Symmetrical Components

- Review of basics
- Sequence Equivalents
- Fault Analysis

References

- Your power systems analysis class text book
- NPAG: Chapter 4 (analysis) Chapter 5 (equipment models)
- J.L. Blackburn, *Protective Relaying: Principles and Applications,* Any Edition: Chapter 4
- P.M. Anderson, *Analysis of Faulted Power Systems*, IEEE Press 1995
- J.L. Blackburn, *Symmetrical Components for Power Systems Engineering*, Marcel-Dekker, 1993.
- Nasser Tleis, *Power Systems Modelling and Fault Analysis: Theory and Practice*. Newnes Power Engineering Series. 2008

History

- Fortescue, 1918
  - » Unbalanced n-phase system can be broken down into sets of balanced n-phase systems
  - » Add using superposition

What is it?

- Method for analysis of multiphase systems under unbalanced conditions
  - » Steady-state conditions
  - » Phasor Analysis
  - » Visualization
- Allows a fast, efficient way to analyze unbalanced condition in real time
- Relays set to look at specific components

Basic Equations

- De-couple voltage or current into 3 balanced 3 phase sets
  - » Positive phase sequence (ABCABC…): V_1
  - » Negative phase sequence (ACBACB…): V_2
  - » Zero phase sequence (A=B=C), V_0
  - » All RMS phasors
  - » Per phase analysis

Per Phase Symmetrical Component Equations

$\mathbf{a} = 1 @ 120^0$

$\mathbf{V}_A = \mathbf{V}_{A0} + \mathbf{V}_{A1} + \mathbf{V}_{A2}$

$\mathbf{V}_B = \mathbf{V}_{B0} + \mathbf{V}_{B1} + \mathbf{V}_{B2}$
$= \mathbf{V}_{A0} + \mathbf{a}^2\mathbf{V}_{A1} + \mathbf{a}\mathbf{V}_{A2}$

$\mathbf{V}_C = \mathbf{V}_{C0} + \mathbf{V}_{C1} + \mathbf{V}_{C2}$
$= \mathbf{V}_{A0} + \mathbf{a}\mathbf{V}_{A1} + \mathbf{a}^2\mathbf{V}_{A2}$

Analysis Equations

$\mathbf{V}_{A0}=\mathbf{V}_0=(\mathbf{V}_A + \mathbf{V}_B + \mathbf{V}_C)/3$

$\mathbf{V}_{A1}=\mathbf{V}_1=(\mathbf{V}_A + \mathbf{aV}_B + \mathbf{a}^2\mathbf{V}_C)/3$

$\mathbf{V}_{A2}=\mathbf{V}_2=(\mathbf{V}_A + \mathbf{a}^2\mathbf{V}_B + \mathbf{aV}_C)/3$

- Same expressions for current
- Can express in Matrix form too

Analysis Equations

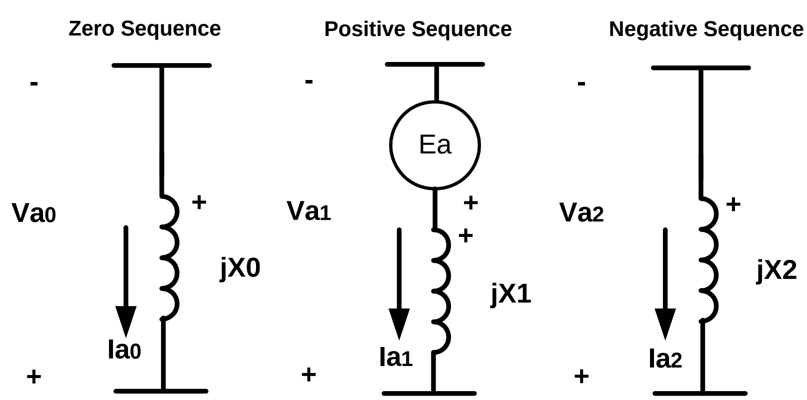
$$\begin{pmatrix} Va0 \\ Va1 \\ Va2 \end{pmatrix} = \frac{1}{3}\begin{pmatrix} 1 & 1 & 1 \\ 1 & a^1 & a^2 \\ 1 & a^2 & a^4 \end{pmatrix}\cdot\begin{pmatrix} Va \\ Vb \\ Vc \end{pmatrix}$$

$$\begin{pmatrix} Va \\ Vb \\ Vc \end{pmatrix} = \begin{pmatrix} 1 & 1 & 1 \\ 1 & a^{3-1} & a^{3-2} \\ 1 & a^{3-2} & a^{3-1} \end{pmatrix}\cdot\begin{pmatrix} Va0 \\ Va1 \\ Va2 \end{pmatrix} = \begin{pmatrix} 1 & 1 & 1 \\ 1 & a^2 & a^1 \\ 1 & a^1 & a^2 \end{pmatrix}\cdot\begin{pmatrix} Va0 \\ Va1 \\ Va2 \end{pmatrix}$$

Circuit Analysis

- Represent power system in per phase sequence networks
- Each network contains voltage and impedance elements for the sequence
- Reduce network to Thevenin Equivalent in each phase sequence
- All sources generally positive sequence

Basic Sequence Networks



Basic Sequence Networks

- Impedance will differ between sequences
- Zero sequence will also include ground impedance
- Connect them as appropriate for different fault types

Fault Analysis

- Fault Types:
  - » Single line to ground
  - » Line to line
  - » Double line to ground
  - » Three phase (positive sequence unless unbalanced fault impedances)
  - » Phase open
  - » Phase open and line to ground
  - » Simultaneous faults

