Power Measurements

Technology Consulting

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Non-Blondel Metering

- What exactly does "Non-Blondel" mean
  - Who the heck was Blondel anyway?

Andre Blondel was a Frenchman born in 1863. His illustrious career included the invention of the high speed oscillograph, creation of the lumen as the unit of measure for light, work on synchronous generators, and pioneering work on high voltage AC transmission lines.

We know him best as author of the fundamental theorem by which we measure electric power.

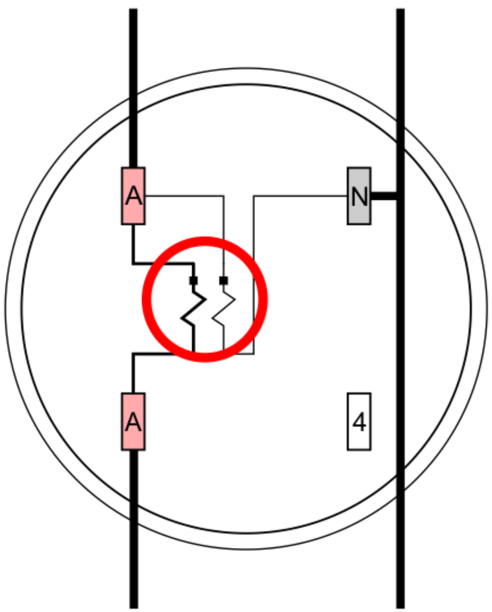
Blondel's Theorem

If energy be supplied to any system of conductors through N wires, the total power in the system is given by the algebraic sum of the readings of N wattmeters, so arranged that each of the N wires contains one current coil, the corresponding voltage coil being connected between that wire and some common point. If this common point is on one of the N wires, the measurement may be made by the use of N-1 wattmeters.

