PREVENTING TRANSFORMER MIS-OPERATIONS FOR EXTERNAL FAULTS

Joe Perez P.E
Protection Engineer
SynchroGrid

Rene Aguilar
Sr. Applications Engineer
Megger

Outline

- **Transformer Protection**
- **Differential Protection**
  - Electromechanical scheme
  - Microprocessor scheme
- **Traditional Test Methods**
- **New Test Methods**
- **Case Study**
  - 138 KV/13.8/4.16 Three Winding Transformer mis-operation due to external fault

Transformers

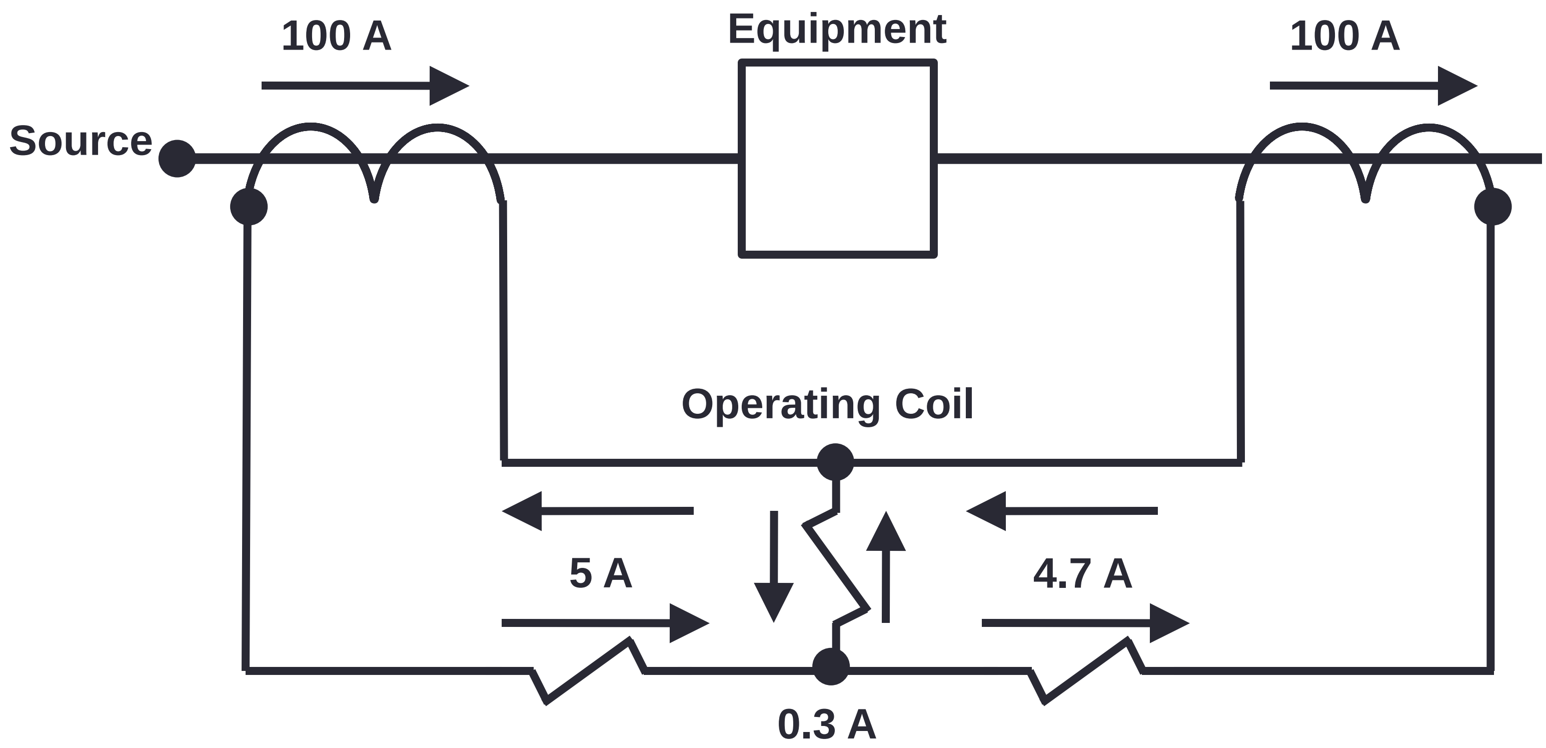
- Used all over the system at various voltage levels
- Sizes vary from 3kVA – 500 MVA
- Many types
  - Step up
  - Step down
  - Autotransformers
- Replacement time is significantly long. Long outage time
- Transformers require protection but this depends on size of transformer.

Transformer Protection

- **>5 MVA**
  - 87T (Differential)
  - 50/51 (Overcurrent)
  - 50G (Ground Overcurrent)
  - 51G (Ground overcurrent backup)
  - 63 & 63X (Sudden Pressure)
- **Types of Faults**
  - Internal (Should Trip)
    - Winding Failures
    - Tap Changer Failures
    - Bushing Failures
    - Core Failures
  - External (Should Trip as backup)
    - faults outside the transformer differential zone of protection