Fault Detection For Protection Purposes

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- Basic fault analysis techniques calculate currents/voltages at fault location
  - » ABC or symmetrical components
- Need fault signature as seen at the relay location
  - » Rough location of fault for correct response

Single Line to Ground Connections

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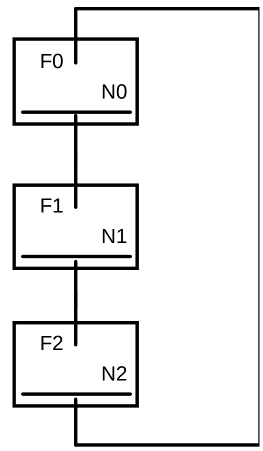
- Constraints at fault location (phase A):
  - » $\mathbf{V}_A=0$
  - » $\mathbf{I}_B=\mathbf{I}_C\cong 0$
- Therefore:
  - » $\mathbf{V}_A = \mathbf{V}_0 + \mathbf{V}_1 + \mathbf{V}_2 =0$
  - » $\mathbf{I}_0=(\mathbf{I}_A + 0 + 0)/3$ and
  - » $\mathbf{I}_1= \mathbf{I}_2 =(\mathbf{I}_A + 0 + 0)/3$ so
  - » $\mathbf{I}_0 = \mathbf{I}_1= \mathbf{I}_2 =(\mathbf{I}_A)/3$

SLG Connections

- To Satisfy these constraints we connect the three networks in series
- Connect reference point of one network to fault location of next one



SLG Faults

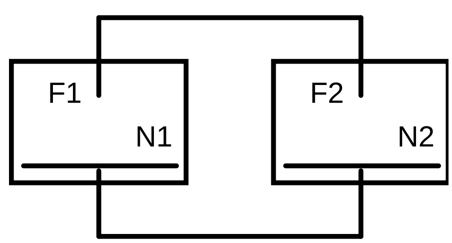
- Solve for $\mathbf{I}_0$, can calculate $\mathbf{I}_A$
- Next solve for $\mathbf{V}_1$, $\mathbf{V}_2$, and $\mathbf{V}_0$ and calculate phase voltage
- Note that in general jX_o will be replaced with $\mathbf{Z}_0=jX_0 + 3\mathbf{Z}_{gr} + 3Z_f$
  - » The factor of 3 results since 0 sequence is the same to all 3 phases

Phase to Phase Faults

- Two phases (often B and C for analysis) shorted together
  - » Not shorted to ground
  - » $\mathbf{V}_B = \mathbf{V}_C$
  - » $\mathbf{I}_B = -\mathbf{I}_C$
- From symmetrical component equations:
  - » $\mathbf{I}_0 = 0$
  - » $\mathbf{I}_1 = -\mathbf{I}_2$ and $\mathbf{V}_1 = \mathbf{V}_2$

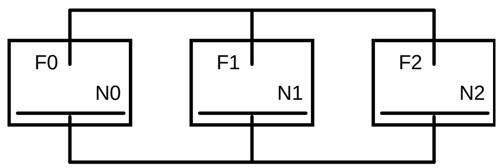
Phase to Phase Faults

- Fault impedance (if any) appears between the networks
- No Zero Sequence Network
- $\mathbf{V}_B = \mathbf{I}_B * \mathbf{Z}_f + \mathbf{V}_C$



Double Line to Ground

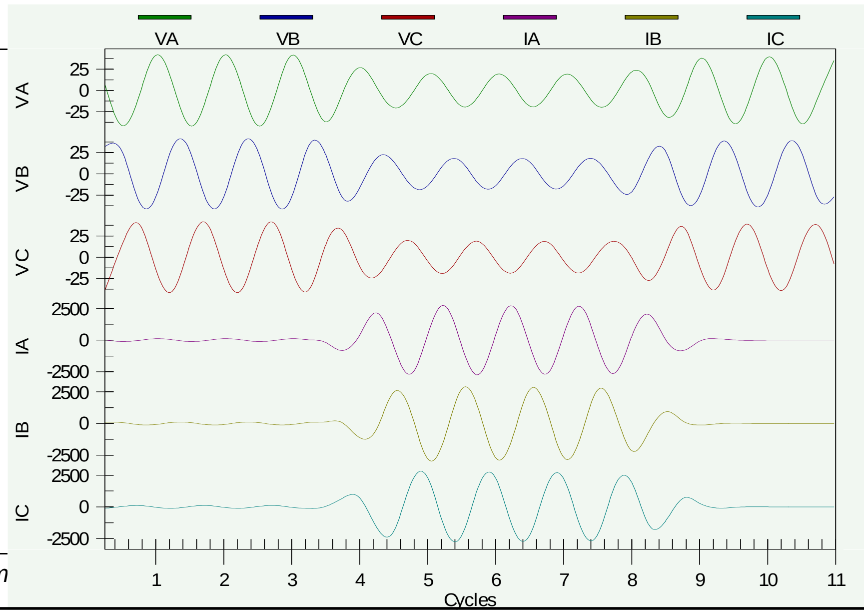
- Two phases shorted together and to ground
- Could have several impedances
  - » $\mathbf{I}_A \cong 0$
  - » $\mathbf{V}_B = (\mathbf{Z}_f + \mathbf{Z}_{gr})*\mathbf{I}_B + \mathbf{Z}_f*\mathbf{I}_f$
  - » $\mathbf{V}_c = (\mathbf{Z}_f + \mathbf{Z}_{gr})*\mathbf{I}_C + \mathbf{Z}_f*\mathbf{I}_f$