Blondel’s Theorem

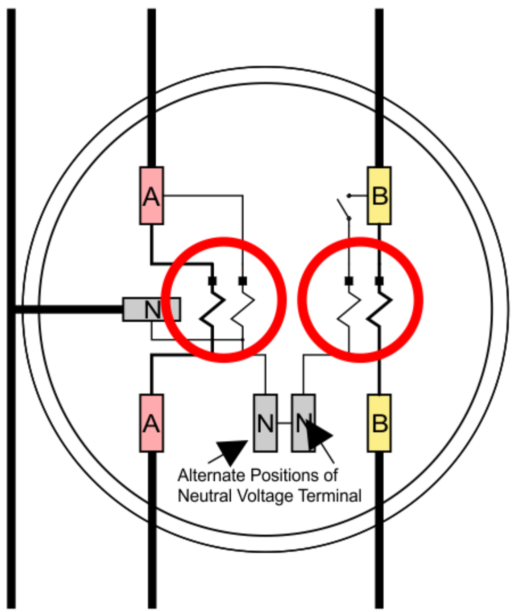
Blondel Compliant Metering

2 Wires
1 Meter



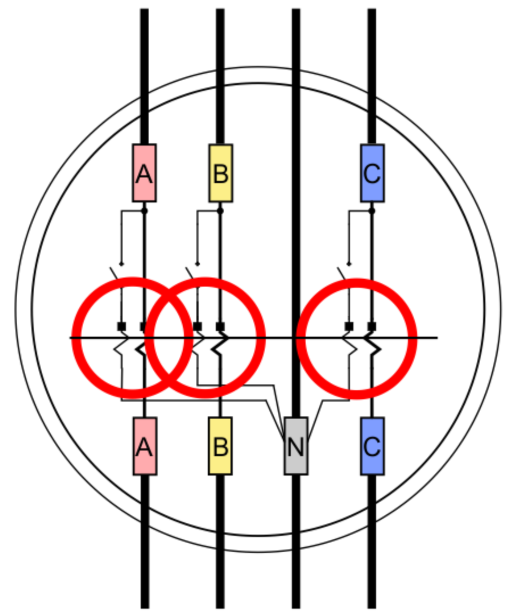
1S

3 Wires
2 Meters



12S

4 Wires
3 Meters

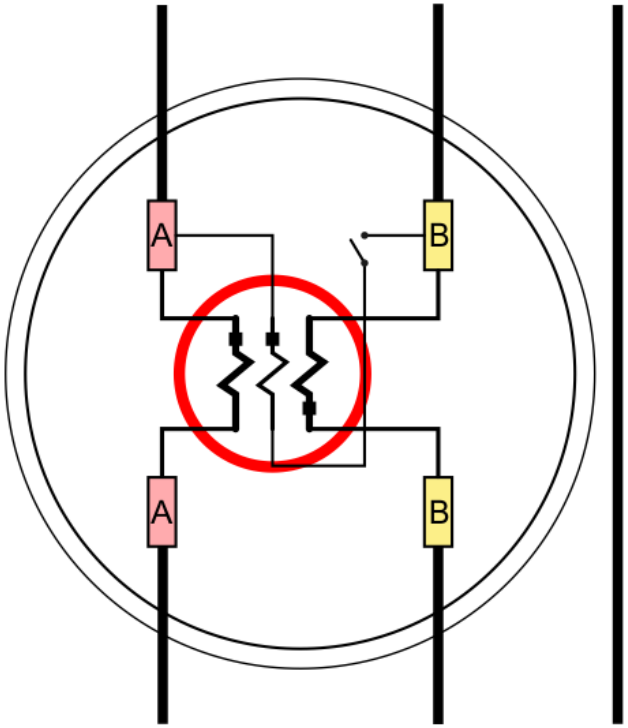


9S

Blondel's Theorem

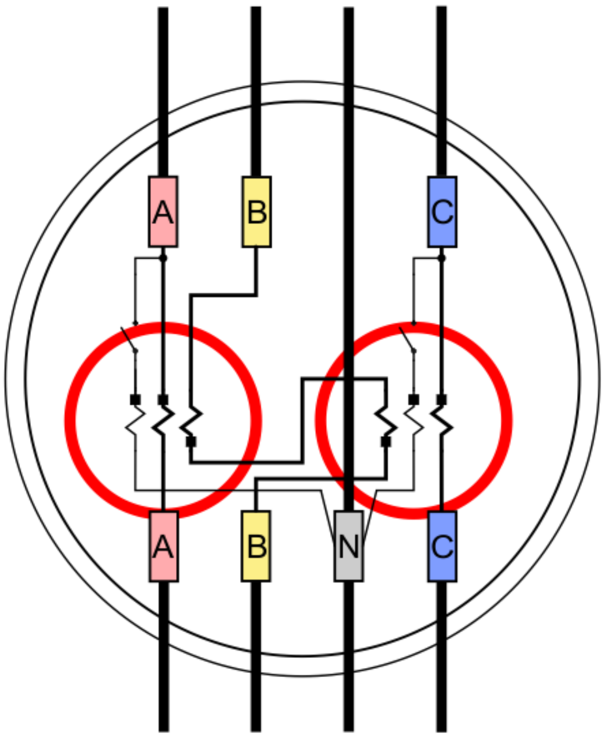
Non-Blondel Compliant Metering

3 Wires
1 Meter



2S

4 Wires
2 Meters



8S

Non-Blondel Metering

- Why is Non-Blondel metering bad?
  - Makes assumption about service
    - For example, balanced voltages
  - Assumption may not be true
  - When assumption isn’t true, then there are power measurement errors even if the meter is working perfectly

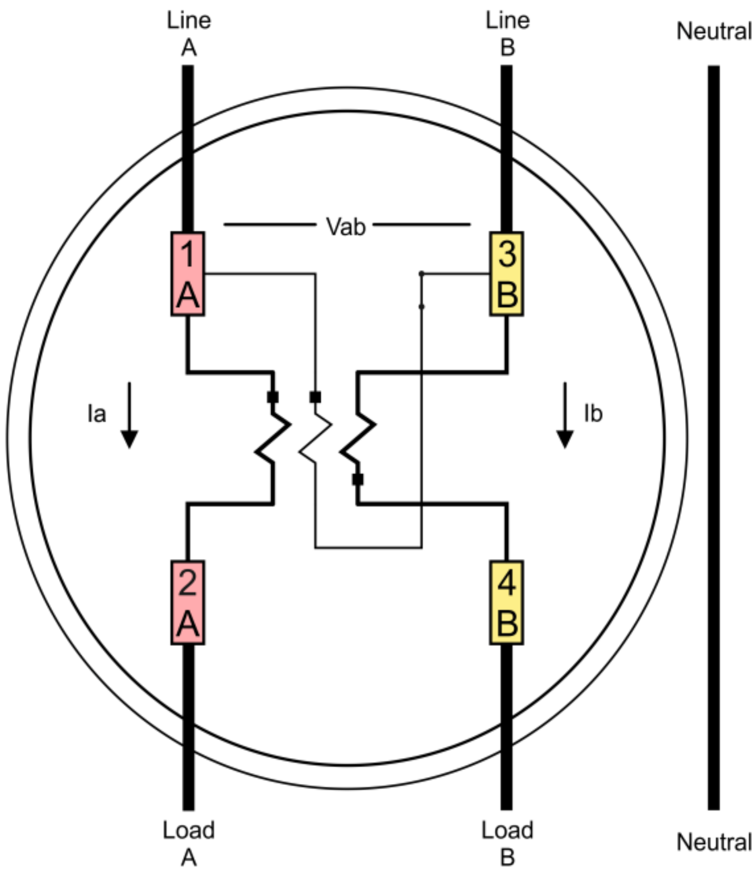
Non-Blondel Metering

- Why were Non-Blondel meters used?
  - Fewer elements (meters) = lower cost
    - Especially true for electromechanical meters
  - Fewer CTs and PTs = lower cost
  - Less wiring and cheaper sockets

