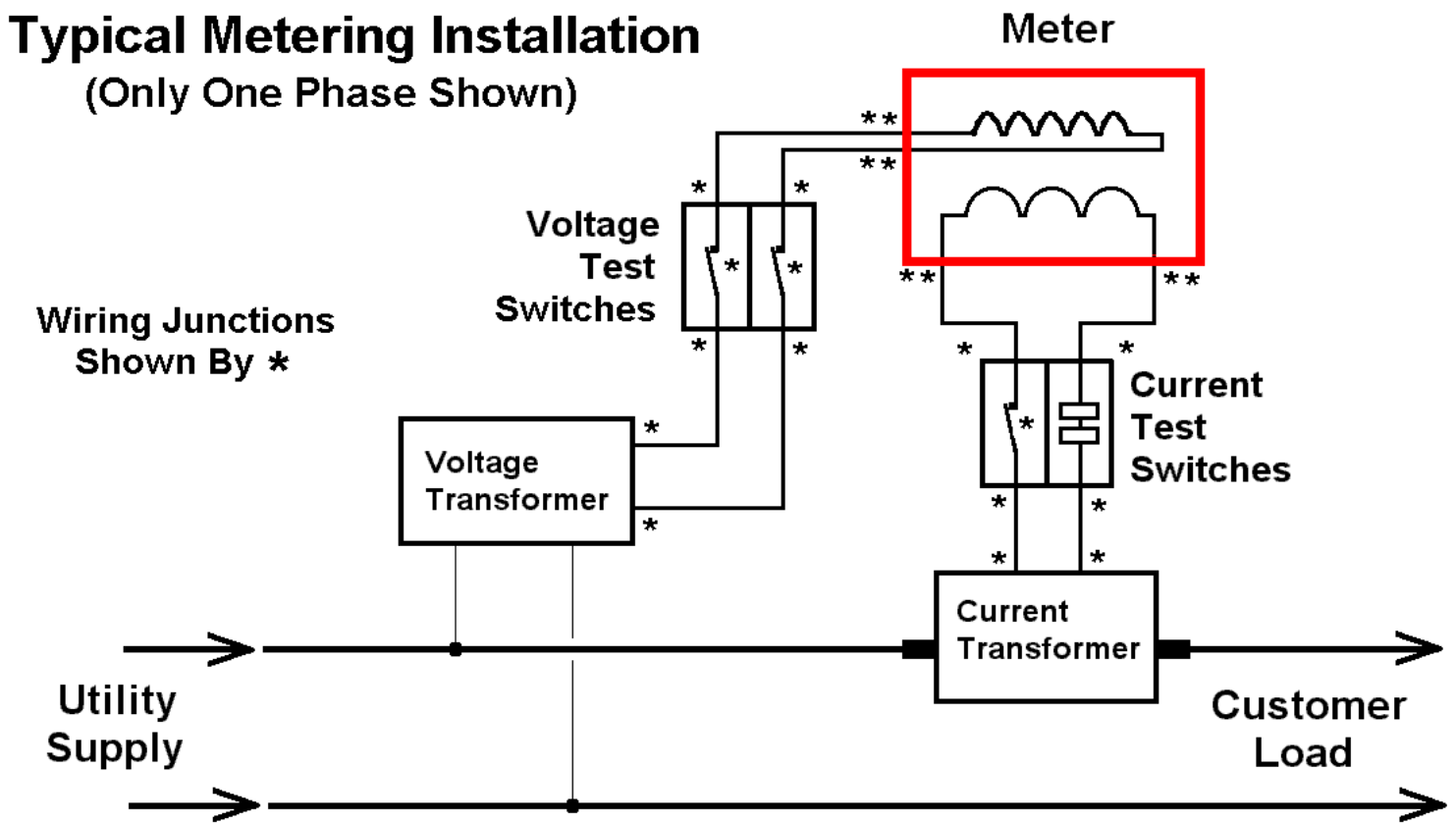
Accuracy Class 0.15S



Slide Courtesy Kent Jones, GE

POWERMETRIX

Errors with Current Transformers



POWERMETRIX

Errors with Current Transformers

- CTs require a lot of care to insure accurate metering.
  - Burden – Over burden reduces CT accuracy.
  - Wiring – Faulty or improper wiring reduces accuracy by increasing burden.
  - Shunt – Failure to remove the safety shunt will not keep the CT from operating but it will reduce the readings by 50-80%

Errors with Current Transformers

- When you see a CT spec sheet it will give you the burden at which the CT meets a specific accuracy Class

Primary Amps	Style Number	IEEE Meter Accuracy B0.1	B0.2	B0.5
50	7524A98G11	2.4		
100	7524A98G01	1.2		
150	7524A98G02	1.2	1.2	
200	7524A98G03	0.6	1.2	2.4
250	7524A98G04	0.6	1.2	2.4
300	7524A98G05	0.6	0.6	0.6
400	7524A98G06	0.6	0.6	0.6
500	7524A98G07	0.3	0.3	0.6
600	7524A98G08	0.3	0.3	0.6
800	7524A98G09	0.3	0.3	0.3
1000	7524A98G10	0.3	0.3	0.3

POWERMETRIX

Errors with Current Transformers

- Many CTs are only rated at B0.1 and B0.2
- #16 wire is 4.5 mΩ/ft
- #14 wire is 2.8 mΩ/ft
- #12 wire is 1.8 mΩ/ft
- #10 wire is 1.1 mΩ/ft
- #8 wire is 0.7 mΩ/ft
- 50 ft of #12 wire is nearly 100 mΩ

Primary Amps	Style Number	IEEE Meter Accuracy B0.1	B0.2	B0.5
200	7524A85G01	0.3	0.3	
300	7524A85G02	0.3	0.3	
400	7524A83G02	0.3	0.3	
600	7524A83G03	0.3	0.3	
200	7524A85G03	0.3	0.3	
300	7524A85G04	0.3	0.3	
400	7524A83G05	0.3	0.3	
600	7524A83G06	0.3	0.3	

Errors with Instrument Transformers

CT - Shunt

- Leaving the shunt in the wrong position produces wrong readings not no readings.

SHUNT CLOSED

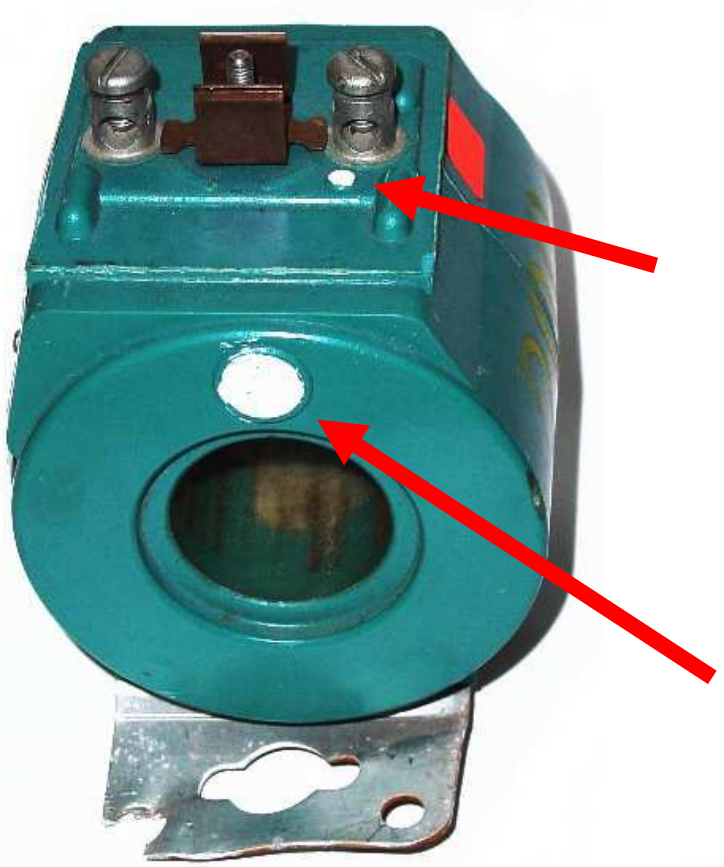
SHUNT OPEN

POWERMETRIX

Errors with Instrument Transformers

CT - Polarity

- Polarity of the connection matters.
- Wrong polarity means totally wrong metering.
- When PF≠0, reversed polarities may not be obvious.



POWERMETRIX

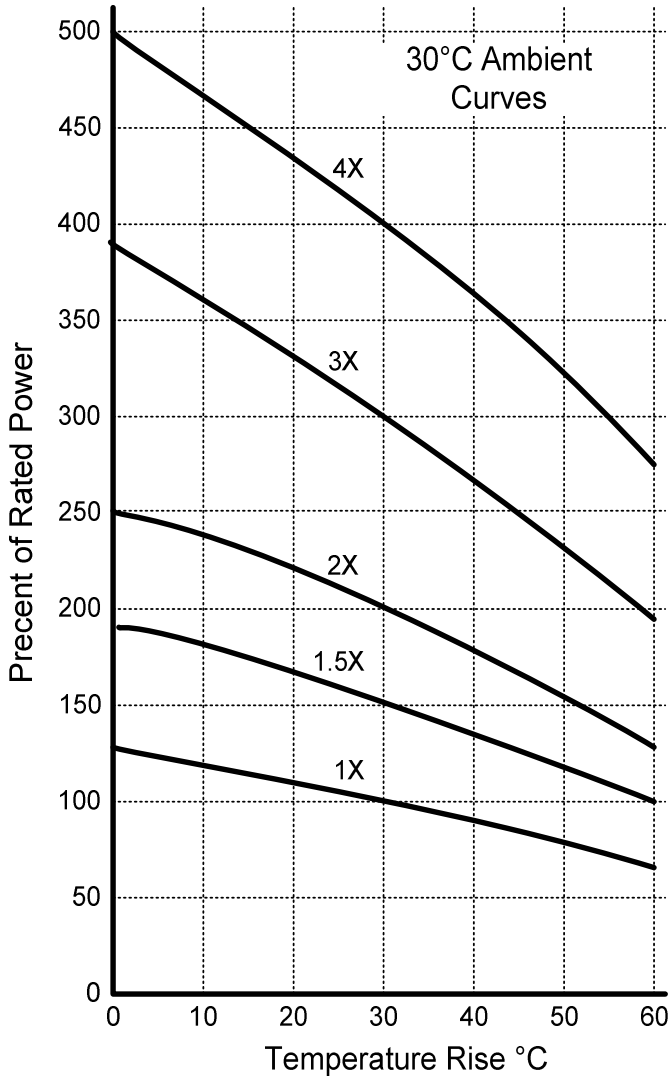
CT Rating Factor
The MOST Misunderstood Spec

- Rating Factor has absolutely nothing to do with burden.
- If a CT has a rating factor of 4 it means that at 30°C it can be used up to 4X its label current and maintain its accuracy Class.