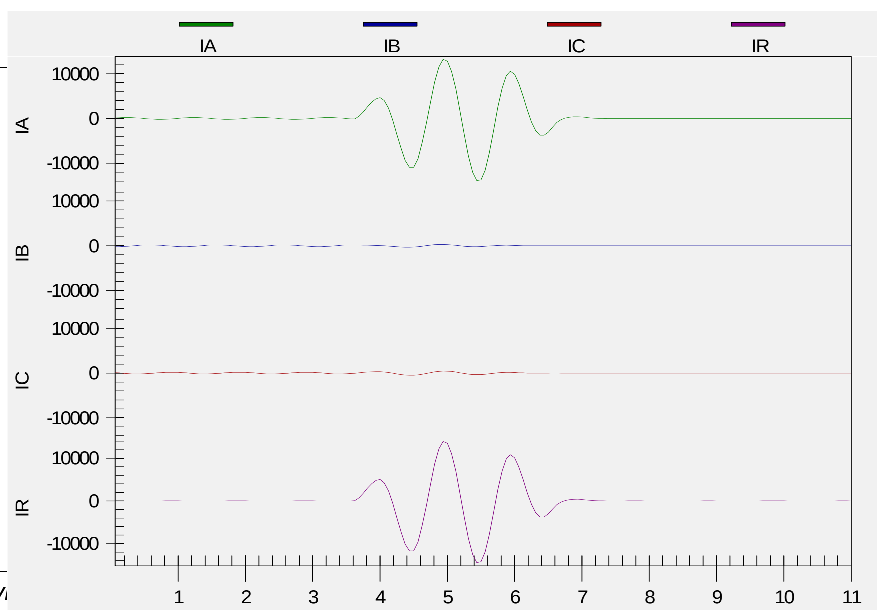
Fault Detection For Protection Purposes

- Basic fault analysis techniques calculate currents/voltages at fault location
  - » ABC or symmetrical components
- Need fault signature as seen at the relay location
  - » Rough location of fault for correct response

What Type of Fault?



What Type of Fault?



What Type of Fault?

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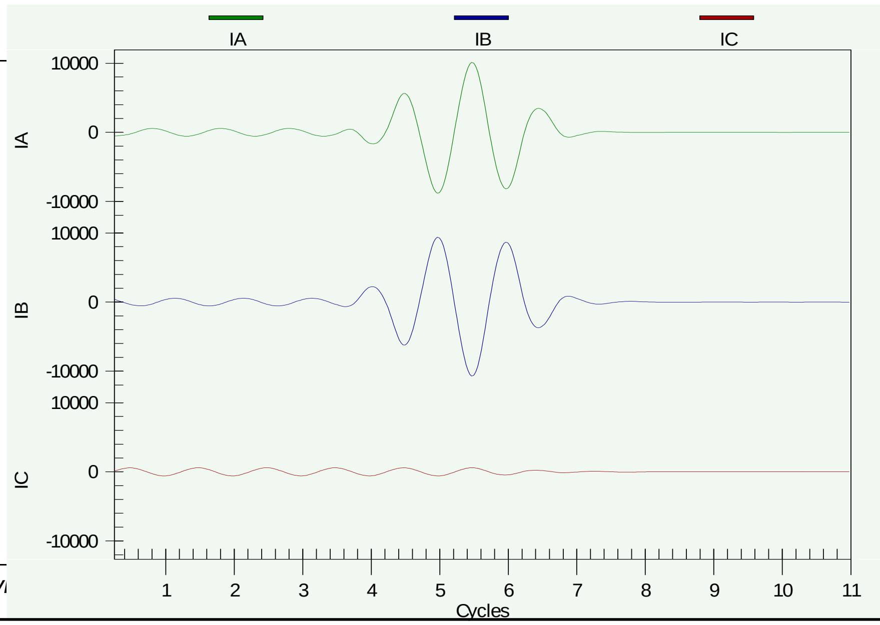

What Type of Fault?