Differential Protection

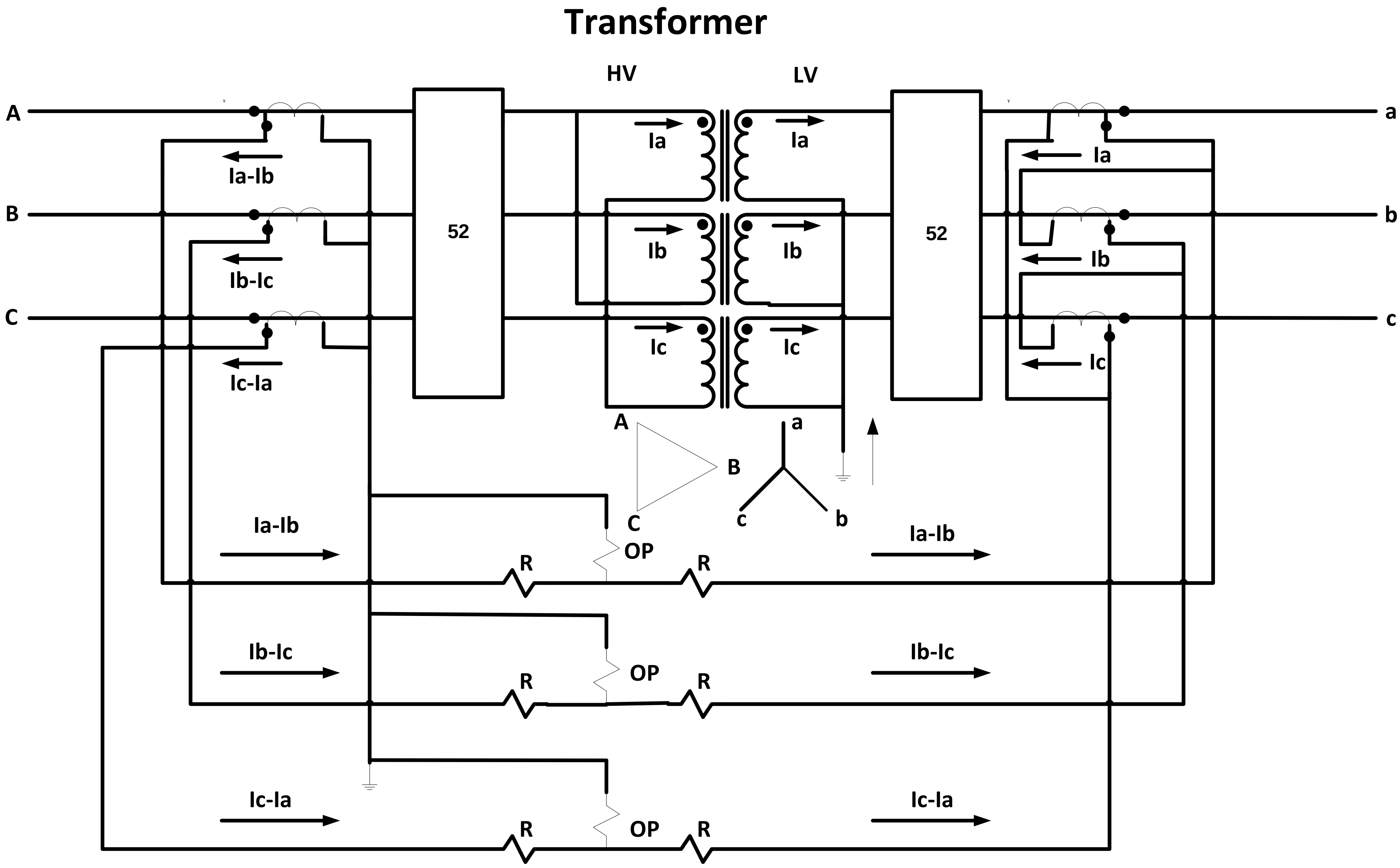
- **Current In = Current Out**



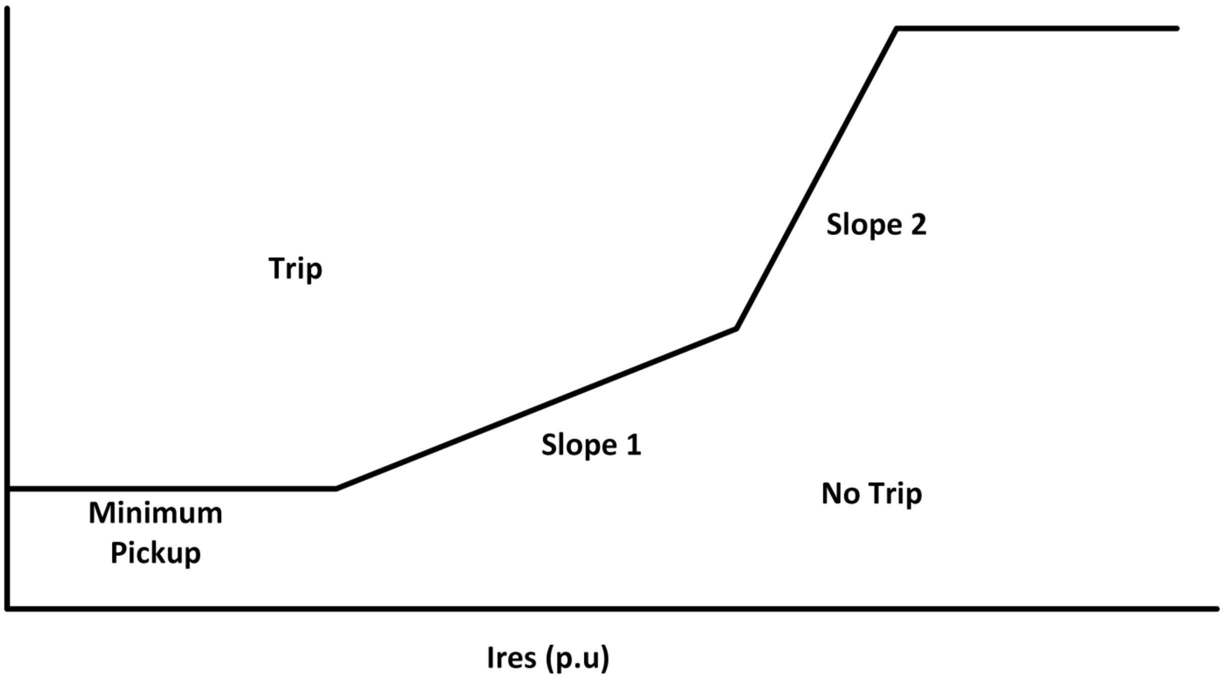
Differential Protection (Challenges)

- **Sources of unbalance**
    - CT Mismatch
        - Differences in CT ratios
    - CT Saturation
        - External faults
    - Magnetizing inrush current
    - Phase shift (vector group)
        - Wye-Delta
        - Delta-Wye
    - Zero sequence current compensation

Differential Protection (E/M Scheme)



Differential Protection (Slope Char.)



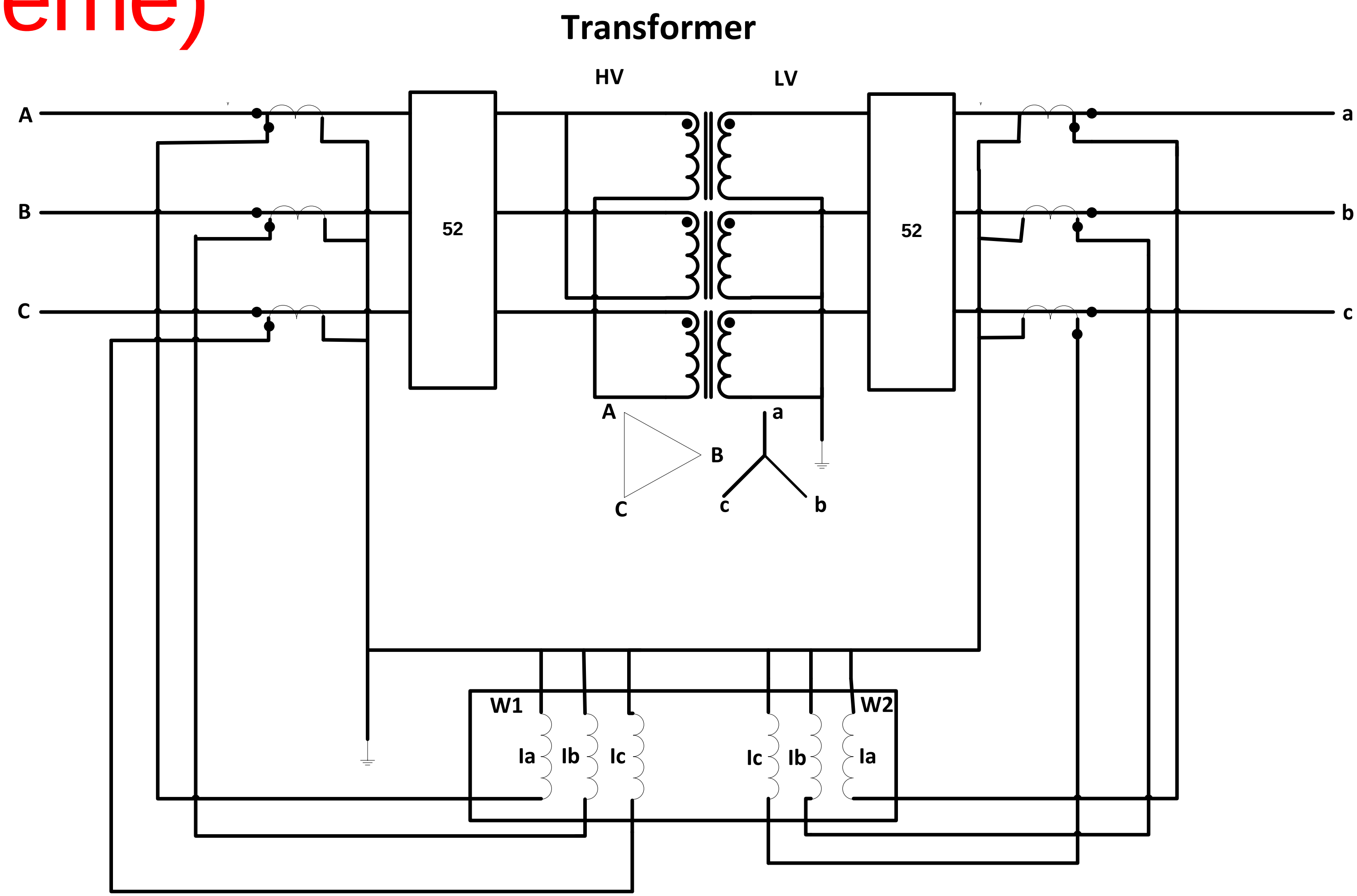
$$I_{OPERATE(PU)} = \frac{I_{Winding1}\angle\Theta_{Winding1}}{Tap_{HV}} + \frac{I_{Winding2}\angle\Theta_{Winding2}}{Tap_{LV}}$$

$$I_{RESTRAINT(PU)} = k \times \left(\frac{\left|I_{Winding1}\angle\Theta_{Winding1}\right|}{Tap_{HV}} + \frac{\left|I_{Winding2}\angle\Theta_{Winding2}\right|}{Tap_{LV}} \right)$$

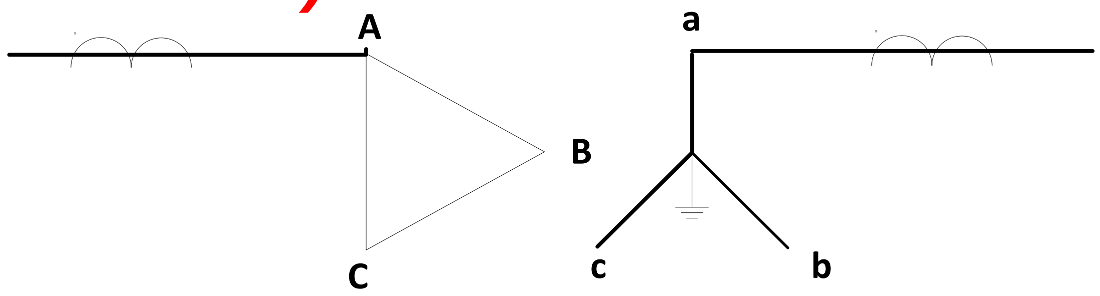
Testing E/M Scheme (Common Test Methods)

