»Electrical Engineers Community - Sharing Knowledge and Expertise

Fault Analysis

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Power System Fault Analysis (1)

All Protection Engineers should have an understanding

TO :-

- **Calculate Power System Currents and Voltages during Fault Conditions**
- **Check that Breaking Capacity of Switchgear is Not Exceeded**
- **Determine the Quantities which can be used by Relays to Distinguish Between Healthy (i.e. Loaded) and Fault Conditions**
- **Appreciate the Effect of the Method of Earthing on the Detection of Earth Faults**
- **Select the Best Relay Characteristics for Fault Detection**
- **Ensure that Load and Short Circuit Ratings of Plant are Not Exceeded**
- **Select Relay Settings for Fault Detection and Discrimination**
- **Understand Principles of Relay Operation**
- **Conduct Post Fault Analysis**

Power System Fault Analysis (2)

Power System Fault Analysis also used to :-

- **Consider Stability Conditions**
  - **Required fault clearance times**
  - **Need for 1 phase or 3 phase auto-reclose**

Computer Fault Calculation Programmes

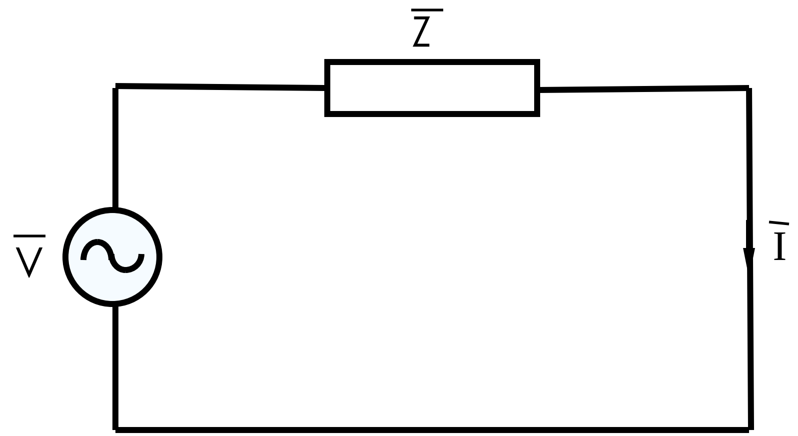
- Widely available, particularly in large power utilities
- Powerful for large power systems
- Sometimes overcomplex for simple circuits
- Not always user friendly
- Sometimes operated by other departments and not directly available to protection engineers
- Programme calculation methods:- understanding is important
- Need for ‘by hand’ spot checks of calculations

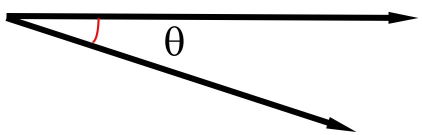
Pocket Calculator Methods

- **Adequate for the majority of simple applications**
- **Useful when no access is available to computers and programmes e.g. on site**
- **Useful for ‘spot checks’ on computer results**

Vectors

Vector notation can be used to represent phase relationship between electrical quantities.

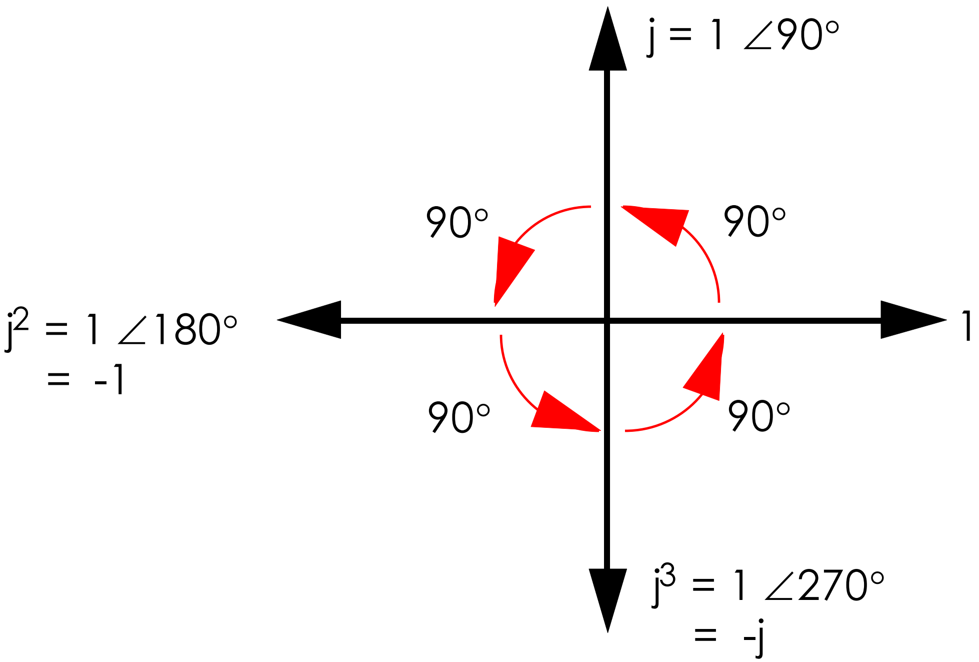




$$V = V\sin wt = V\angle 0^\circ$$

$$\overline{I} = I\angle -\theta^\circ = I\sin(wt-\theta)$$

Rotates vectors by 90° anticlockwise :