POWERMETRIX

CT Rating Factor

- Rating Factor is a strong function of temperature.
- If a CT has a rating factor of 4 it means that at 30°C it can be used up to 4X its label current and maintain its accuracy Class.
- Operating temperature affects Rating Factor significantly.
  - A CT with RF=4 at 30°C is only RF=3 at 55°C



POWERMETRIX

CT Testing

- Three Approaches in use today
  - Direct RATIO measurement with applied burden
    - Most accurate approach tells us exactly what we want to know
    - Measures directly the quantity we care about CT Ratio
    - Is more complicated to perform.

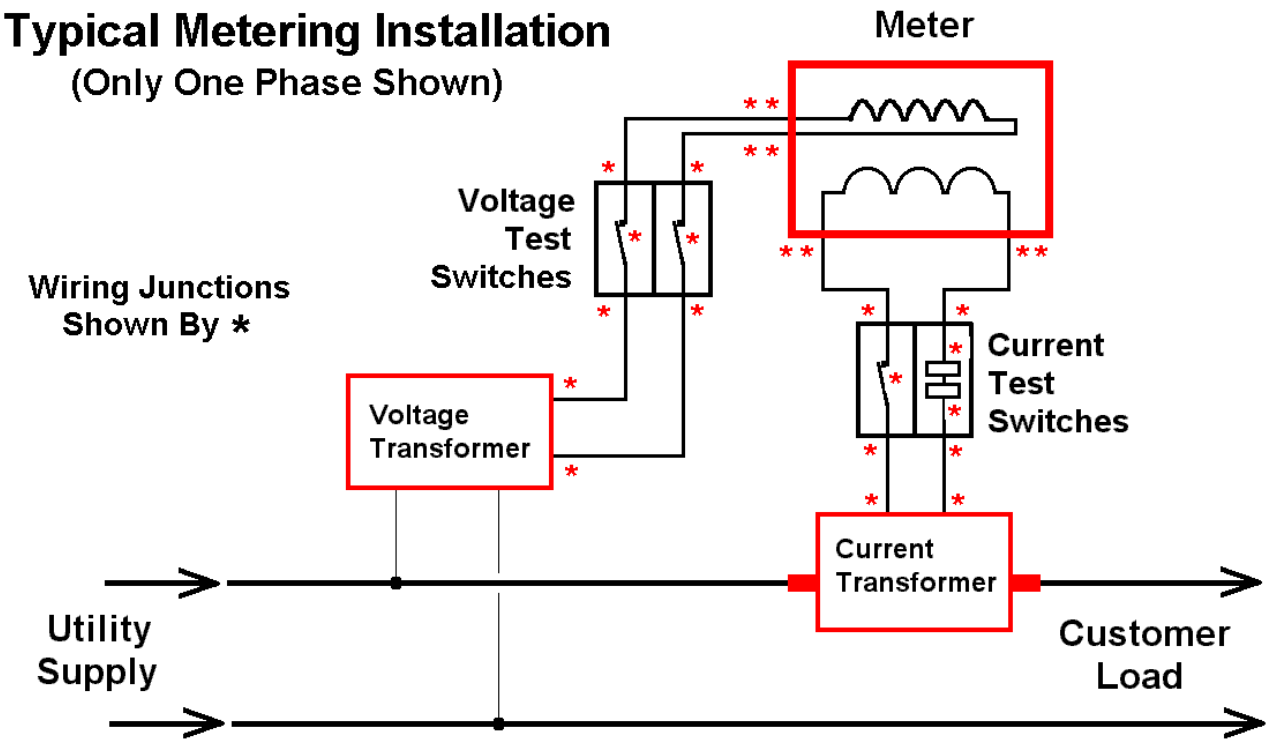
POWERMETRIX

CT Testing

- Alternate Approaches
  - Burden only
    - A compromise: tells us if circuit is stable under excess burden
    - Can’t give us the ratio which is what we really care about.
  - Admittance Testing
    - Allows us to look for changes from previous measurements.
    - Doesn’t directly give ratio
    - Accuracy typically ±5%

On Site CT Testing

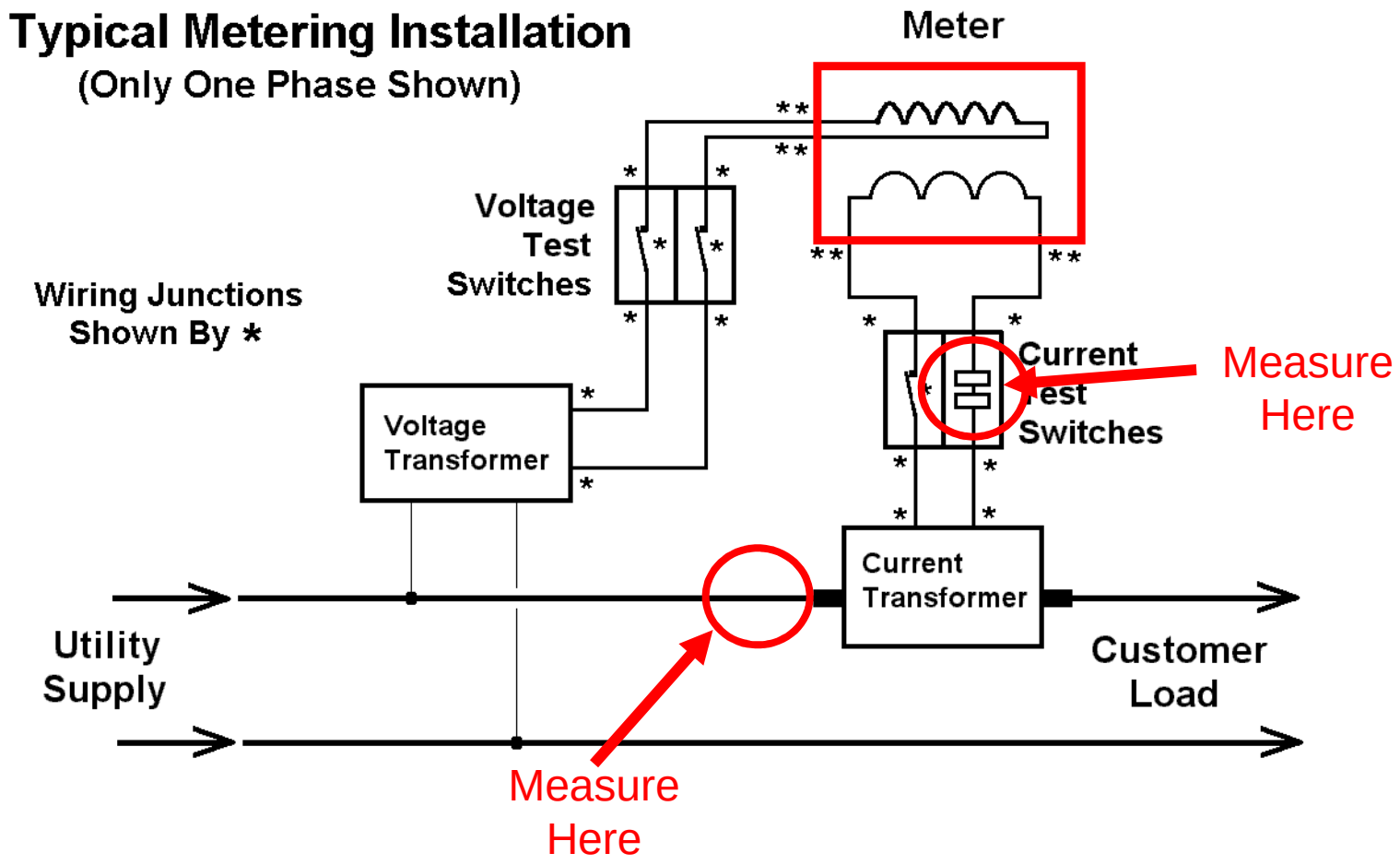
- The meter measures ONLY the voltage and current reaching the meter terminals.
- To verify that the CT is working at the site we have to test the entire circuit.



POWERMETRIX

CT Transformers

Field Verification – Full Ratio Measurement



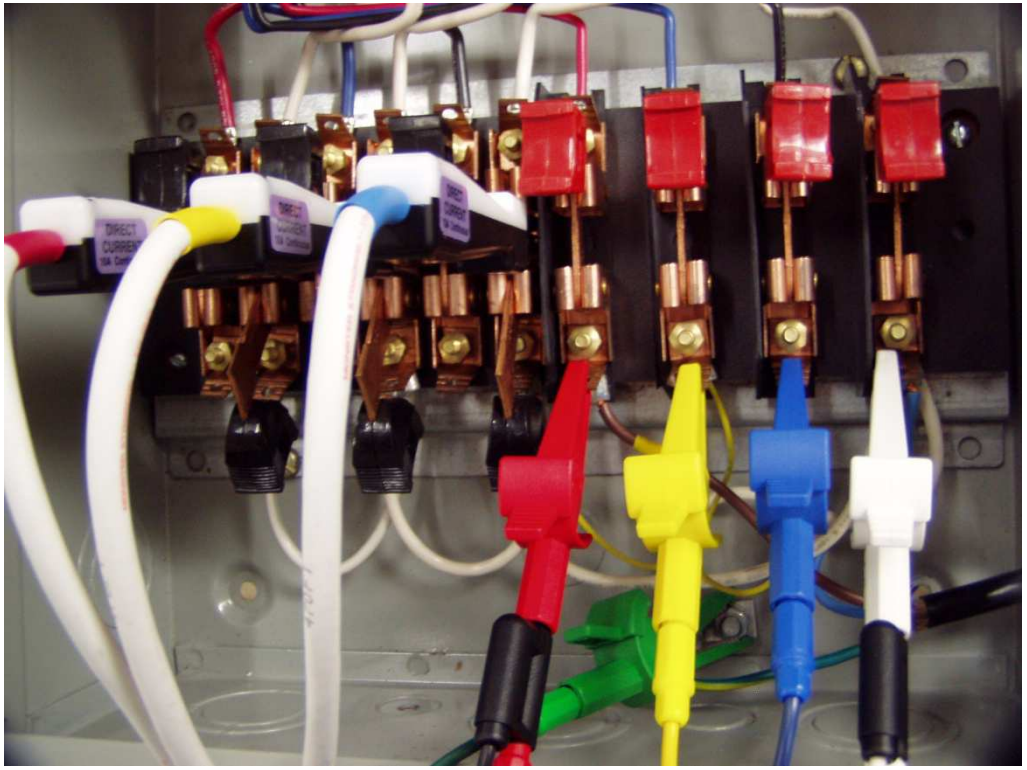
POWERMETRIX

CT Ratio with Burden Testing

- Ratio Testing is the preferred approach when we can gain access to the CT primary.
- Various types of probes can be used for primary side.
  - Flex
  - HV

POWERMETRIX

CT Ratio with Burden Testing



- Secondary connection is made through the test switch
- Same connection that is used for the rest of the site testing.