- **Single Phase**
  - One relay per phase
  - Primarily concerned with verification of relay for internal faults not necessarily external faults
  - External fault verification was performed either by primary or secondary injection of differential circuits
  - Does not simulate realistic system conditions (not an issue for E/M schemes)
  - However, some of these test methods are still being used to verify operation of microprocessor transformer differential relay.
    - This can lead to erroneous results

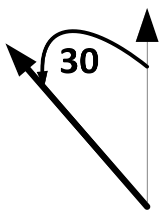
Differential Protection (Microprocessor Scheme)



Differential Protection (Vector Compensation)



Dy1



$$\begin{bmatrix} W1A_{COMP} \\ W1B_{COMP} \\ W1C_{COMP} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 1 & 0 \end{bmatrix} \times \begin{bmatrix} Ia \\ Ib \\ Ic \end{bmatrix}$$

$$\begin{bmatrix} W2A_{COMP} \\ W2B_{COMP} \\ W2C_{COMP} \end{bmatrix} = \frac{1}{\sqrt{3}} \times \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} Ia \\ Ib \\ Ic \end{bmatrix}$$

Differential Protection (Zero Seq. Elimination)

$$\begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \propto^2 & \propto \\ 1 & \propto & \propto^2 \end{bmatrix} \begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix}$$

$$I_a = I_0 + \ I_1 + I_2$$

$$I_b = I_0 + \propto^2 \ I_1 + \propto I_2$$

$$IWPA = I_a - I_b = (I_0 - I_0) + I_1(1 - \propto) + I_2(1 - \propto^2)$$

$$IWSA = I_a = I_0 + \ I_1 + I_2$$

$$IWSA_{COMP} = \frac{1}{\sqrt{3}} \times (IWSA \text{ - } IWSB)$$

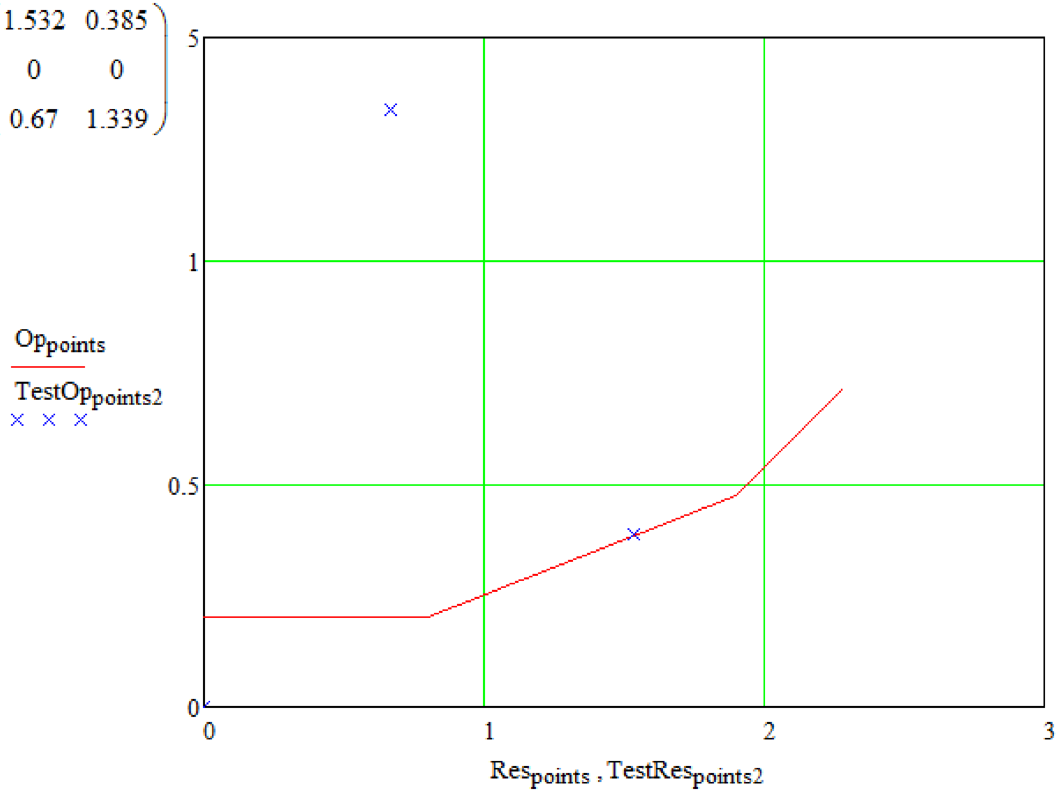
Testing Microprocessor Differential Schemes (Common Test Methods)

- **Single Phase**
  - Relay is three phase
  - Does not simulate realistic system conditions, as only one phase is injected at a time.
    - This can lead to erroneous results

Testing Microprocessor Differential Schemes (Common Test Methods)

	Ia-W1	Ib-W1	Ic-W1	Ia	Ib	Ic
Magnitude	**10.76 A**	0 A	0 A	**10.02 A**	0 A	0 A
Angle	**0 °**	120 °	240 °	**180 °**	120 °	240 °

$$\text{Test} = \begin{pmatrix} 1.532 & 0.385 \\ 0 & 0 \\ 0.67 & 1.339 \end{pmatrix}$$



External Faults

- **Out of Zone Fault**
  - Differential protection should not operate for this type of fault.
  - Downstream devices should clear fault if not then a OC/Inst element on the transformer protection should clear.
  - Type of fault that the transformer will experience more
- **Verification**
  - Typically not tested using traditional test methods
    - Minimum Pickup, Slope, harmonic restraint
  - Mis-operation for external faults due to settings error
    - Incorrect Vector Compensation
    - Zero sequence current elimination
  - New test methods are required in order to verify relay stability for external faults.

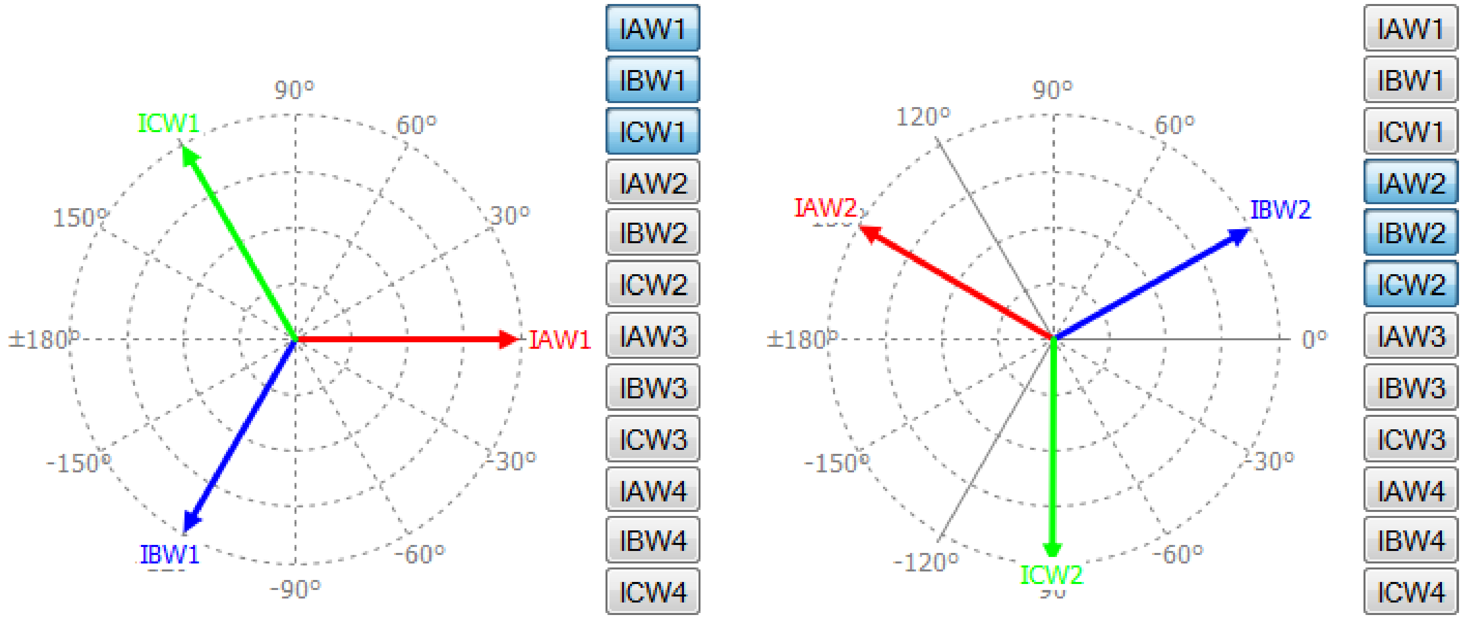
Testing Microprocessor Differential Schemes (New Test Methods)