Non-Blondel Metering

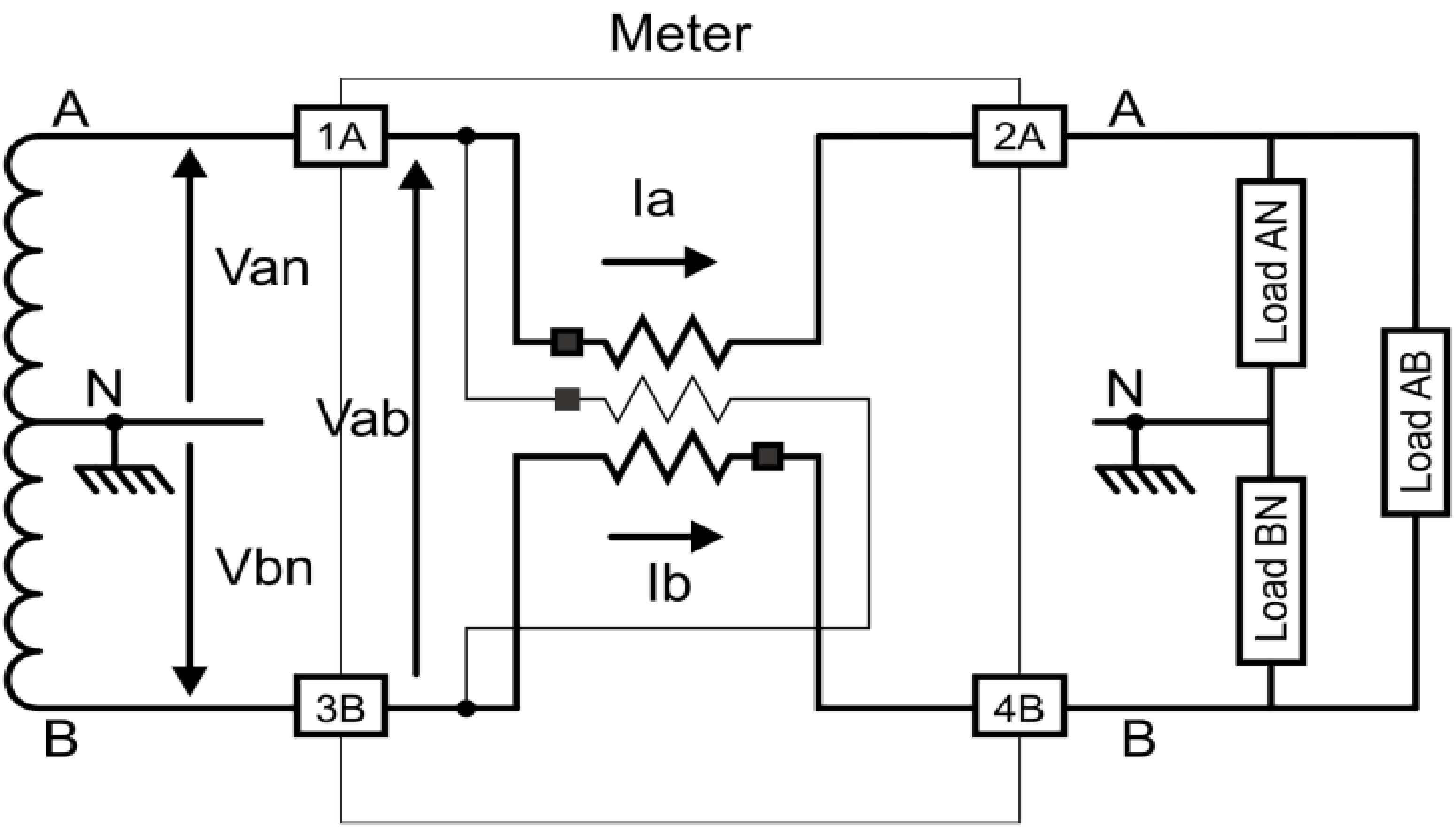
Gp	Application	Power Blondel (Vector Notation)	Power as Metered (Vector Notation)
1	Single Phase (1V 2I) 2S, 4S Internal circuitry does current differencing.	$P = \overrightarrow{Van} \cdot \vec{Ia} + \overrightarrow{Vbn} \cdot \vec{Ib}$	$P = 0.5 * \overrightarrow{Vab} \cdot (\vec{Ia} - \vec{Ib})$
2	4-Wire Wye (2V 2I) (2PT 3CT) 5S, 26S, 45S, 66S External CTs do current differencing.	$P = \overrightarrow{Van} \cdot \vec{Ia} + \overrightarrow{Vbn} \cdot \vec{Ib} + \overrightarrow{Vcn} \cdot \vec{Ic}$	$P = \overrightarrow{Van} \cdot (\vec{Ia} - \vec{Ib}) + \overrightarrow{Vcn} \cdot (\vec{Ic} - \vec{Ib})$
3	4-Wire Wye (2V 3I) (2PT 3CT) 6S, 7S, 14S, 29S, 36S, 46S Internal circuitry does current differencing.	$P = \overrightarrow{Van} \cdot \vec{Ia} + \overrightarrow{Vbn} \cdot \vec{Ib} + \overrightarrow{Vcn} \cdot \vec{Ic}$	$P = \overrightarrow{Van} \cdot (\vec{Ia} - \vec{Ib}) + \overrightarrow{Vcn} \cdot (\vec{Ic} - \vec{Ib})$
4	4-Wire Delta 5S, 45S (2V 2I) (2CT 2PT) External CTs do current differencing.	$P = \overrightarrow{Van} \cdot \vec{Ia} + \overrightarrow{Vbn} \cdot \vec{Ib} + \overrightarrow{Vcn} \cdot \vec{Ic}$	$P = \overrightarrow{Vab} \cdot (\vec{Ia} - \vec{Ib}) + 2 * \overrightarrow{Vcn} \cdot \vec{Ic}$ Meter measures 2x actual unless CT Ratio set to ½ actual
5	4-Wire Delta (2V 3I) (3CT 2PT) 8S, 15S, 24S Internal circuitry does current differencing.	$P = \overrightarrow{Van} \cdot \vec{Ia} + \overrightarrow{Vbn} \cdot \vec{Ib} + \overrightarrow{Vcn} \cdot \vec{Ic}$	$P = 0.5 * \overrightarrow{Vab} \cdot (\vec{Ia} - \vec{Ib}) + \overrightarrow{Vcn} \cdot \vec{Ic}$

2S Meters



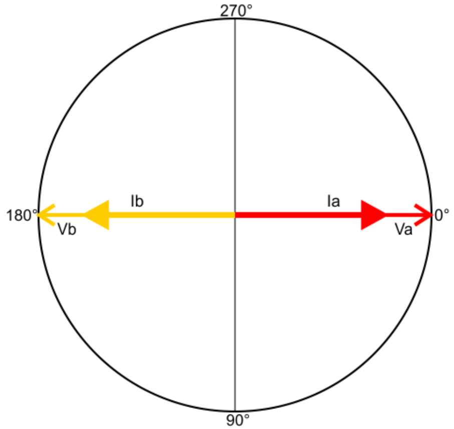
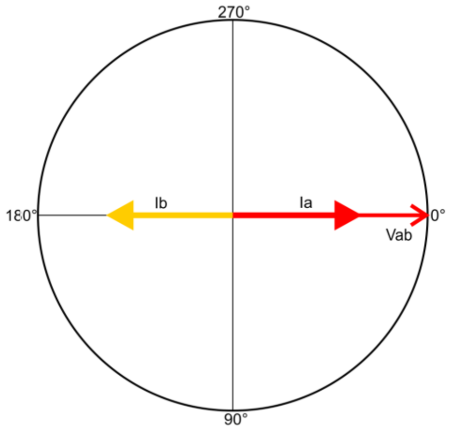
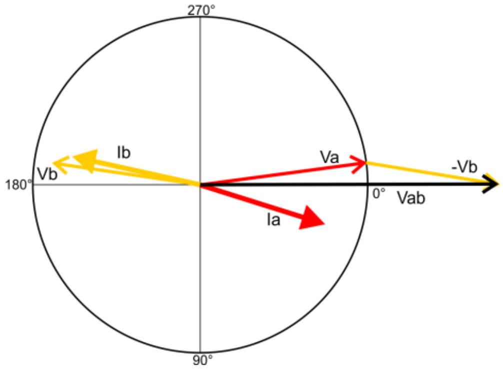
Most common US meter
Residential meter of choice