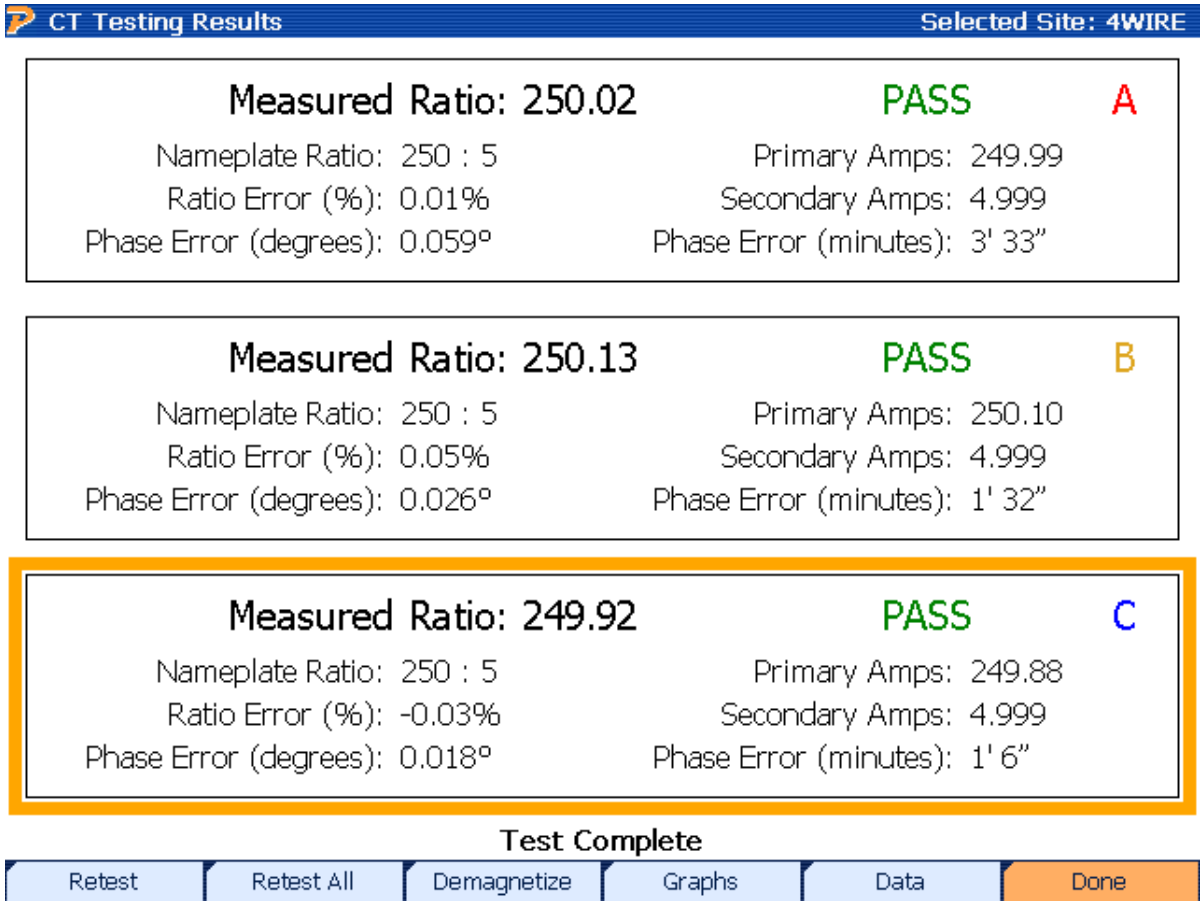
Ratio Testing with applied burden is the most accurate and complete approach for testing at CT in service.

POWERMETRIX

Testing Current Transformers

Ratio vs Applied Burden

- CT testing can be done with very high accuracy



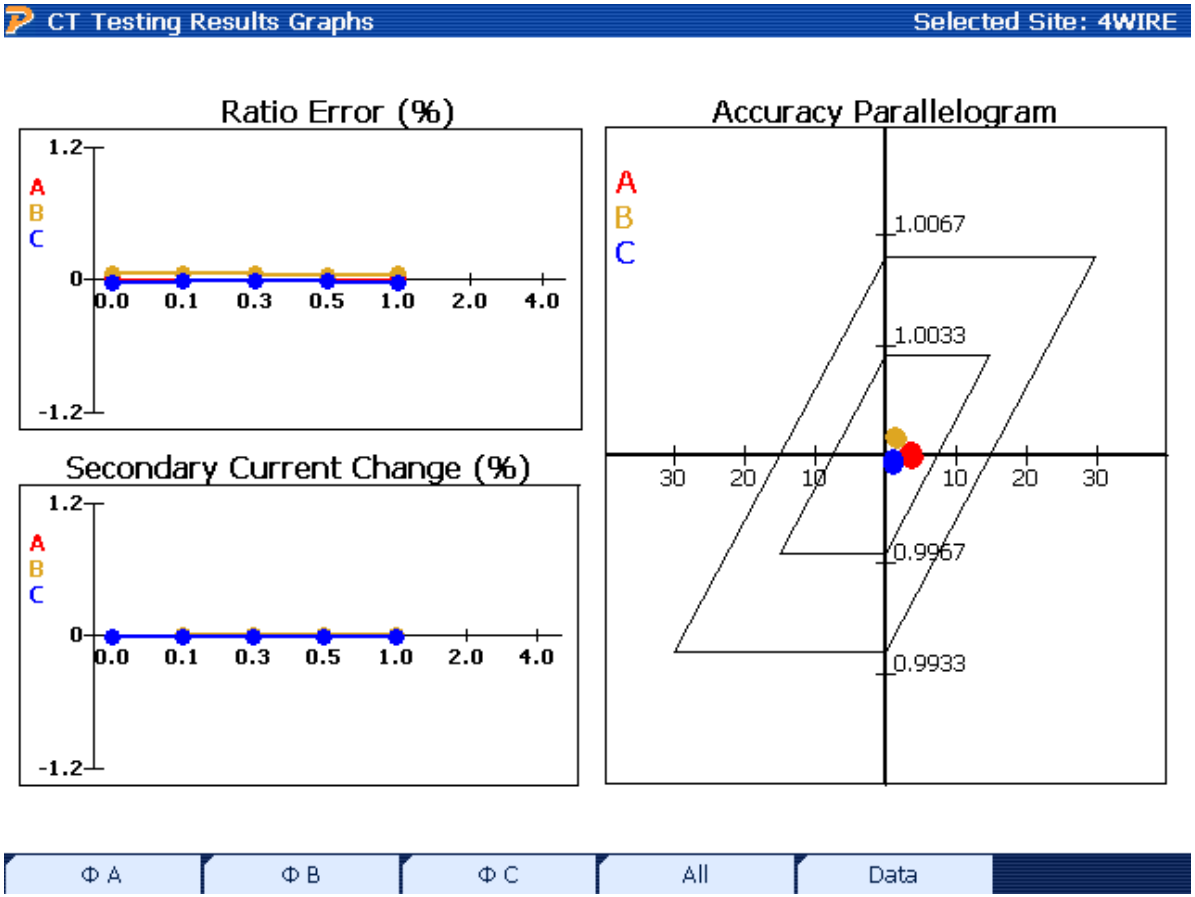
Reference CT measured using PowerMaster with 752 clamp-on probes. Essentially NO ratio error, phase shift, or change in secondary current versus applied burden.

POWERMETRIX

Testing Current Transformers

Ratio vs Applied Burden

- CT testing can be done with very high accuracy



Reference CT measured using PowerMaster with 752 clamp-on probes. Essentially NO ratio error, phase shift, or change in secondary current versus applied burden.

POWERMETRIX

Testing Current Transformers

Ratio vs Applied Burden

- CT testing can be done with very high accuracy

CT Testing Results — Selected Site: 4WIRE

% Change in Secondary Amps

Phase	Ref	0.0Ω	0.1Ω	0.3Ω	0.5Ω	1.0Ω	2.0Ω	4.0Ω
A		0.000	0.000	0.000	0.000	0.000	N/A	N/A
B		0.000	0.001	0.001	0.001	0.001	N/A	N/A
C		0.000	-0.001	-0.001	0.000	0.000	N/A	N/A

Ratio Data

Phase	Ref	0.0Ω	0.1Ω	0.3Ω	0.5Ω	1.0Ω	2.0Ω	4.0Ω
A	250:5	250.02	249.98	249.96	249.98	250.02	N/A	N/A
B	250:5	250.13	250.13	250.13	250.12	250.13	N/A	N/A
C	250:5	249.92	249.97	249.96	249.96	249.96	N/A	N/A

Ratio Error (%)

Phase	Ref	0.0Ω	0.1Ω	0.3Ω	0.5Ω	1.0Ω	2.0Ω	4.0Ω
A		0.01	-0.01	-0.02	-0.01	0.01	N/A	N/A
B		0.05	0.05	0.05	0.05	0.05	N/A	N/A
C		-0.03	-0.01	-0.02	-0.02	-0.02	N/A	N/A

Relative Phase Data (degrees)

Phase	Ref	0.0Ω	0.1Ω	0.3Ω	0.5Ω	1.0Ω	2.0Ω	4.0Ω
A		0.06	0.07	0.06	0.07	0.06	N/A	N/A
B		0.03	0.03	0.02	0.03	0.02	N/A	N/A
C		0.02	0.02	0.02	0.02	0.02	N/A	N/A