- **Multi Phase**
  - Provide verification for internal and external faults
  - Does simulate realistic system conditions
  - These new test methods are mostly focused on verifying the relays response to external faults. However, these methods can be used for internal faults
  - Most of the test set manufacturers provide these new tools
  - New methods discussed
    - Metering Test
    - External fault Tests

Metering Test

- **Multi Phase**
  - Helps identify any issues with settings and wiring problems
  - Aids in verification of vector compensation
  - Information that most users do not realize is available and it serves as an excellent troubleshooting tool
  - Some manufacturers even provide the differential quantities such as the operate and restraint currents, as well as the uncompensated and compensated currents

Metering Test



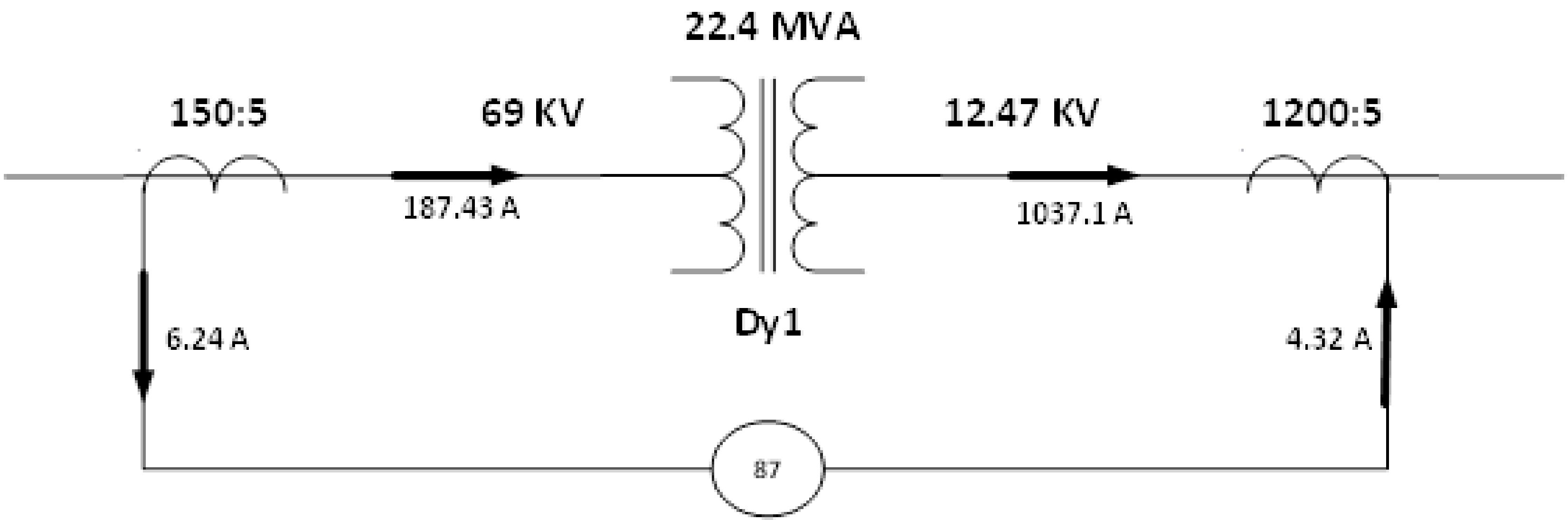
	Operate Currents			Restraint Currents		
	IOP1	IOP2	IOP3	IRT1	IRT2	IRT3
I (Mult. of Tap)	0.01	0.00	0.02	1.00	1.00	1.01

	Second Harmonic Currents			Fifth Harmonic Currents		
	I1F2	I2F2	I3F2	I1F5	I2F5	I3F5
I (Mult. of Tap)	0.00	0.00	0.00	0.00	0.00	0.00

External Fault Simulations Test

- **Multi Phase**
  - Helps identify any issues with settings and wiring problems
  - Aids in verification of:
    - vector compensation
    - Zero sequence current removal
  - Test values can be derived by:
    - Determining the current flows thru transformer for certain fault types
    - Symmetrical Components analysis
    - Fault records
  - Three types of fault described
    - 3 Phase
    - Phase-Phase
    - Phase-Ground

External Fault Simulations

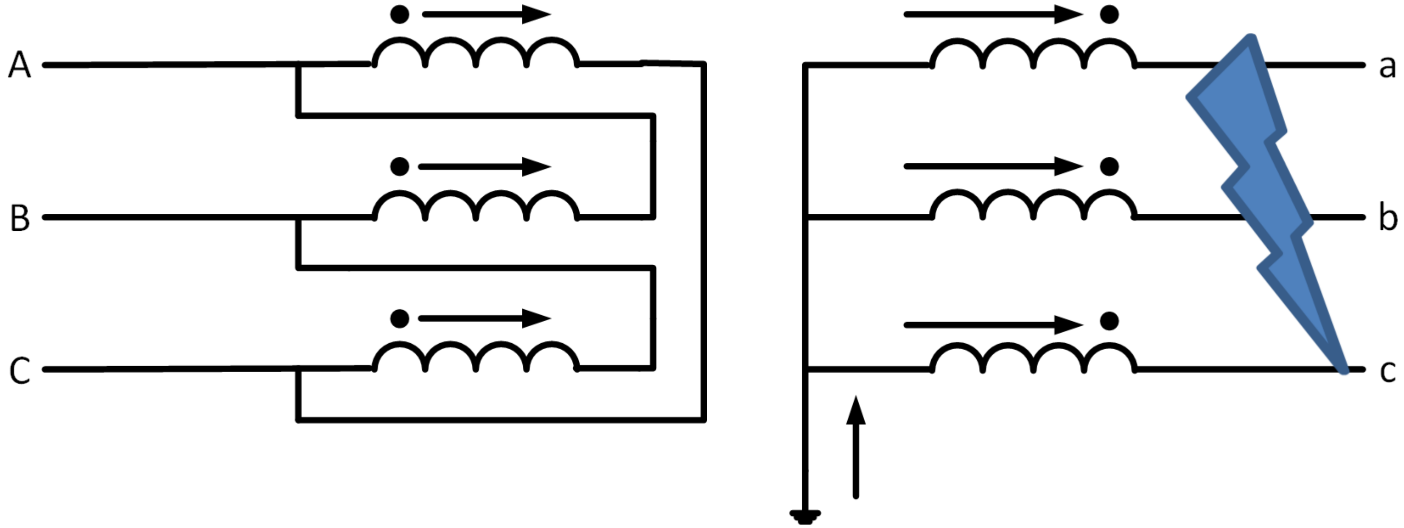


$$Irated_{HV} = \frac{MVA}{\sqrt{3} \times KV_{P-P(HV)}} = 187.43\ Amps \qquad Tap_{HV} = \frac{Irated_{HV}}{CTR_{HV}} = \frac{187.43}{30} = 6.24$$

$$Irated_{LV} = \frac{MVA}{\sqrt{3} \times KV_{P-P(LV)}} = 1037.1\ Amps \qquad Tap_{LV} = \frac{Irated_{LV}}{CTR_{LV}} = \frac{1037.1}{240} = 4.32$$