2S Meters



Meter
A
1A
2A
A
Ia
Van
Load AN
N
Vab
N
Load AB
Vbn
Ib
Load BN
3B
4B
B
B

2S Meters

Blondel Meter	**Non-Blondel 2S Meter**	**General Case**
Va and Vb are equal and opposite and loads balanced under ideal conditions.	Only Vab is measured.	Unbalanced Voltages and Currents
		

A Bit of Math

When we calculate power based on trigonometric functions, our calculation sounds simple:

Power = V I Cos(θ) where θ is the angle between the voltage and current

The challenge comes in calculating θ when the voltage and current appear at arbitrary angles.

There is a different and simpler approach available by couching the problem in a different way. This “vector” approach is easier to apply and compute in more complex applications, AND provides a natural extension to the computation of VA and VAR.

If you have two vectors and then the dot product of the two vectors is:

$$V \cdot I = VICos(\theta) = Vx * Ix + Vy * Iy$$

A Bit of Math

By using the Cartesian representation in our calculations, the formulization becomes very straight forward. All we need to remember is that:

$$Vx = VCos(\varphi_v) \quad Vy = VSin(\varphi_v)$$

To calculate the power for a voltage V at a phase and a current I at a phase we have:

$$Power = VICos(\varphi_v - \varphi_i) = VCos(\varphi_v) * ICos(\varphi_i) + VSin(\varphi_v) * ISin(\varphi_i) = Vx * Ix + Vy * Iy$$

Now we'll use this approach to analyze the errors due to the assumptions in the common non-Blondel metering applications.

2S Metering Analysis

In a 2S meter we measure:

$$P = 0.5 * \overrightarrow{Vab} \cdot (\overrightarrow{Ia} - \overrightarrow{Ib})$$

$$P = 0.5 * \left[(Vanx - Vbnx) * (Iax - Ibx) + (Vany - Vbny) * (Iay - Iby) \right]$$

Under what circumstances are there NO errors?

The error associated with this metering approach is:

Err = P(as measured by 2S) - P(as measured by 12S)

$$Err = -0.5 * \left[(Vanx + Vbnx) * (Ibnx + Ianx) + (Vany + Vbny) * (Ibny + Iany) \right]$$

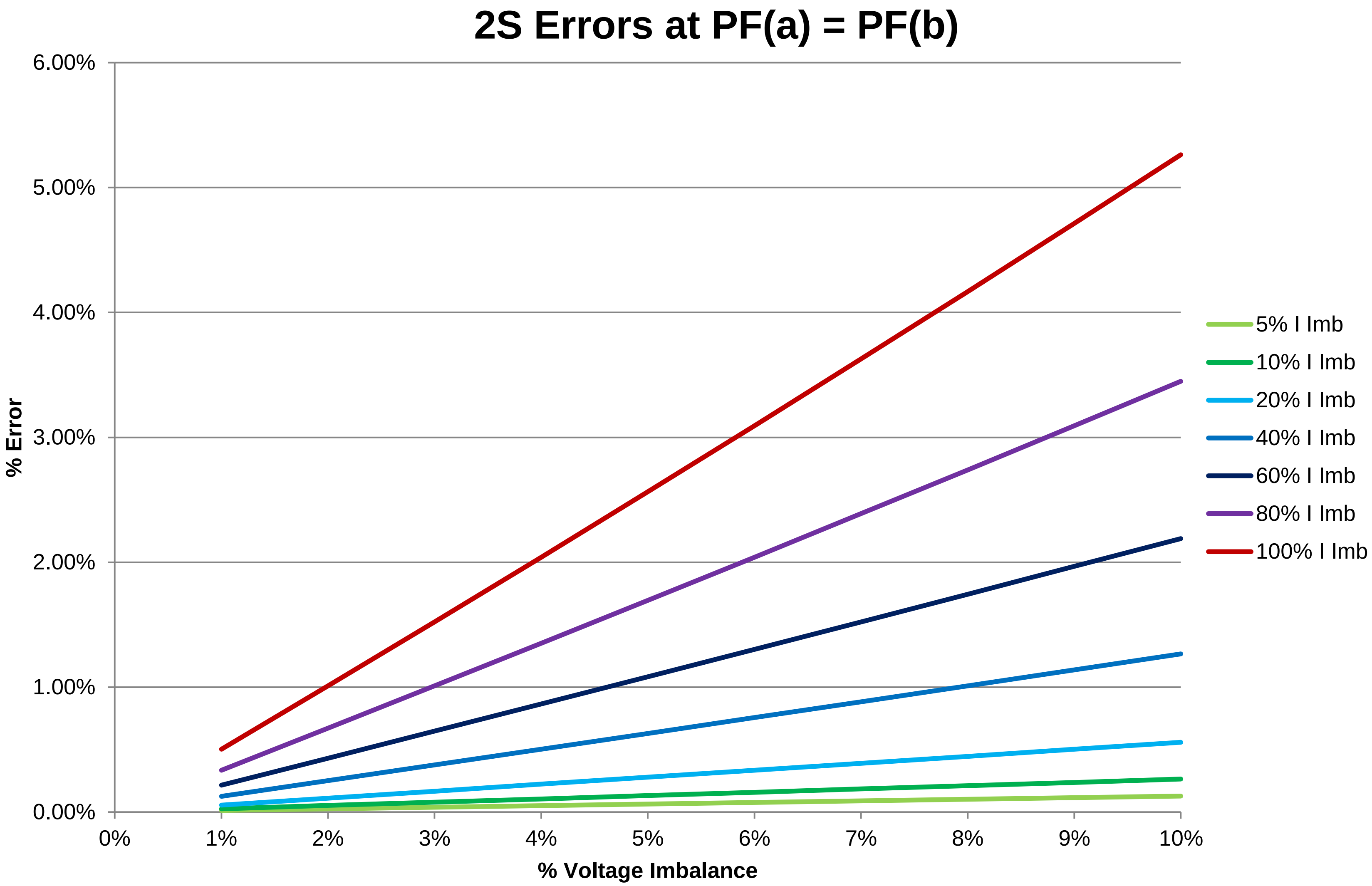
The errors will be zero if:

$$\overrightarrow{Ia} = -\overrightarrow{Ib} \quad \text{or} \quad \overrightarrow{Va} = -\overrightarrow{Vb}$$

2S Metering Analysis

Condition	% V	% I	Phase A				Phase B				Blondel	non-Blondel Error	non-Blondel % Error
	Imb	Imb	V	ϕvan	I	ϕian	V	ϕvbn	I	ϕibn			
All balanced	0	0	120	0	100	0	120	180	100	180	24000	0.0	0.00%
Unbalanced voltages PF=1	18%	0%	108	0	100	0	132	180	100	180	24000	0.0	0.00%
Unbalanced current PF=1	0%	18%	120	0	90	0	120	180	110	180	24000	0.0	0.00%
Unbalanced V&I PF=1	5%	18%	117	0	90	0	123	180	110	180	24060	-60.0	-0.25%
Unbalanced V&I PF=2	8%	18%	110	0	90	0	120	180	110	180	23100	-100.0	-0.43%
Unbalanced V&I PF=3	8%	50%	110	0	50	0	120	180	100	180	17500	-250.0	-1.43%
Unbalanced V&I PF=1	18%	40%	108	0	75	0	132	180	125	180	24600	-600.0	-2.44%
Unbalanced voltages PF≠1 PFa = PFb	18%	0%	108	0	100	30	132	180	100	210	20785	0.0	0.00%
Unbalanced current PF≠1 PFa = PFb	0%	18%	120	0	90	30	120	180	110	210	20785	0.0	0.00%
Unbalanced V&I PF≠1 PFa = PFb	18%	18%	108	0	90	30	132	180	110	210	20992	-207.8	-0.99%
Unbalanced V&I PF≠1 PFa = PFb	18%	40%	108	0	75	30	132	180	125	210	21304	-519.6	-2.44%
Unbalanced voltages PF≠1 PFa ≠ PFb	18%	0%	108	0	100	60	132	180	100	210	16832	-439.2	-2.61%
Unbalanced current PF≠1 PFa ≠ PFb	0%	18%	120	0	90	60	120	180	110	210	16832	0.0	0.00%
Unbalanced V&I PF≠1 PFa ≠ PFb	18%	18%	108	0	90	60	132	180	110	210	17435	-603.2	-3.46%
Unbalanced V&I PF≠1 PFa ≠ PFb	18%	40%	108	0	75	60	132	180	125	210	18339	-849.0	-4.63%

