Protective Relaying for DER Integration

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CAUTION CONCERNING FORWARD-LOOKING STATEMENTS:

This document contains "forward-looking statements" – that is, statements related to future events that by their nature address matters that are, to different degrees, uncertain. For details on the uncertainties that may cause our actual future results to be materially different than those expressed in our forward-looking statements, see http://www.ge.com/investor-relations/disclaimer-caution-concerning-forwardlooking-statements as well as our annual reports on Form 10-K and quarterly reports on Form 10-Q. We do not undertake to update our forward-looking statements. This document also includes certain forward-looking projected financial information that is based on current estimates and forecasts. Actual results could differ materially. to total risk-weighted assets.]

NON-GAAP FINANCIAL MEASURES:

In this document, we sometimes use information derived from consolidated financial data but not presented in our financial statements prepared in accordance with U.S. generally accepted accounting principles (GAAP). Certain of these data are considered “non-GAAP financial measures” under the U.S. Securities and Exchange Commission rules. These non-GAAP financial measures supplement our GAAP disclosures and should not be considered an alternative to the GAAP measure. The reasons we use these non-GAAP financial measures and the reconciliations to their most directly comparable GAAP financial measures are posted to the investor relations section of our website at www.ge.com. [We use non-GAAP financial measures including the following:

- Operating earnings and EPS, which is earnings from continuing operations excluding non-service-related pension costs of our principal pension plans.
- GE Industrial operating & Verticals earnings and EPS, which is operating earnings of our industrial businesses and the GE Capital businesses that we expect to retain.
- GE Industrial & Verticals revenues, which is revenue of our industrial businesses and the GE Capital businesses that we expect to retain.
- Industrial segment organic revenue, which is the sum of revenue from all of our industrial segments less the effects of acquisitions/dispositions and currency exchange.
- Industrial segment organic operating profit, which is the sum of segment profit from all of our industrial segments less the effects of acquisitions/dispositions and currency exchange.
- Industrial cash flows from operating activities (Industrial CFOA), which is GE’s cash flow from operating activities excluding dividends received from GE Capital.
- Capital ending net investment (ENI), excluding liquidity, which is a measure we use to measure the size of our Capital segment.
- GE Capital Tier 1 Common ratio estimate is a ratio of equity

Outline

- Why we need protection
- How we provide equipment protection
  - Models and Examples
- How we provide System Protection
  - Example

Why We Need Protection?

- Prevent damages of power system components

  (Equipment Protection)

  – From excessive currents over designed limits

  – From excessive voltages over designed limits

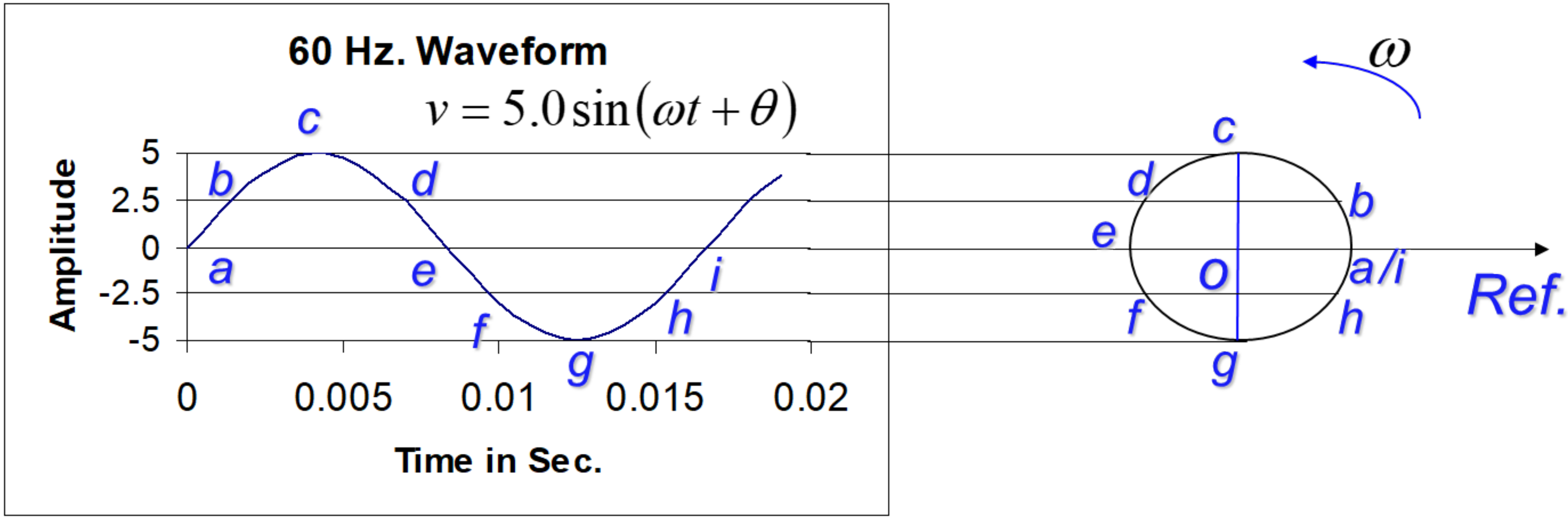
- Prevent partial collapse or blackout of power system

  (System Protection)

Protection Challenges with DER Integration

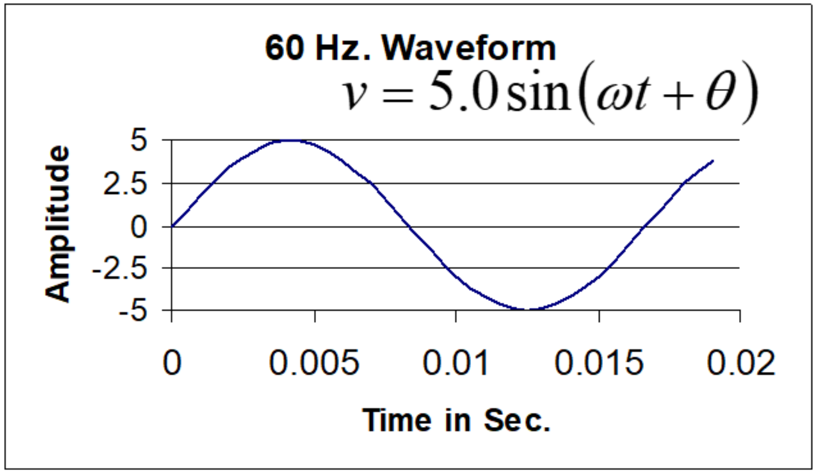
- Ensuring fault is isolated from all sources
- Maintaining security for varying fault current levels
- Avoiding desensitization of protective relaying
  - Avoiding overvoltage
- Avoiding unnecessary DER unavailability due to
  - transient faults
  - permanent faults

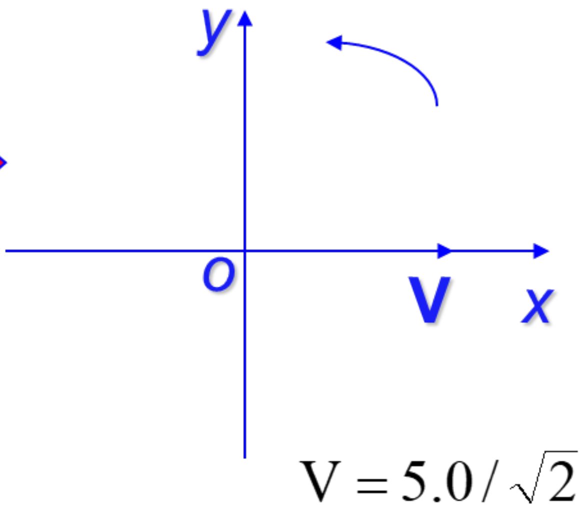
Phasor

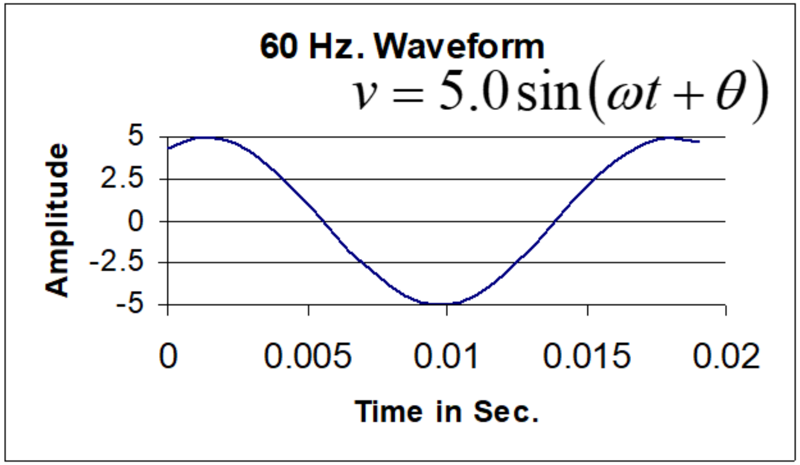


Time domain → *Frequency domain*

Phasor


60 Hz. Waveform
$v = 5.0\sin(\omega t + \theta)$
Amplitude
5
2.5
0
-2.5
-5
0
0.005
0.01
0.015
0.02
Time in Sec.


y
o
V
x
$V = 5.0/\sqrt{2}$


60 Hz. Waveform
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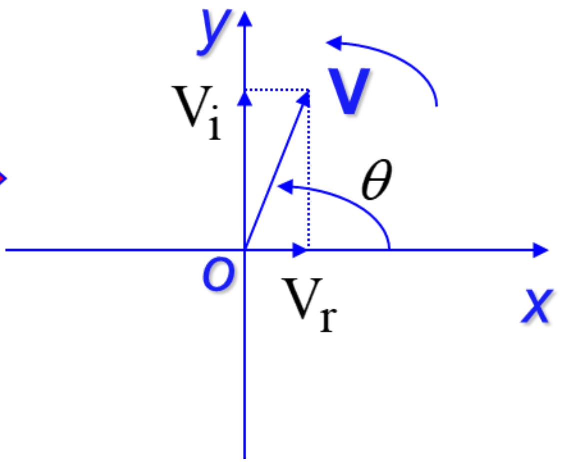
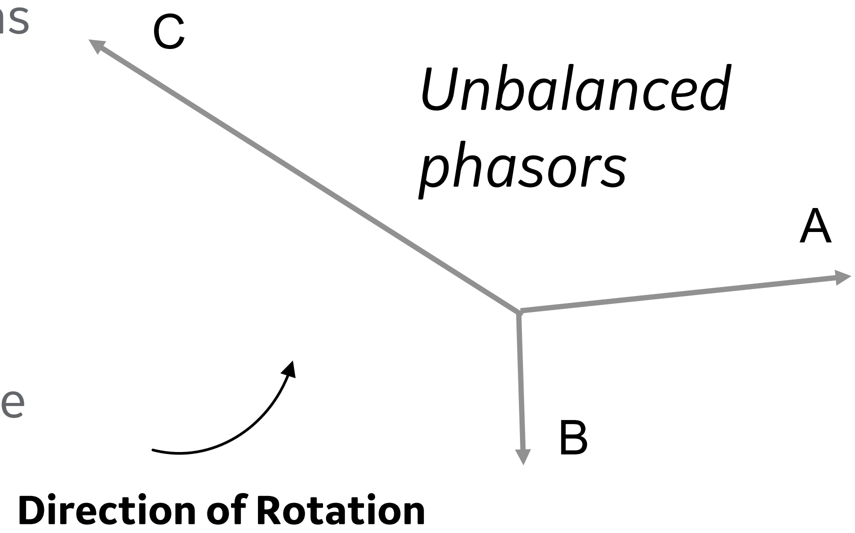
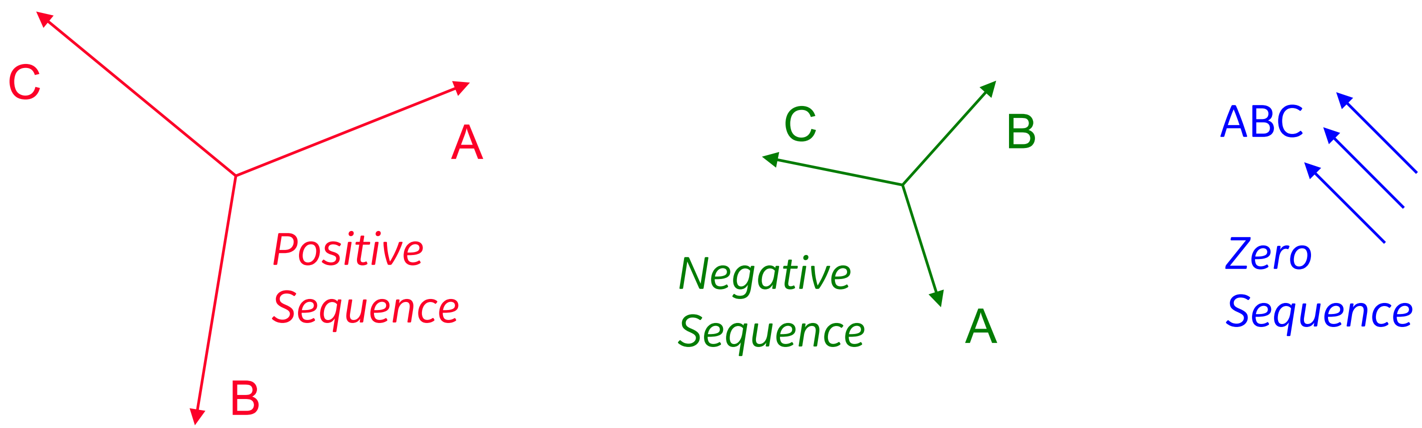

y
V_i
V
θ
o
V_r
x

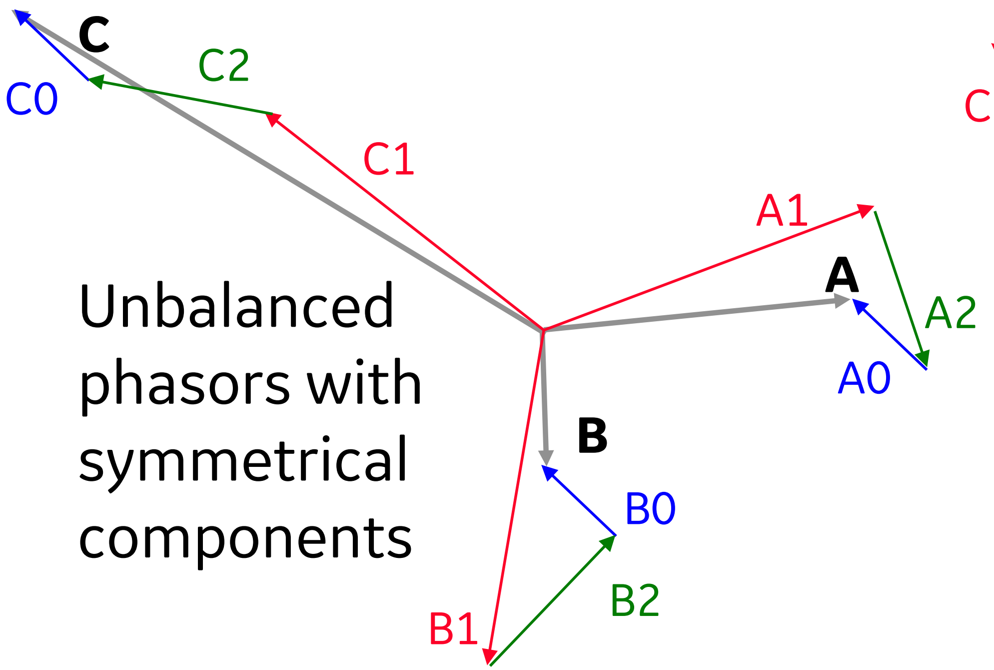
Symmetrical Components

Symmetrical component theory as applied to three phase power systems recognizes that any unbalanced three phase system of phasors may be resolved into three symmetrical systems of phasors, namely positive, negative and zero sequence components.

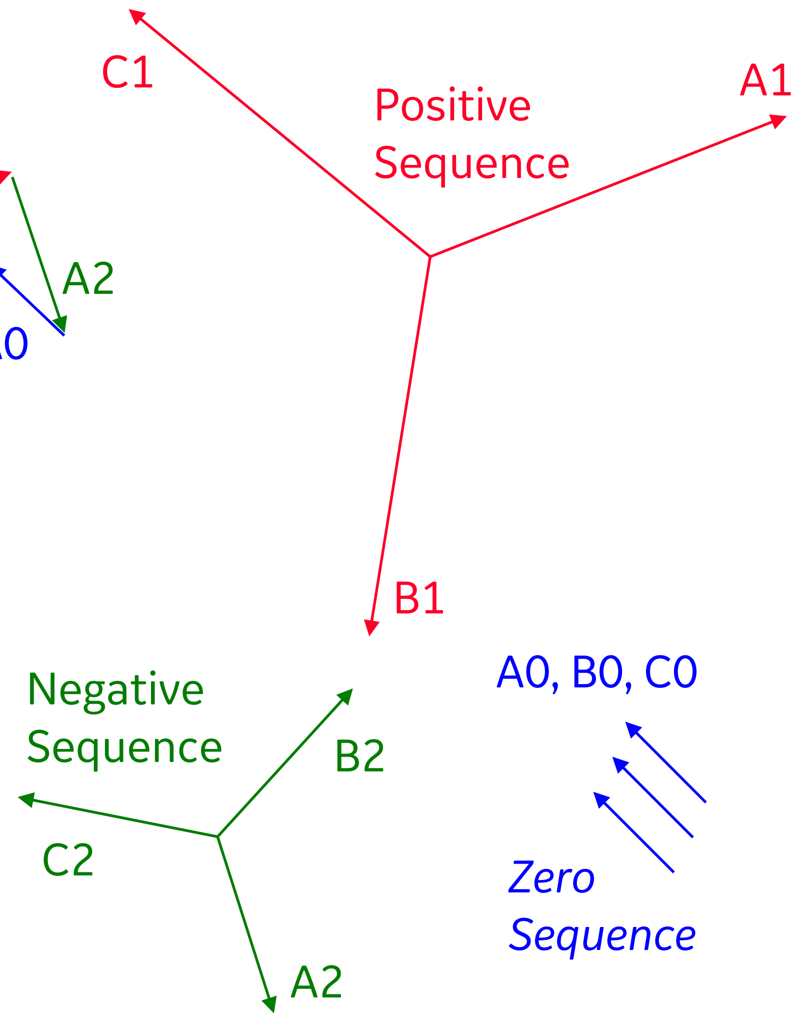




Symmetrical Components



Unbalanced phasors with symmetrical components



$$A = A1 + A2 + A0$$

$$B = B1 + B2 + B0$$

$$C = C1 + C2 + C0$$

Symmetrical Components

Properties of the phasor operator “a”

$1 = e^{j0} = 1$

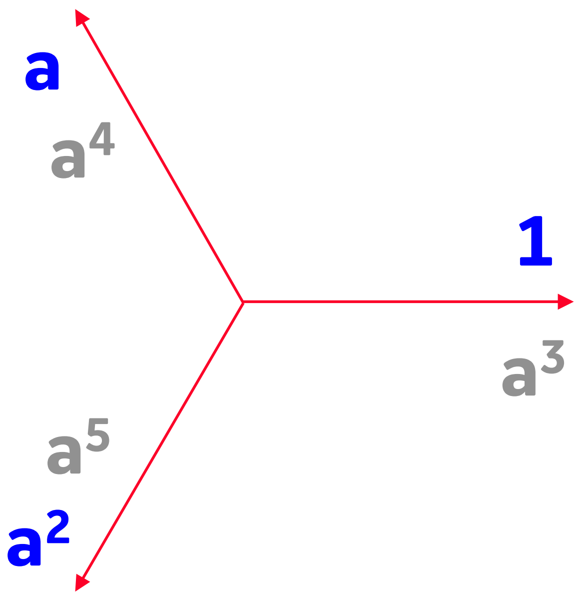
$a = e^{j120} = -0.5 + j0.866$

$a^2 = e^{j240} = -0.5 - j0.866$

$a^3 = e^{j360} = e^{j0} = 1$

$a^4 = e^{j480} = e^{j120} = a$

$a^5 = e^{j600} = e^{j240} = a^2$



- Operator “a” rotates a phasor 120^{O} in the counter-clockwise direction
- Operator “-a” rotates a phasor 120^{O} in the clockwise direction