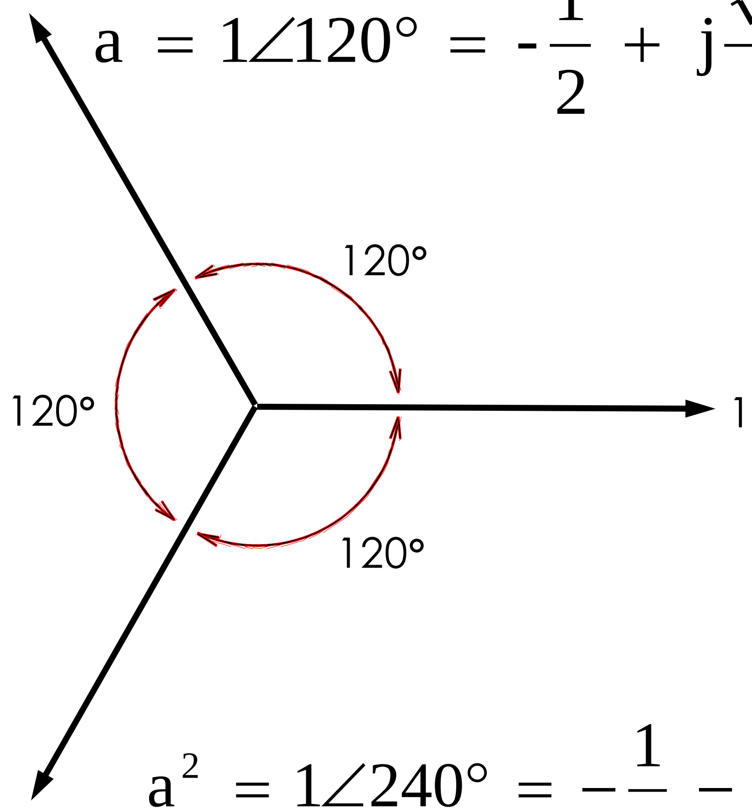
Used to express vectors in terms of "real" and "imaginary" parts.

$a = 1\angle 120°$

Rotates vectors by 120° anticlockwise

Used extensively in “Symmetrical Component Analysis”

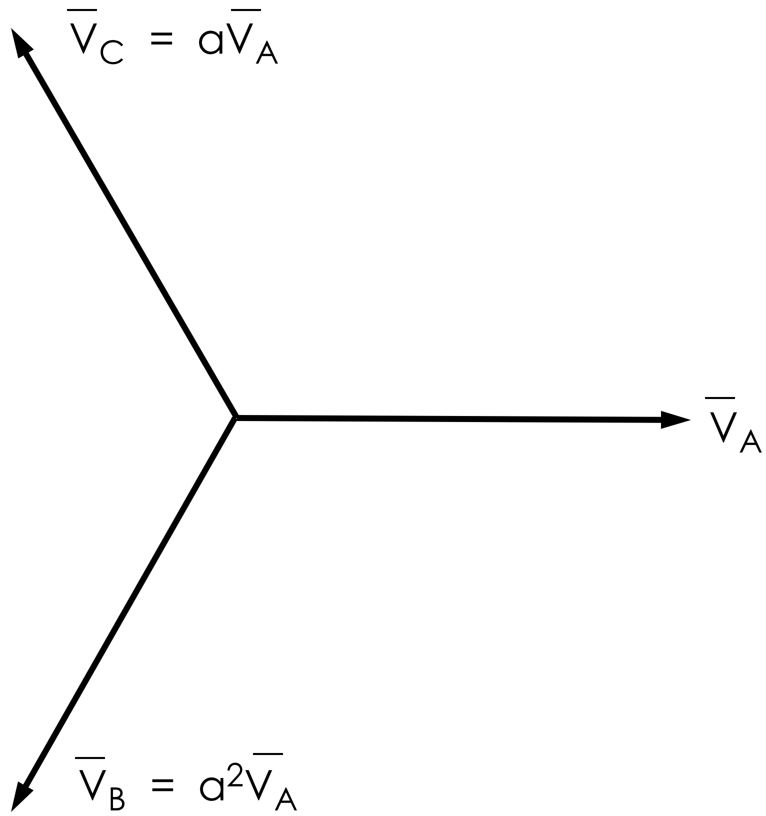
$$a = 1\angle 120° = -\frac{1}{2} + j\frac{\sqrt{3}}{2}$$



$$a^2 = 1\angle 240° = -\frac{1}{2} - j\frac{\sqrt{3}}{2}$$

$$a = 1 \angle 120°$$

Balanced 3Ø voltages :-



$$a^2 + a + 1 = 0$$

Balanced Faults

AREVA

Balanced (3Ø) Faults (1)