2S Metering Analysis



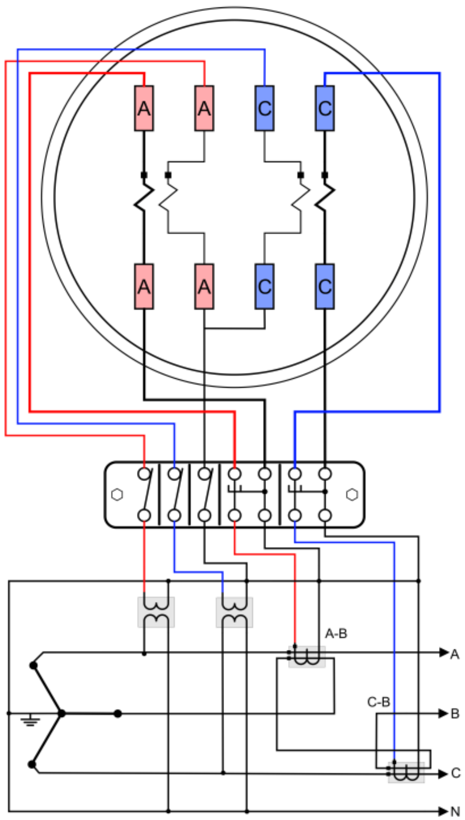
4-Wire WYE

Non-Blondel Metering

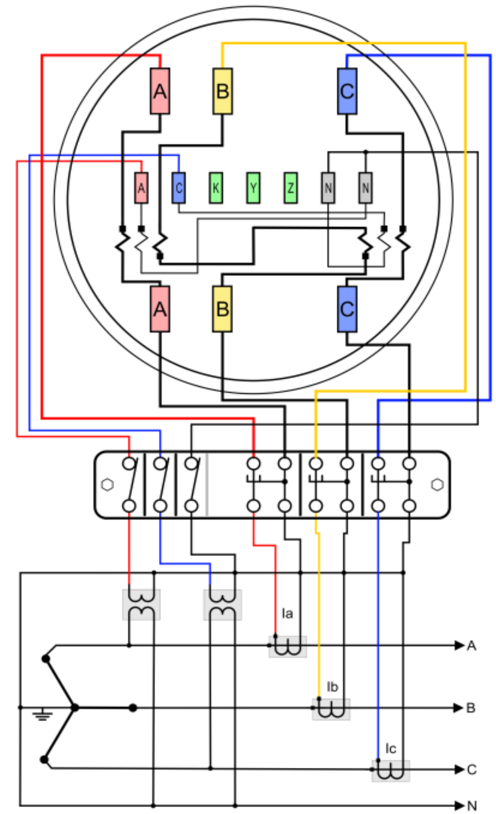
- Two families of meters for this application
  - 2 Element meters (5S Family)
    - 5S, 26S, 45S, 66S
    - Utilize CTs with two phases per CT
  - 2.5 Element meters (6S Family)
    - 6S, 7S, 14S, 29S, 36S, 46S

4-Wire Wye Metering

5S Family



6S Family



$$P = \overrightarrow{Van} \cdot (\overrightarrow{Ia} - \overrightarrow{Ib}) + \overrightarrow{Vcn} \cdot (\overrightarrow{Ic} - \overrightarrow{Ib})$$

4-Wire Wye Analysis

In a these meters we measure:

$$P = \overrightarrow{Van} \cdot (\overrightarrow{Ia} - \overrightarrow{Ib}) + \overrightarrow{Vcn} \cdot (\overrightarrow{Ic} - \overrightarrow{Ib})$$

The error associated with this metering approach is:

Err = P(as measured by 6S) - P(as measured by 9S)

$$Err = Ibnx * (Vanx + Vbnx + Vbnx) + Ibny * (Vany + Vbny + Vcny)$$

The errors will be zero if:

$$0 = \overrightarrow{Va} + \overrightarrow{Vb} + \overrightarrow{Vc}$$

The vectorial sum of voltages is zero.

4-Wire Wye Analysis

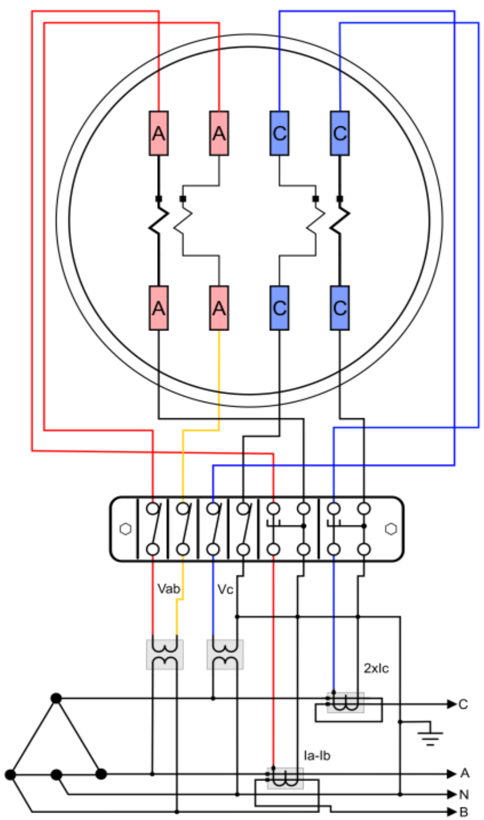
	% V	% I	Phase A				Phase B				Phase C				Blondel	non-Blondel	non-Blondel
Condition	**Imb**	**Imb**	**V**	**φvan**	**I**	**φian**	**V**	**φvbn**	**I**	**φibn**	**V**	**φvcn**	**I**	**φicn**		**Error**	**% Error**
All balanced	0%	0%	120	0	100	0	120	120	100	120	120	240	100	240	36000	0	0.00%
Unbalanced voltages PF=1	5%	25%	118	0	100	0	123	120	100	120	119	240	120	240	38380	450	1.17%
Unbalanced current PF=1	5%	40%	118	0	100	0	123	120	80	120	119	240	120	240	35920	360	1.00%
Unbalanced voltages PF=1	5%	71%	118	0	100	0	123	120	60	120	119	240	120	240	33460	270	0.81%
Unbalanced current PF=1	5%	108%	118	0	100	0	123	120	40	120	119	240	120	240	31000	180	0.58%
Unbalanced V&I PF≠1	10%	0%	115	0	100	30	125	120	100	150	117	240	100	270	30917	866	2.80%
Unbalanced V&I PF≠1	10%	0%	115	0	100	60	125	120	100	180	117	240	100	300	17850	600	3.36%
Unbalanced V&I PF≠1	10%	0%	115	0	100	0	125	122	100	120	117	238	100	240	35685	1250	3.50%
Unbalanced V&I PF≠1	10%	73%	115	0	60	30	125	122	100	150	117	238	60	240	24028	1486	6.18%
Unbalanced V&I PF≠1	8%	71%	115	0	60	60	125	115	100	180	120	240	120	300	15933	-217	-1.36%
Unbalanced V&I PF≠1	8%	40%	115	0	80	60	125	119	120	120	120	240	100	240	31598	898	2.84%
Unbalanced V&I PF≠1	8%	40%	115	0	80	30	125	120	120	150	120	240	100	210	31350	1039	3.31%
Unbalanced V&I PF≠1	10%	77%	125	0	80	60	117	125	120	150	115	245	60	270	23978	-1469	-6.12%