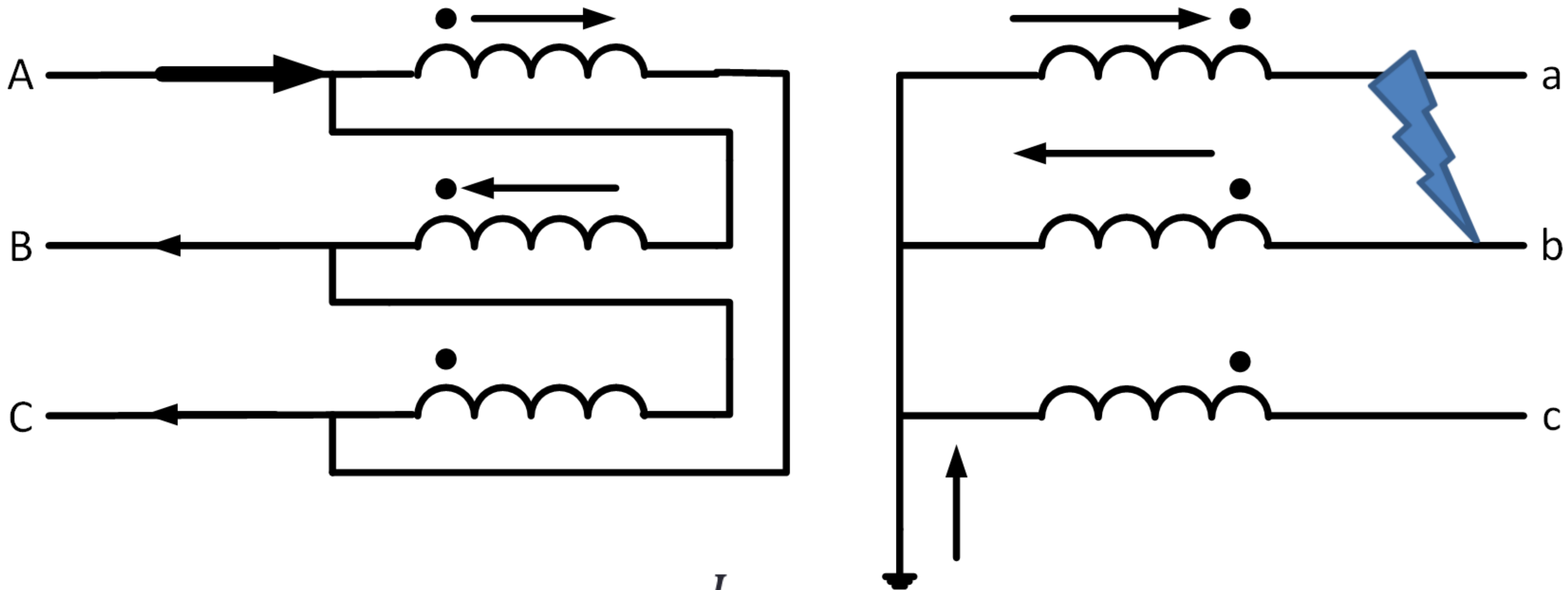
3 Phase External Fault Simulation

- **Must consider phase shift**



$$\begin{bmatrix} W2_A \\ W2_B \\ W2_C \end{bmatrix} = \begin{bmatrix} (8.64\angle 210°) \\ (8.64\angle 330°) \\ (8.64\angle 90°) \end{bmatrix}$$

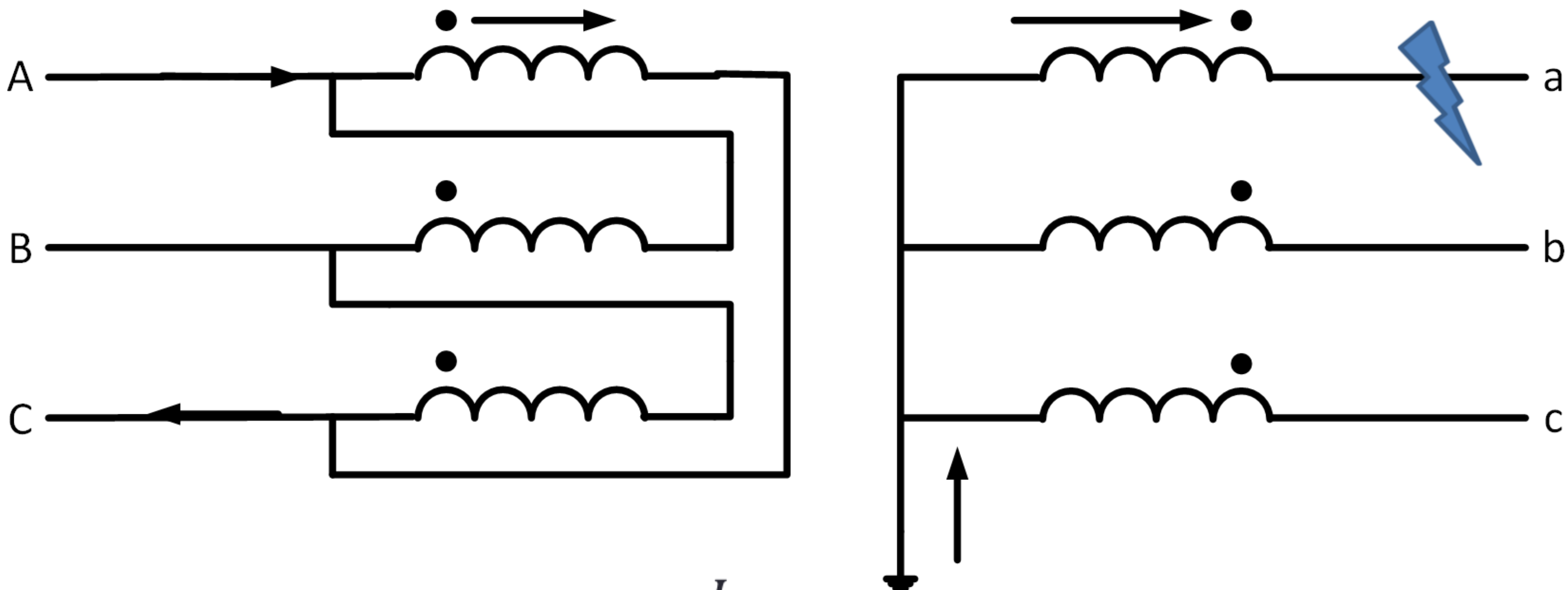
Phase to Phase External Fault



$$I_{Pri} = I_{Delta} \times 2 \qquad I_{Delta} = \frac{I_F}{\sqrt{3}} \qquad I_{Sec} = I_F$$

$$\begin{bmatrix} IAW1 \\ IBW1 \\ ICW1 \end{bmatrix} = \begin{matrix} 14.43\angle 0° \\ 7.205\angle 180° \\ 7.205\angle 180° \end{matrix} \qquad \begin{bmatrix} IAW2 \\ IBW2 \\ ICW2 \end{bmatrix} = \begin{matrix} 8.64\angle 180° \\ 8.64\angle 0° \\ 0\angle 180° \end{matrix}$$