Symmetrical Components

Analysis

$$V_{A0} = 1/3\,(\,V_A + \quad V_B + \quad V_C\,)$$

$$V_{A1} = 1/3\,(\,V_A + \,aV_B + a^2V_C\,)$$

$$V_{A2} = 1/3\,(\,V_A + a^2V_B + \,aV_C\,)$$

Synthesis

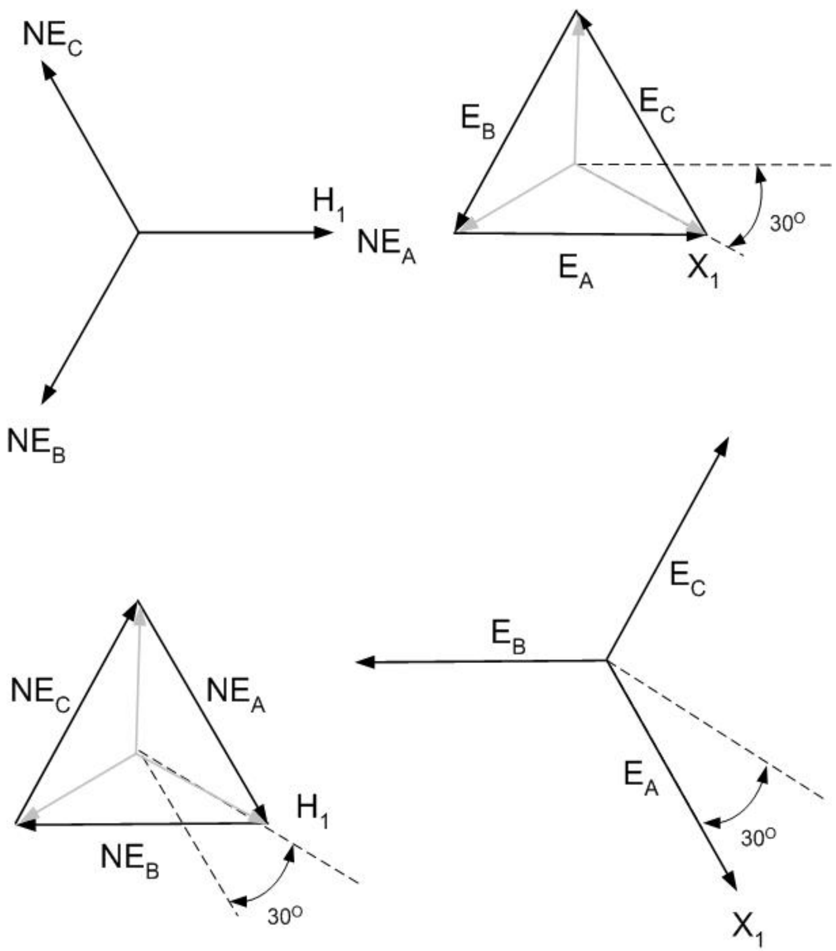
$$V_A = V_{A1} + V_{A2} + V_{A0}$$

$$V_B = V_{B1} + V_{B2} + V_{B0} = a^2V_{A1} + aV_{A2} + V_{A0}$$

$$V_C = V_{C1} + V_{C2} + V_{C0} = aV_{A1} + a^2V_{A2} + V_{A0}$$

ANSI Standard Connections for Transformers

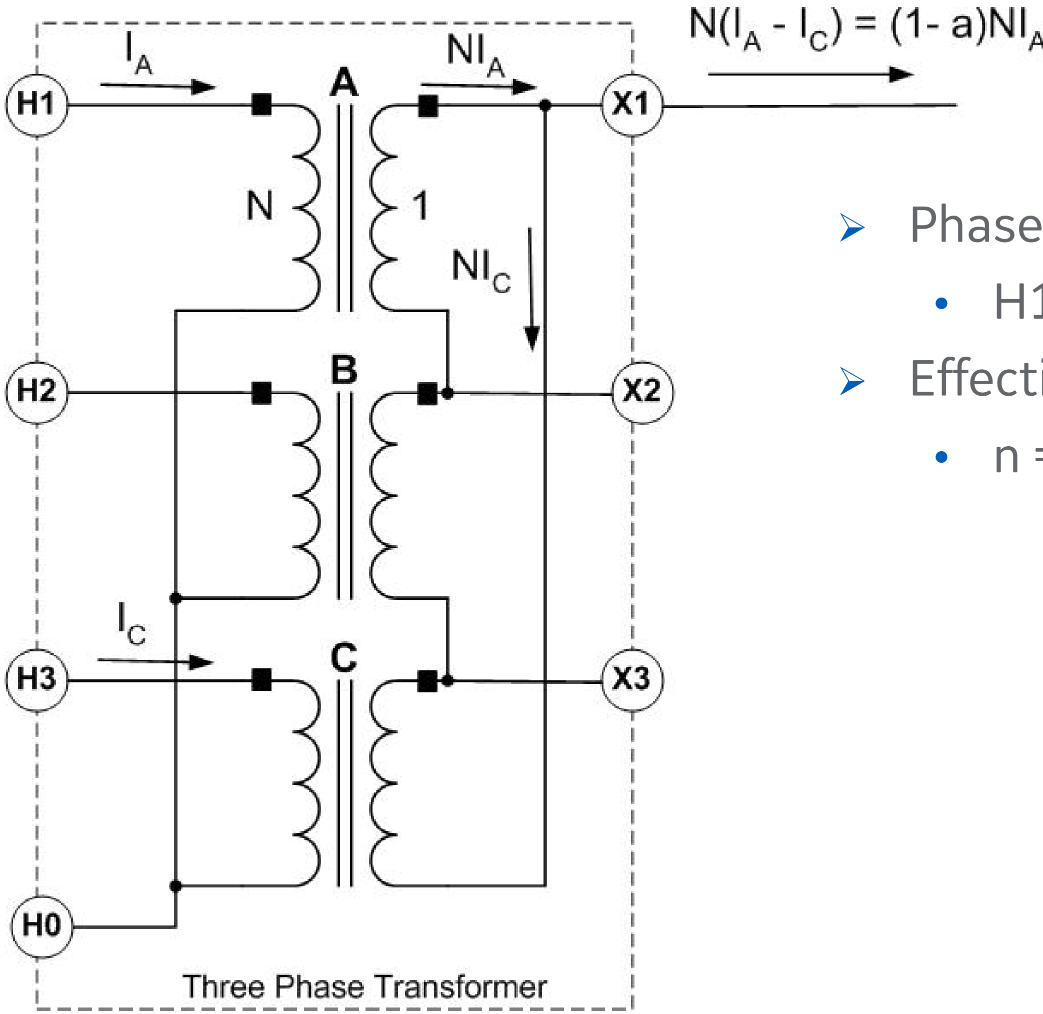
High Voltage Low Voltage



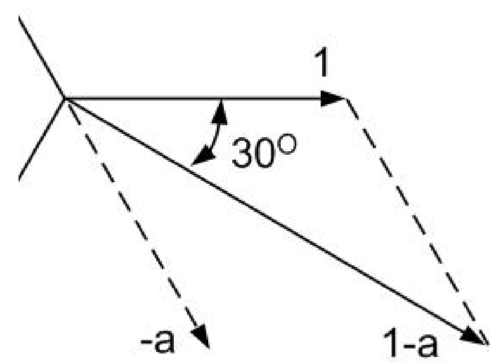
High voltage reference phase voltage leads the low voltage reference phase voltage by 30^O

- Wye-delta
- Delta-wye

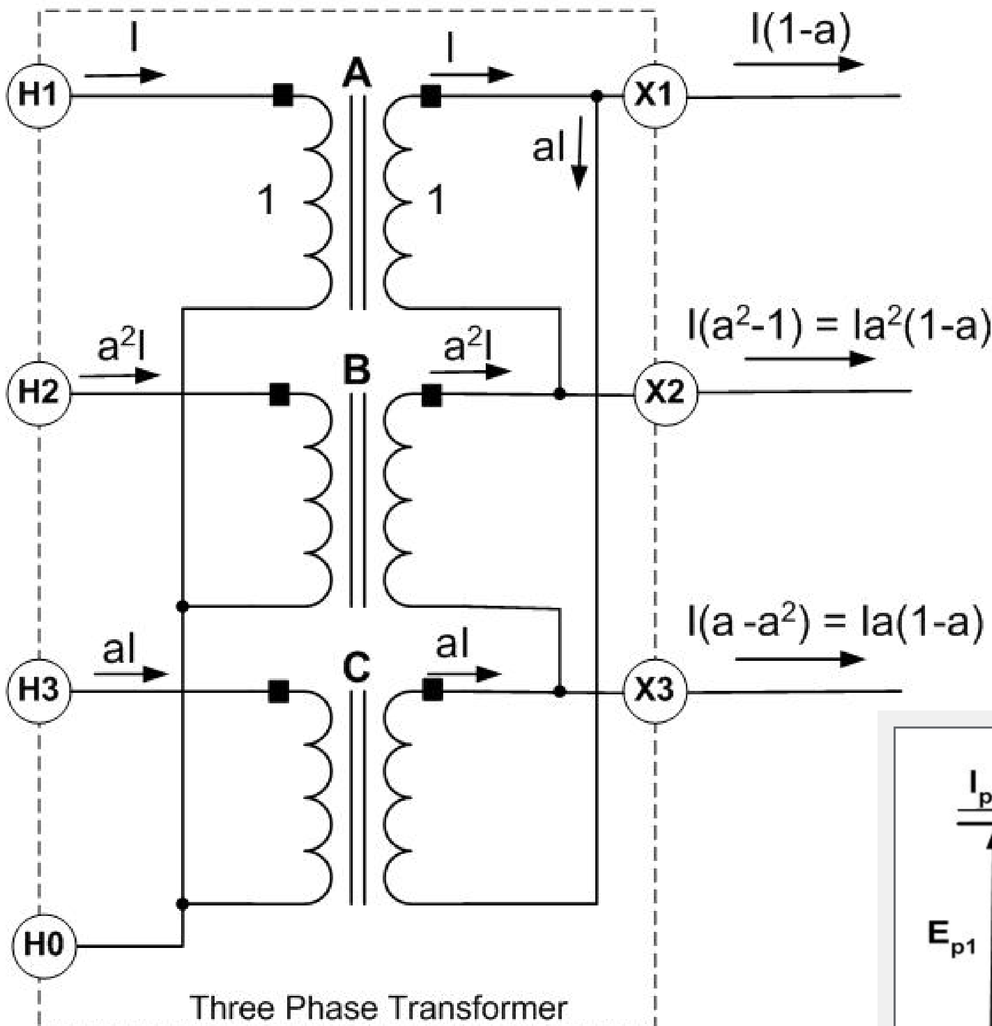
Wye-delta Connected Transformer



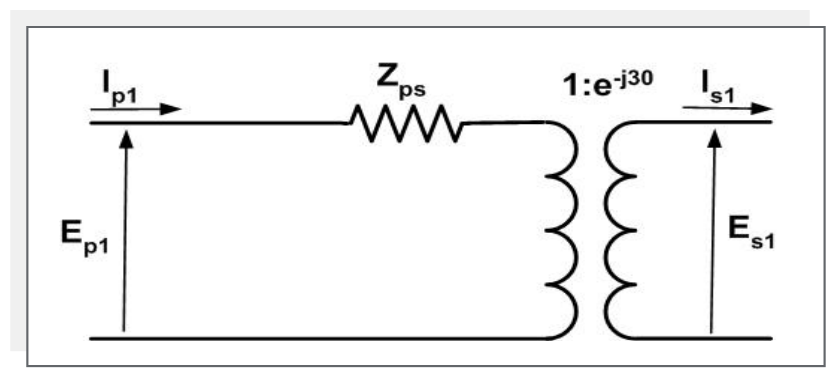
- Phase Shift
  - H1 leads X1 by 30^{O}
- Effective Turns Ratio
  - n = $N\sqrt{3}$



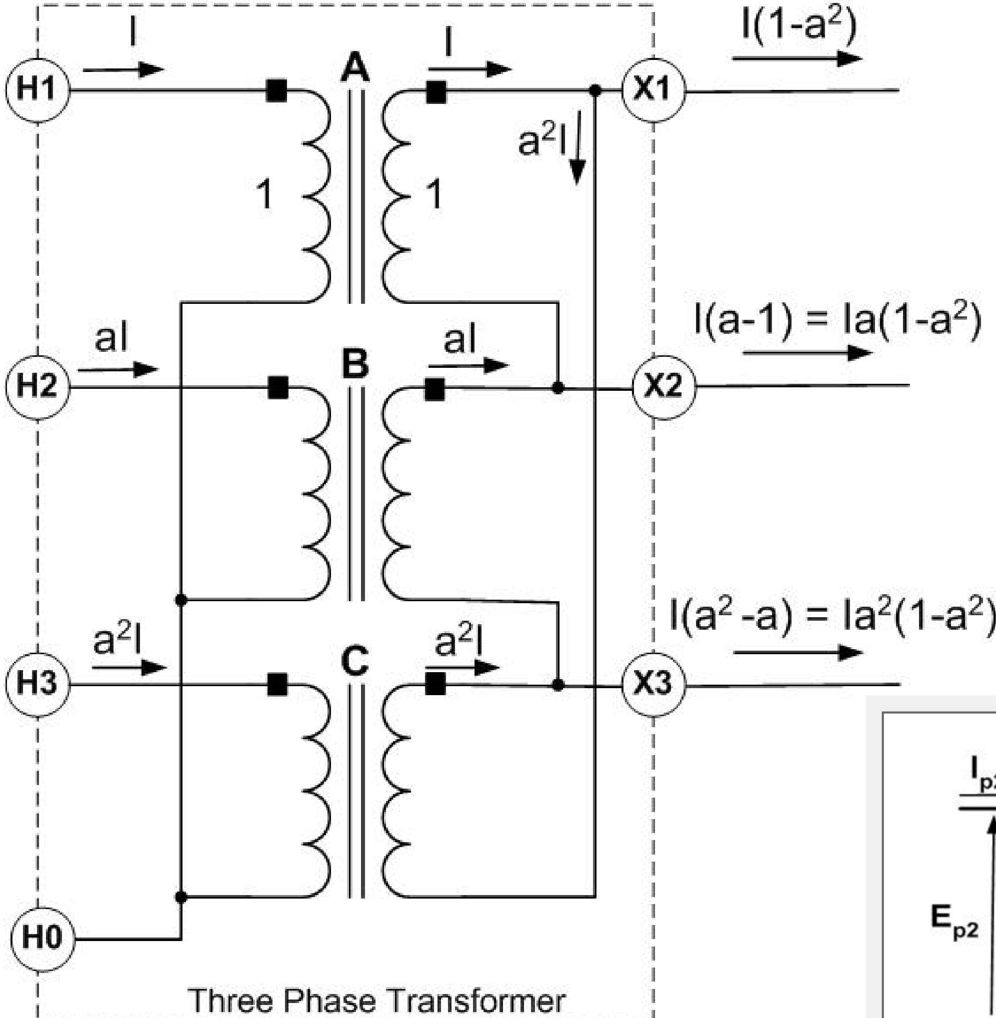
Positive Sequence Circuit



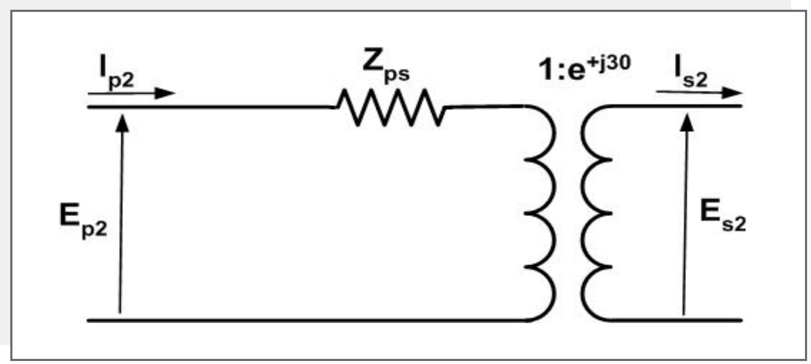
$$1-a=\sqrt{3}e^{-j30}$$



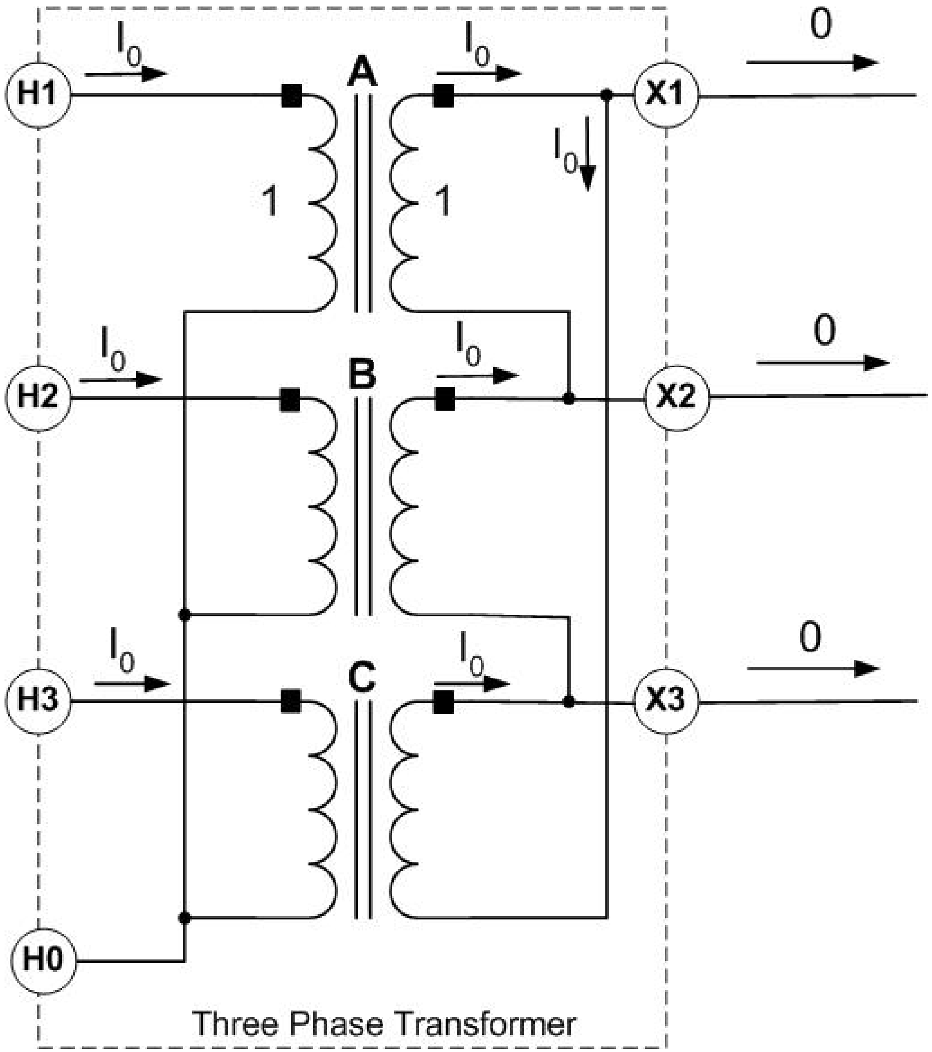
Negative Sequence Circuit



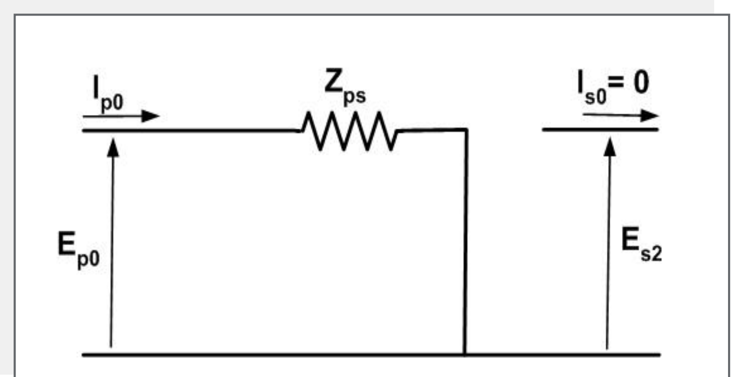
$$1-a^2=\sqrt{3}e^{+j30}$$



Zero Sequence Circuit



- Zero sequence current
  - flows in the high voltage system side of H1
  - flows in the high voltage wye connected windings
  - circulates in the delta connected winding
- Zero sequence current does not flows in the low voltage system side of X1 (the delta side)