4-Wire Delta
Non-Blondel Metering

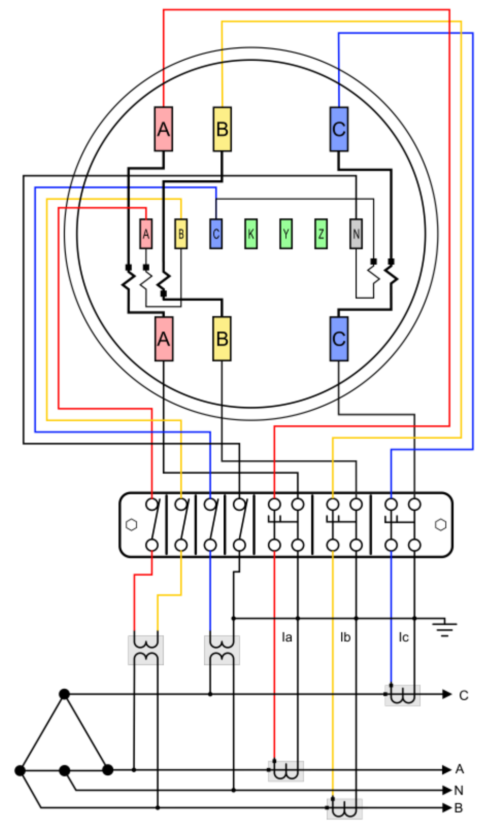
- Two families of meters for this application
  - 2 Element meters (5S Family)
    - 5S, 45S
    - Utilize CTs with two phases per CT
    - Measures 2X actual, Xfmr ratio must be adjusted
  - 2.5 Element meters (8S Family)
    - 8S, 15S, 24S

4-Wire Delta Metering

5S Family



8S Family



$$P = 0.5 * \overrightarrow{Vab} \cdot (\overrightarrow{Ia} - \overrightarrow{Ib}) + \overrightarrow{Vcn} \cdot \overrightarrow{Ic}$$

4-Wire Delta Analysis

In a these meters we measure:

$$P = 0.5 * \overrightarrow{Vab} \cdot (\overrightarrow{Ia} - \overrightarrow{Ib}) + \overrightarrow{Vcn} \cdot \overrightarrow{Ic}$$

The error associated with this metering approach is:

Err = P(as measured by 8S) - P(as measured by 9S)

$$Err = -0.5 * \left[(Vanx + Vbnx) * (Ianx + Ibnx) + (Vany + Vbny) * (Iany + Ibny) \right]$$

Note: There is no error associated with phase C.

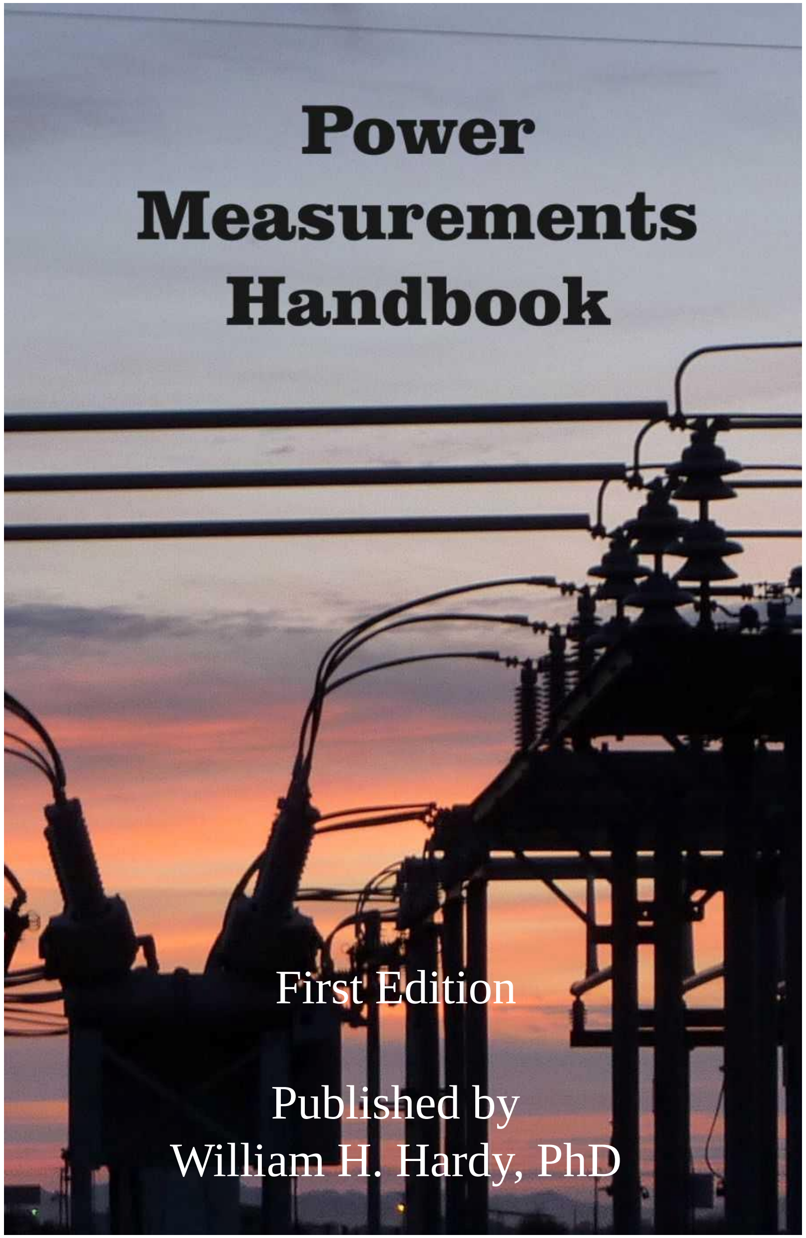
For phase A & B the error is the same as a 2S meter.