- **RARE :- Majority of Faults are Unbalanced**
- **CAUSES :-**
  1. **System Energisation with Maintenance Earthing Clamps still connected.**
  2. **1Ø Faults developing into 3Ø Faults**
- **3Ø FAULTS MAY BE REPRESENTED BY 1Ø CIRCUIT**

Valid because system is maintained in a BALANCED state during the fault

Voltages equal and 120° apart

Currents equal and 120° apart

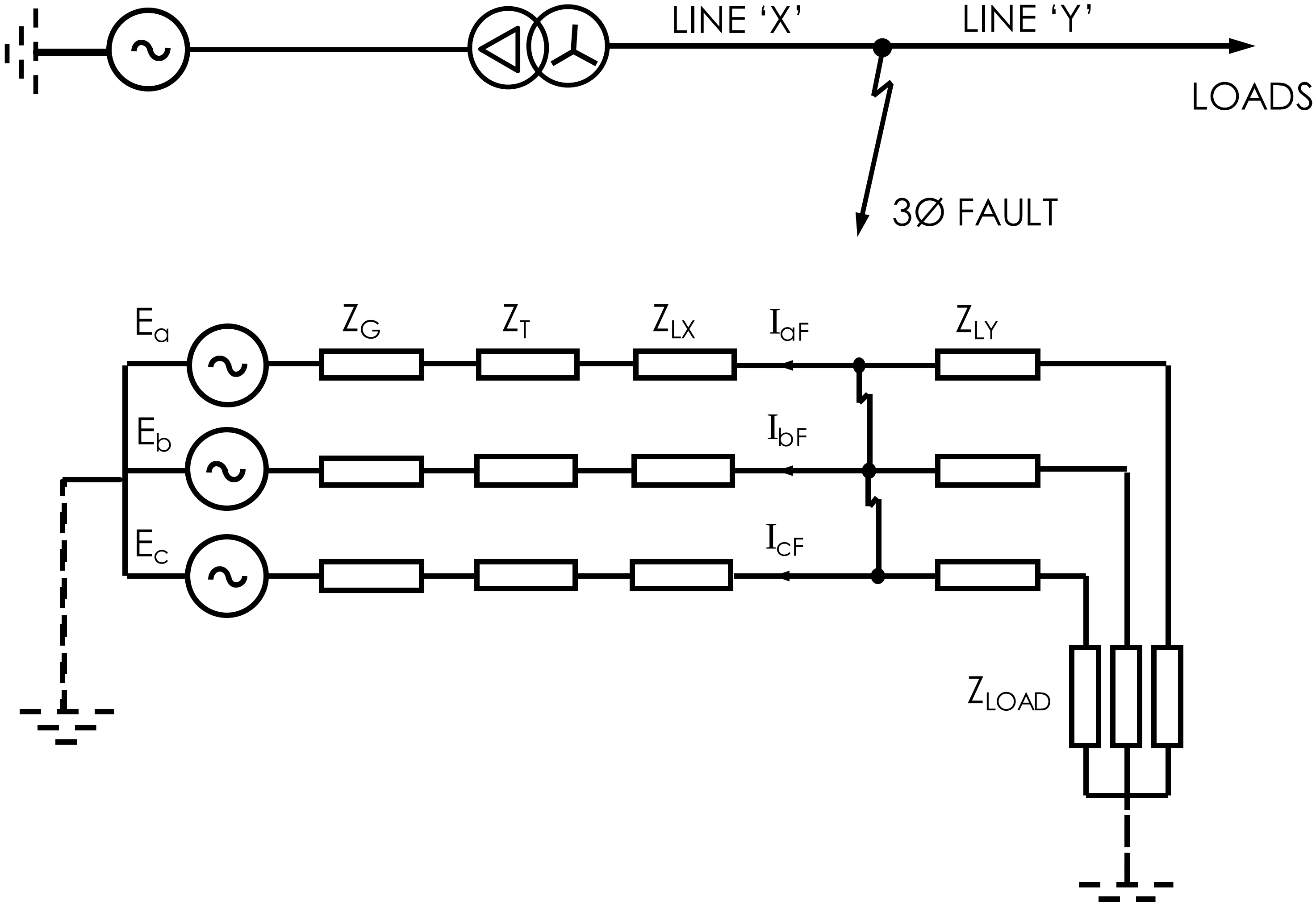
Power System Plant Symmetrical

Phase Impedances Equal