Graphs

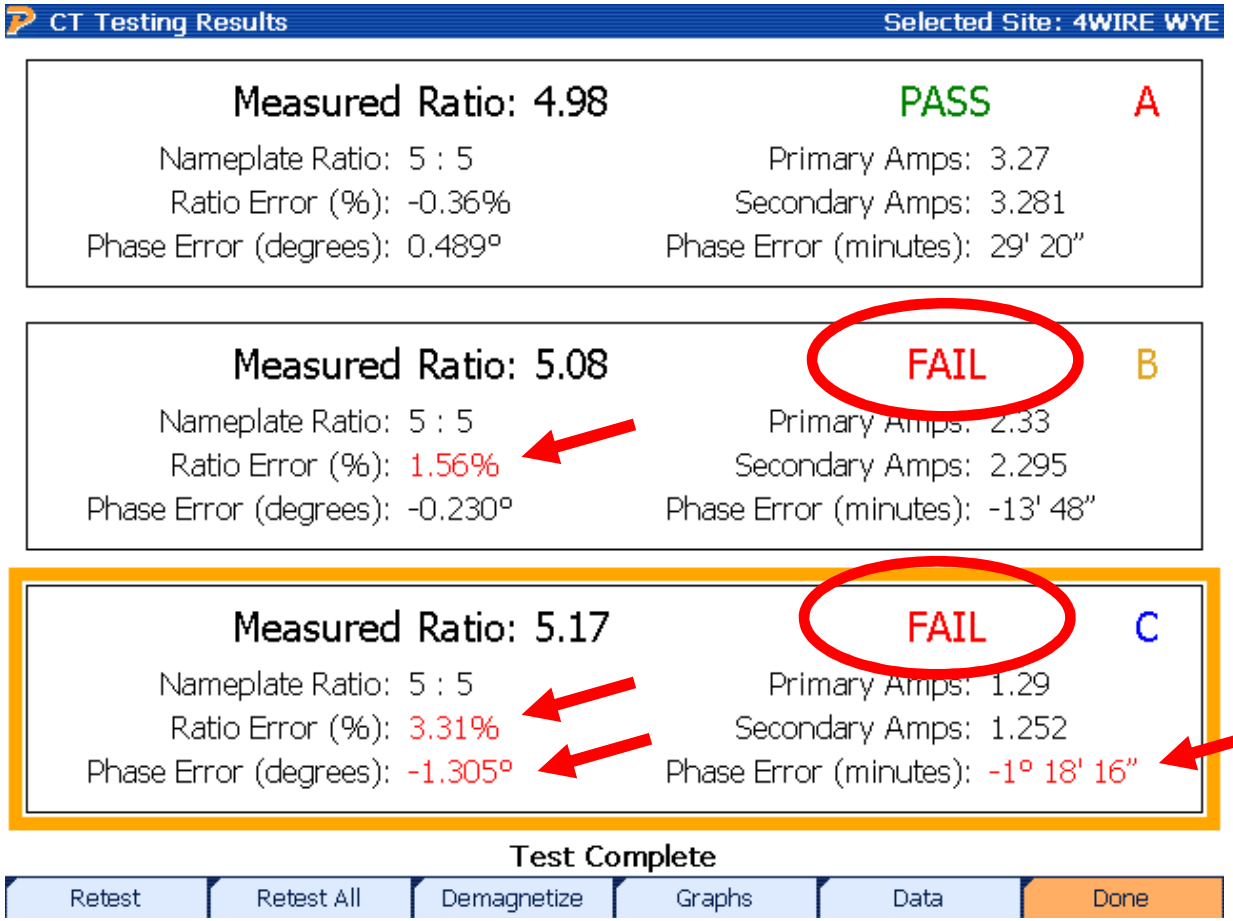
Reference CT measured using PowerMaster with 752 clamp-on probes. Essentially NO ratio error, phase shift, or change in secondary current versus applied burden.

POWERMETRIX

Testing Current Transformers

Ratio vs Applied Burden

- CTs installations can be fully verified in the field



Burden Class 0.1 CTs various issues: too small gauge wire, bad connections, high harmonic content.

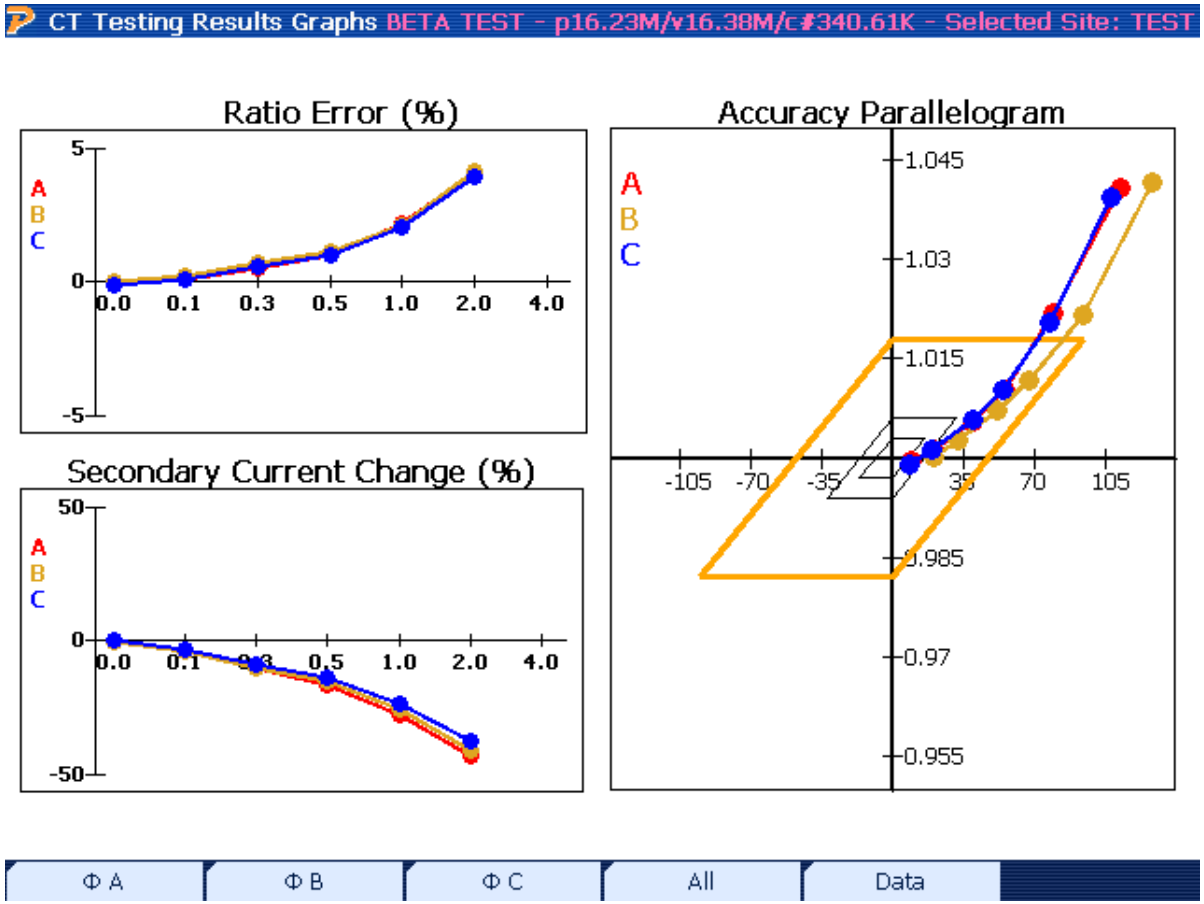
We can verify that the ratio is correct and constant as burden changes.

POWERMETRIX

Testing Current Transformers

Ratio vs Applied Burden

- CTs installations can be fully verified in the field



Burden
Class 0.1
CTs

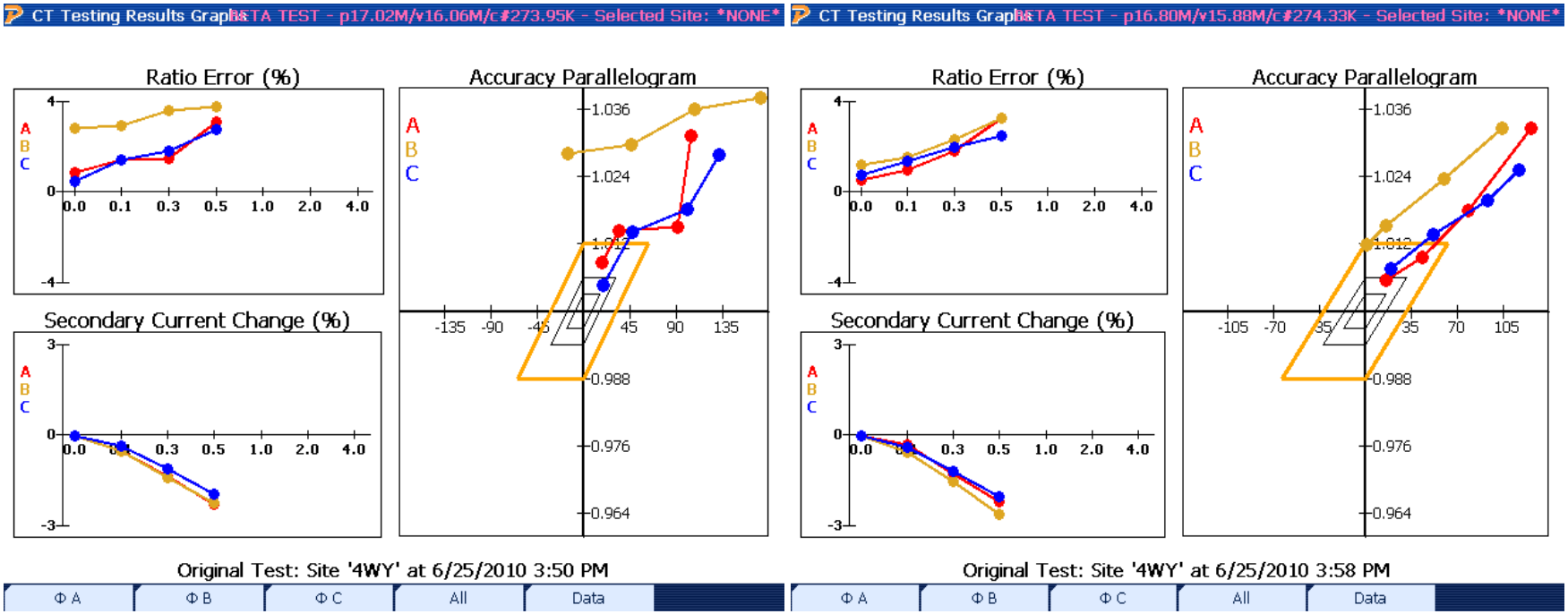
We can verify that the ratio is correct and constant as burden changes.

POWERMETRIX

Testing Current Transformers

Ratio vs Applied Burden

- CTs installations can be fully verified in the field



CT Phase B highly harmonic load.

CT Phase B harmonic load removed.