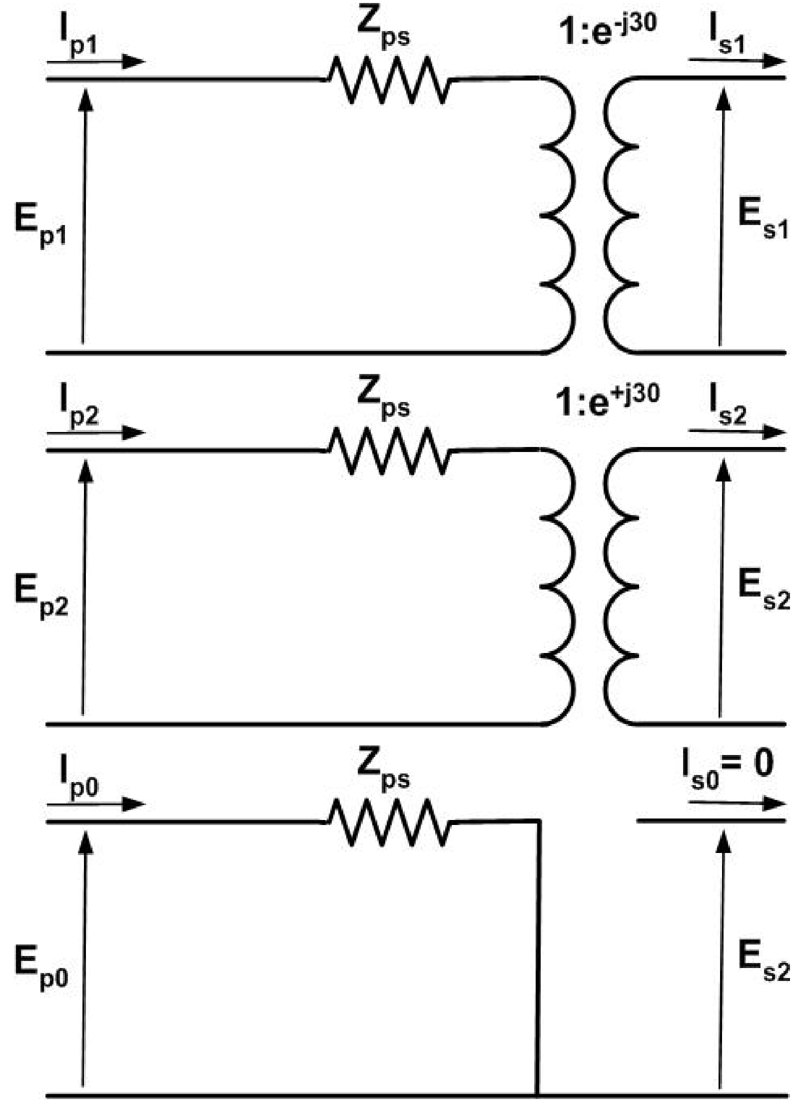


Sequence Circuits for Wye-ground-delta Transformers

Positive Sequence Network

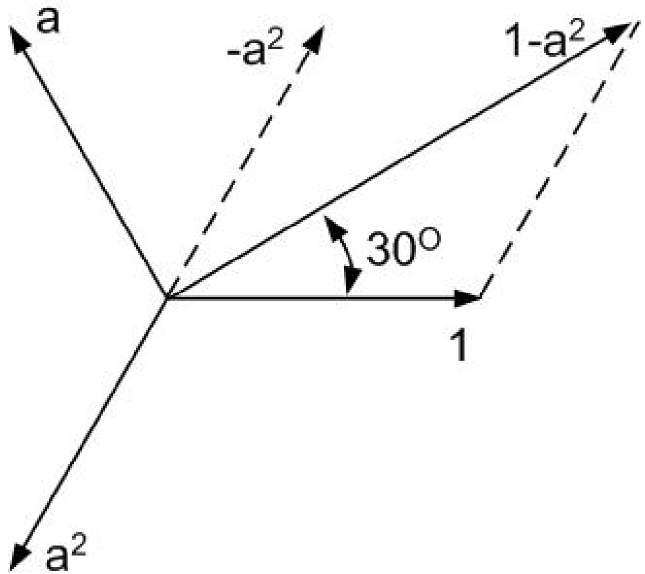
Negative Sequence Network

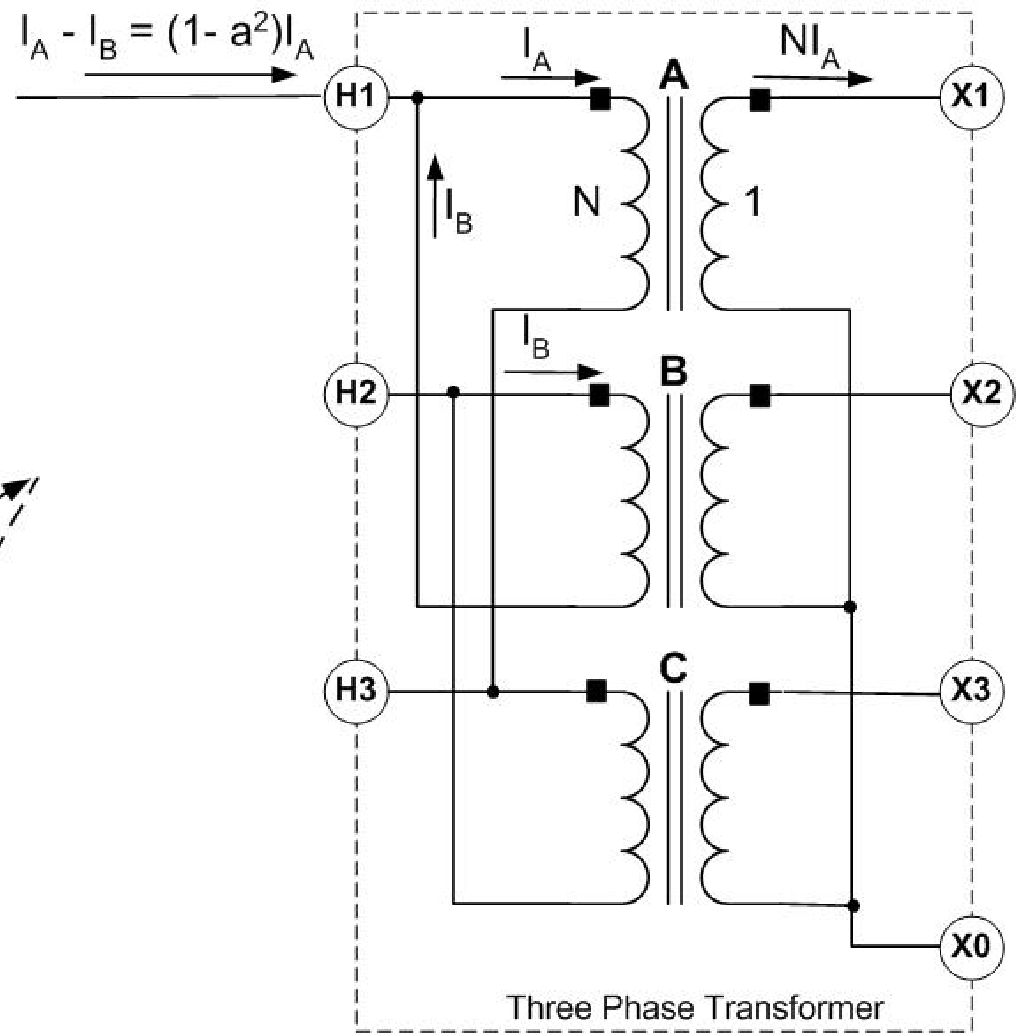
Zero Sequence Network



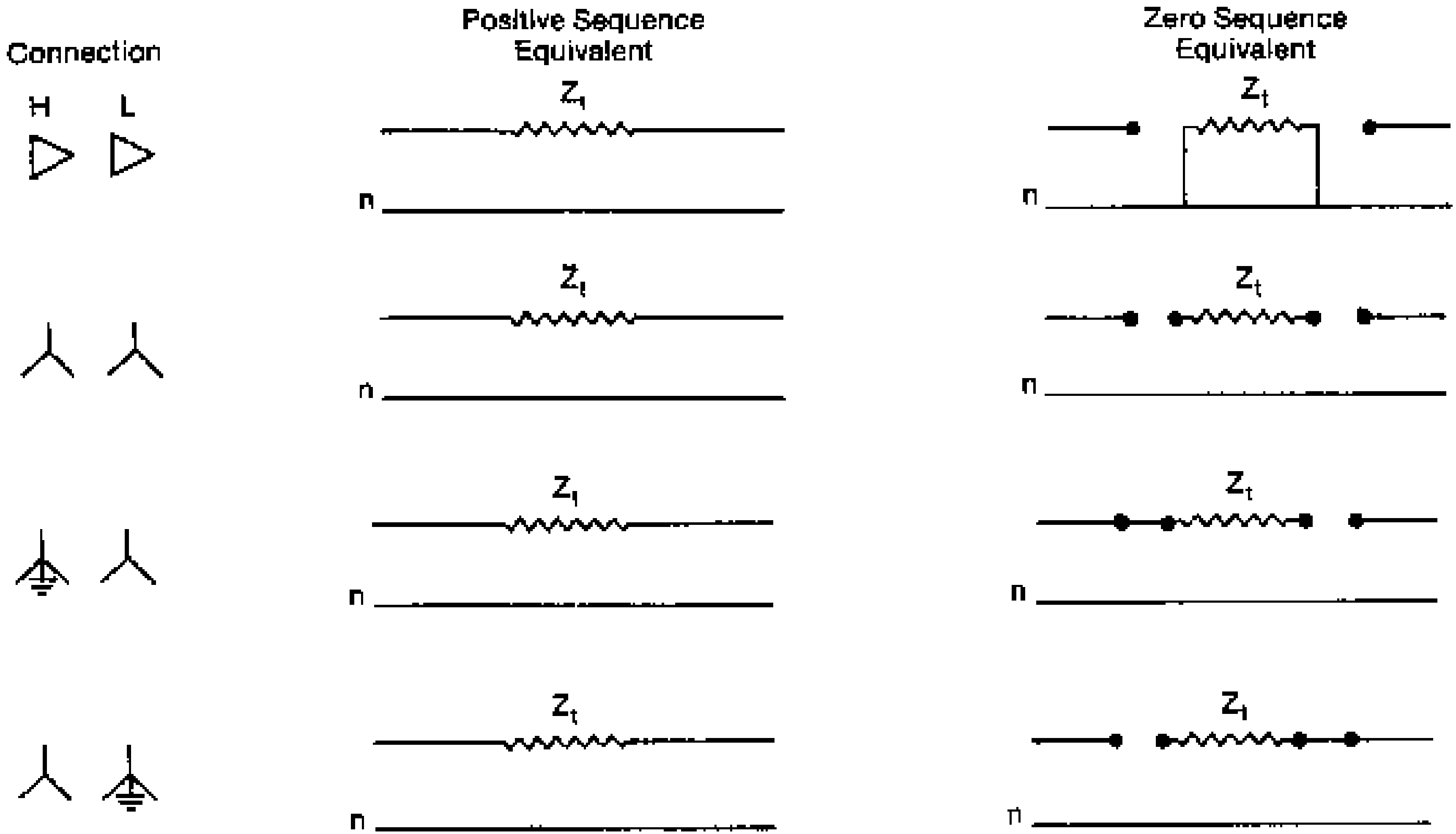
Delta-wye Connected Transformer

- Phase Shift
  - H1 leads X1 by 30^{O}
- Effective Turns Ratio
  - $n = N/\sqrt{3}$