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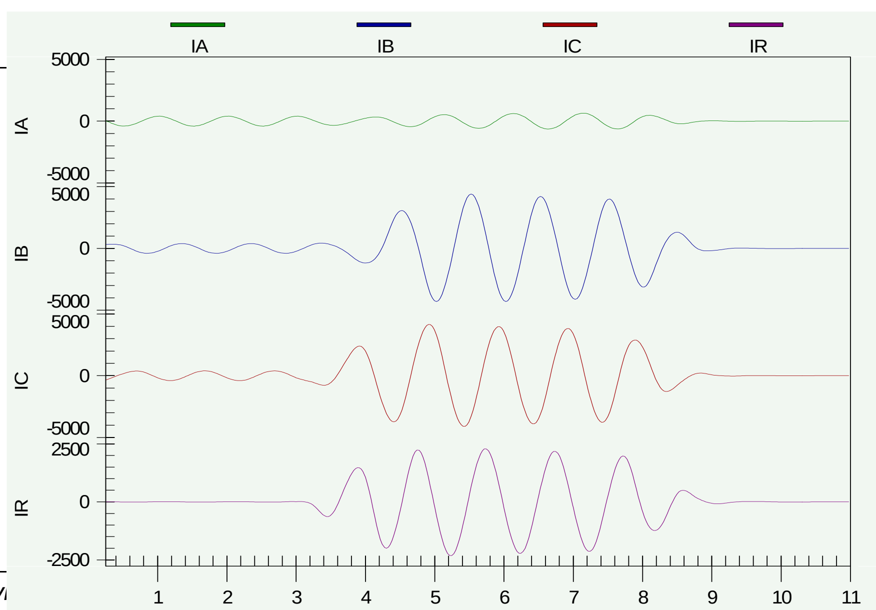
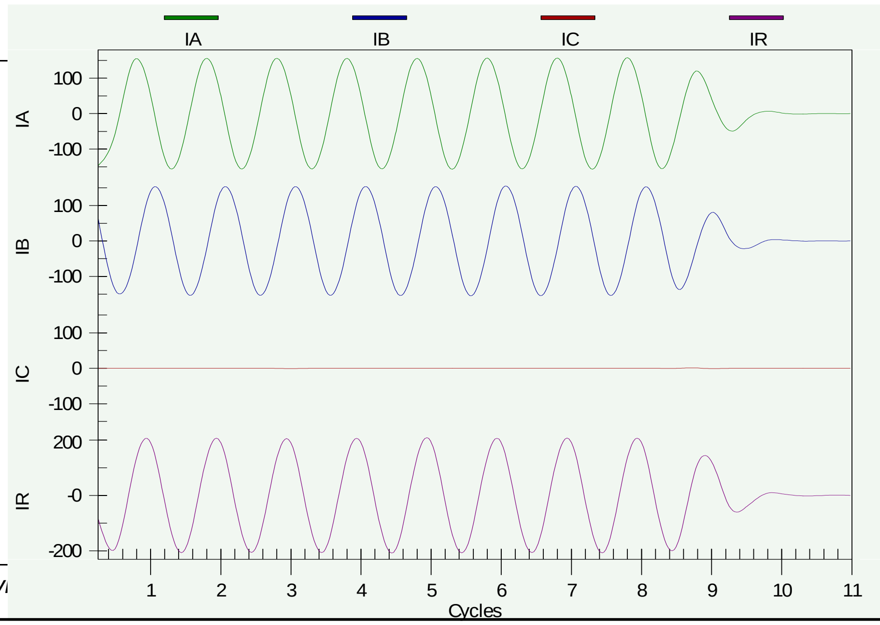
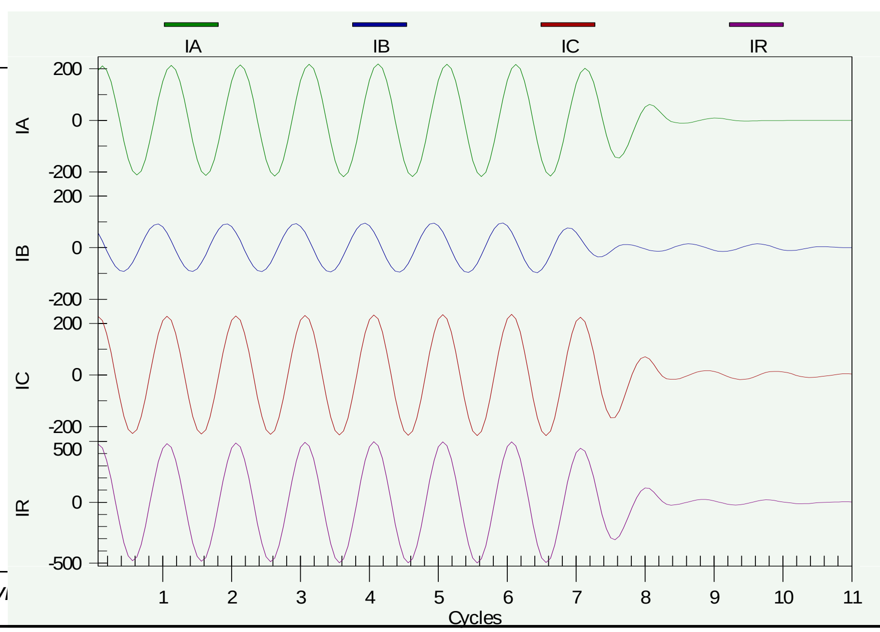


What Type of Fault?



What Type of Fault?



What Type of Fault?

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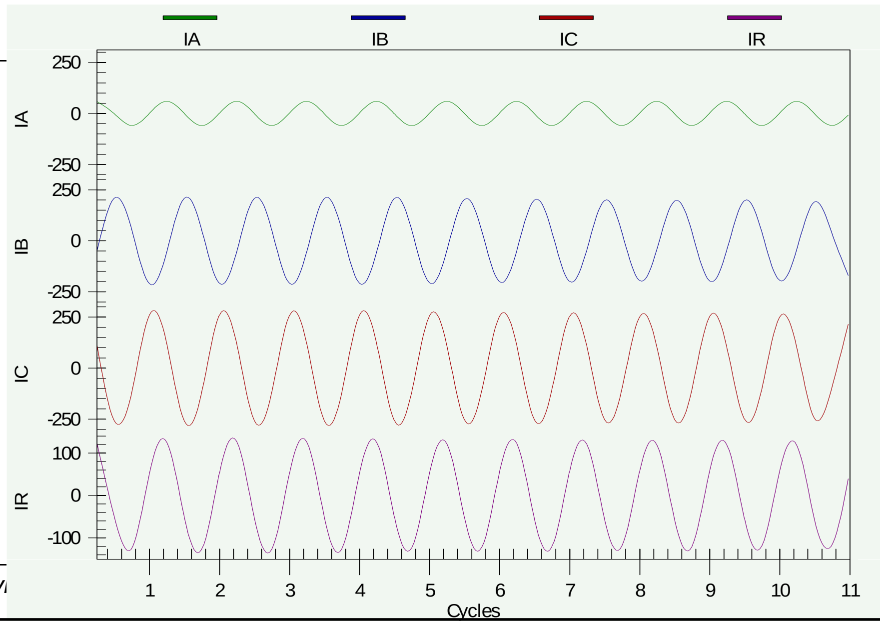

Three Phase Fault, Right?