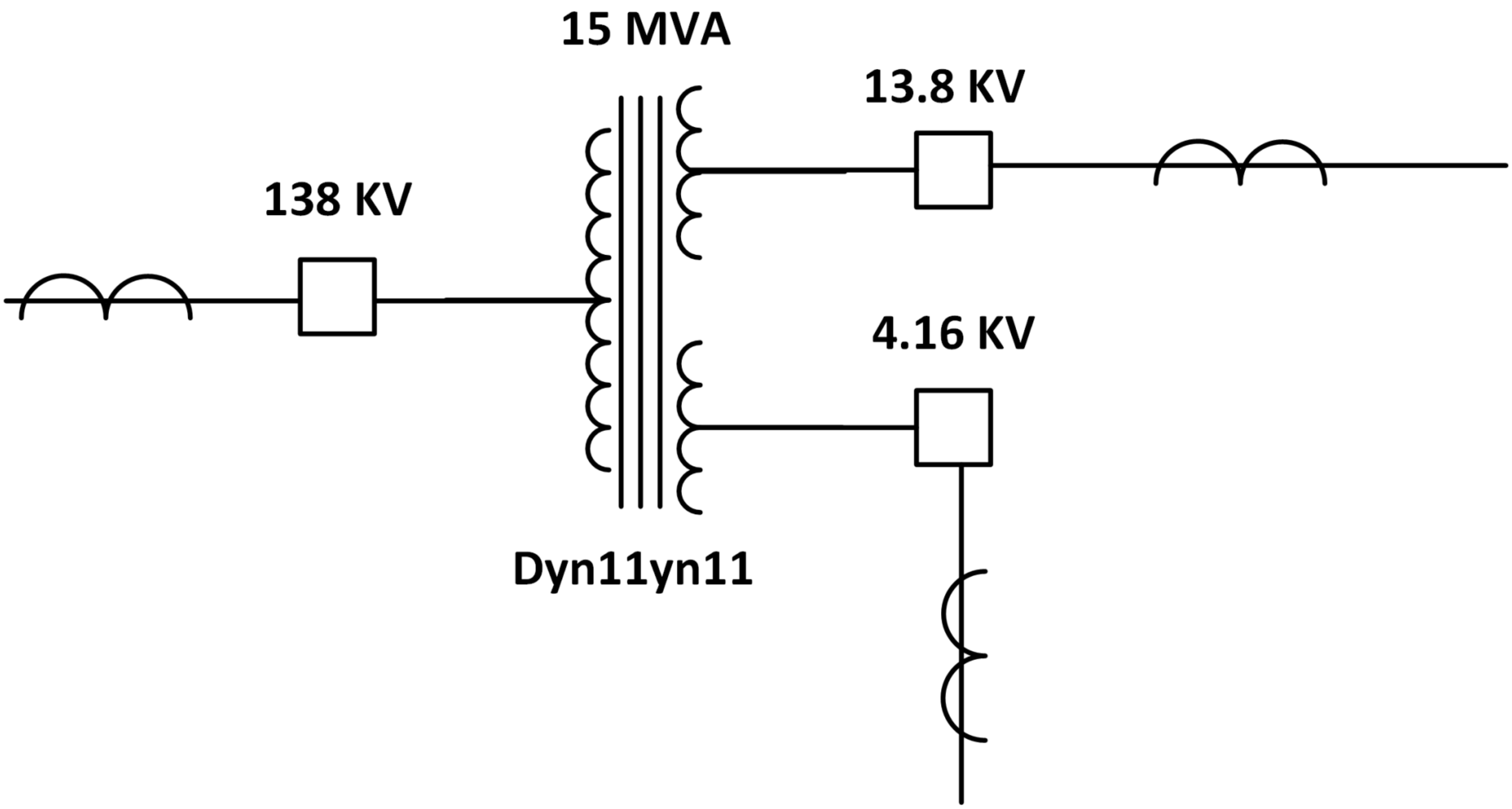
Phase to Ground External Fault



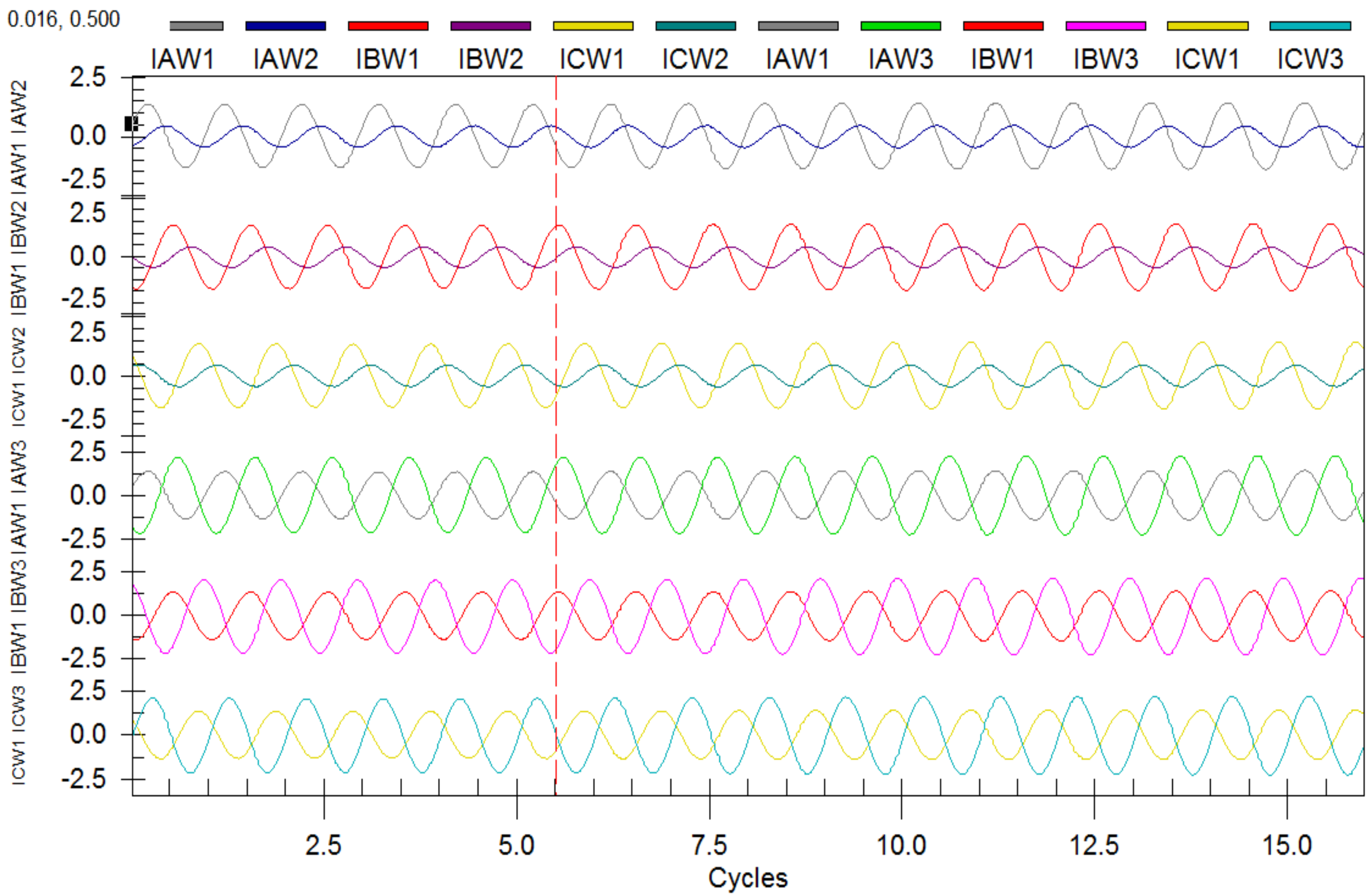
$$I_{Pri} = I_{Delta} \qquad I_{Delta} = \frac{I_F}{\sqrt{3}} \qquad I_{Sec} = I_F$$

$$\begin{bmatrix} IAW1 \\ IBW1 \\ ICW1 \end{bmatrix} = \begin{matrix} 7.205\angle 0° \\ 0\angle 180° \\ 7.205\angle 180° \end{matrix} \qquad \begin{bmatrix} IAW2 \\ IBW2 \\ ICW2 \end{bmatrix} = \begin{matrix} 8.64\angle 180° \\ 0\angle 180° \\ 0\angle 180° \end{matrix}$$

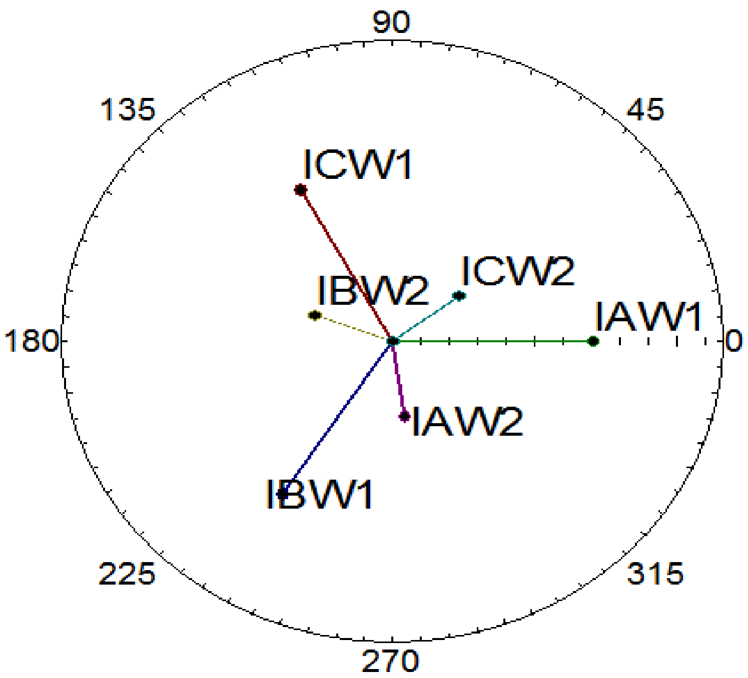
Case Study

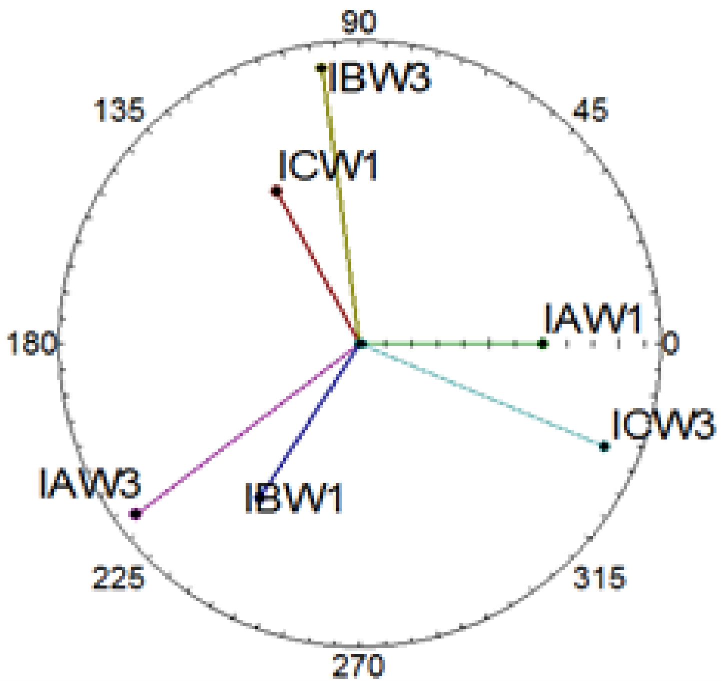


Case Study (Waveforms)