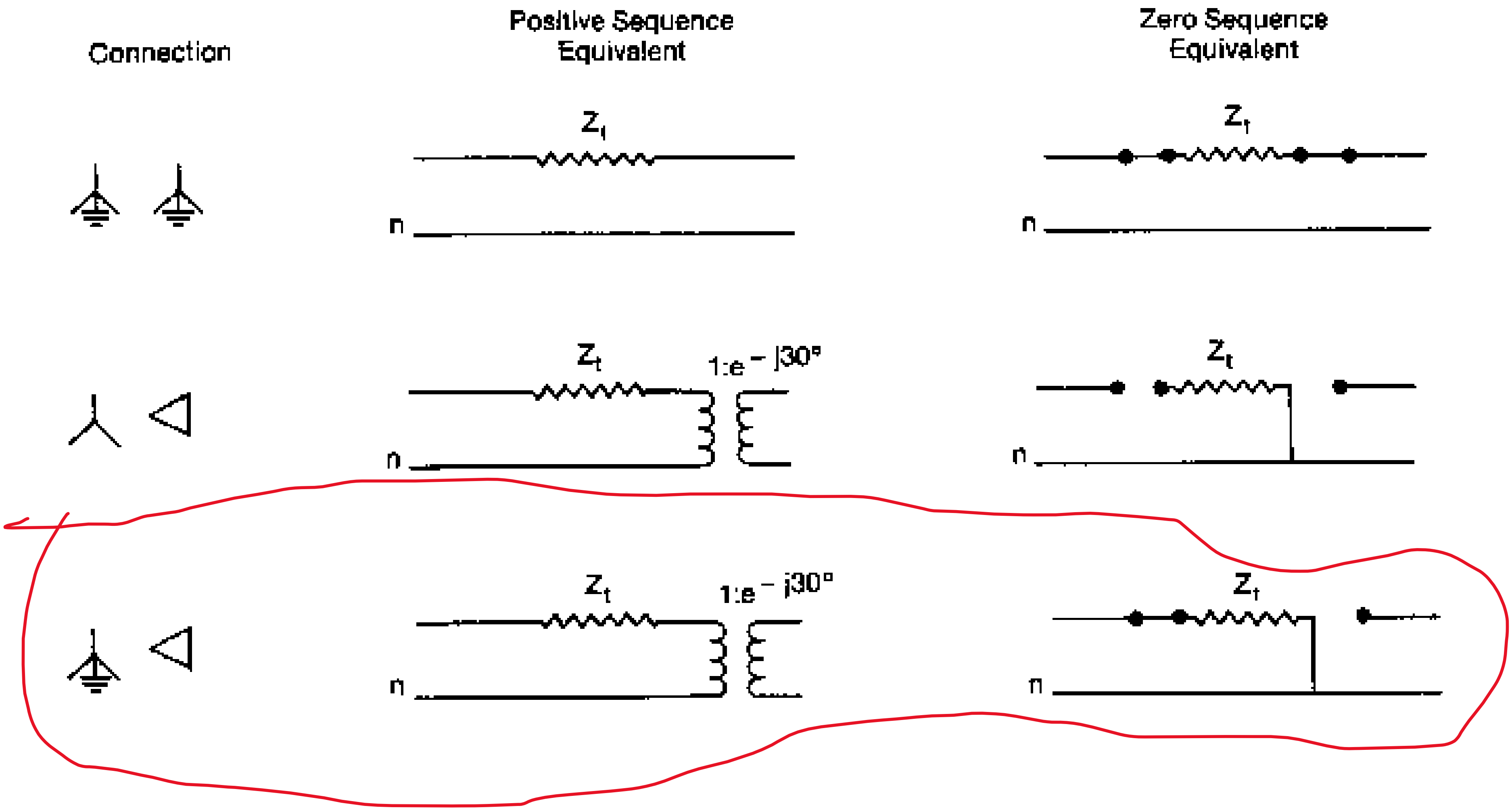




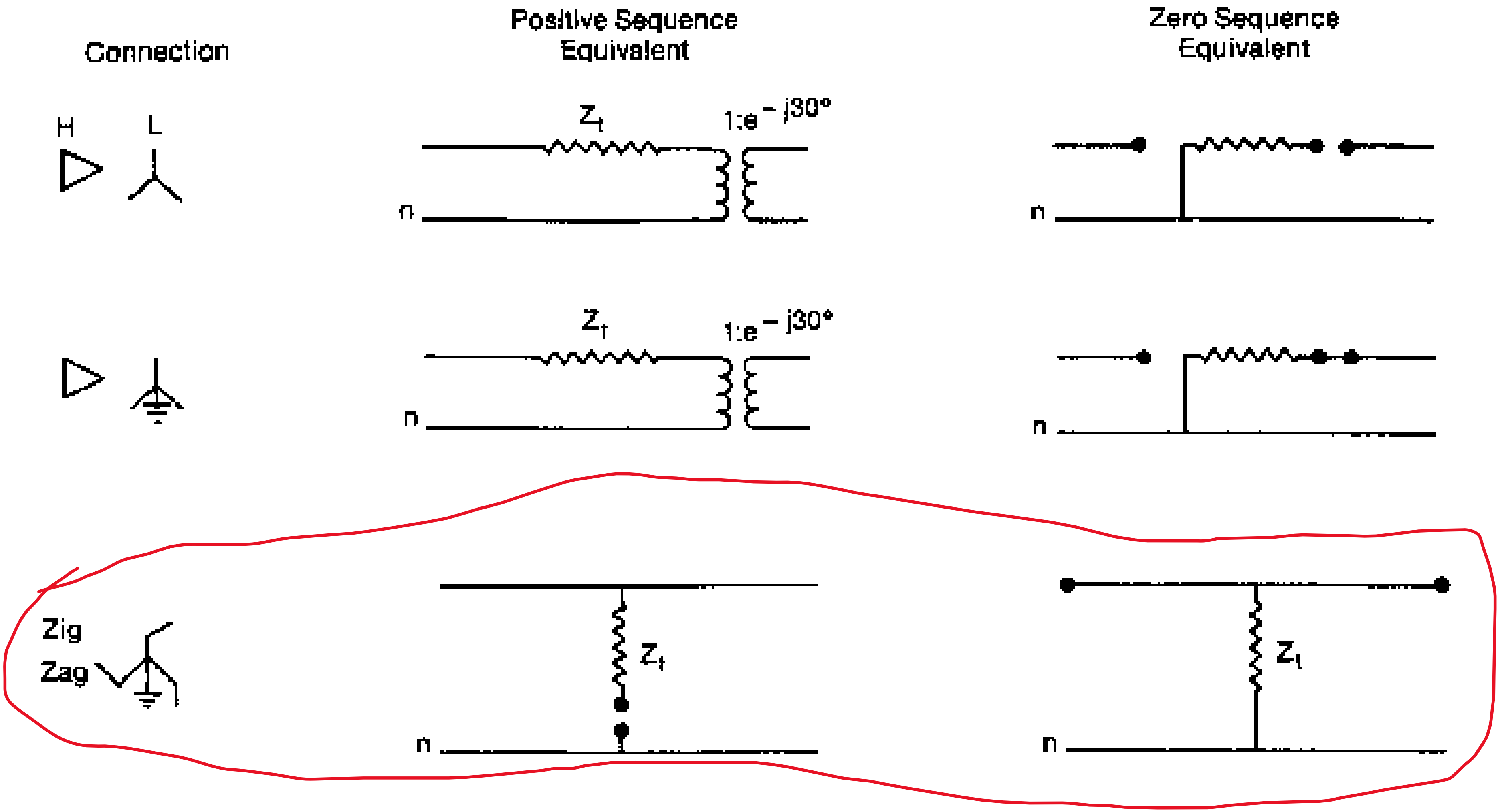
Equivalent Circuits - Two Winding



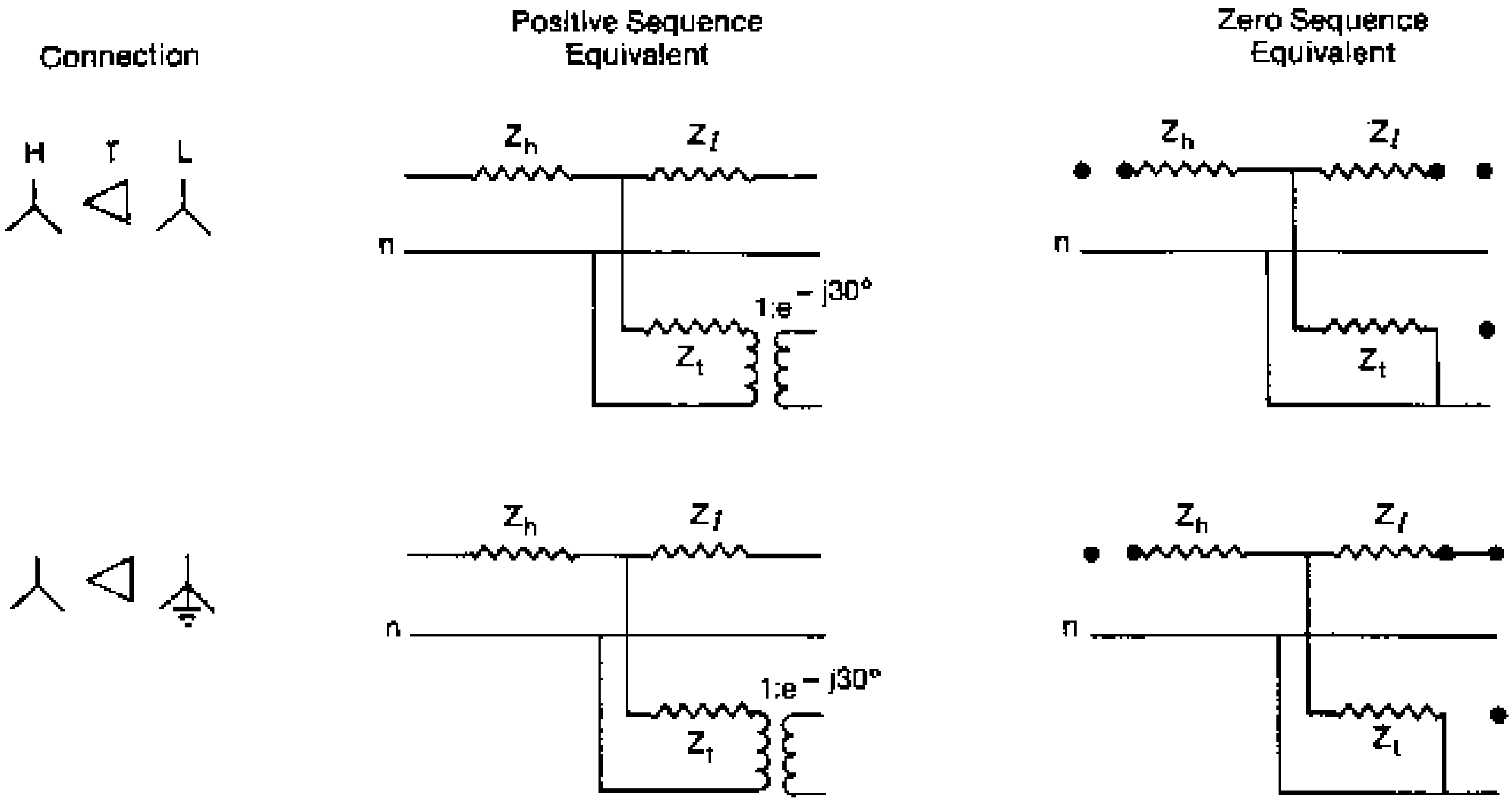
Equivalent Circuits - Two Winding



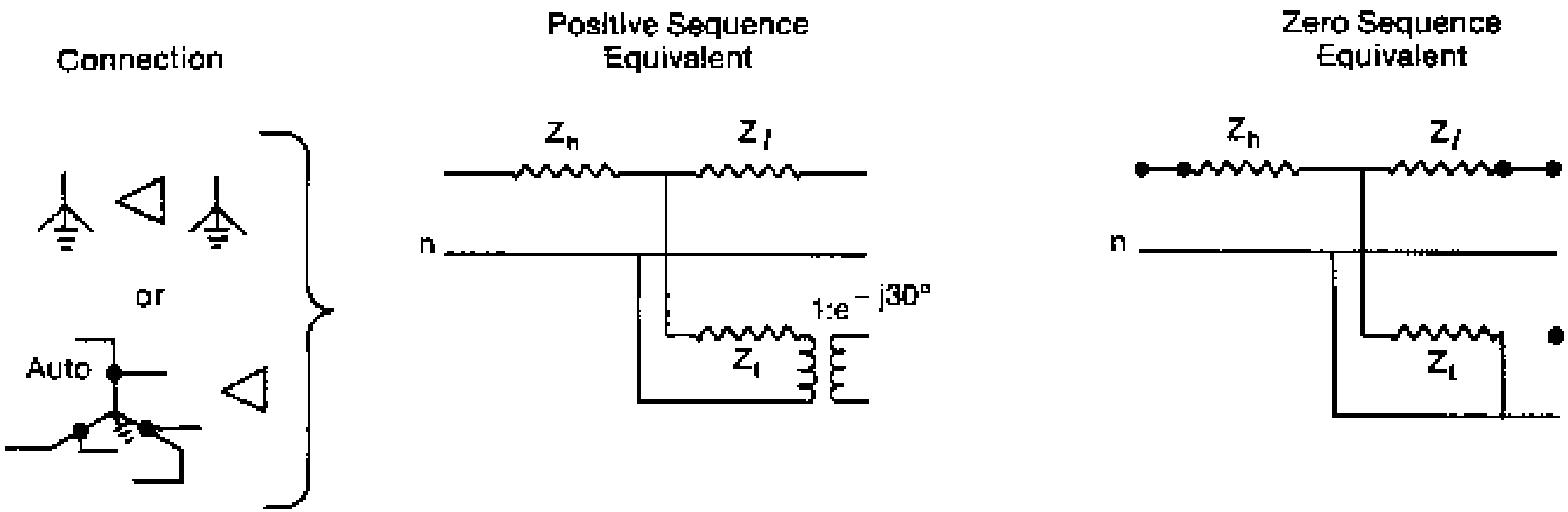
Equivalent Circuits - Two Winding



Equivalent Circuits - Three Winding



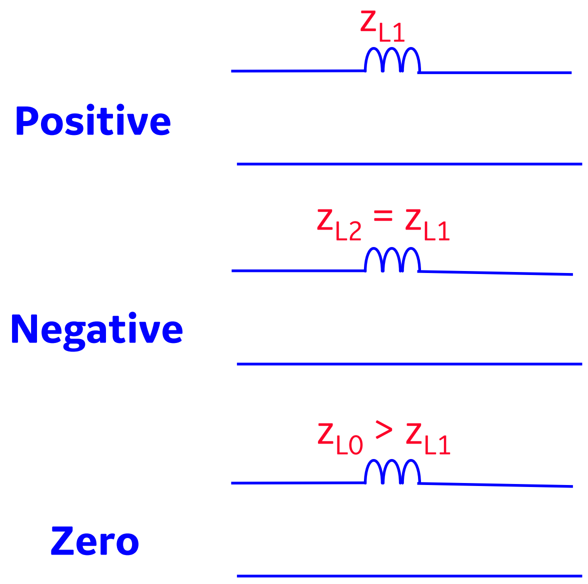
Equivalent Circuits - Three Winding



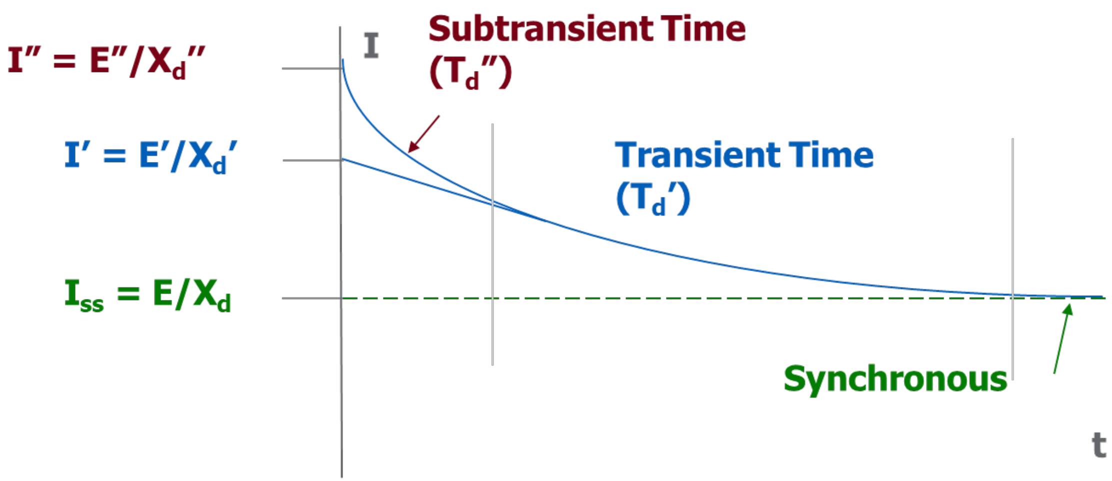
Symmetrical Components – Line Model

Z2 = Z1 for transposed lines. For non-transposed line, there may be some variance.

Z0 > Z1 due to mutual coupling between phases. Mutual coupling to adjacent circuits must be considered.



Symmetrical Components – Generator Short Circuit



$$I_{ss} = (E''/X_d'' - E'/X_d')\, e^{-t/T_d''} + (E'/X_d' - E/X_d)\, e^{-t/T_d'} + E/X_d$$

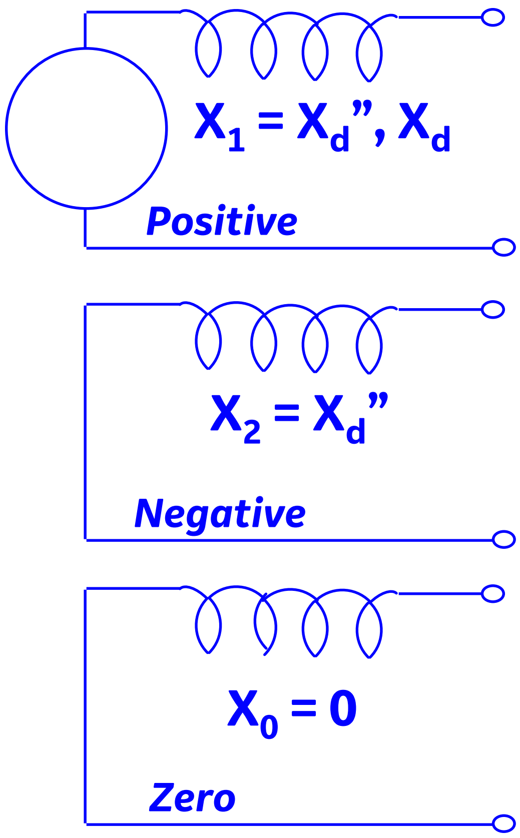
- Modeling is very well understood and repeatable
  - Manufacturers provide test data for the required parameters
- Existing fault simulation software provides good modeling which has been validated with actual fault data
- Traditional protection relays are designed around these characteristics

- X”d Subtransient : High level fault current (**8-12pu**) typically lasts approximately **5-6 cycles**
- X’d Transient: Lasts **10-12** cycles
- Xs Synchronous: Fault current magnitude can range from **1.0 – 1.2 pu.**
- **Produces I2 and I0 current.**
- **Voltage source model**

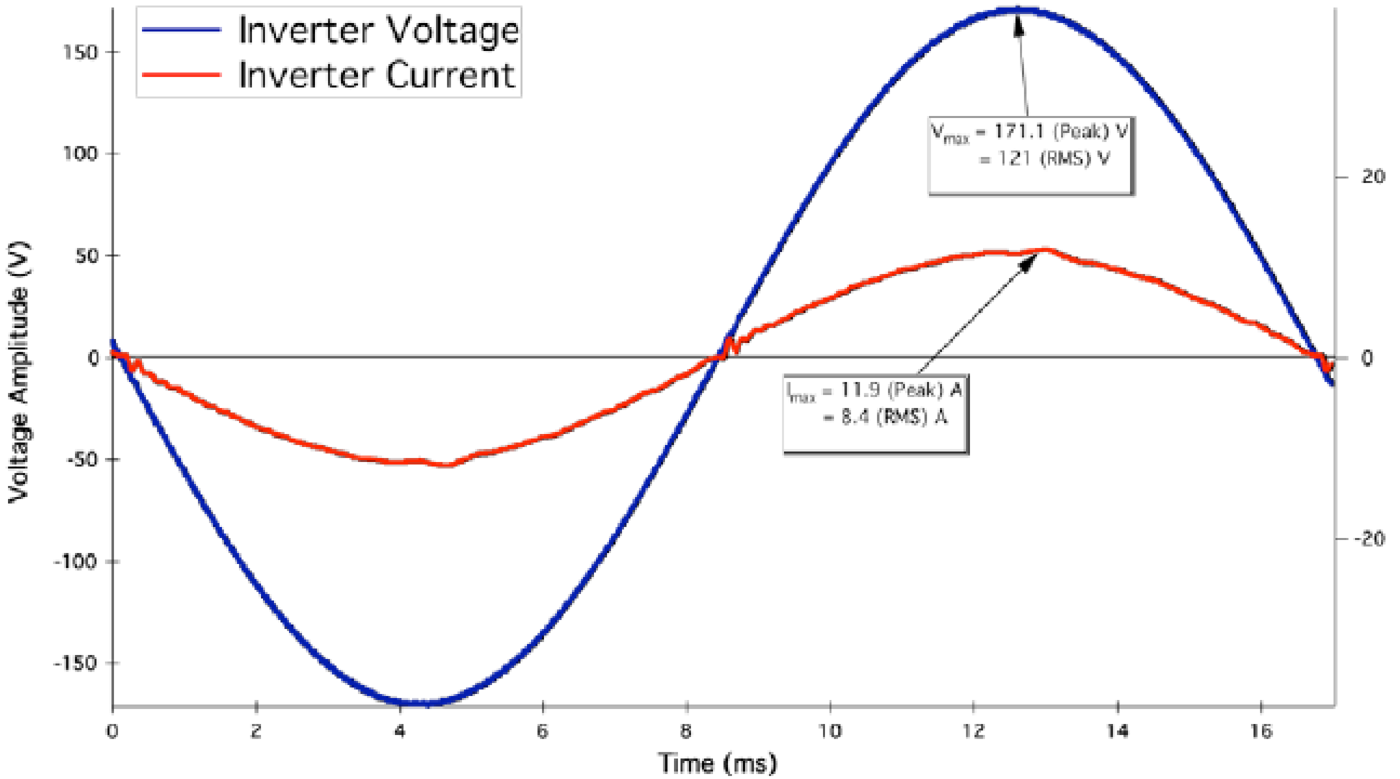
Symmetrical Components – Generator Model

Typical Sequence quantities to use

Sequence	Steady State	Fault
Positive	X_d	X_d''
Negative	X_d''	X_d''
Zero	0	0

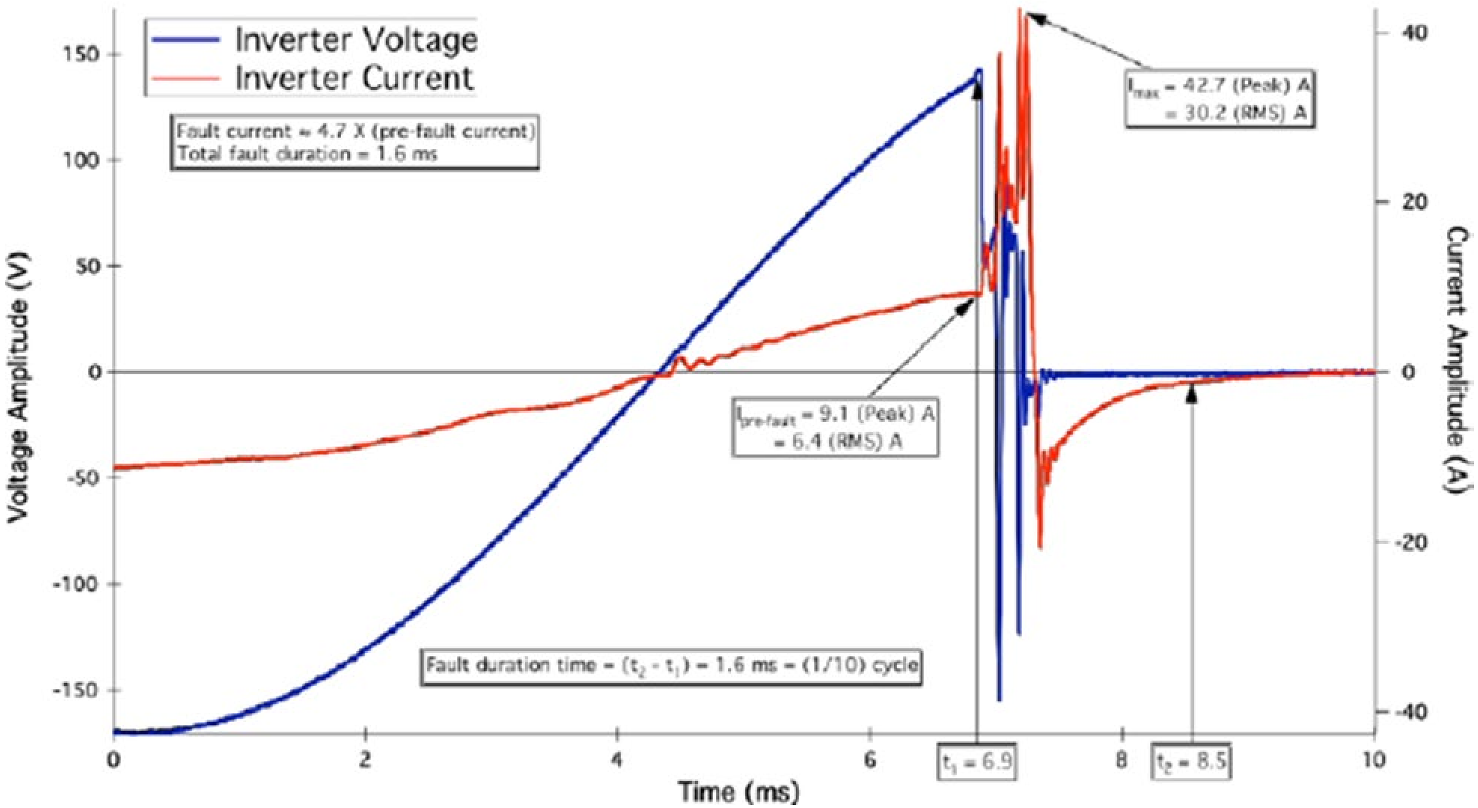


Symmetrical Components – Type 4, 1-Phase 1 kW Inverter Prefault Voltage & Current