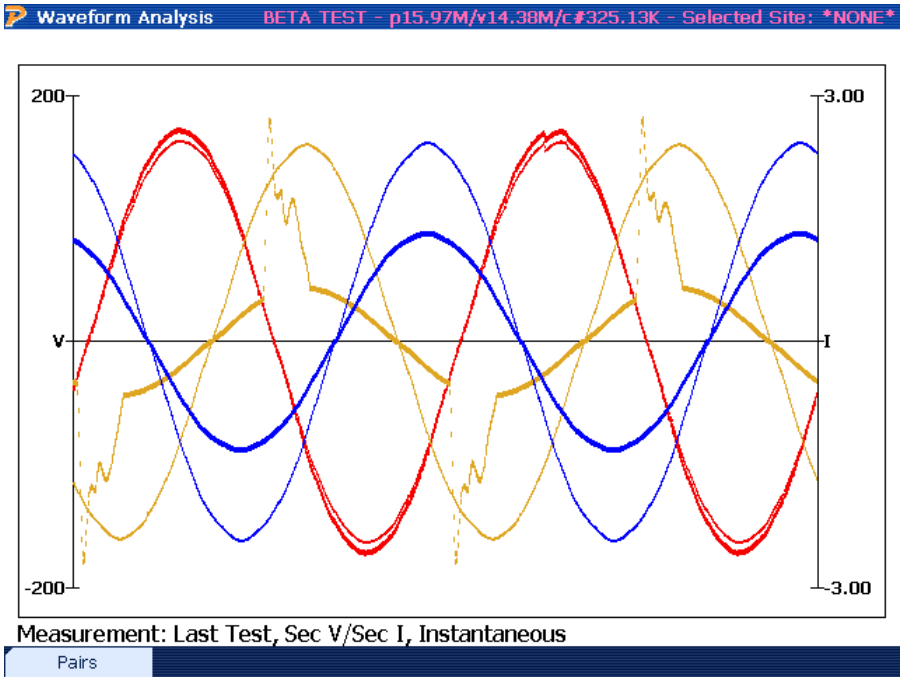
Same CT in BOTH cases.

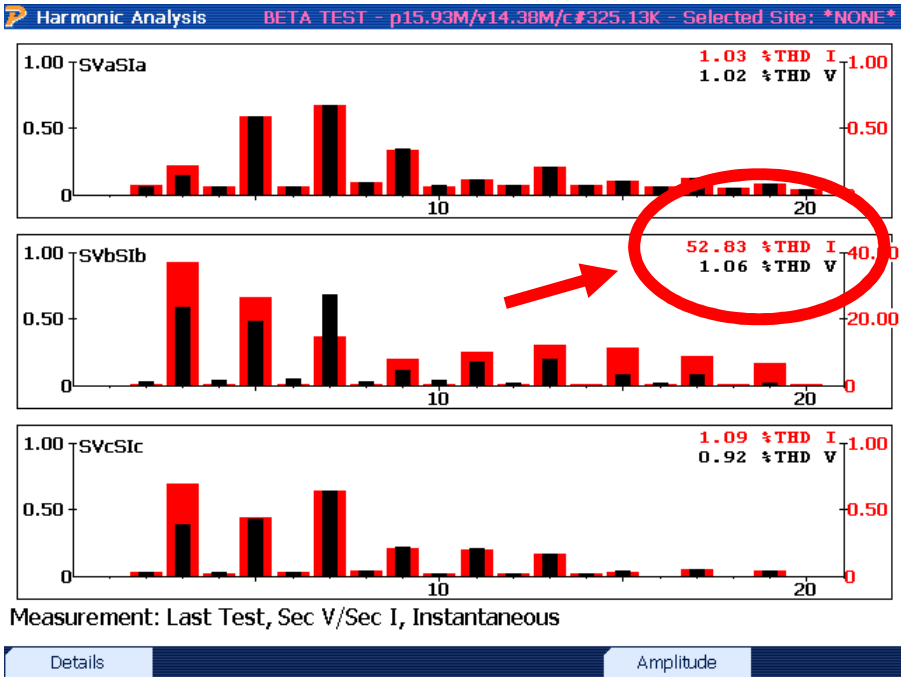
POWERMETRIX

Testing Current Transformers

Ratio vs Applied Burden

- CTs installations can be fully verified in the field





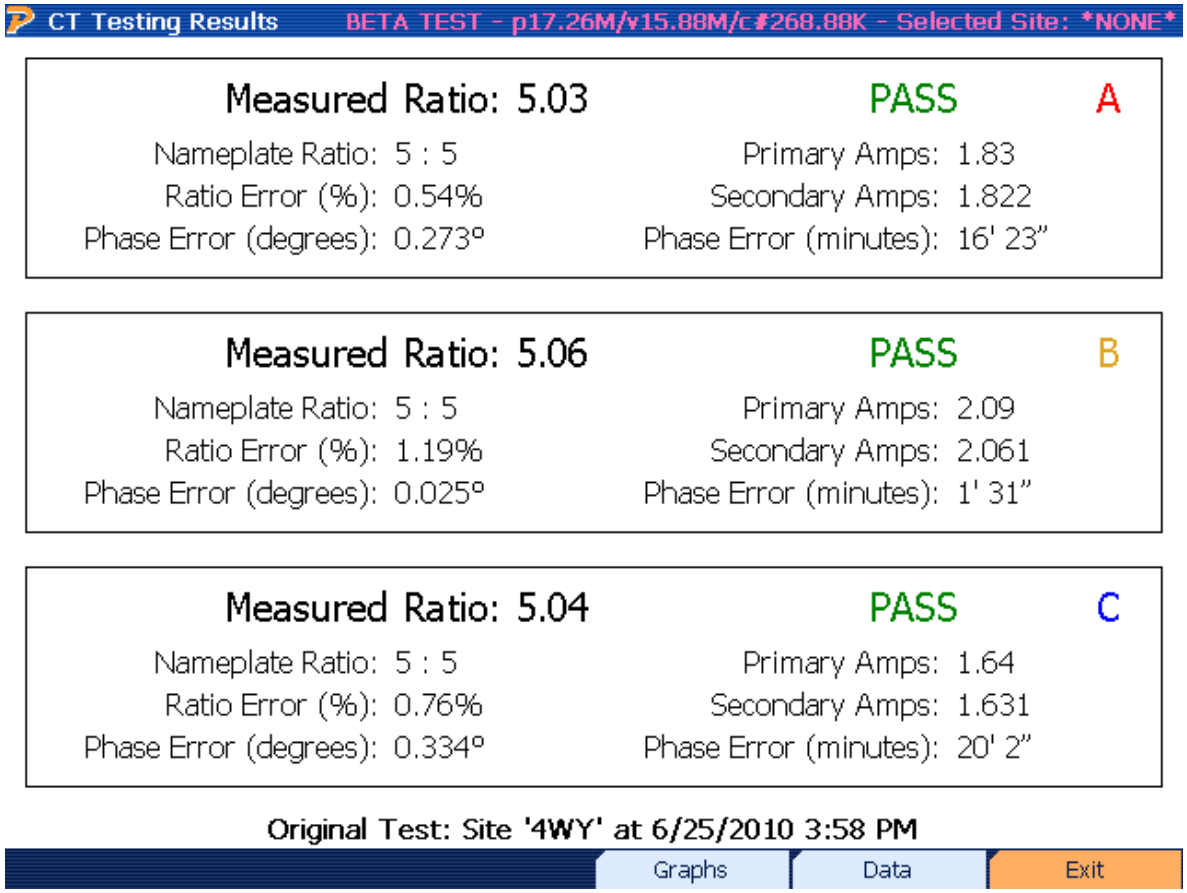
These are the waveforms and harmonics when the CT failed.

POWERMETRIX

Testing Current Transformers

Ratio vs Applied Burden

- CTs installations can be fully verified in the field



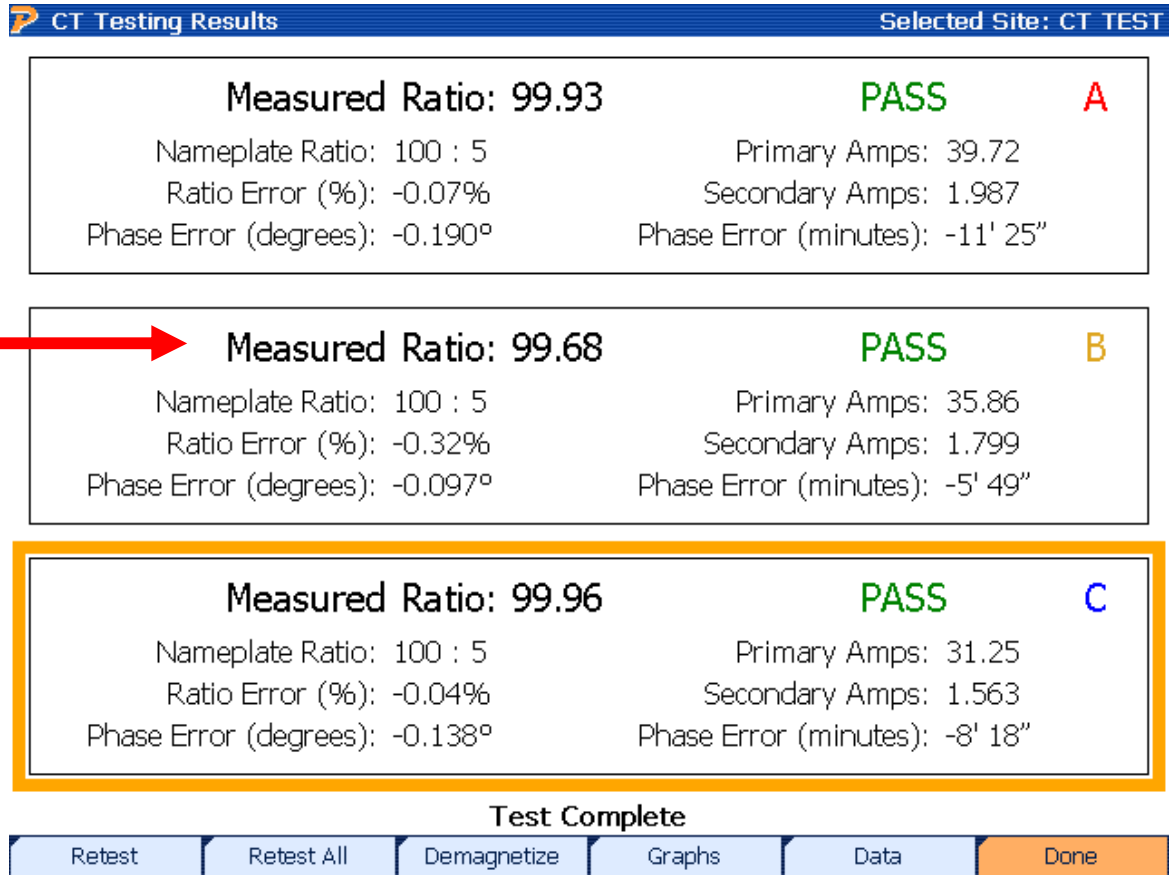
Without the harmonic load this CT passed it's test.

POWERMETRIX

Testing Current Transformers

Ratio Error – In Whose Favor?

I did at CT ratio test. What does it mean when I measure a ratio of 99.68:5 on a 100:5 CT?



POWERMETRIX

Testing Current Transformers

Ratio Error – In Whose Favor?

In the phase B test we measured 35.86 amps on the primary and 1.799 secondary amps.