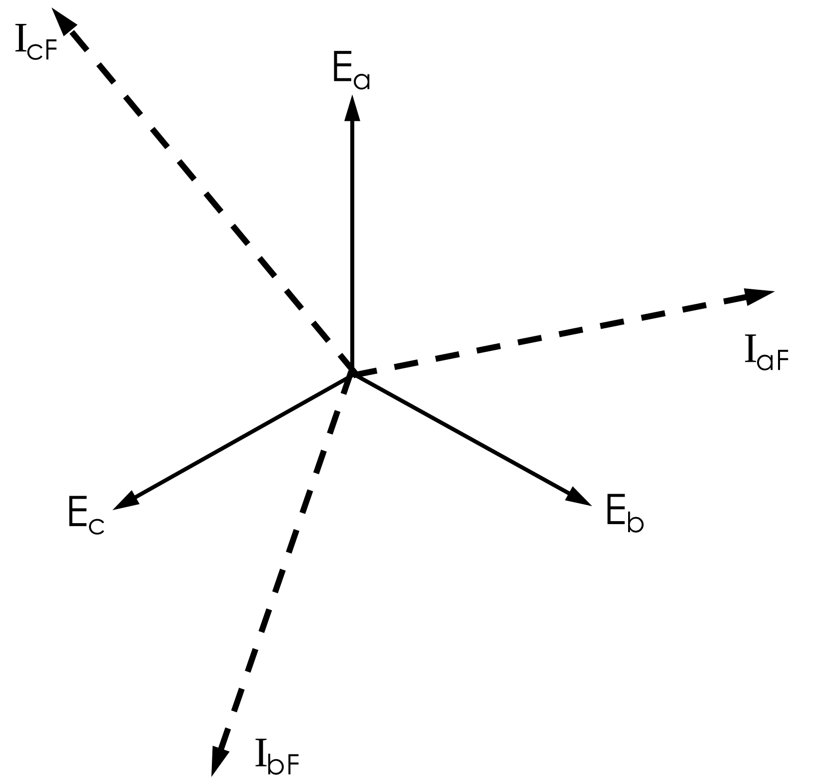
Mutual Impedances Equal

Shunt Admittances Equal

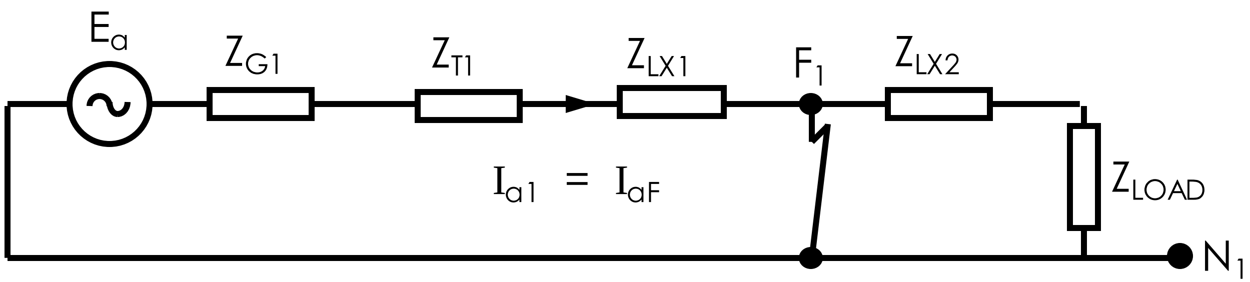
Balanced (3Ø) Faults (2)



Balanced (3Ø) Faults (3)



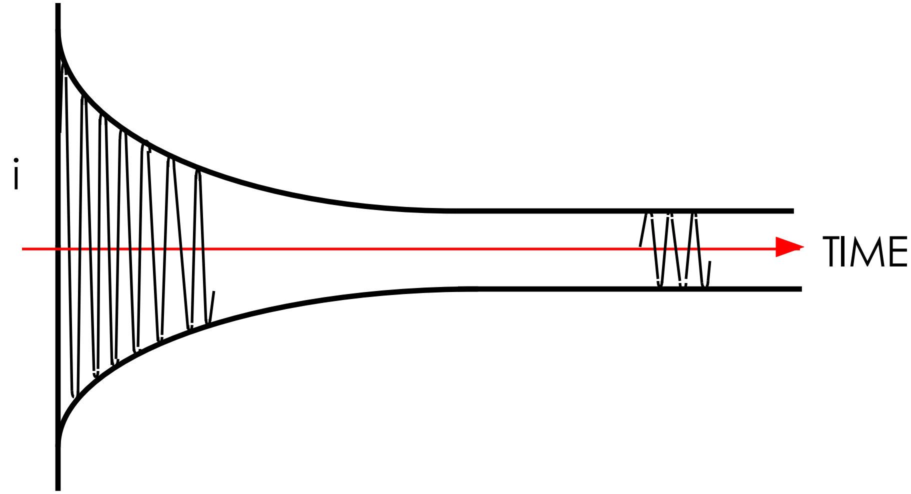
Positive Sequence (Single Phase) Circuit :-



Representation of Plant

Generator Short Circuit Current

The AC Symmetrical component of the short circuit current varies with time due to effect of armature reaction.