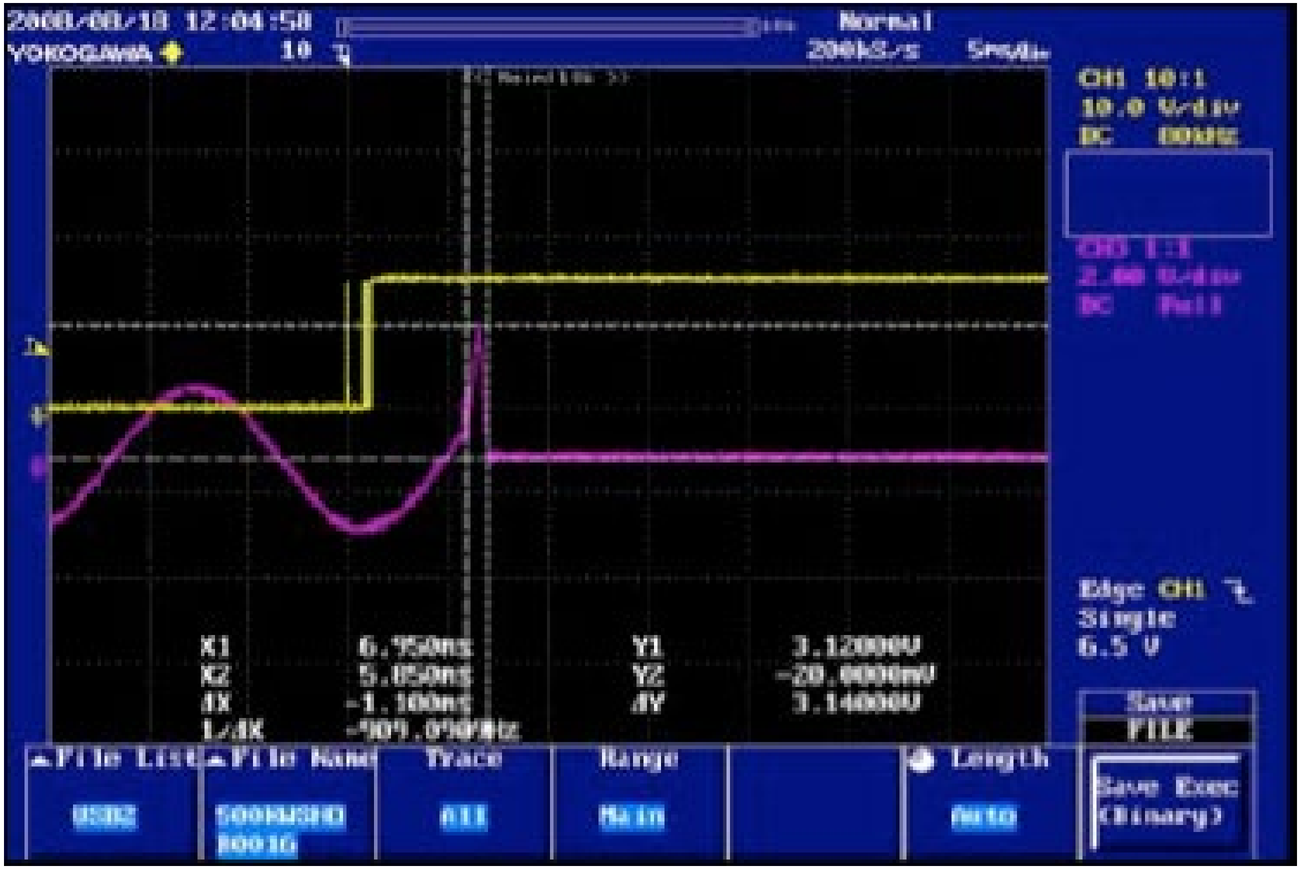
Reference:
J. Keller and B. Kroposki, "Understanding Fault Characteristics of Inverter-Based Distributed Energy Resources", Technical Report, NREL/TP-550-46698, Figure 16, Page 28, January 2010

Symmetrical Components – Type 4, 1-Phase 1 kW Inverter Fault Voltage & Current



Reference:
J. Keller and B. Kroposki, "Understanding Fault Characteristics of Inverter-Based Distributed Energy Resources ", Technical Report, NREL/TP-550-46698, Figure 17, Page 28, January 2010

Symmetrical Components – Type 4, 3-phase 500 kVA Inverter Fault Voltage & Current



Reference:
J. Keller and B. Kroposki, "Understanding Fault Characteristics of Inverter-Based Distributed Energy Resources ", Technical Report, NREL/TP-550-46698, Figure 17, Page 28, January 2010

Fault current is approximately 2 to 3 times the rated peak output current with a duration time of approximately 1.1 to 4.25 ms for different fault types.

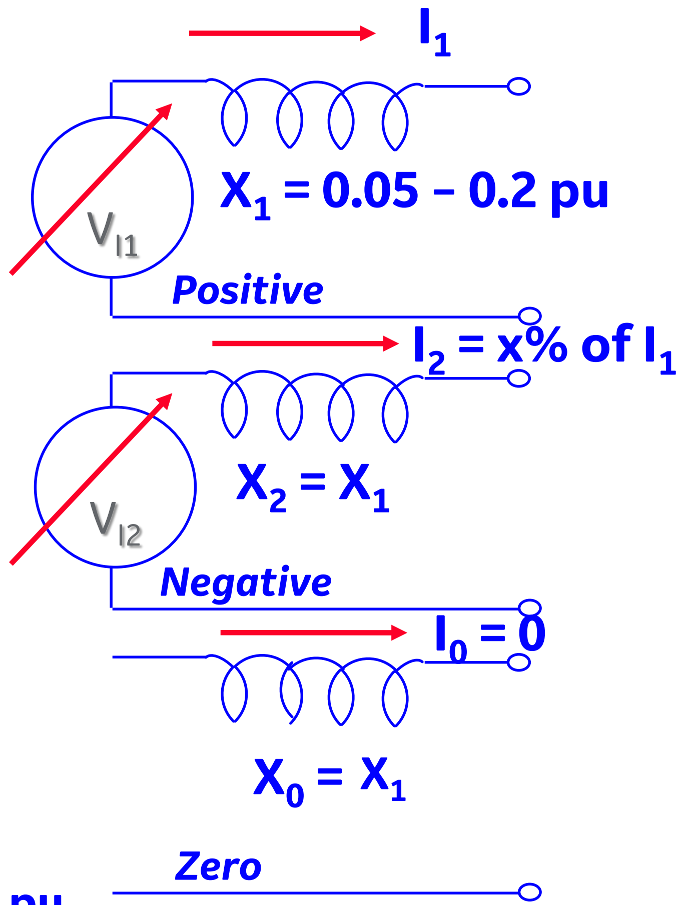
Symmetrical Components – Inverter Model

- Do not have the rotational inertia of the rotor and excitation of the field
- **Generally a current source with variable voltage support**
- Traditional protection methods will not work
- Produce low level fault current typically 1.1-1.5 pu except for very short duration high transient current
  - Many inverter models do not produce I_2 or I_0
  - Fault characteristic depends on the inverter control
    - varies among manufacturers
  - *Traditional fault software not configured to accurately represent inverters*
  - Most simulation software presently use synchronous generator model
    - Modified to approximate the characteristics of an inverter
    - Still a voltage source model that does not adequately represent the actual fault current characteristics

Symmetrical Components – Type 4
Inverter Model: *Current Source with Variable Voltage*

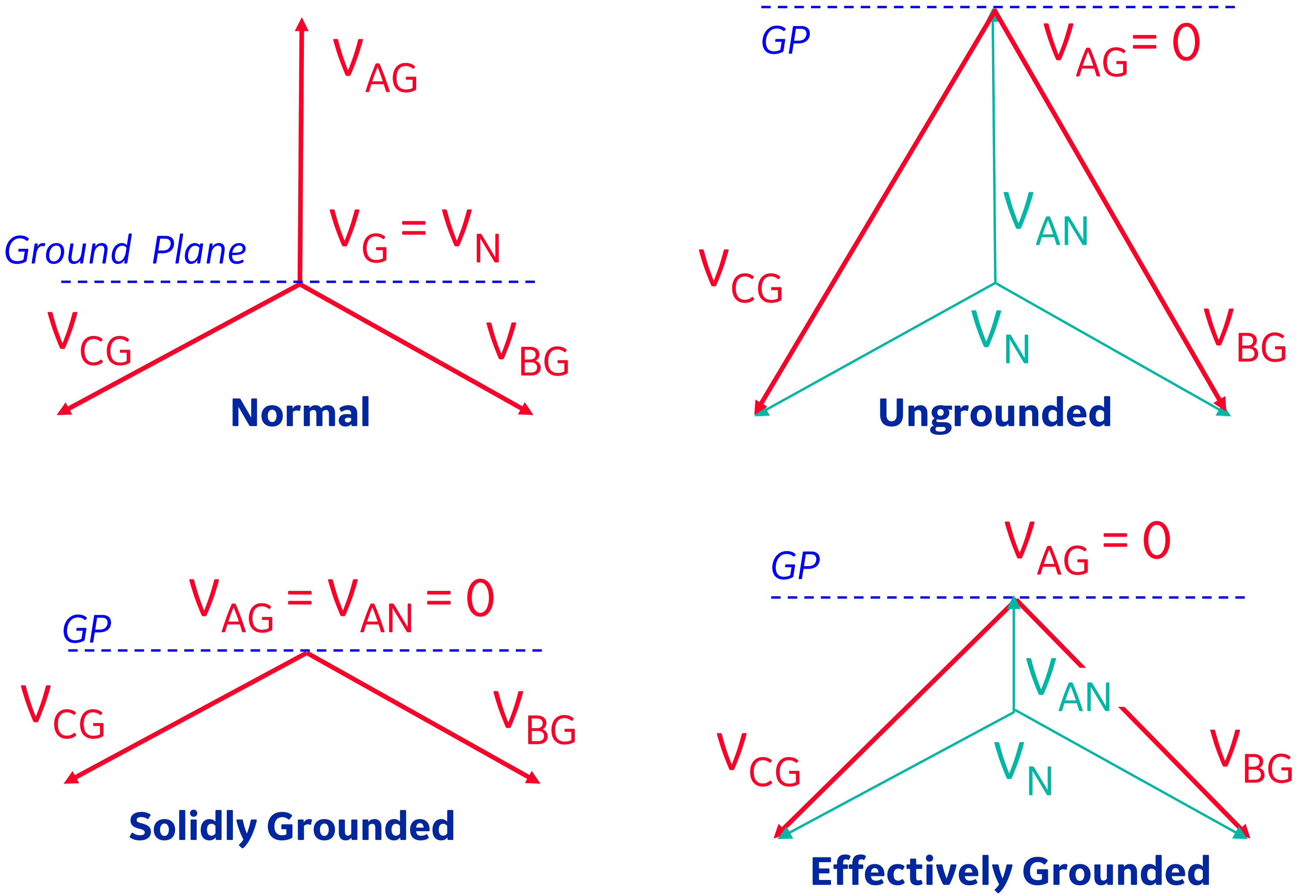
Typical Sequence quantities to use for analysis

Sequence	Steady State	Fault
Positive	X_1	X_1
Negative	X_1	X_1
Zero	X_1	X_1



$I_1 + I_2 + I_0 = 1.1\text{-}1.5$ pu

System Shunt Faults – Voltages



Protection Challenges with DER Integration

- Ensuring fault is isolated from all sources
- Maintaining security for varying fault current levels
- Avoiding desensitization of protective relaying
  - Avoiding overvoltage
- Avoiding unnecessary DER unavailability due to
  - transient faults
  - permanent faults

Protection Challenges with DER Integration

- ✓ Ensuring fault is isolated from all sources
- Maintaining security for varying fault current levels
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- Avoiding unnecessary DER unavailability due to
  - transient faults
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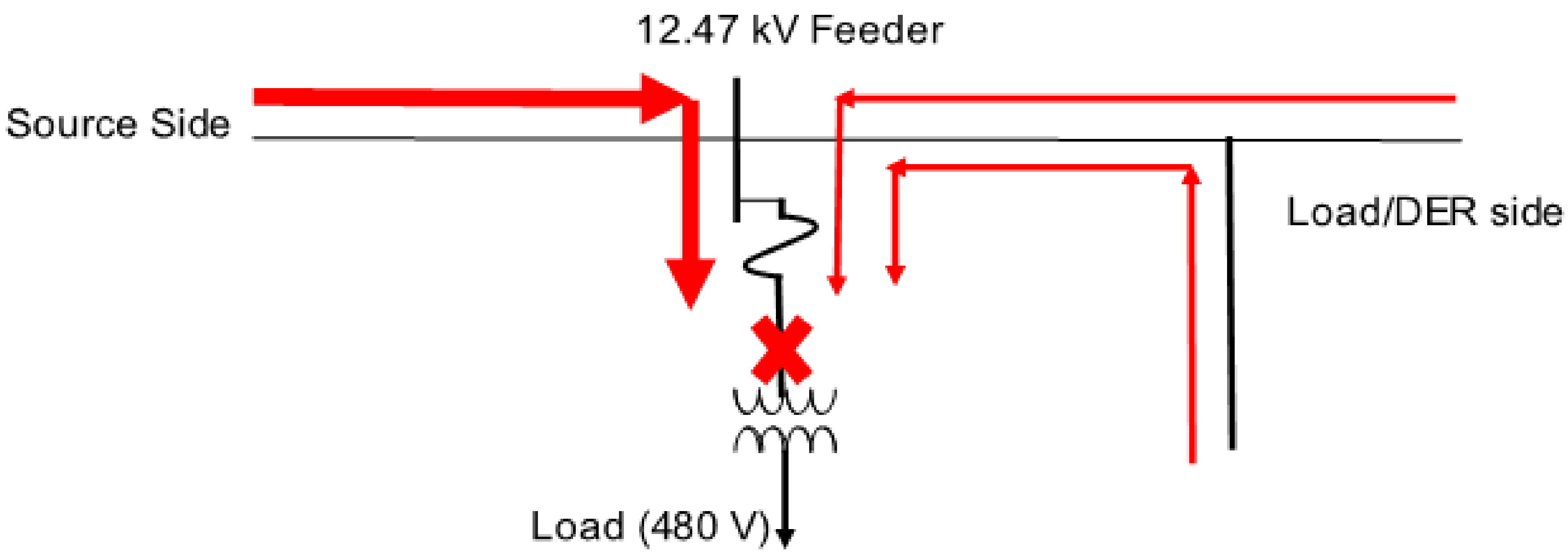
Protection Issue: Case Study 1

Dependability for grid-connected and islanded mode

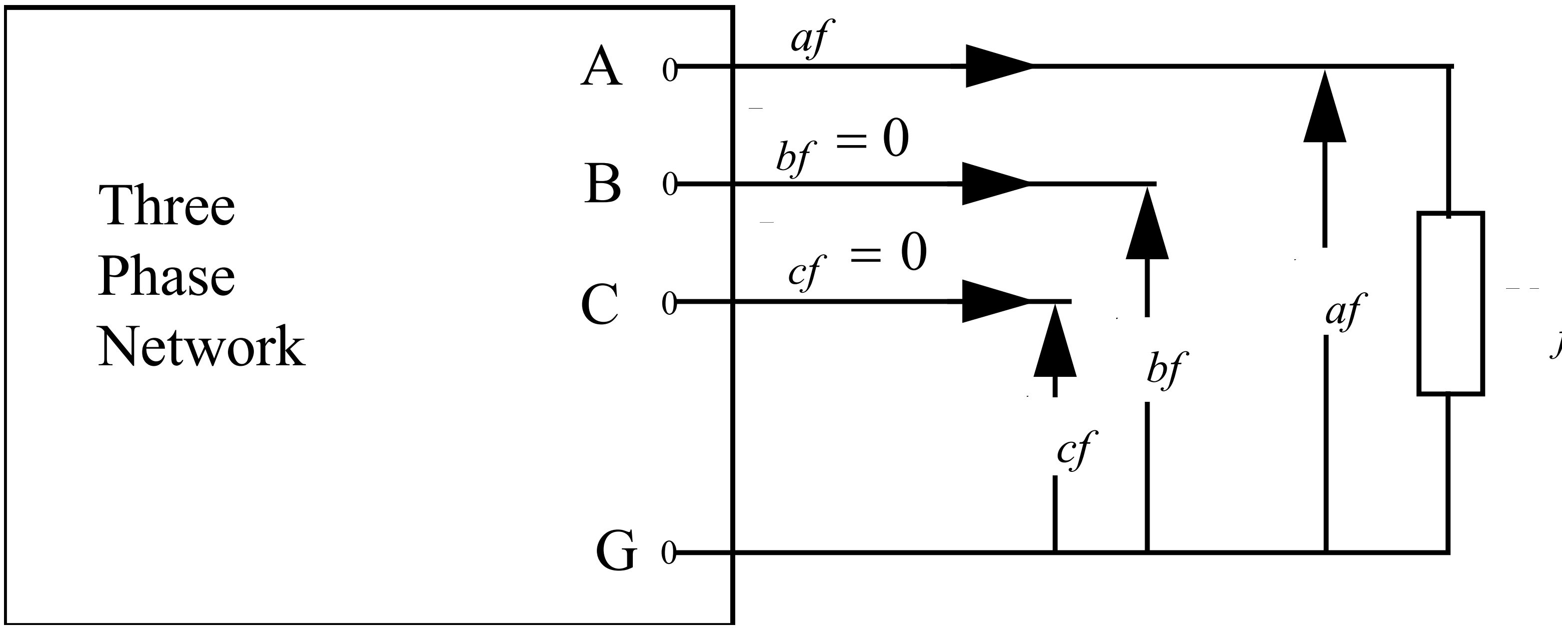


IEEE Power System Relaying and Control (PSRC) Committee WG C30 - working document. Work in progress.

Types of System Shunt Faults

Type	Phase Combinations
Three-phase	ABC
Three-phase-to-ground	ABCG
Phase-to-ground	AG, BG, CG
Phase-to-phase	AB, BC, CA
Two-phase-to-ground	ABG, BCG, CAG