Ratio = 5.0 * (Primary / Secondary) = 99.68

If the ratio had been 100:5 and the primary was 35.86 amps we should have measured 1.793 amps on the secondary.

We measured 1.799 – MORE than we should have.

Therefore a tested ratio of 99.68 means that we are measuring more current than we should. This error is in our favor.

Testing Current Transformers

Ratio Error – In Whose Favor?

Suppose we add burden to the metering circuit.

CT Testing Results — Selected Site: CT TEST

% Change in Secondary Amps

Phase	Ref	0.0Ω	0.1Ω	0.3Ω	0.5Ω	1.0Ω	2.0Ω	4.0Ω
A		0.000	-4.468	-10.751	-16.377	N/A	N/A	N/A
B		0.000	-4.072	-9.727	-14.820	N/A	N/A	N/A
C		0.000	-3.490	-8.405	-12.873	N/A	N/A	N/A

Ratio Data

Phase	Ref	0.0Ω	0.1Ω	0.3Ω	0.5Ω	1.0Ω	2.0Ω	4.0Ω
A	100:5	99.93	100.20	100.85	101.42	N/A	N/A	N/A
B	100:5	99.68	99.96	100.54	101.01	N/A	N/A	N/A
C	100:5	99.96	100.17	100.71	101.23	N/A	N/A	N/A

Ratio Error (%)

Phase	Ref	0.0Ω	0.1Ω	0.3Ω	0.5Ω	1.0Ω	2.0Ω	4.0Ω
A		-0.07	0.20	0.85	1.42	N/A	N/A	N/A
B		-0.32	-0.04	0.54	1.01	N/A	N/A	N/A
C		-0.04	0.17	0.71	1.23	N/A	N/A	N/A

Relative Phase Data (degrees)

Phase	Ref	0.0Ω	0.1Ω	0.3Ω	0.5Ω	1.0Ω	2.0Ω	4.0Ω
A		-0.19	-0.51	-0.89	-1.17	N/A	N/A	N/A
B		-0.10	-0.38	-0.79	-1.11	N/A	N/A	N/A
C		-0.14	-0.42	-0.81	-1.07	N/A	N/A	N/A

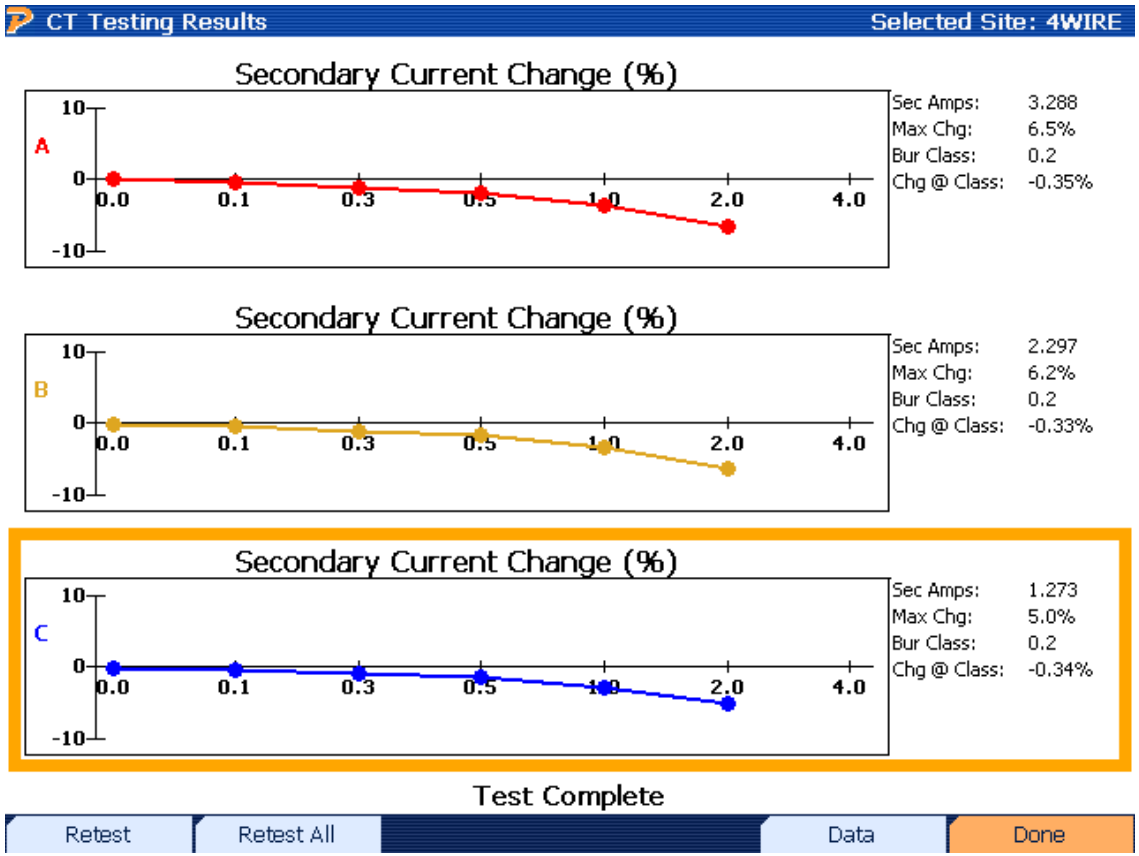
Graphs

Notice that the ratio increases as we apply burden. With 0.3 Ohms of burden the ratio switches from less than 100:5 to greater than 100:5. This is the point where things swing to being in favor of the customer.

POWERMETRIX

Testing Current Transformers
Burden Test Only

- If we cannot get to the primary side of the CT we can check that the output is constant as burden changes.

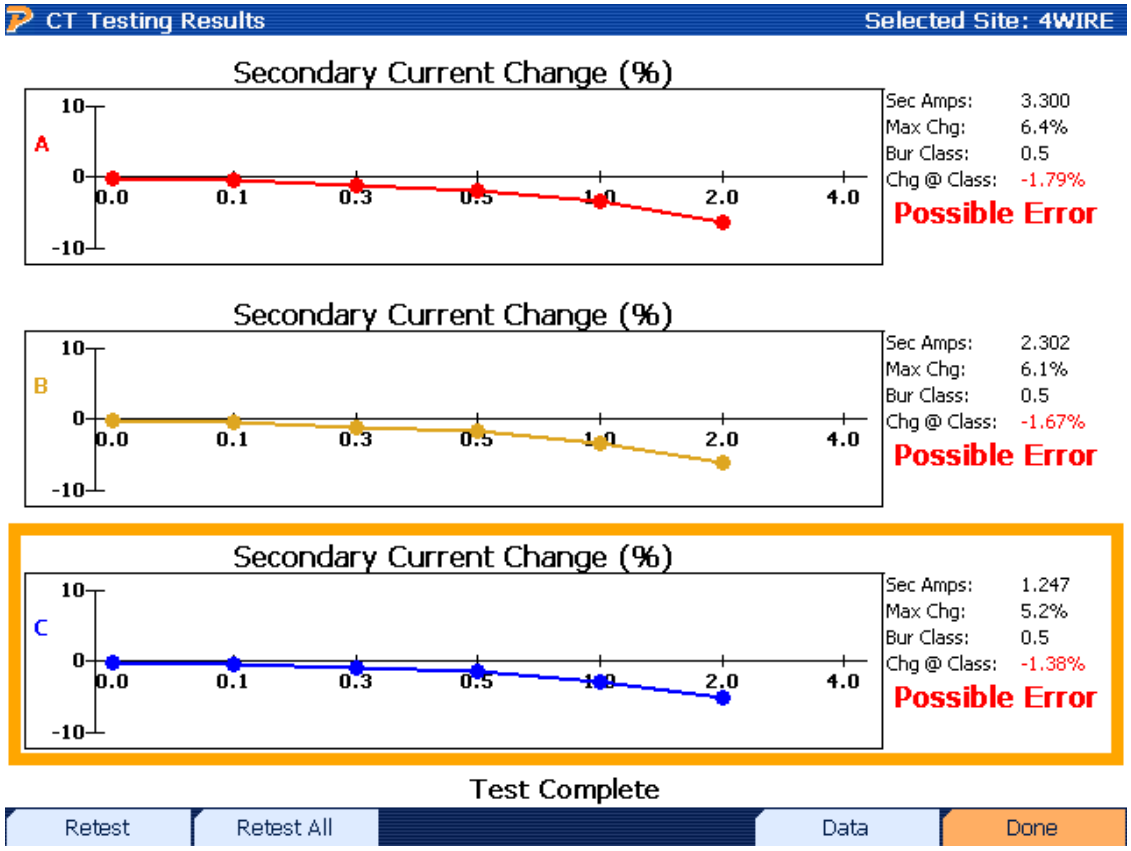


Burden Class 0.2 CTs can look quite bad but actually be within specs.

POWERMETRIX

Testing Current Transformers
Burden Test Only

- If we cannot get to the primary side of the CT we can check that the output is constant as burden changes.