Magnitude (RMS) of current at any time t after instant of short circuit :

$$I_{ac} = (I'' - I')e^{-t/Td''} + (I' - I)e^{-t/Td'} + I$$

where :

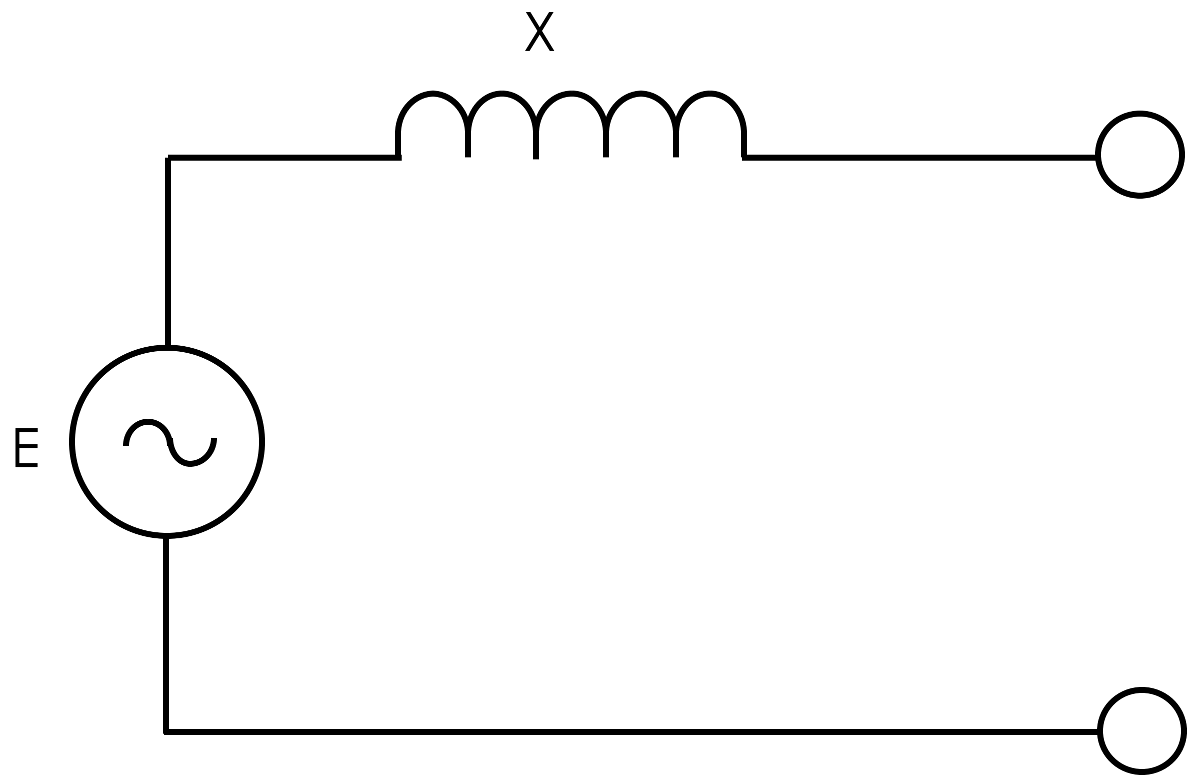
I'' = **Initial Symmetrical S/C Current or Subtransient Current = E/Xd″ ≈ 50ms**

I' = **Symmetrical Current a Few Cycles Later ≈ 0.5s or Transient Current = E/Xd′**