System Faults: Single-Phase-to-Ground



At fault point,

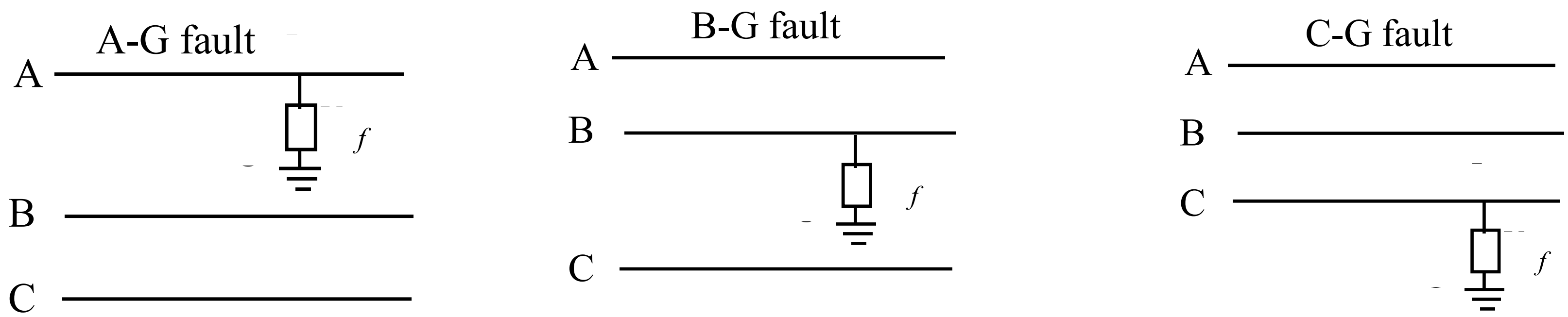
$$I_{bf} = I_{cf} = 0$$

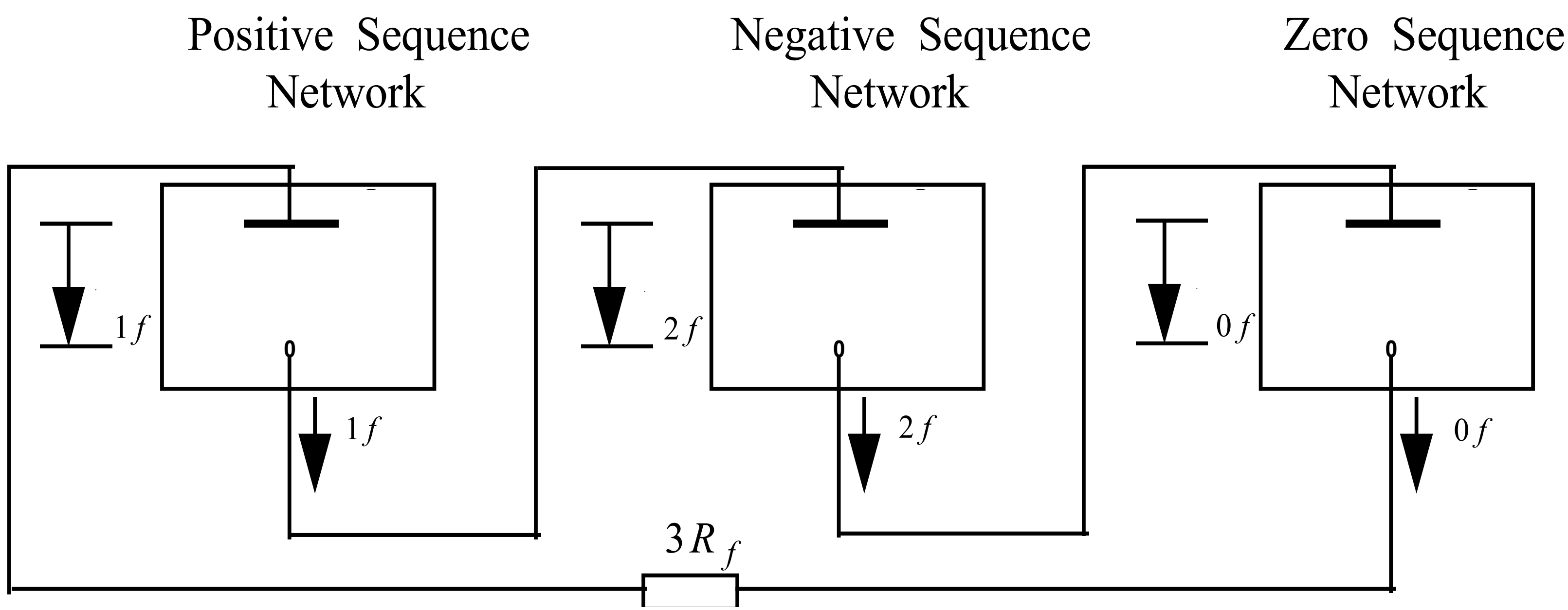
$$V_{af} = I_{af} R_f$$

$$I_{0f} = I_{1f} = I_{2f} = \frac{1}{3}\left(I_{af}\right)$$

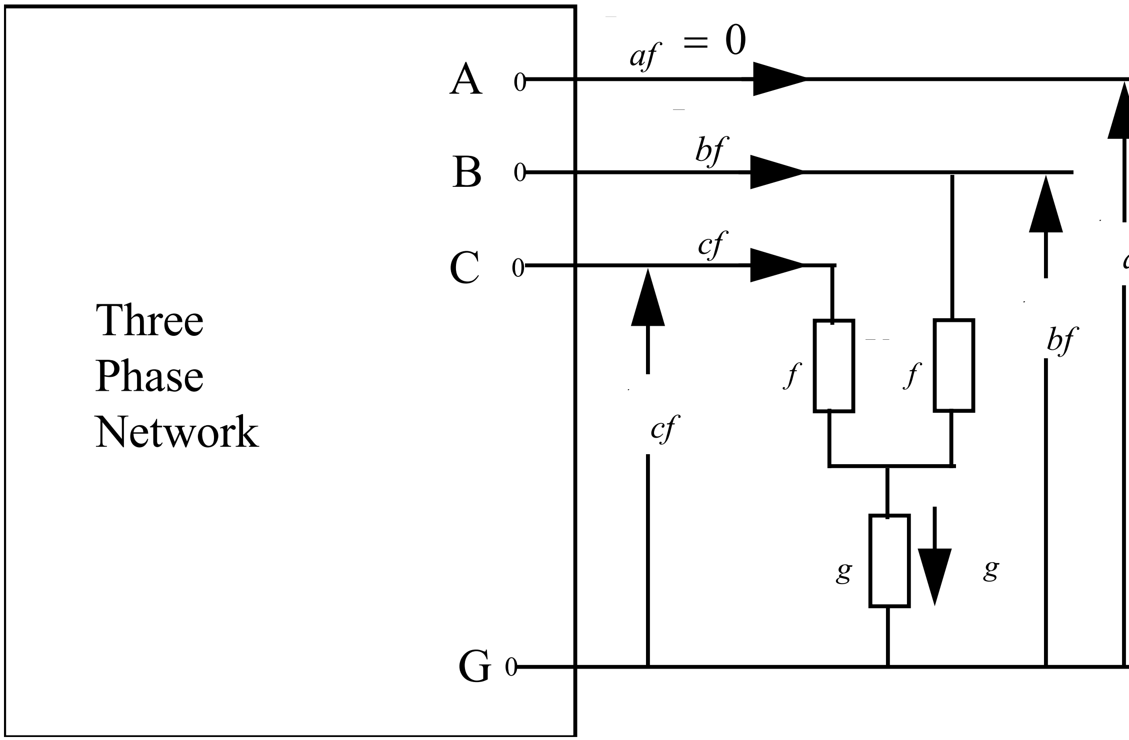
$$V_{0f} + V_{1f} + V_{2f} = I_{0f}(3R_f)$$

System Faults: Single-Phase-to-Ground





System Faults: Two-Phase-to-Ground



At fault point,

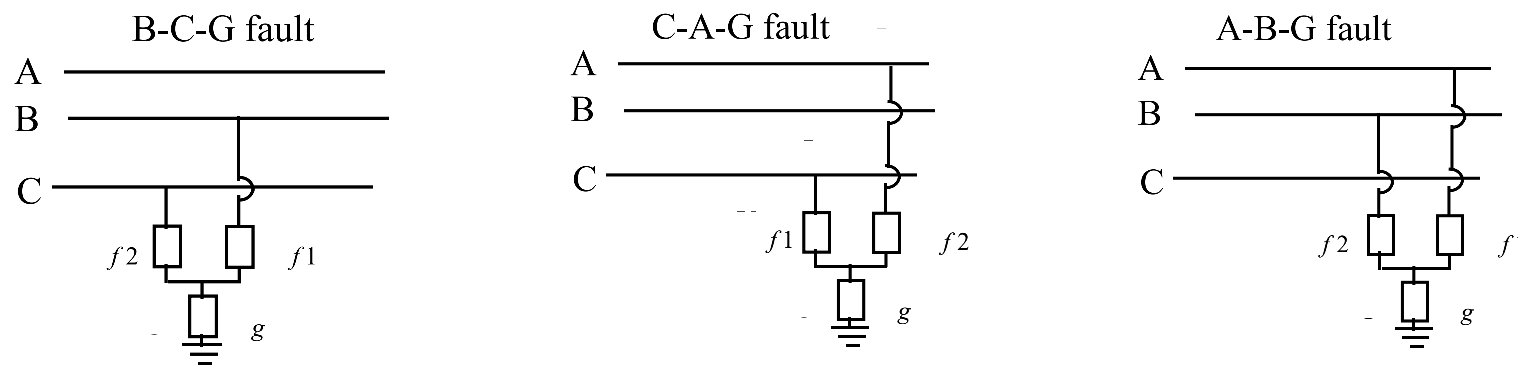
$$I_{af} = 0 \quad \text{and} \quad I_{bf} + I_{cf} = I_g$$

$$V_{bf} = I_{bf} R_f + I_g R_g$$

$$V_{cf} = I_{cf} R_f + I_g R_g$$

$$\rightarrow \left(V_{1f} - I_{1f} R_f\right) = \left(V_{2f} - I_{2f} R_f\right) = \left[V_{0f} - I_{0f}\left(R_f + 3R_g\right)\right]$$

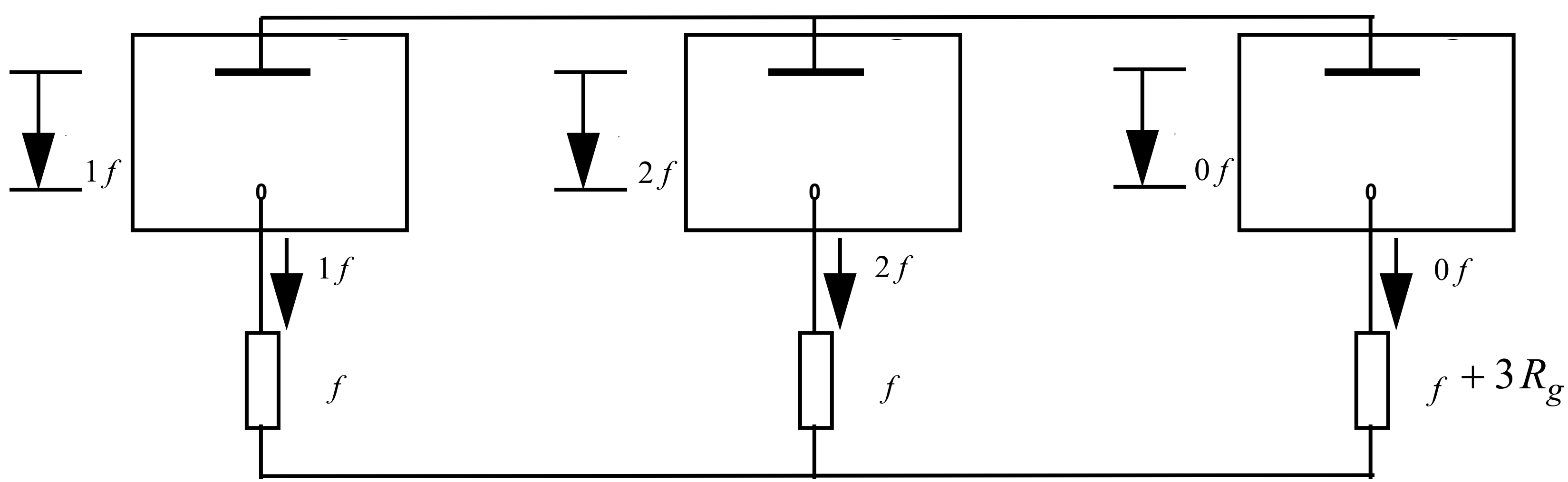
System Faults – Two-Phase-to-Ground



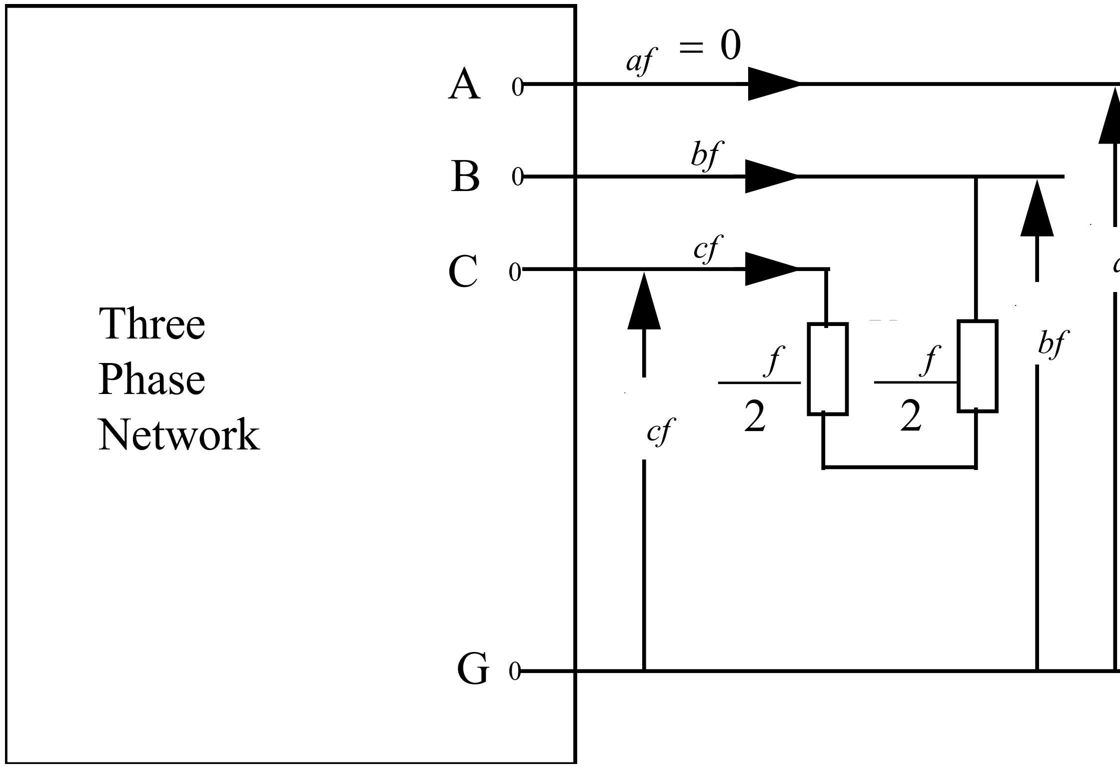
Positive Sequence Network

Negative Sequence Network

Zero Sequence Network



System Faults: Phase-to-Phase

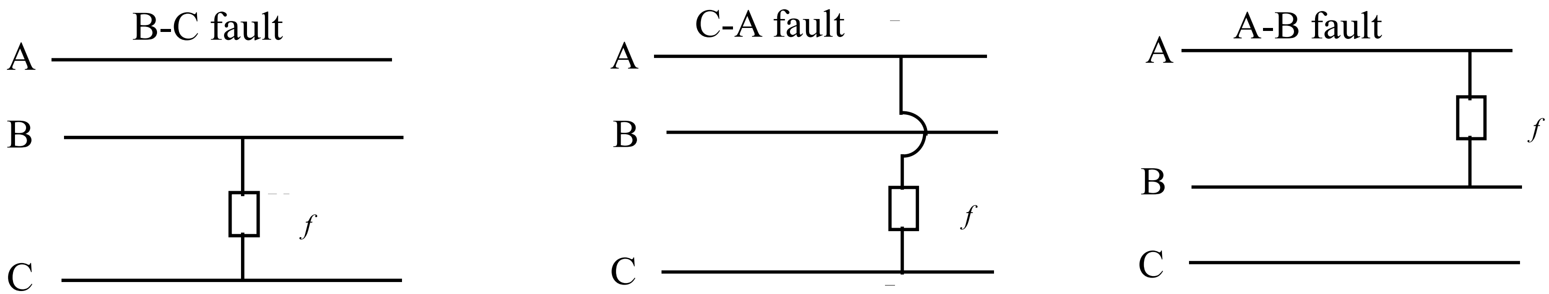


At fault point,

$$I_{af} = 0 \quad \text{and} \quad I_{bf} + I_{cf} = 0$$

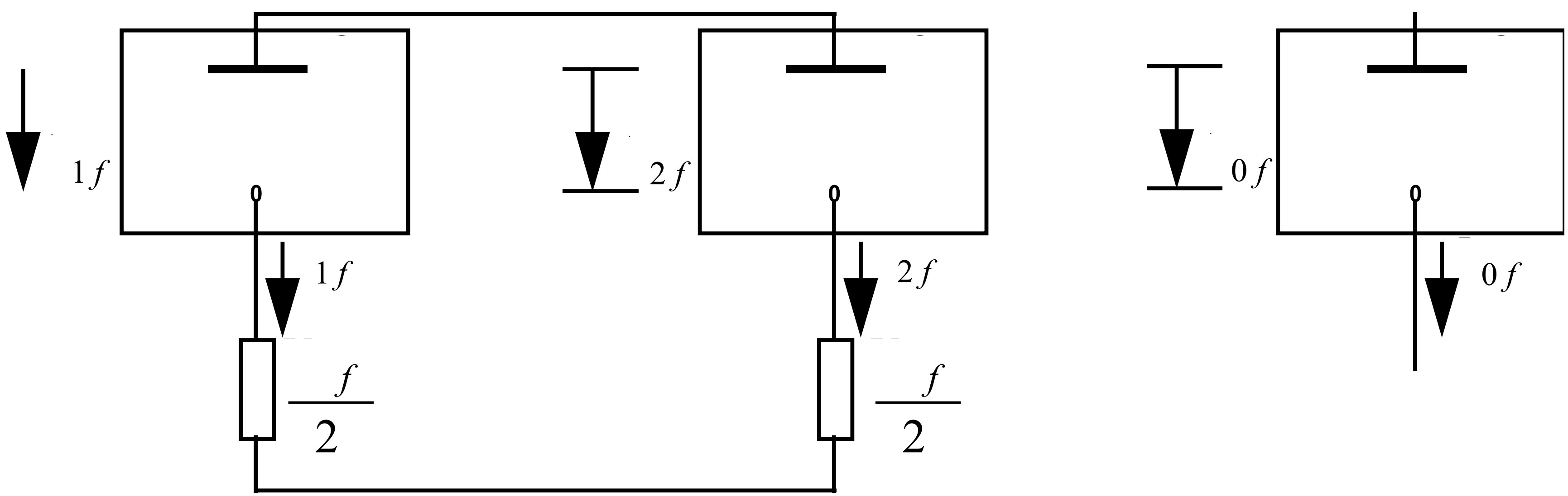
$$V_{bf} - I_{bf}\left(\frac{R_f}{2}\right) = V_{cf} - I_{cf}\left(\frac{R_f}{2}\right) \quad \Rightarrow \quad \left[V_{1f} - I_{1f}\left(\frac{R_f}{2}\right)\right] = \left[V_{2f} - I_{2f}\left(\frac{R_f}{2}\right)\right]$$