The errors will be zero if:

$$\overrightarrow{Ia} = -\overrightarrow{Ib} \qquad \overrightarrow{Va} = -\overrightarrow{Vb}$$

4-Wire Delta Analysis

	% V	% I	Phase A				Phase B				Phase C	Blondel Power	non-Blondel Error	non-Blondel % Error
Condition	Imb	Imb	V	Φ van	I	Φ ian	V	Φ vbn	I	Φ ibn	Power			
All balanced	0	0	120	0	100	0	120	180	100	180	20800	24000	0.0	0.00%
Unbalanced voltages PF=1	20%	0%	108	0	100	0	132	180	100	180	20800	24000	0.0	0.00%
Unbalanced current PF=1	0%	20%	120	0	90	0	120	180	110	180	20800	24000	0.0	0.00%
Unbalanced V&I PF=1	20%	20%	108	0	90	0	132	180	110	180	20800	24240	-240.0	-0.53%
Unbalanced V&I PF=1	20%	50%	108	0	75	0	132	180	125	180	20800	24600	-600.0	-1.32%
Unbalanced voltages PF≠1 PFa = PFb	20%	0%	108	0	100	30	132	180	100	210	10400	20785	0.0	0.00%
Unbalanced current PF≠1 PFa = PFb	0%	20%	120	0	90	30	120	180	110	210	10400	20785	0.0	0.00%
Unbalanced V&I PF≠1 PFa = PFb	20%	20%	108	0	90	30	132	180	110	210	10400	20992	-207.8	-0.66%
Unbalanced V&I PF≠1 PFa = PFb	20%	50%	108	0	75	30	132	180	125	210	10400	21304	-519.6	-1.64%
Unbalanced voltages PF≠1 PFa ≠ PFb	20%	0%	108	0	100	60	132	180	100	210	10400	16832	-439.2	-1.61%
Unbalanced current PF≠1 PFa ≠ PFb	0%	20%	120	0	90	60	120	180	110	210	10400	16832	0.0	0.00%
Unbalanced V&I PF≠1 PFa ≠ PFb	20%	20%	108	0	90	60	132	180	110	210	10400	17435	-603.2	-2.17%
Unbalanced V&I PF≠1 PFa ≠ PFb	20%	50%	108	0	75	60	132	180	125	210	10400	18339	-849.0	-2.95%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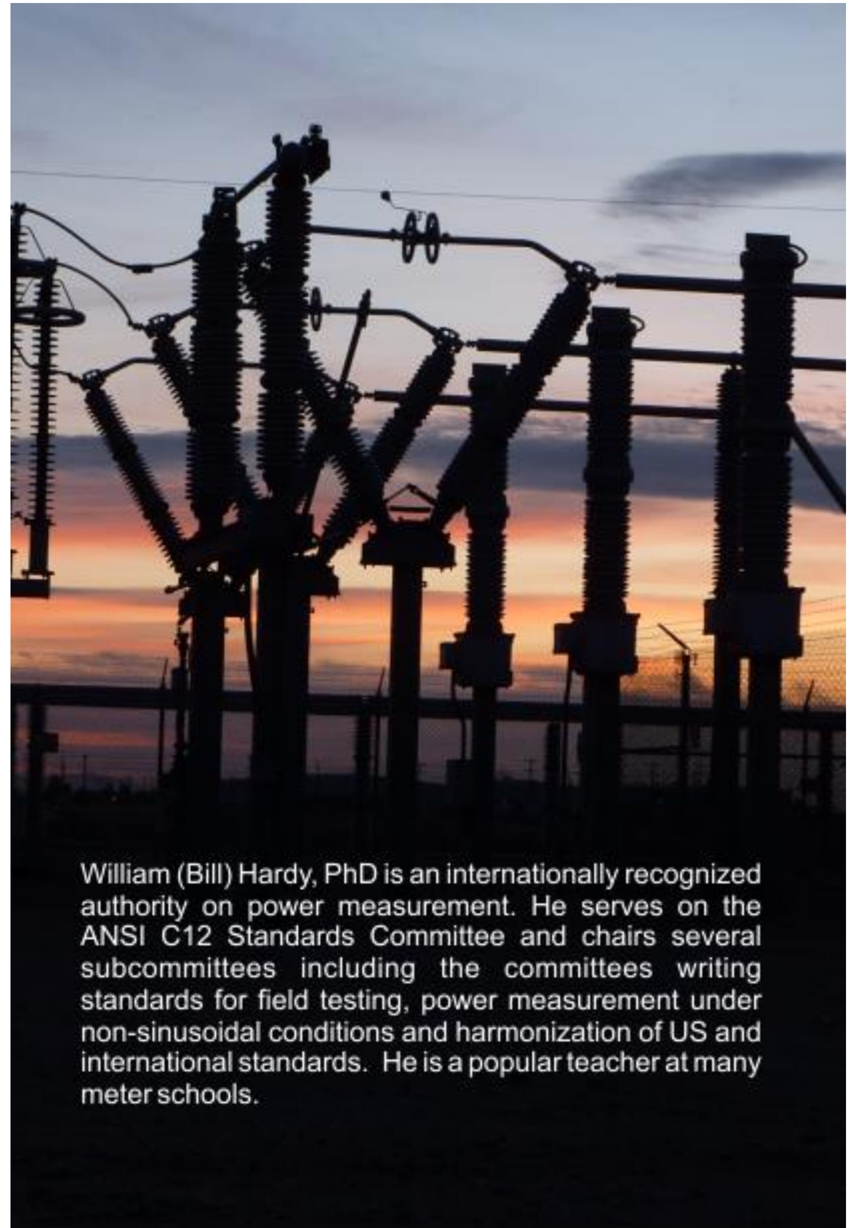
William (Bill) Hardy, PhD is an internationally recognized authority on power measurement. He serves on the ANSI C12 Standards Committee and chairs several subcommittees including the committees writing standards for field testing, power measurement under non-sinusoidal conditions and harmonization of US and international standards. He is a popular teacher at many meter schools.