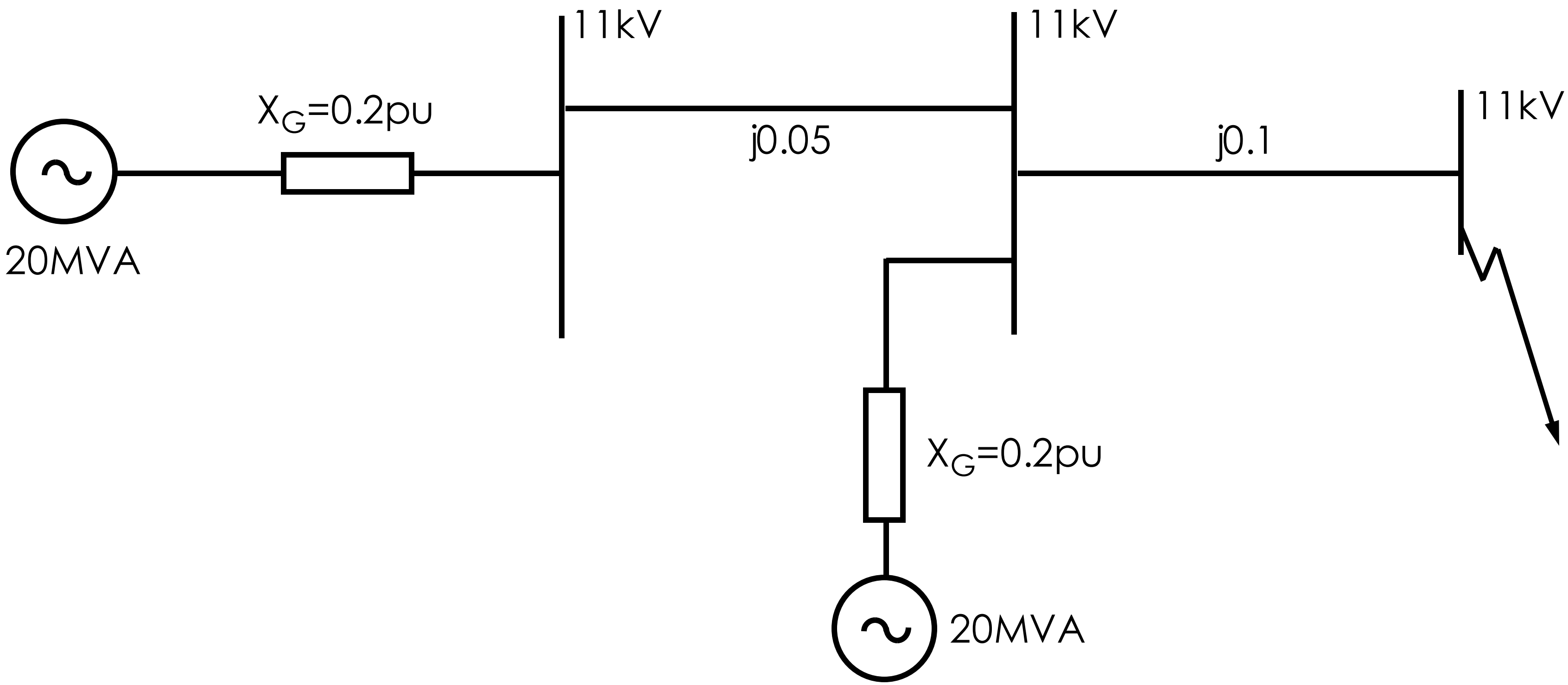
I = **Symmetrical Steady State Current = E/Xd**