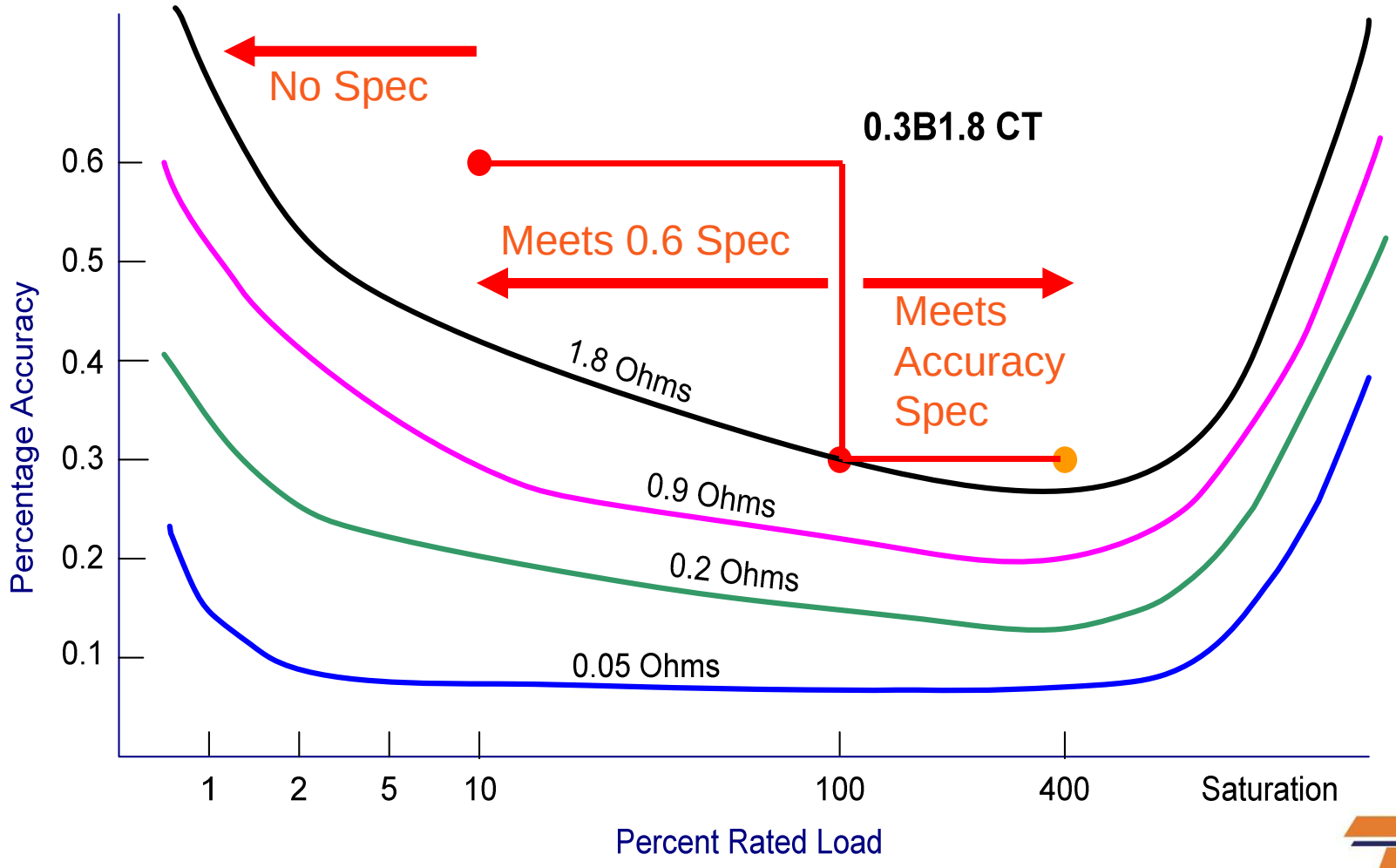


Same performance from Burden Class 0.5 CTs is well out of specification.

A burden only test that is GOOD probably means the CT is GOOD. A test that is bad may mean nothing.

POWERMETRIX

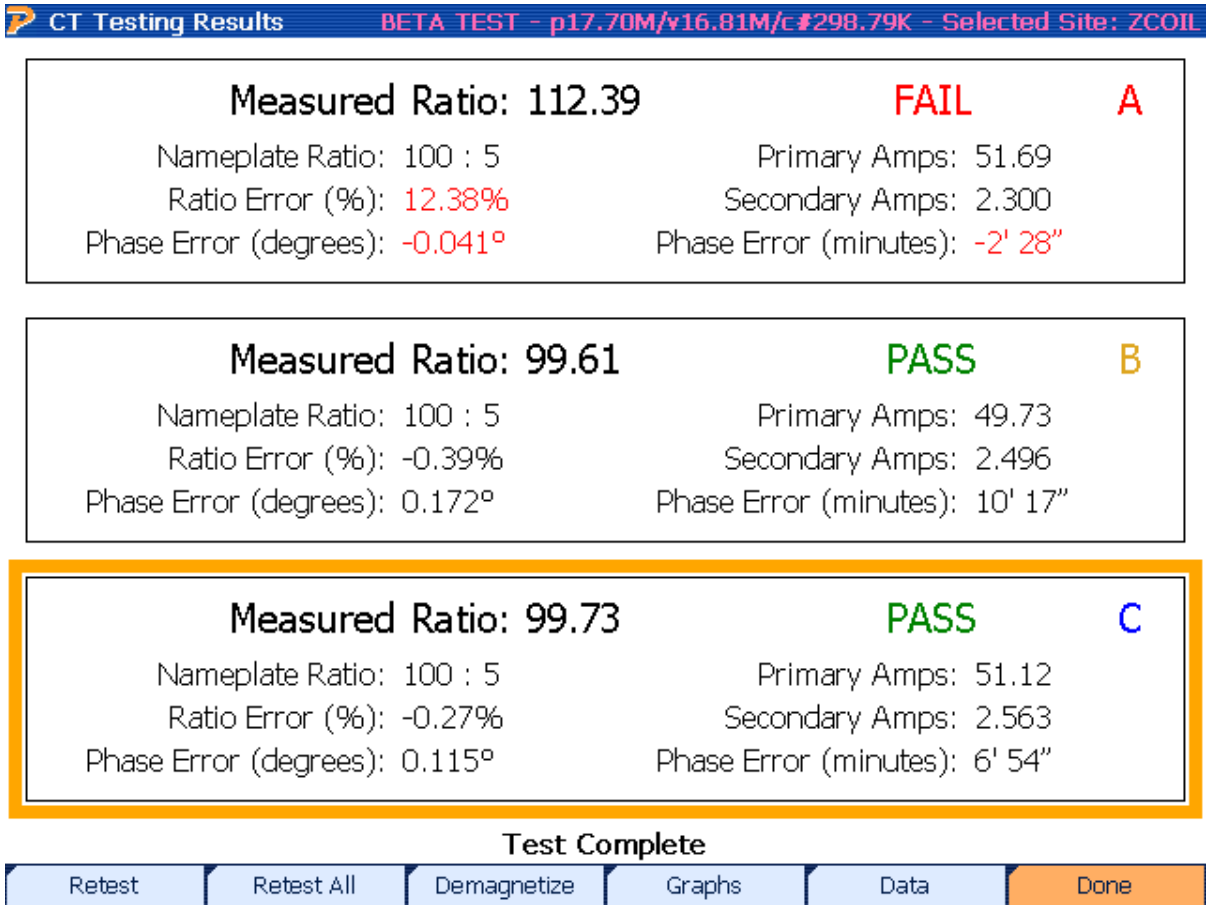
CT – Accuracy – Burden - Load



POWERMETRIX

Testing Current Transformers
What's Wrong?

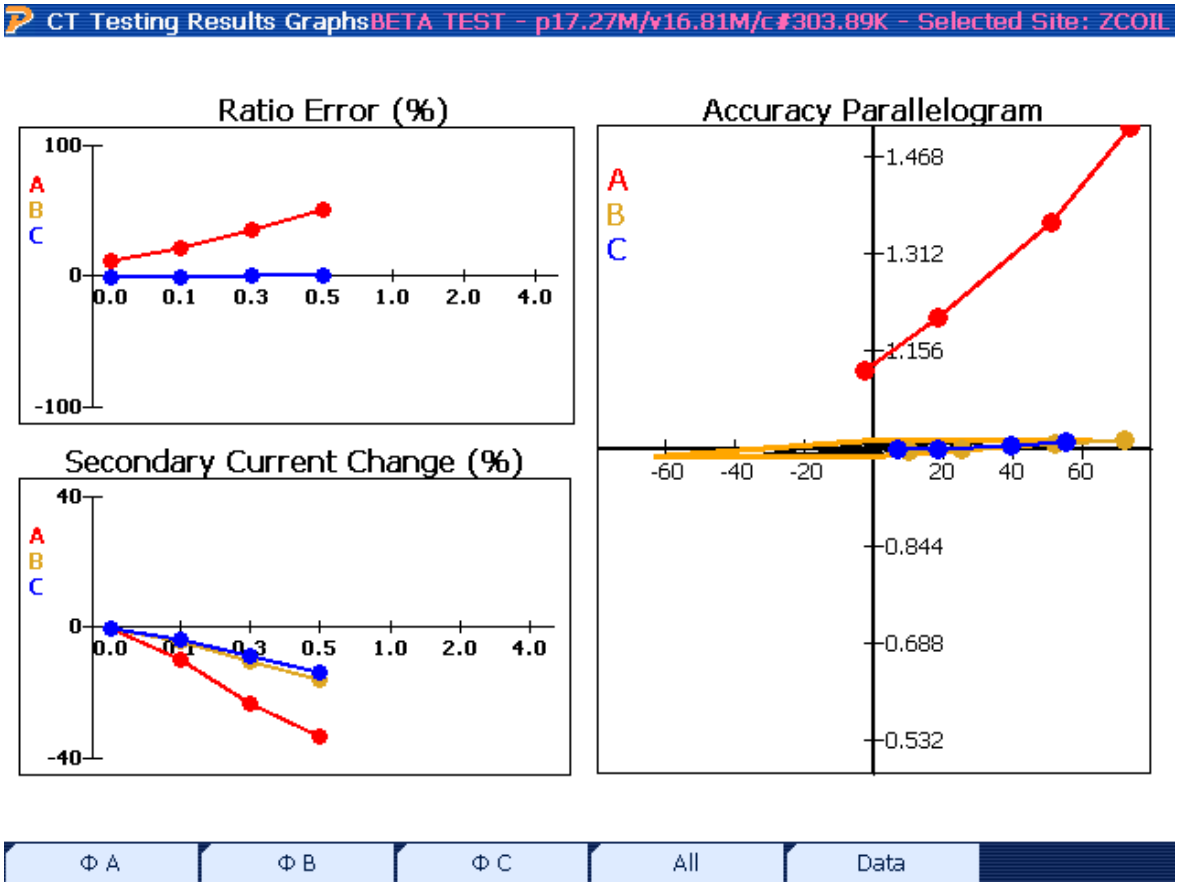
- Same site as above: What went wrong???



POWERMETRIX

Testing Current Transformers
What's Wrong?