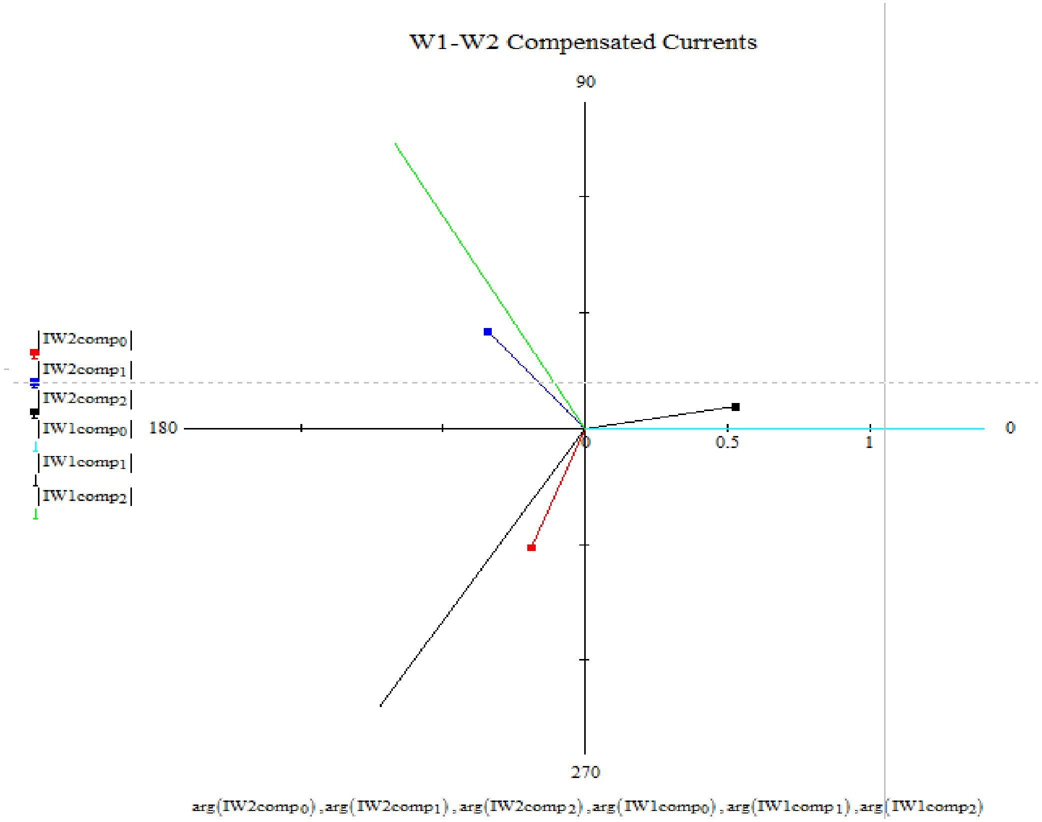


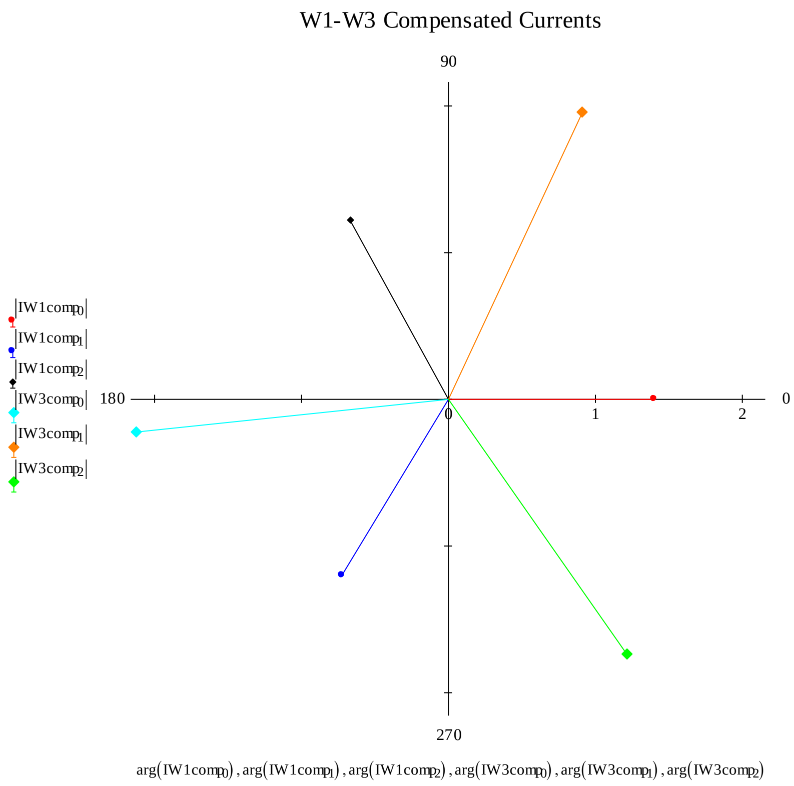
Case Study (Phasors)



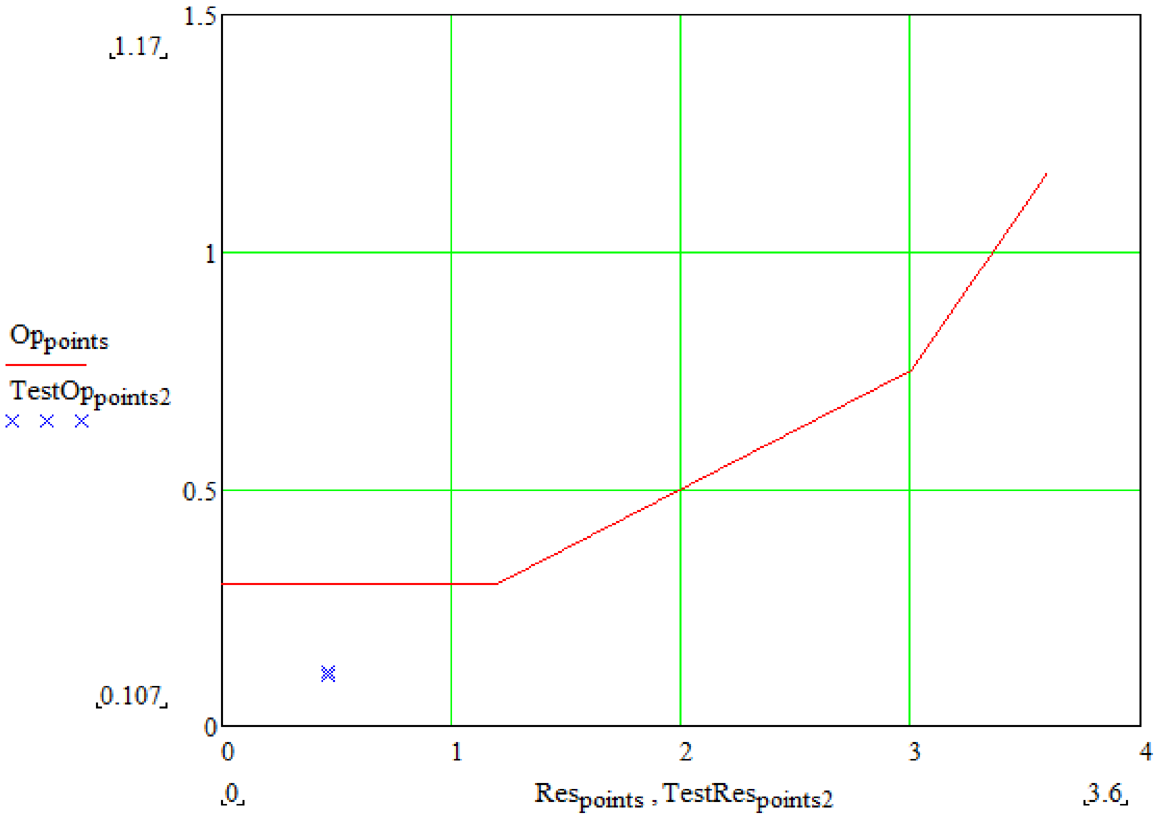


Case Study (Phasors)