System Faults: Phase-to-Phase

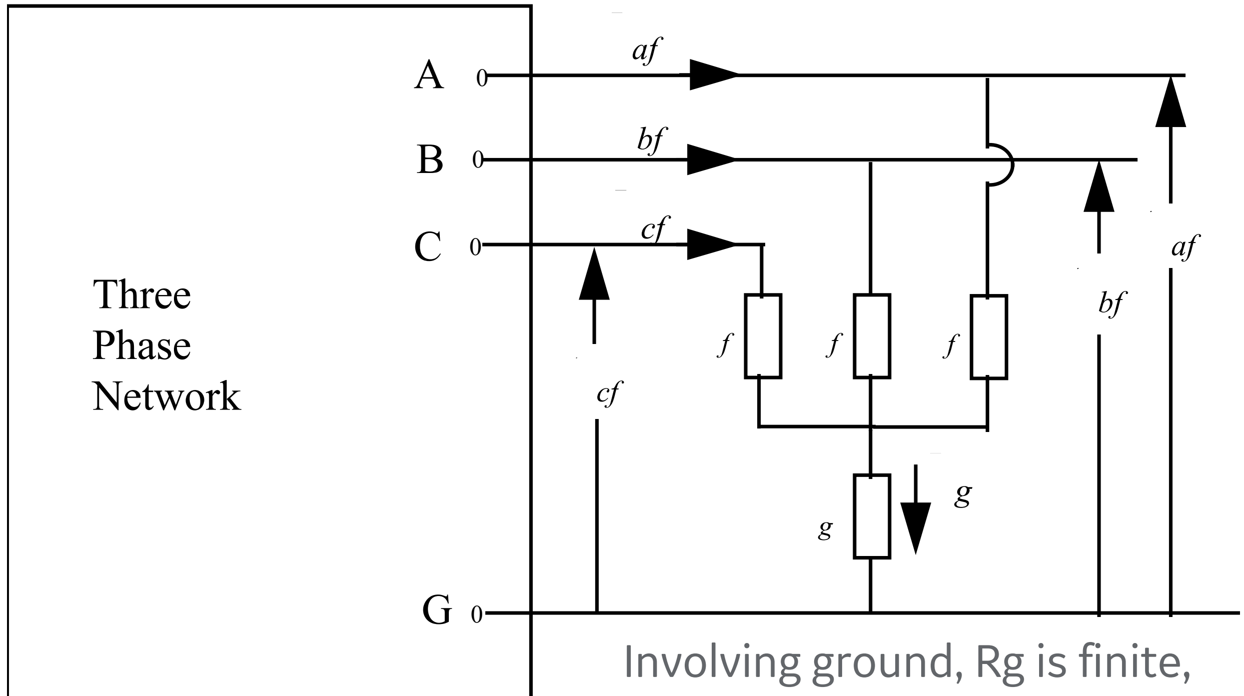


Positive Sequence Network

Negative Sequence Network



System Faults: Balanced Three Phase



Involving ground, Rg is finite,
Without ground, Rg is infinite

At fault point,

$$I_{af} + I_{bf} + I_{cf} = I_g$$

$$V_{af} = I_{af}R_f + I_g R_g$$

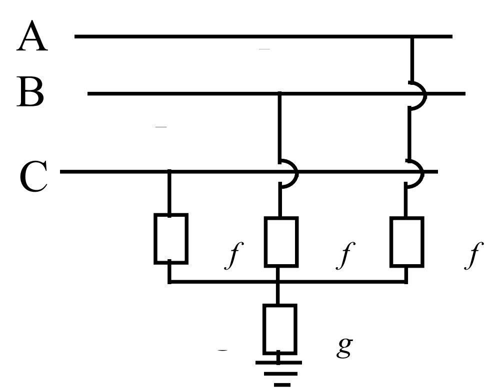
$$V_{bf} = I_{bf}R_f + I_g R_g$$

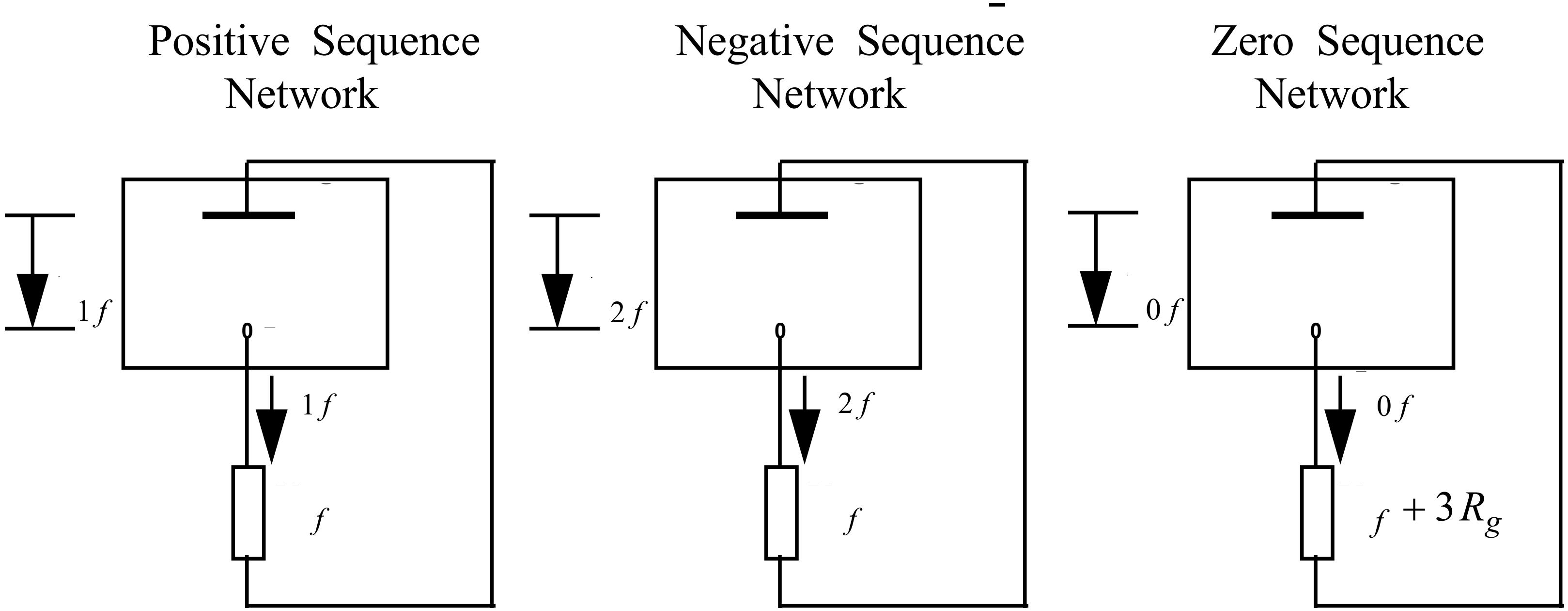
$$V_{cf} = I_{cf}R_f + I_g R_g$$

$$\rightarrow \left(V_{1f} - I_{1f}R_f\right) = \left(V_{2f} - I_{2f}R_f\right) = \left[V_{0f} - I_{0f}\left(R_f + 3R_g\right)\right] = 0$$

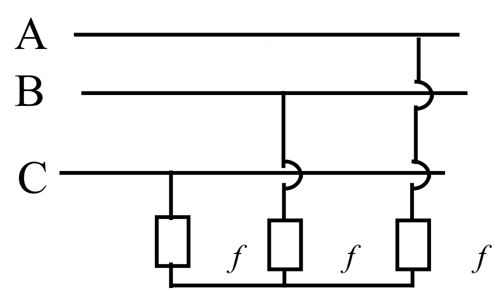
System Faults: Balanced Three Phase involving ground

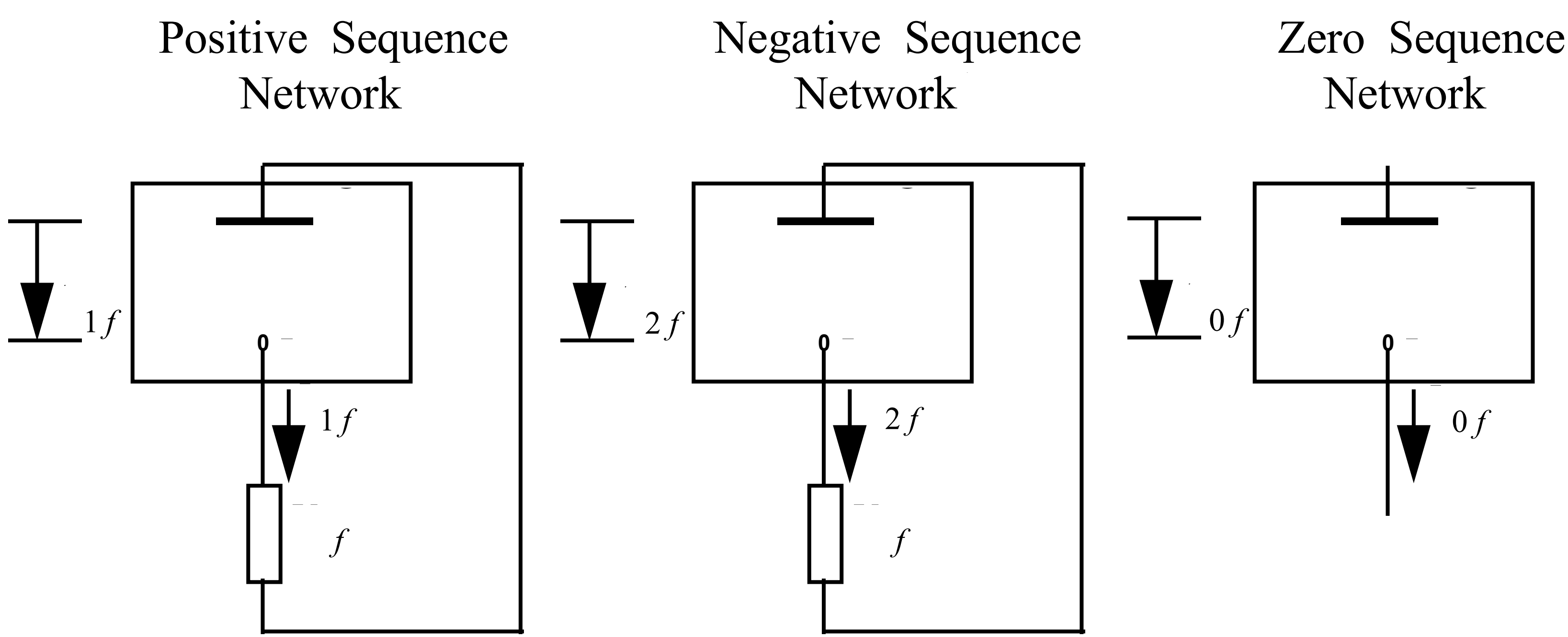
Three-phase-to-ground fault



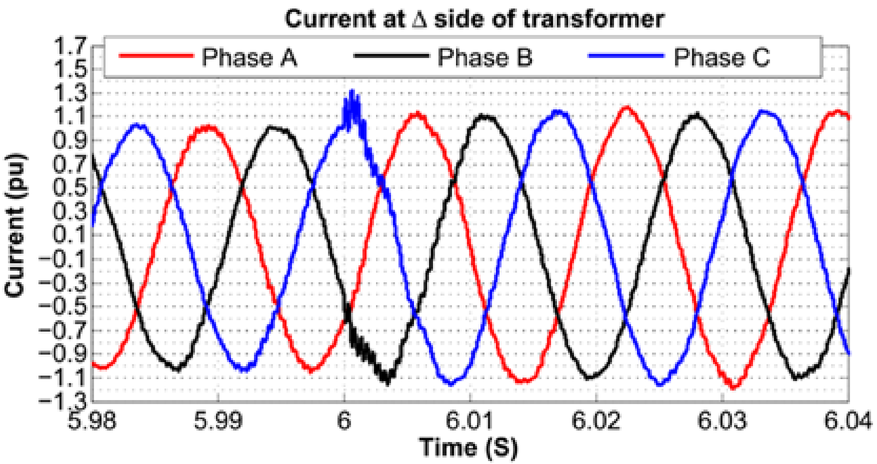


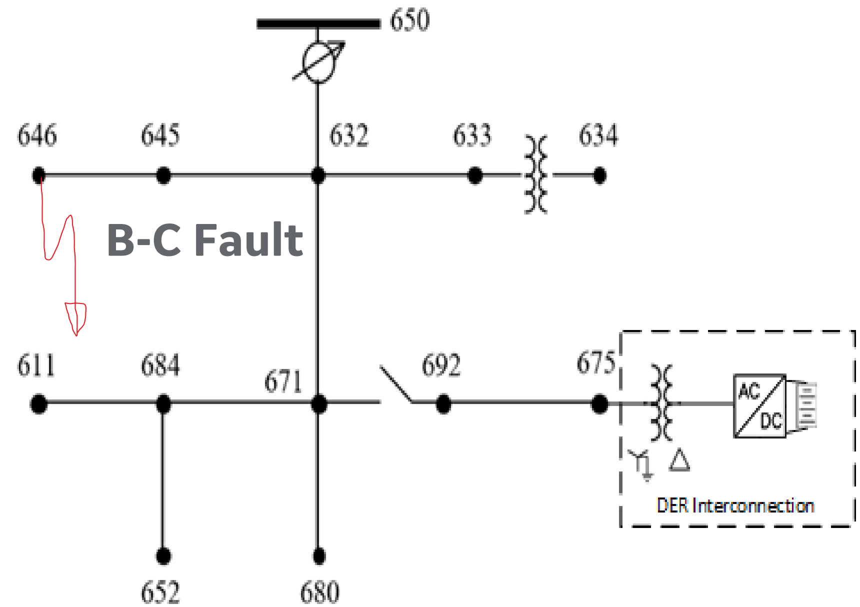
System Faults: Balanced Three Phase without ground

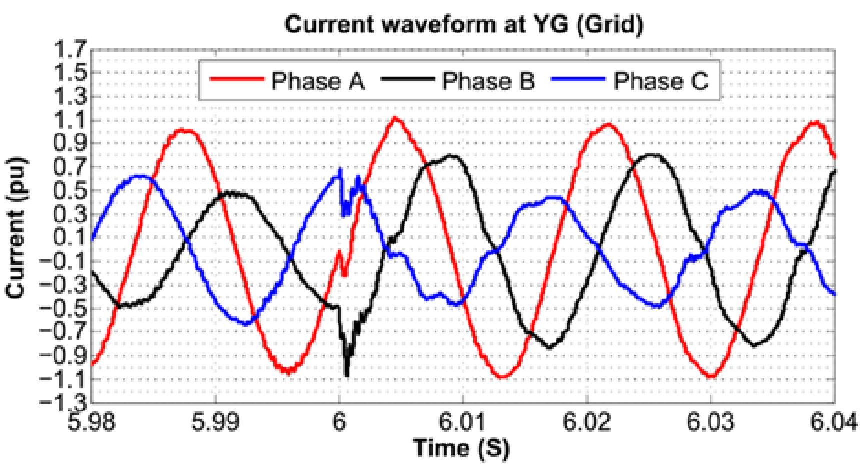




Protection Issue: Case Study 2

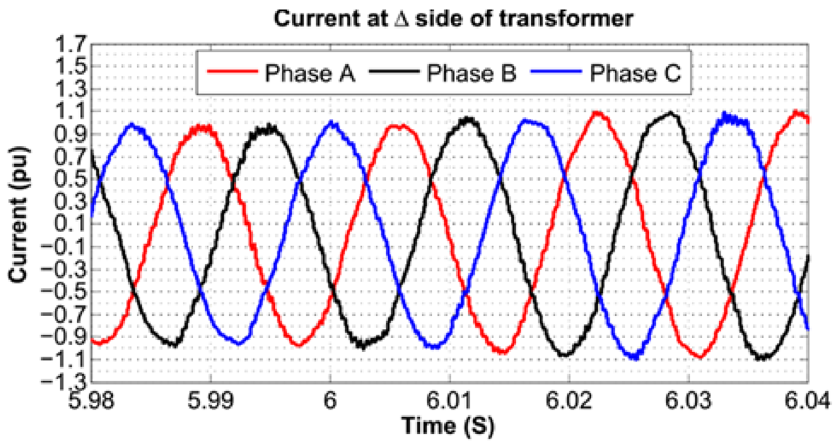


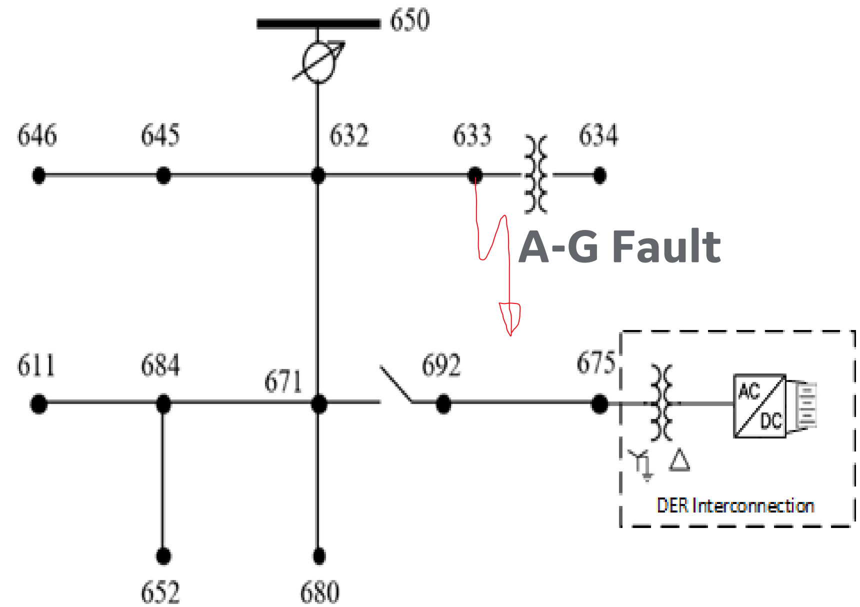


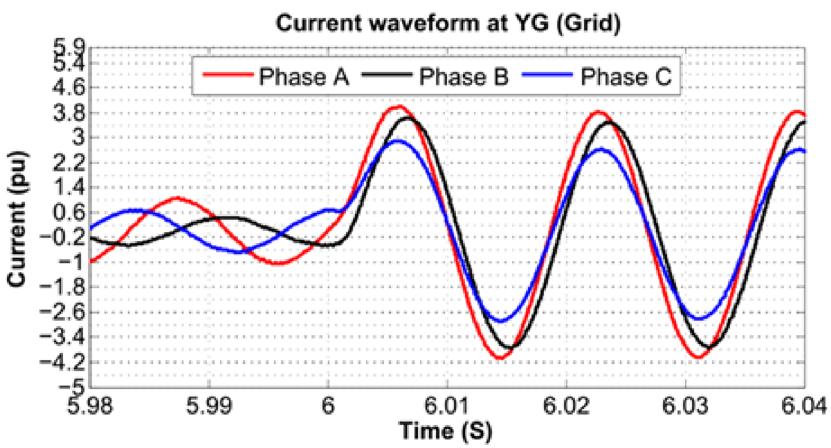


Reference:
IEEE Power System Relaying and Control (PSRC) Committee WG C30 - working document.
Work in progress.

Protection Issue: Case Study 2







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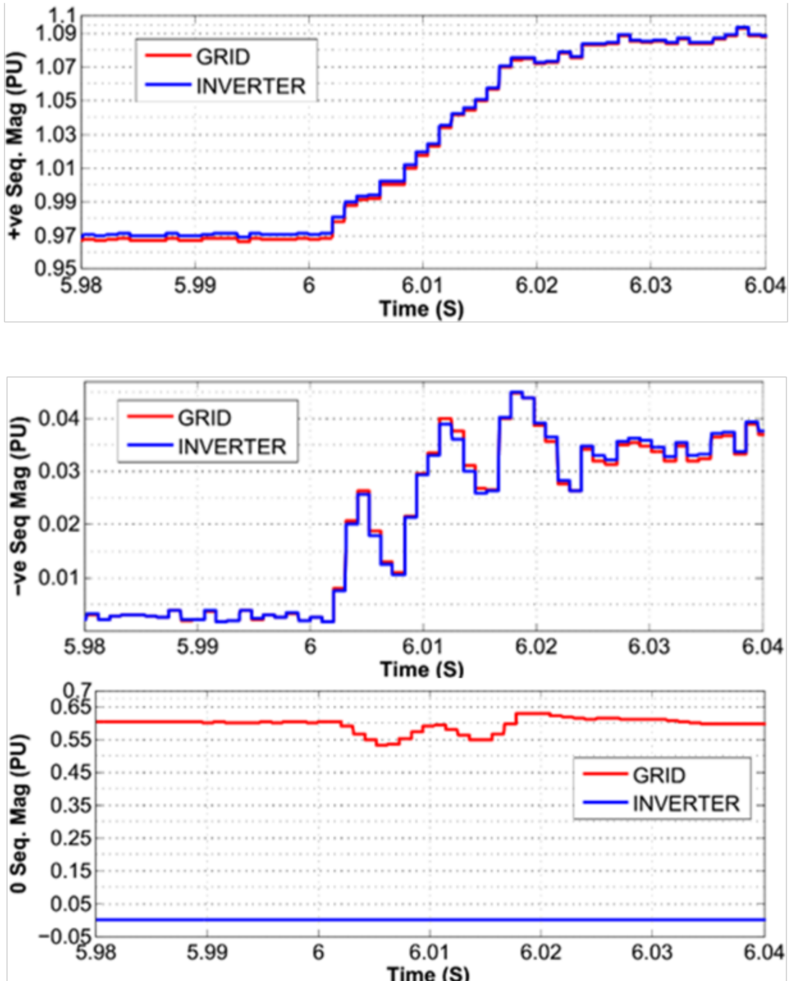
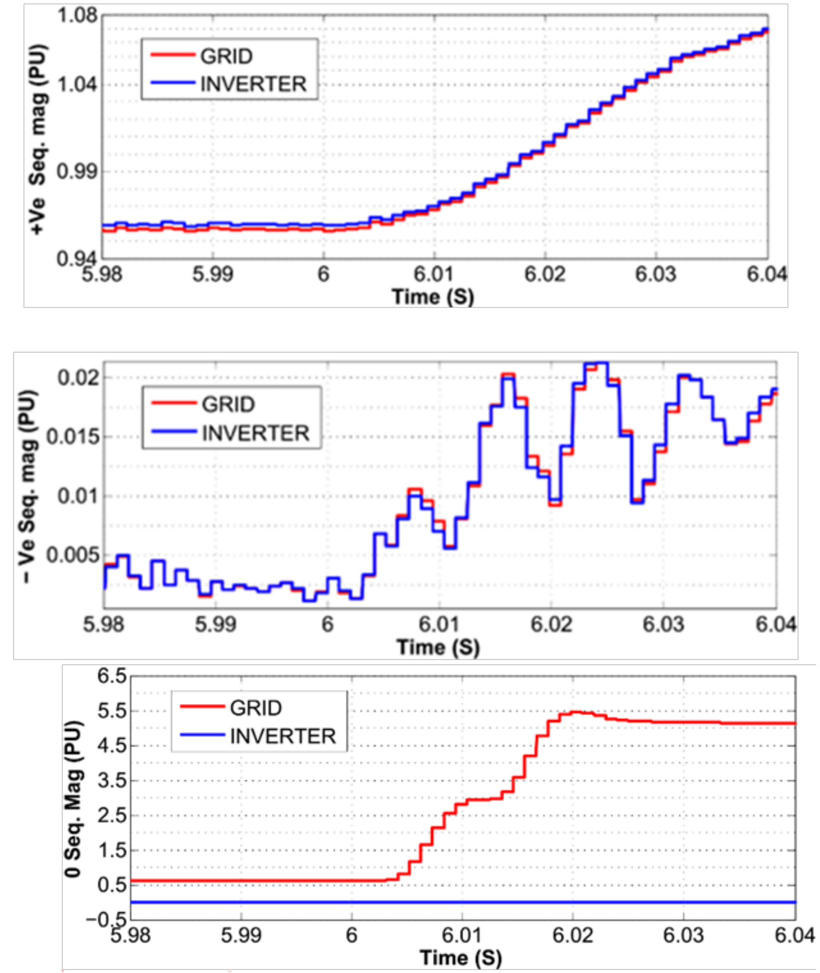
Work in progress.