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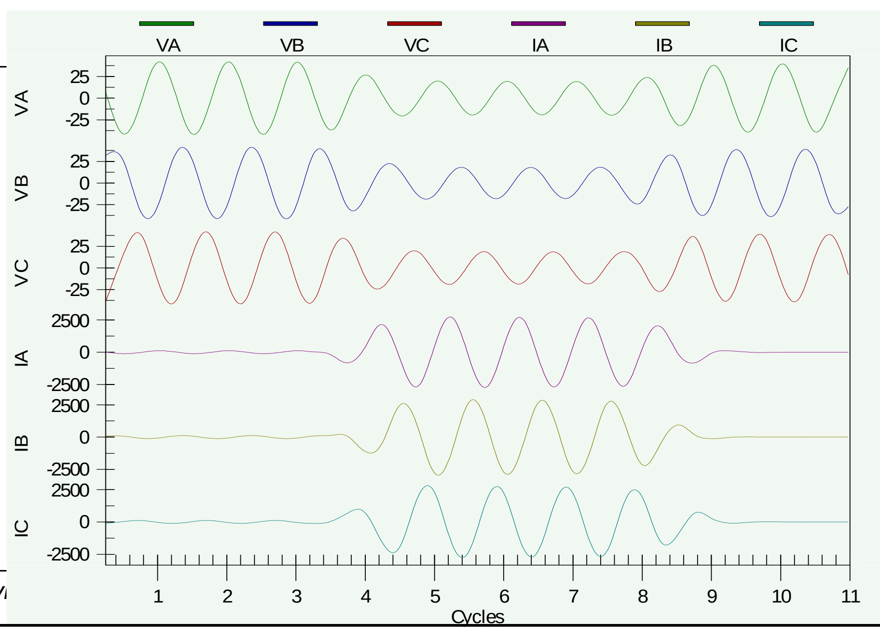
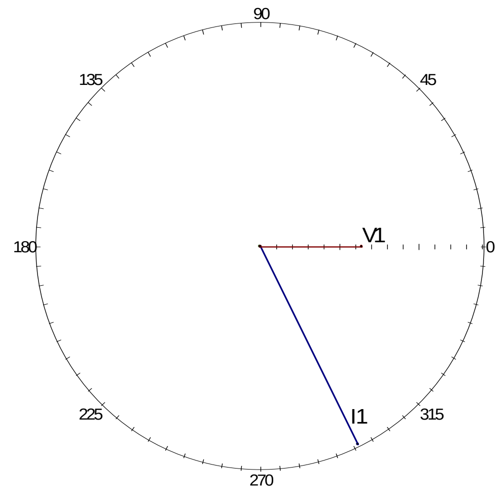
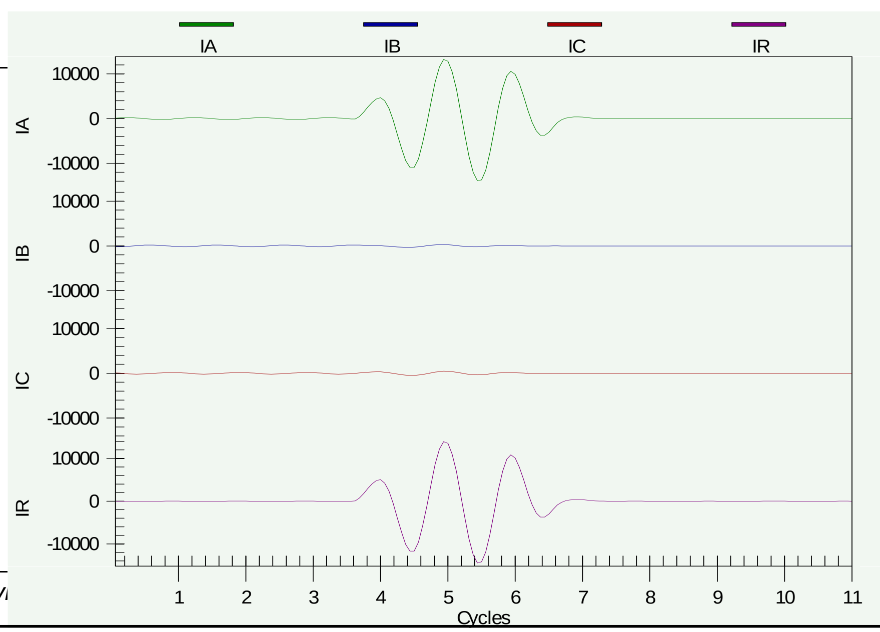


A Symmetrical Component View of an Three-Phase Fault

A-Ground Fault		
Component	**Magnitude**	**Angle**
Ia0	**7.6**	**175**
Ia1	**2790**	**-64**
Ia2	**110**	**75.8**
Va0	**0**	**0**
Va1	**18.8**	**0**

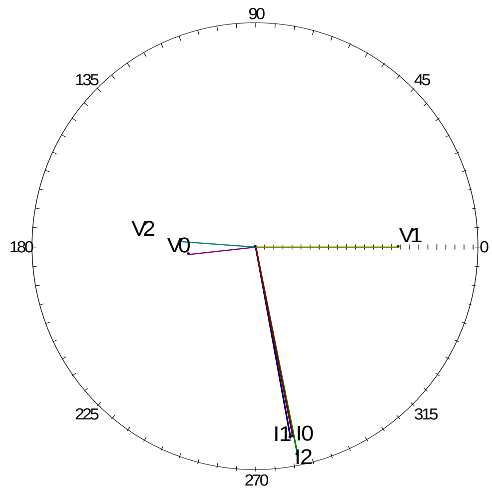


A to Ground Fault, Okay?