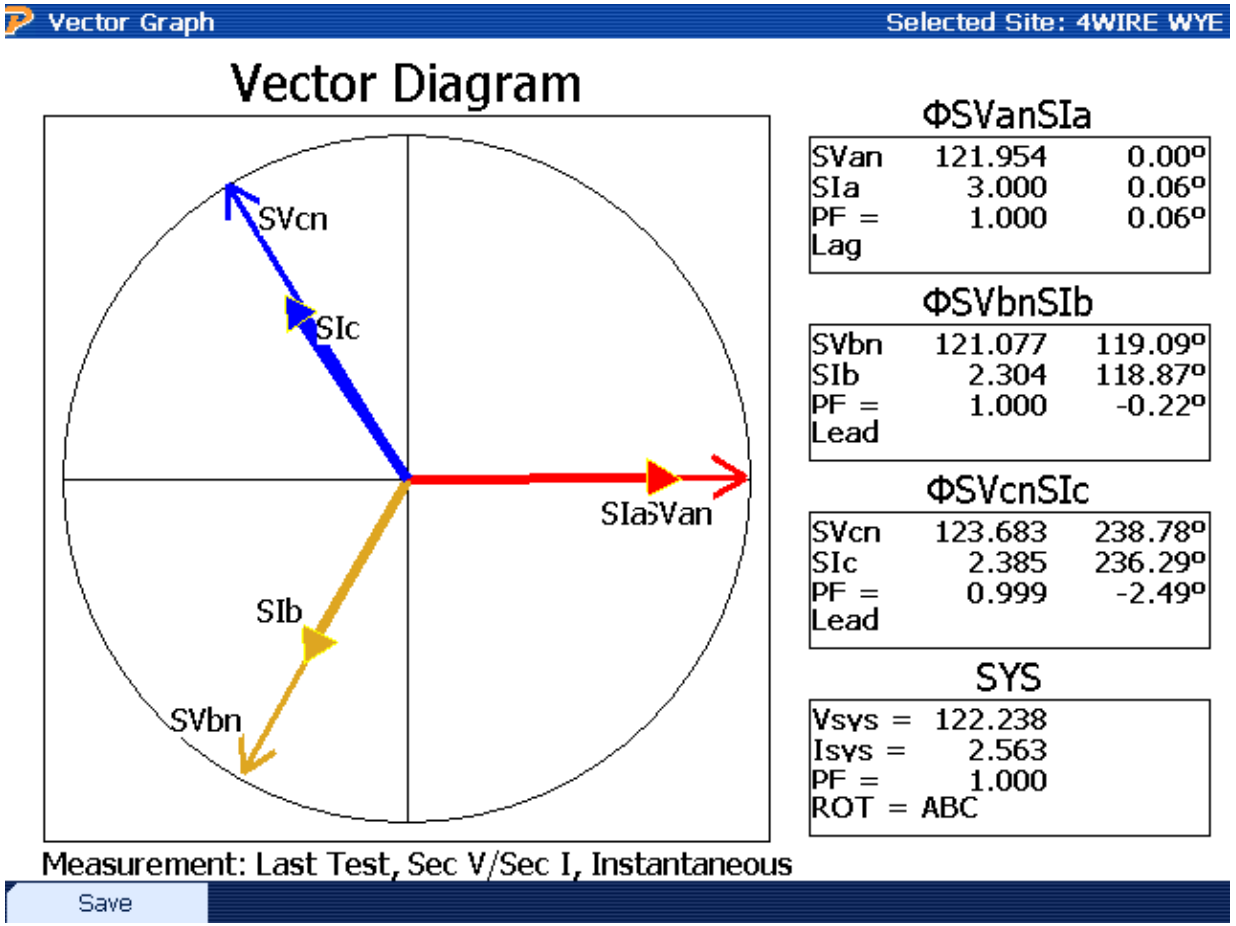
- Same site as above: What went wrong???



POWERMETRIX

Testing Current Transformers
What's Wrong?

- Same site as above: What went wrong???



POWERMETRIX

Testing Current Transformers

What's Wrong? → Power Theft

A simple piece of wire wrapped around the CT.

Power thefts surge in bad times

It's dangerous, and other consumers pick up the tab

By Paul Davidson
USA TODAY

As the dismal economy spawns desperate measures, some Americans are resorting to a hazardous practice: stealing electricity.

Many utilities say energy theft has risen sharply during the economic downturn. Culprits include

vice was turned off in early 2008, 30% were illegally using electricity late last year, utility PECO says.

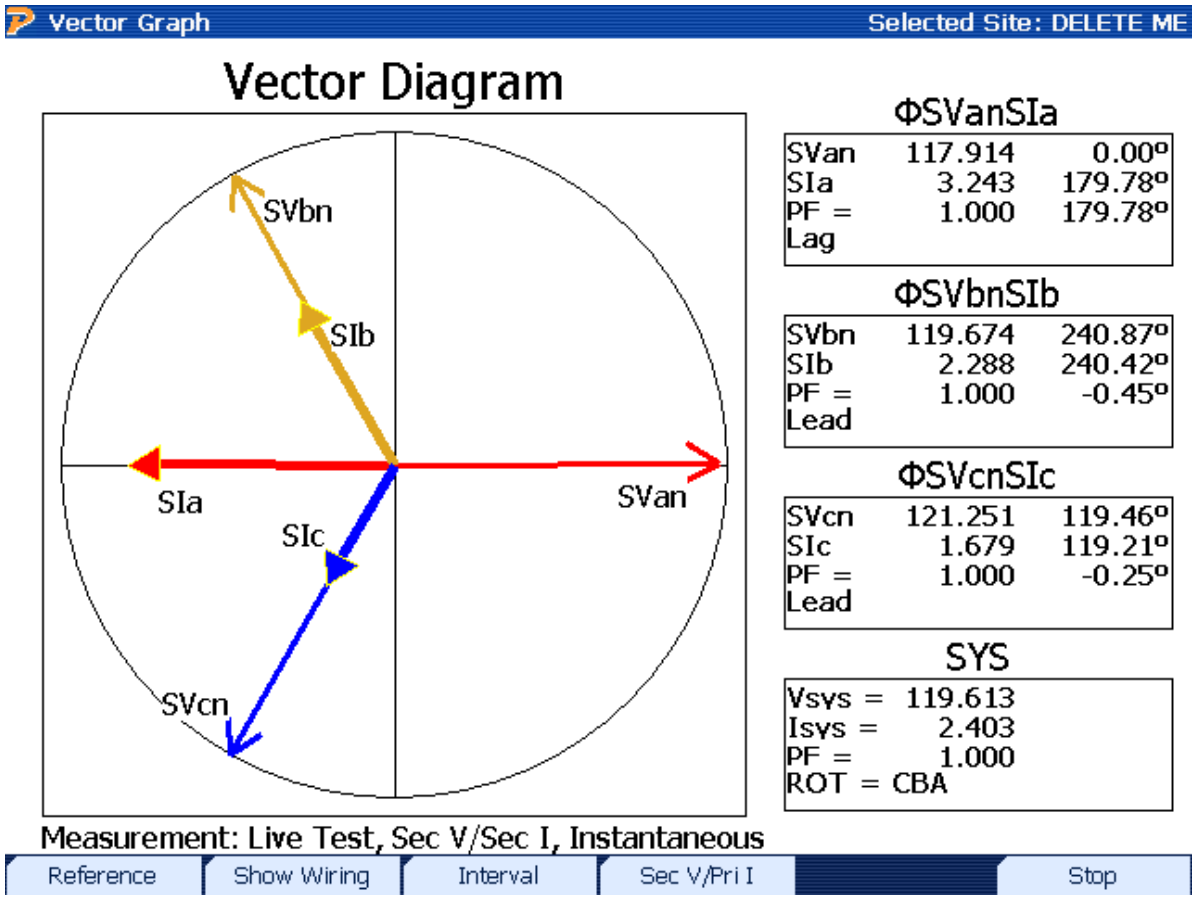
Customers have stolen power for decades, costing utilities 1% to 3% of revenue — or about $6 billion industrywide — each year, according to *Electric Light & Power* magazine. Losses are borne by other customers. Many thieves operate home-based marijuana farms that use lots of lights.

But the problem is mushrooming. In Pennsylvania, utility PPL says thefts rose 16% last year, with fewer drug-related incidents and more tied to ser-

POWERMETRIX

Testing Current Transformers

What's Wrong?

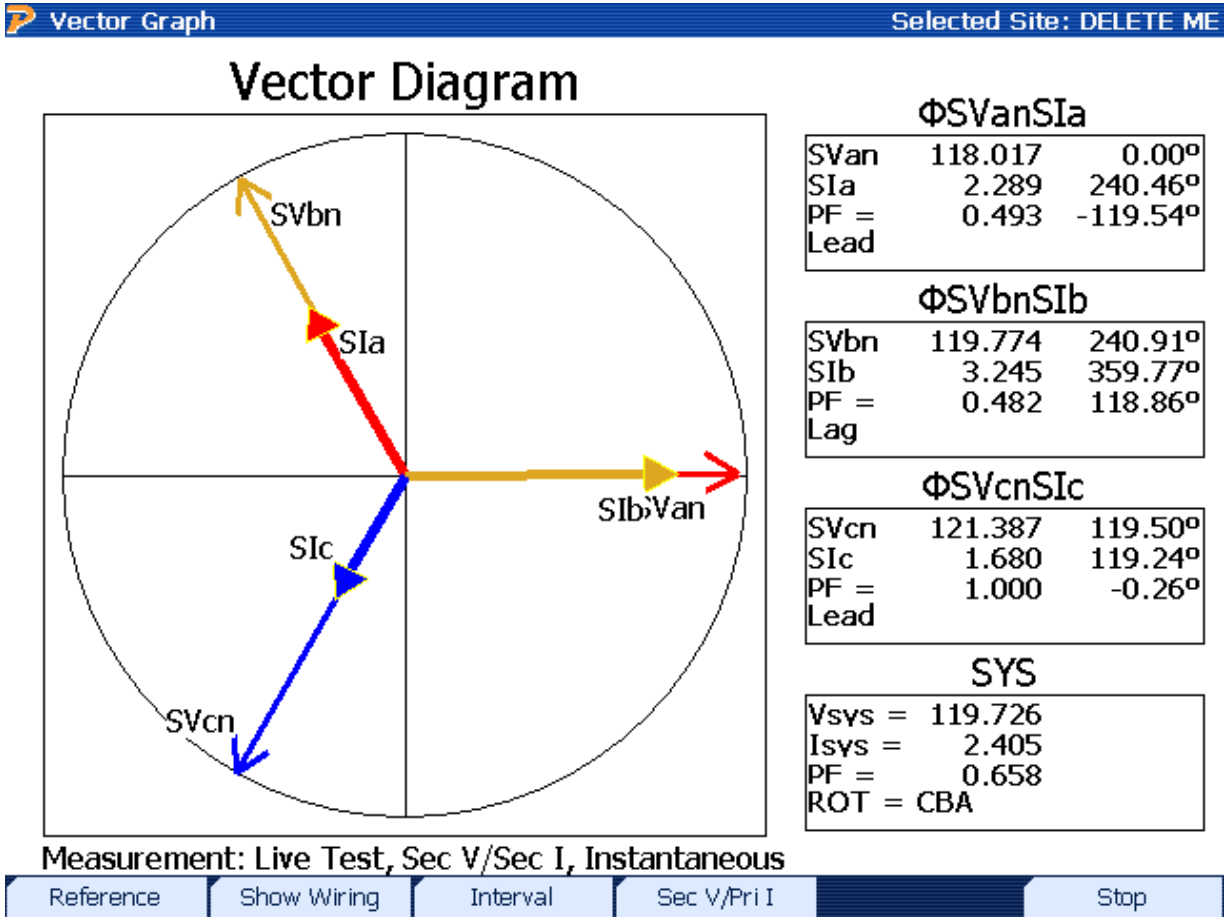


Phase A CT reversed.

POWERMETRIX

Testing Current Transformers

What's Wrong?



Phase A & B CTs swapped.

POWERMETRIX