Protection Issue: Case Study 2



B-C Fault



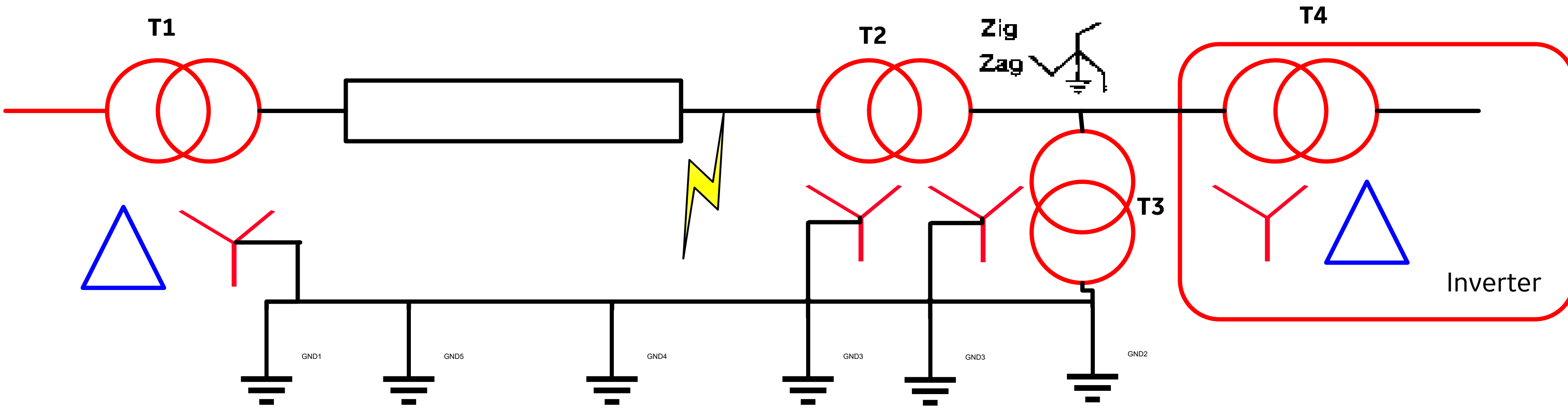
A-G Fault

Reference:
IEEE Power System Relaying and Control (PSRC) Committee WG C30 - working document. Work in progress.

Protection Challenges with DER Integration

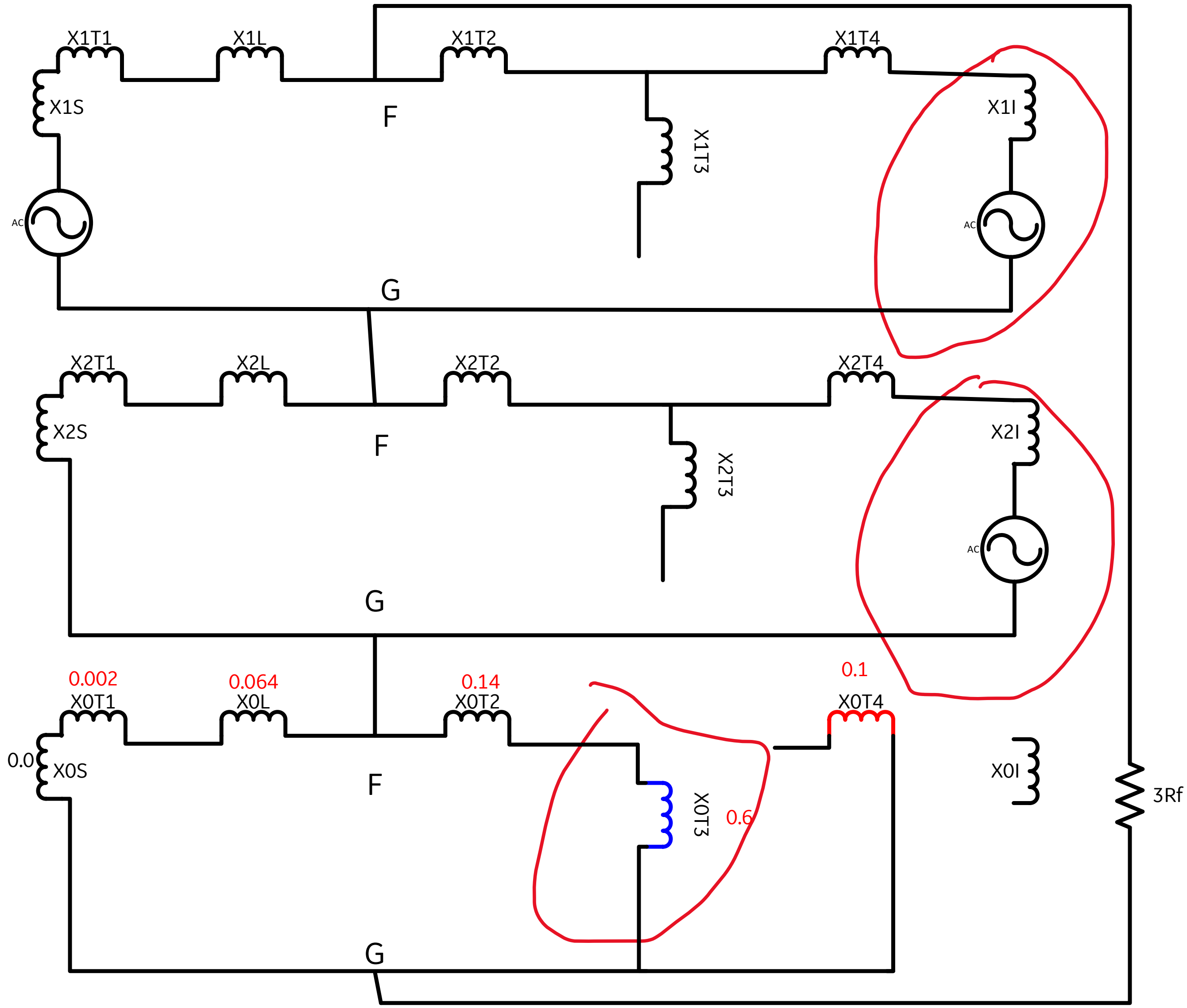
- ✓ Ensuring fault is isolated from all sources
- ✓ Maintaining security for varying fault current levels
- Avoiding desensitization of protective relaying
  - Avoiding overvoltage
- Avoiding unnecessary DER unavailability due to
  - transient faults
  - permanent faults

Example of DER Interface to the Grid



Reference:
Soonwook Hong, Il Do Yoo, Terry Bruno J.M. and Michael Zuercher-Martinson, White Paper, “Effective Grounding for PV Plants”, SRCW00101, Solectria Renewables.

Single-line-to-ground-fault Analysis



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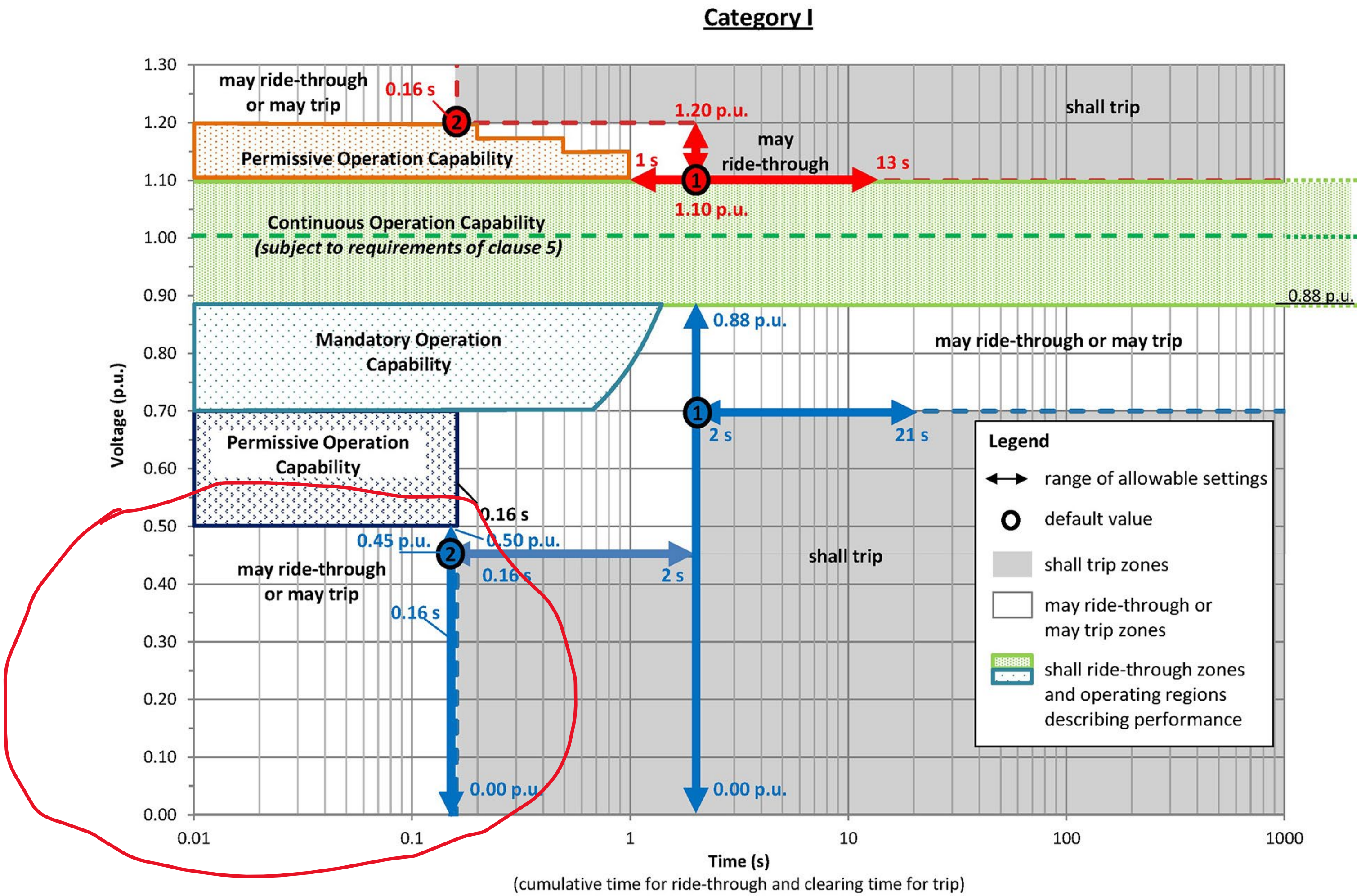
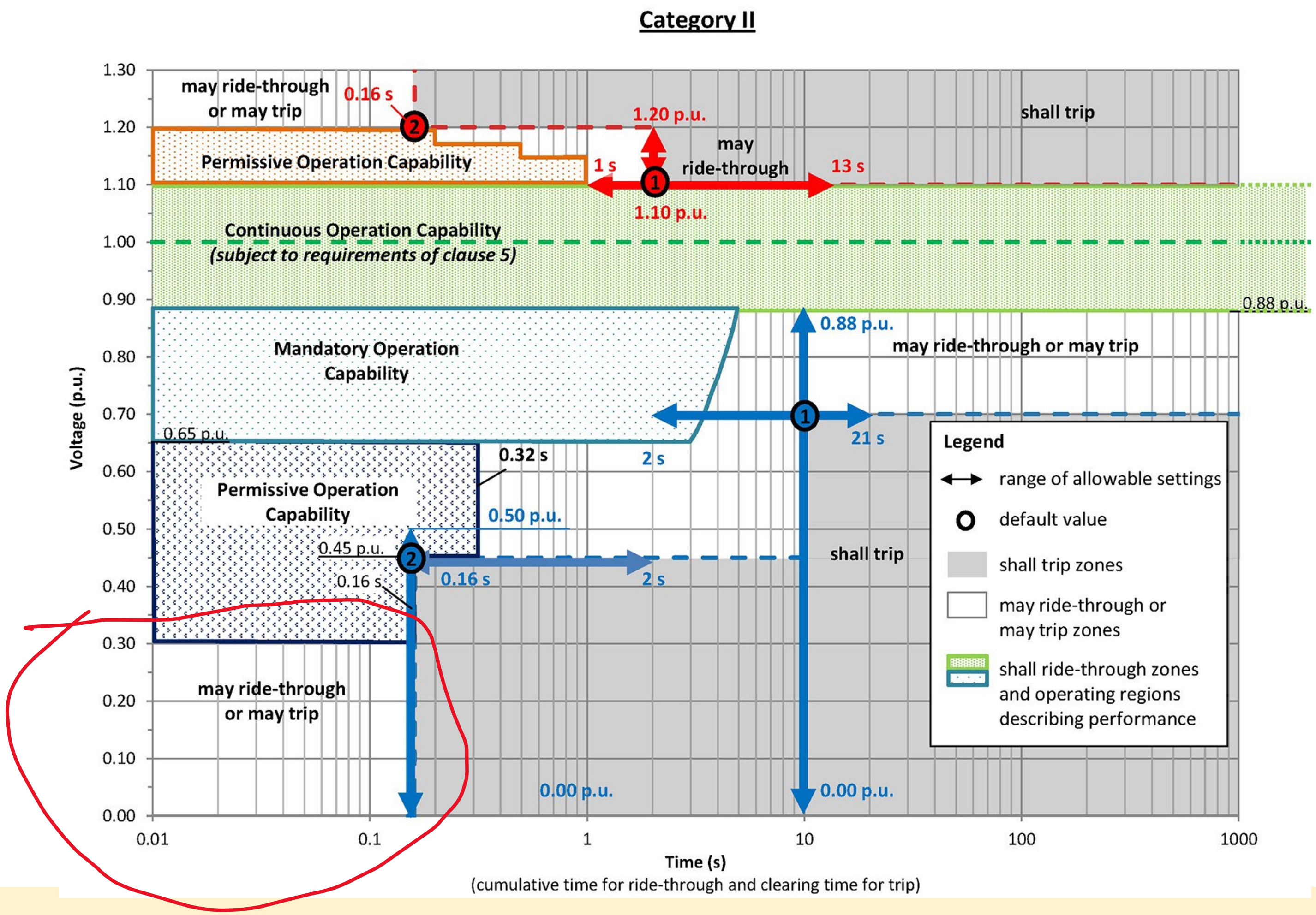
Voltage Ride Through Capability



Reference:
IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces, IEEE Std. 1547™-2018.

Voltage Ride Through Capability



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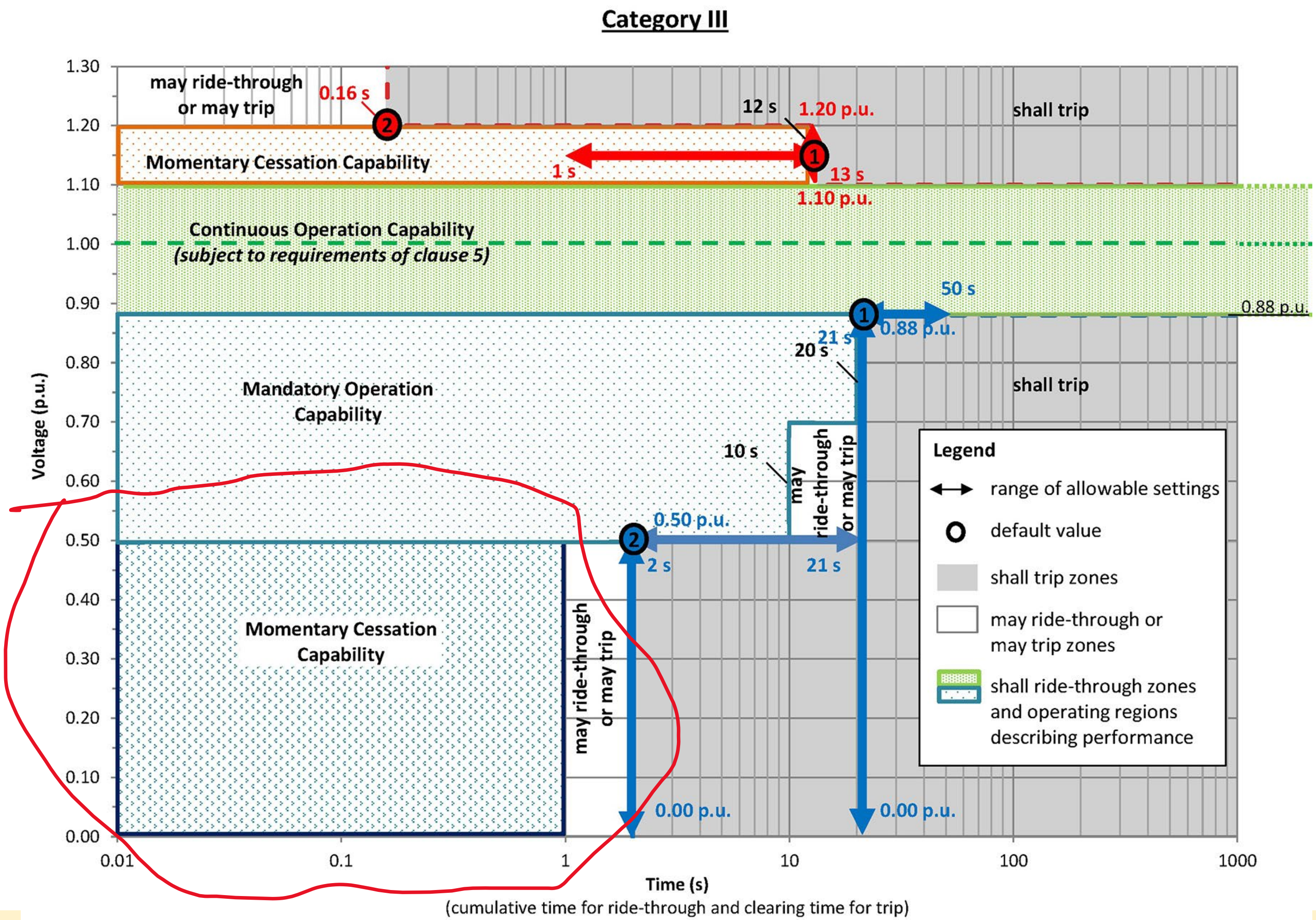
Voltage Ride Through Capability



Reference:
IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces, IEEE Std. 1547TM-2018.

DER Cessation Functionality

- No active power delivery
- Limited reactive power exchange
- Inverter is blocked (Inverter can take 5-15 minutes if tripped and DER have to follow reentry process)
- DER Cessation function is better than tripping
  - Fault usually happens in a small part of the system (line/bus/equipment) and proper clearance of fault disconnects faulted part of the system with some load and/or generation and related DERs
  - Voltage will be dipped in healthy part of the system during fault
  - *Tripping of DERs in healthy part of the system due to voltage dip will disturb load-generation balance after fault clearance and can cause grid disturbance*

What We Discussed

- Why we need protection
- How we provide equipment protection
  – Models and Examples
- How we provide System Protection
  – Example

Imagination at work