A Symmetrical Component View of an A-Phase to Ground Fault

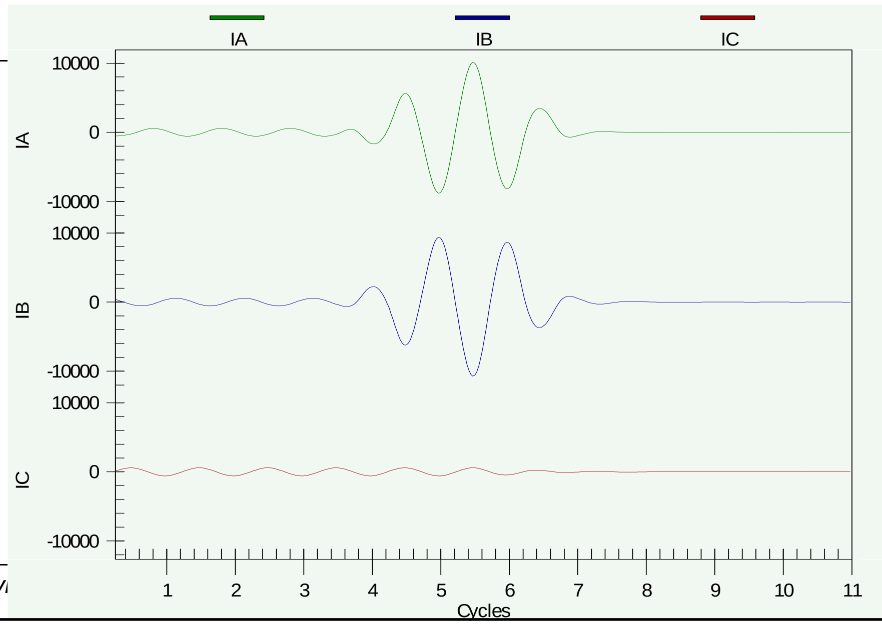
A-Ground Fault		
Component	Magnitude	Angle
Ia0	7340	-79
Ia1	6447	-79
Ia2	6539	-79
Va0	46	204
Va1	123	0



Single Line to Ground Fault

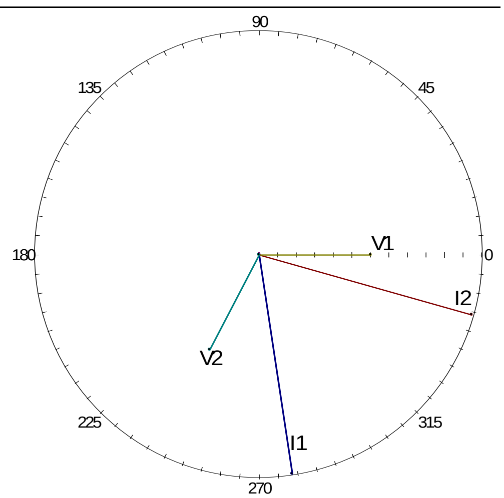
- Voltage
  - » Negative and zero sequence 180° out of phase with positive sequence
- Current
  - » All sequence are in phase

A to B Fault, Easy?



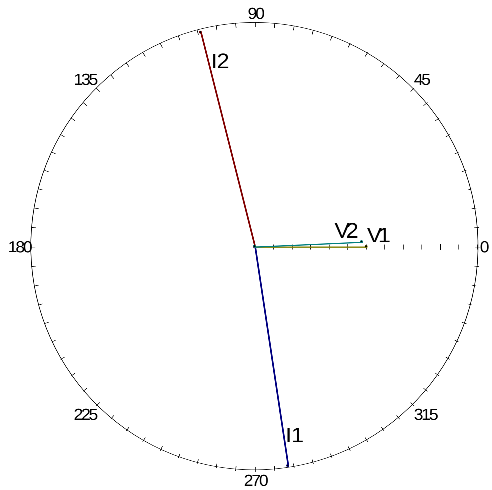
A Phase Symmetrical Component View of an A to B Phase Fault

	A-B Fault	
Component	**Magnitude**	**Angle**
Ia0	**3**	**-102**
Ia1	**5993**	**-81**
Ia2	**5961**	**-16**
Va0	**1**	**45**
Va1	**99**	**0**