Simple Generator Models

Generator model X will vary with time. Xd" - Xd' - Xd

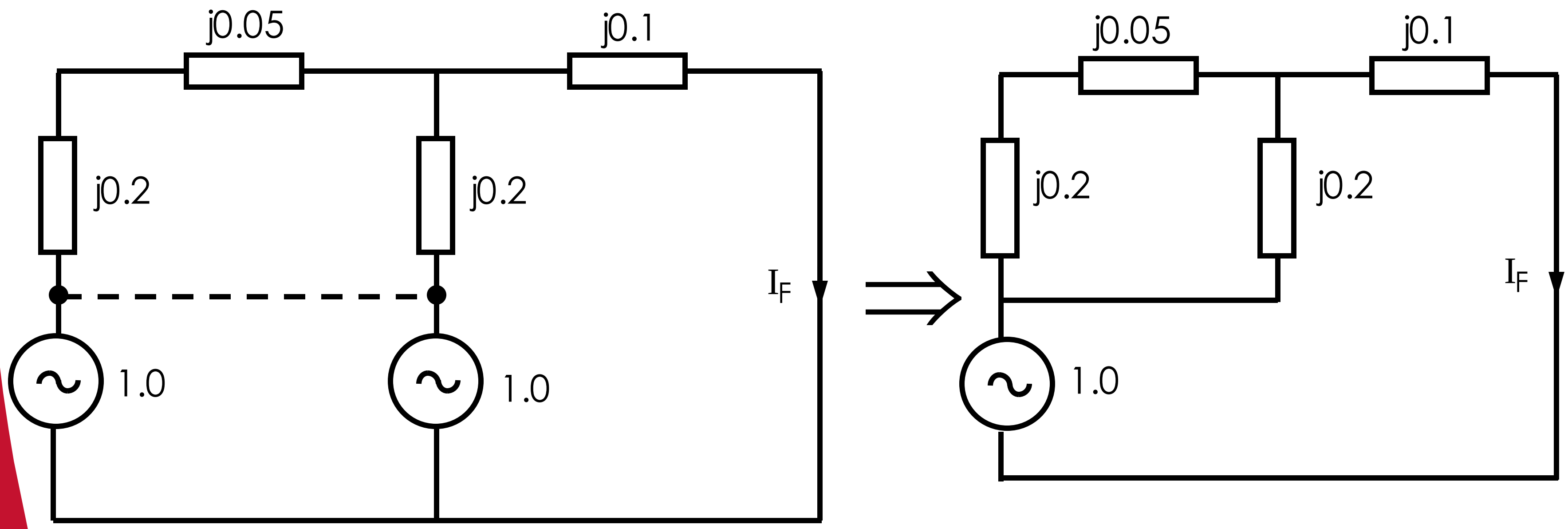


Parallel Generators



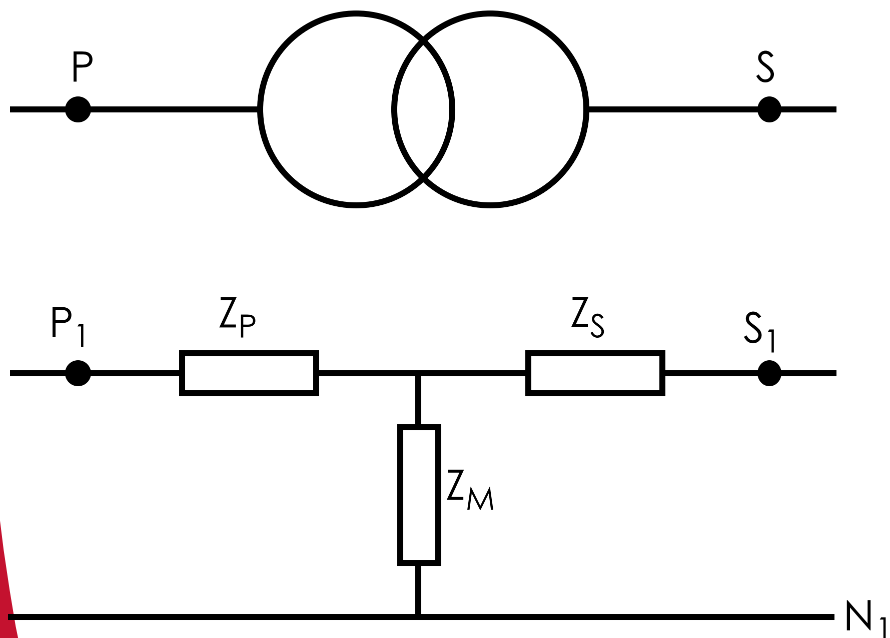
If both generator EMF's are equal ∴ they can be thought of as resulting from the same ideal source - thus the circuit can be simplified.

P.U. Diagram



Positive Sequence Impedances of Transformers

2 Winding Transformers



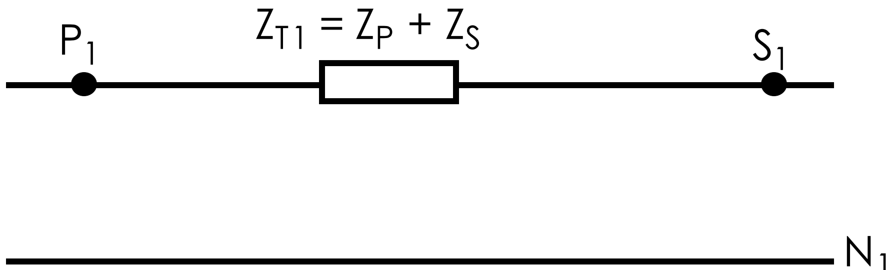
Z_P = **Primary Leakage Reactance**

Z_S = **Secondary Leakage Reactance**

Z_M = **Magnetising impedance**
= **Large compared with Z_P and Z_S**

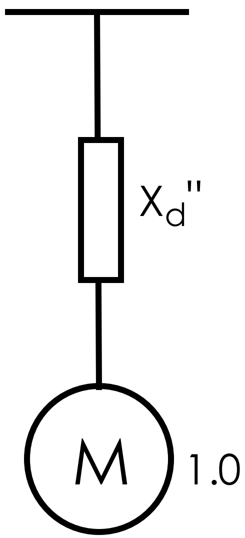
$Z_M \rightarrow$ **Infinity** $\therefore$ **Represented by an Open Circuit**

Z_{T1} = $Z_P + Z_S$ = **Positive Sequence Impedance**



Z_P and Z_S both expressed on same voltage base.