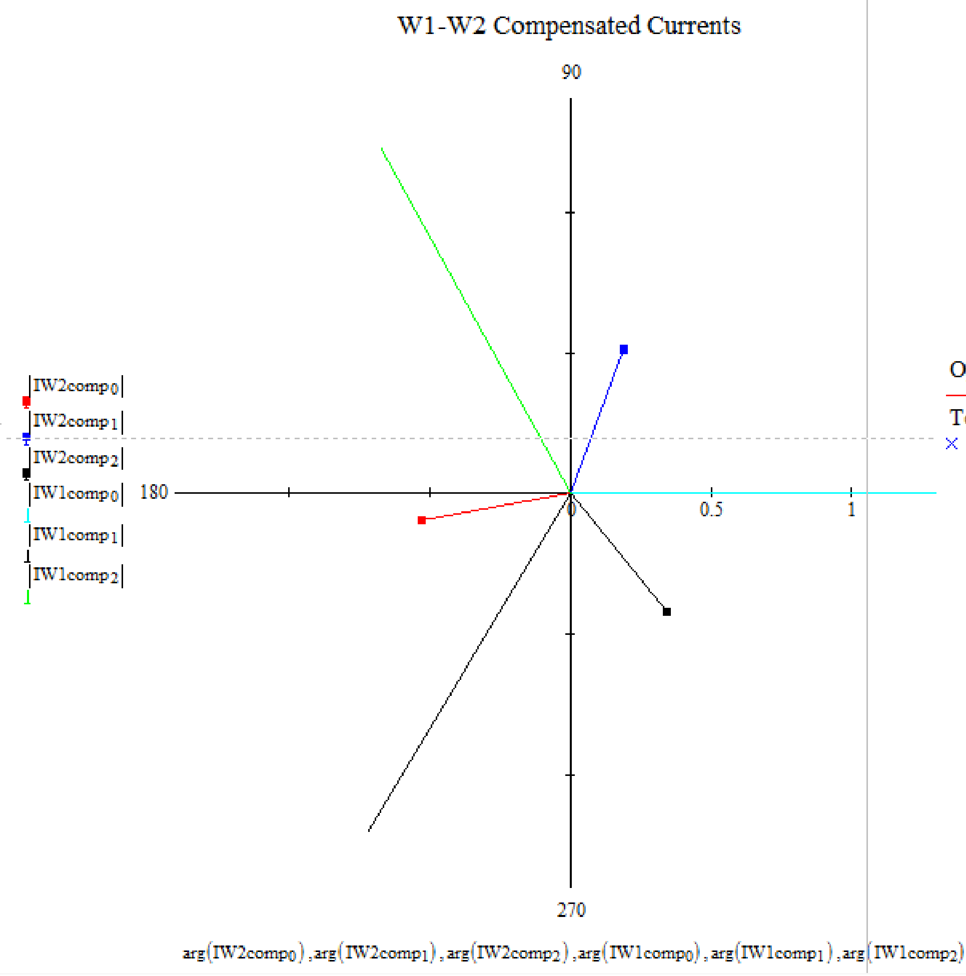


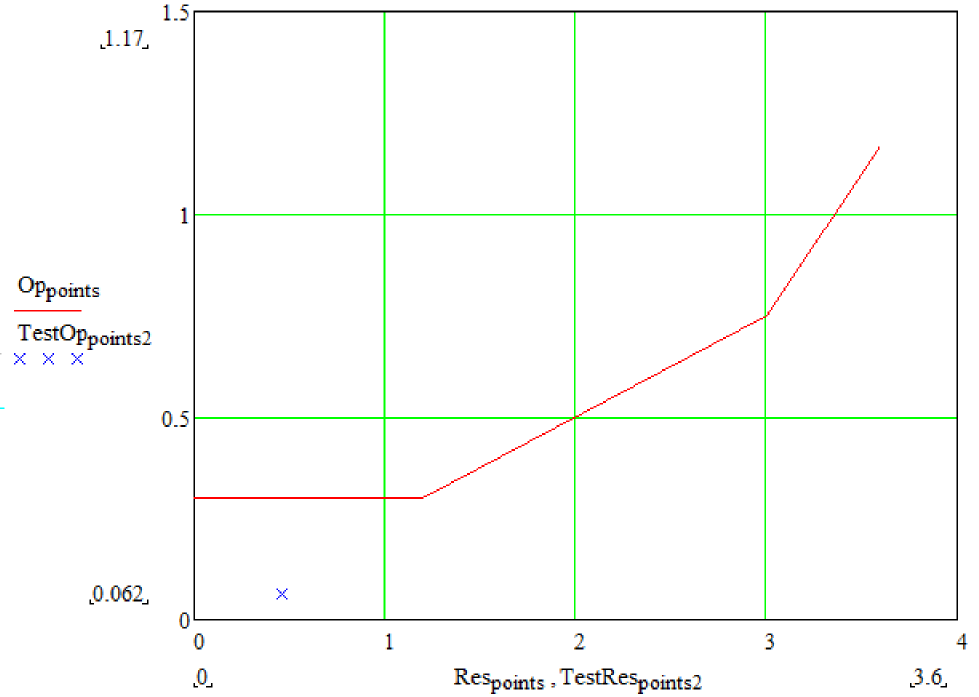


Case Study (Slope Char)

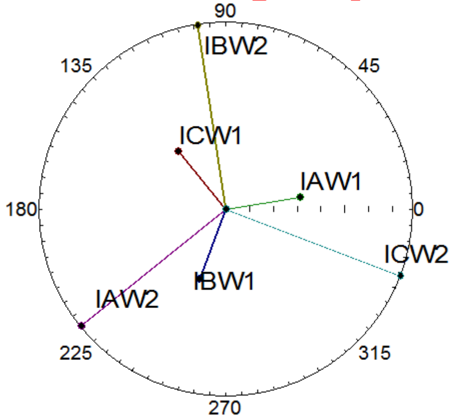


Case Study (Issue Resolved)



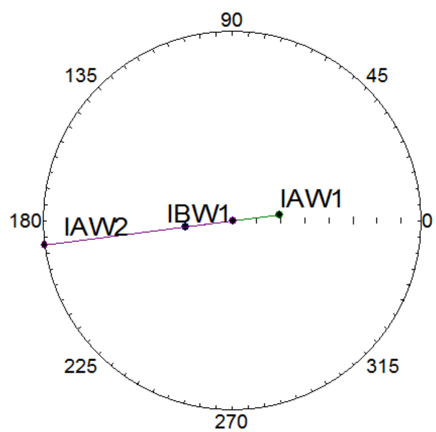


Case Study (Ext. Fault Simulations)



	Operate Currents			Restraint Currents		
	IOP1	IOP2	IOP3	IRT1	IRT2	IRT3
I (Mult. of Tap)	0.01	0.02	0.02	2.00	2.00	2.00
	Second Harmonic Currents			Fifth Harmonic Currents		
	I1F2	I2F2	I3F2	I1F5	I2F5	I3F5
I (Mult. of Tap)	0.01	0.01	0.00	0.00	0.00	0.00

Simulated 3 Phase Fault on W1-W2



	Operate Currents			Restraint Currents		
	IOP1	IOP2	IOP3	IRT1	IRT2	IRT3
I (Mult. of Tap)	0.00	0.00	0.00	1.16	1.16	0.00
	Second Harmonic Currents			Fifth Harmonic Currents		
	I1F2	I2F2	I3F2	I1F5	I2F5	I3F5
I (Mult. of Tap)	0.00	0.00	0.00	0.00	0.00	0.00

Simulated Phase-G Fault on W1-W2

Conclusion

- **Single phase testing is the traditional method of testing differential relays. Not adequate for newer microprocessor based relays.**
- **Multi Phase testing is the recommended method for modern numerical transformer differential relays.**
- **Metering tests provide useful information about the status of the differential scheme. Can help the user detect wiring and setting problems.**
- **External fault simulations aid in the verification of differential scheme stability.**

Questions?