C Phase Symmetrical Component View of an A to B Phase Fault

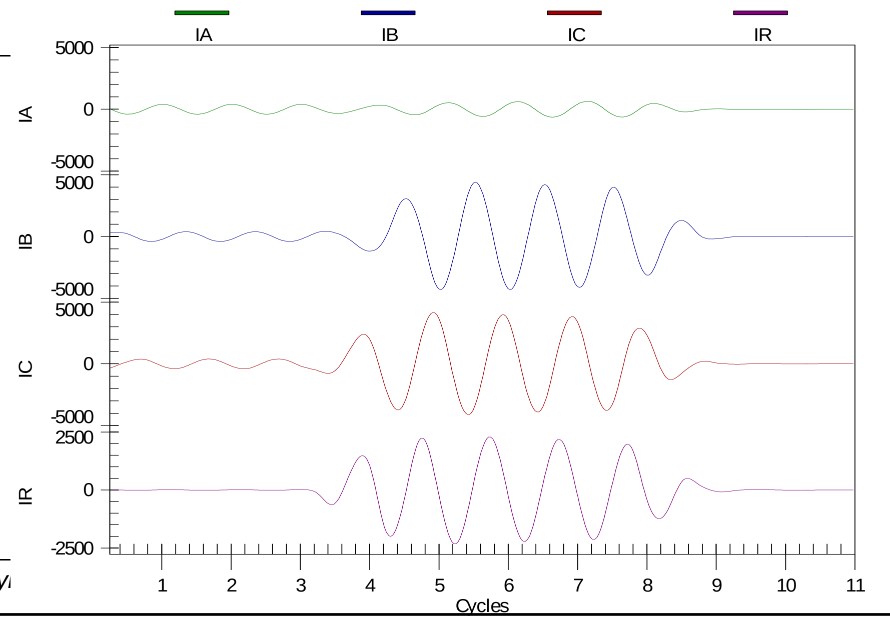
Component	Magnitude	Angle
Ic0	3	138
Ic1	5993	279
Ic2	5961	104
Vc0	1	-75
Vc1	99	0
Vc2	95	2.5



Line to Line Fault

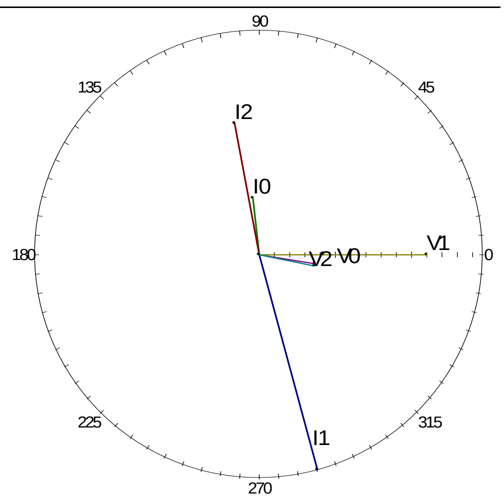
- Voltage
  - » Negative in phase with positive sequence
- Current
  - » Negative sequence 180° out of phase with positive sequence

B to C to Ground



A Symmetrical Component View of a B to C to Ground Fault

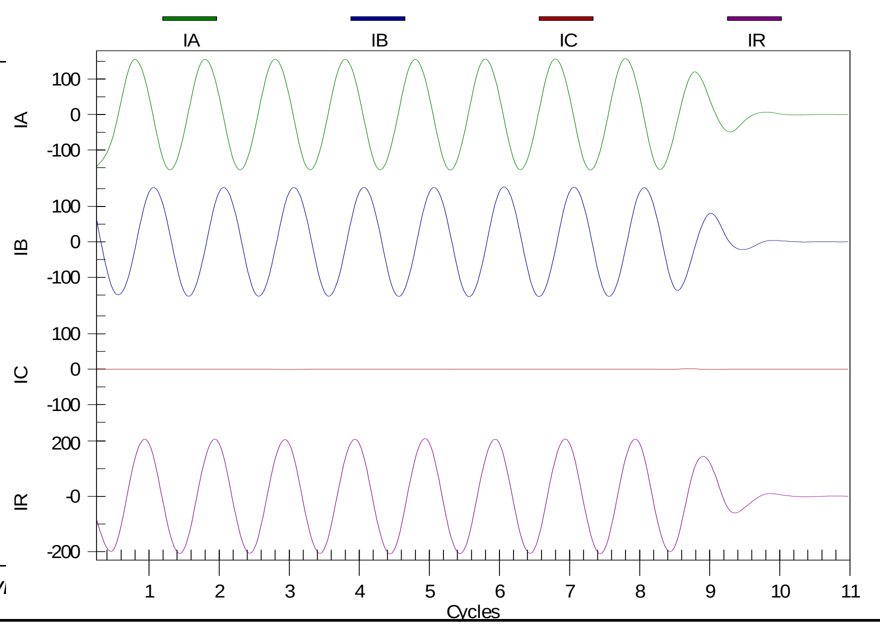
Component	Magnitude	Angle
Ia0	748	97
Ia1	2925	-75
Ia2	1754	101
Va0	8	351
Va1	101	0
Va2	18	348



Line to Line to Ground Fault

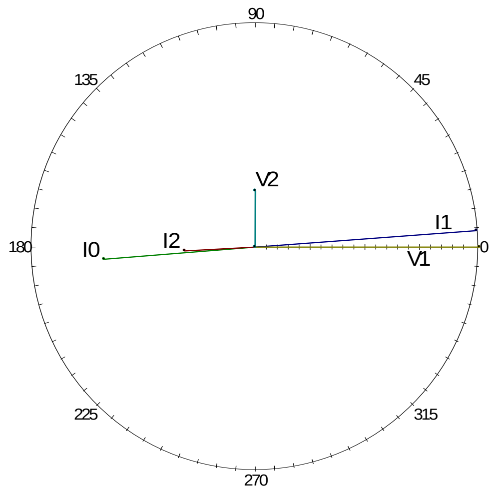
- Voltage
  - » Negative and zero in phase with positive sequence
- Current
  - » Negative and zero sequence 180° out of phase with positive sequence

Again, What Type of Fault?



C Symmetrical Component View of a C-Phase Open Fault

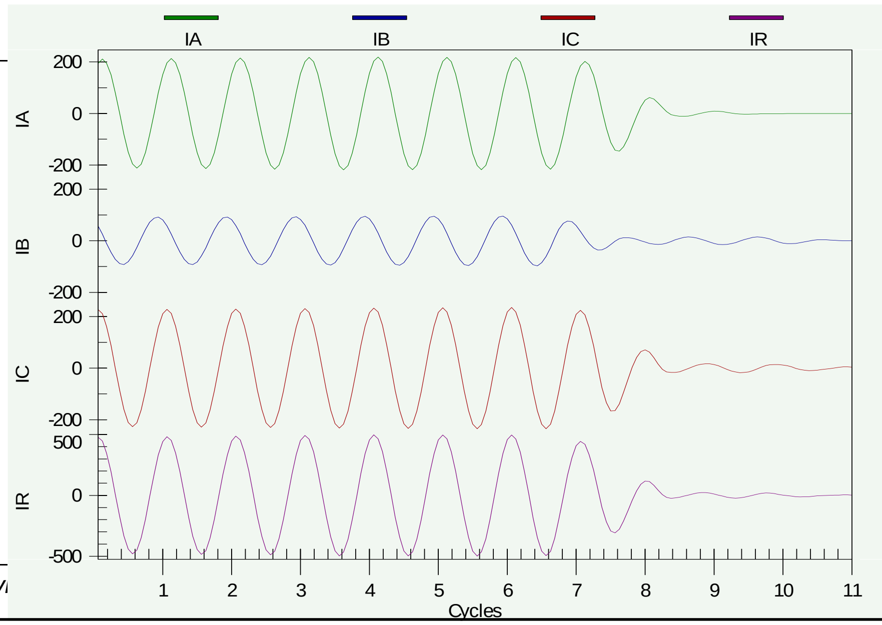
Component	Magnitude	Angle
Ic0	69	184
Ic1	101	4
Ic2	32	183
Vc0	0	162
Vc1	79	0
Vc2	5	90



One Phase Open (Series) Faults

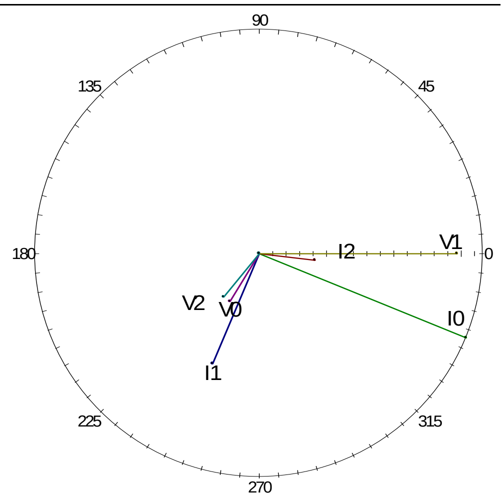
- Voltage
  - » No zero sequence voltage
  - » Negative 90° out of phase with positive sequence
- Current
  - » Negative and zero sequence 180° out of phase with positive sequence

What About This One?

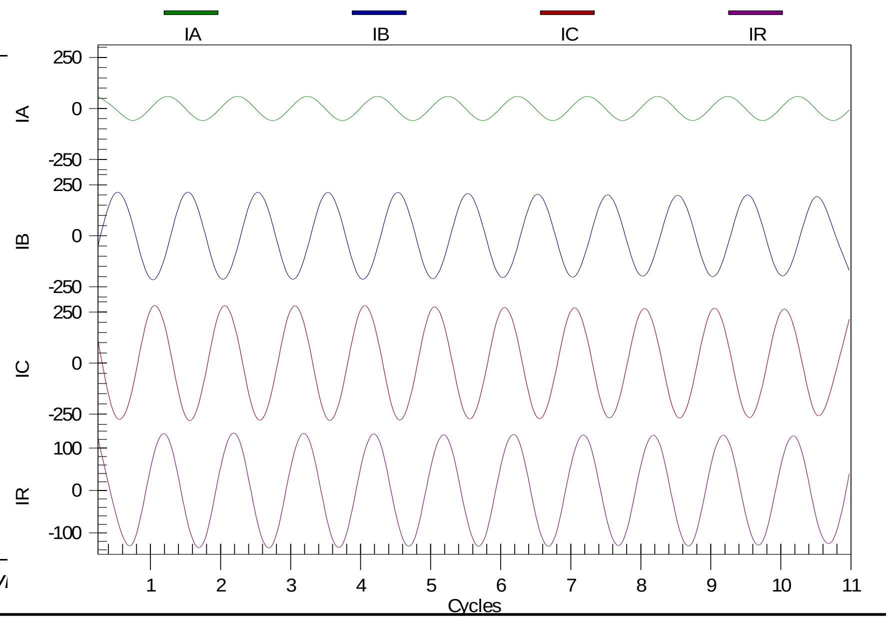


Ground Fault with Reverse Load

Ic0	164	-22
Ic1	89	-113
Ic2	41	-6
Vc0	4	-123
Vc1	38	0
Vc2	6	-130



Finally, The Last One!



Fault on Distribution System with Delta – Wye Transformer

Component	Magnitude	Angle
Ic0	45	40
Ic1	153	-4
Ic2	132	180
Vc0	0.5	331
Vc1	40	0
Vc2	0.5	93