- Fault current contribution decays with time
- Decay rate of the current depends on the system. From tests, typical decay rate is 100 - 150mS.
- Typically modelled as a voltage behind an impedance



Induction Motors – IEEE Recommendations

Small Motors

Motor load <35kW neglect

Motor load >35kW SC_M = 4 x sum of FLC_M

Large Motors

$$SC_M \approx \frac{\text{motor full load amps}}{Xd''}$$

Approximation : SC_M = locked rotor amps

SC_M = 5 x FLC_M ≈ assumes motor impedance 20%

Synchronous Motors – IEEE Recommendations

Large Synchronous Motors

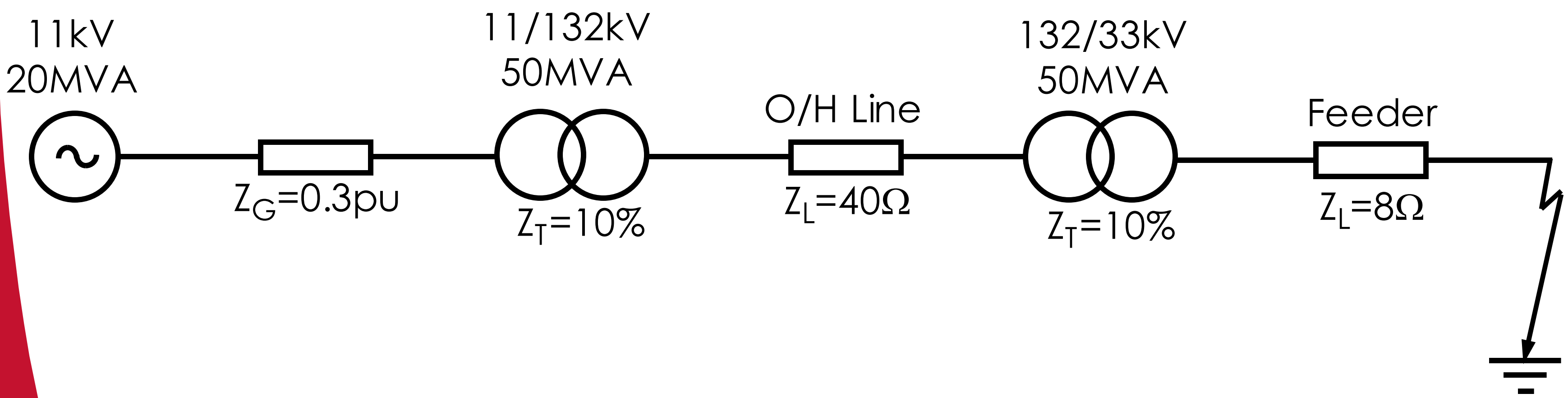
SC_M ≈ 6.7 x FLC_M for 1200 rpm — Assumes X″d = 15%

≈ 5 x FLC_M for 514 - 900 rpm — Assumes X″d = 20%

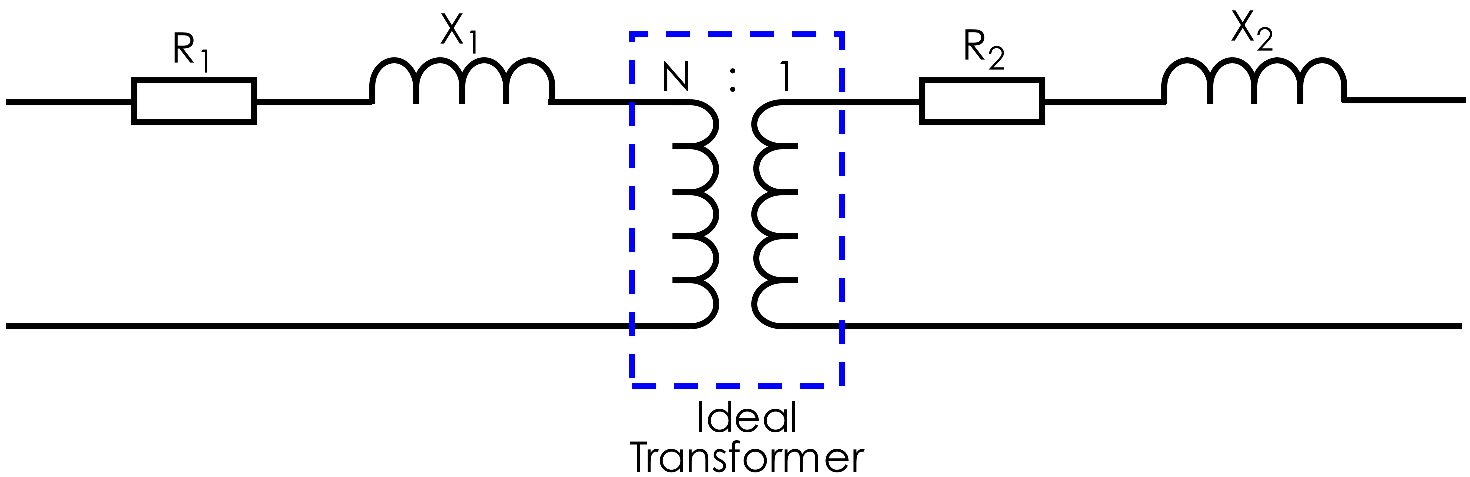
≈ 3.6 x FLC_M for 450 rpm or less — Assumes X″d = 28%

Analysis of Balanced Faults

Different Voltages – How Do We Analyse?

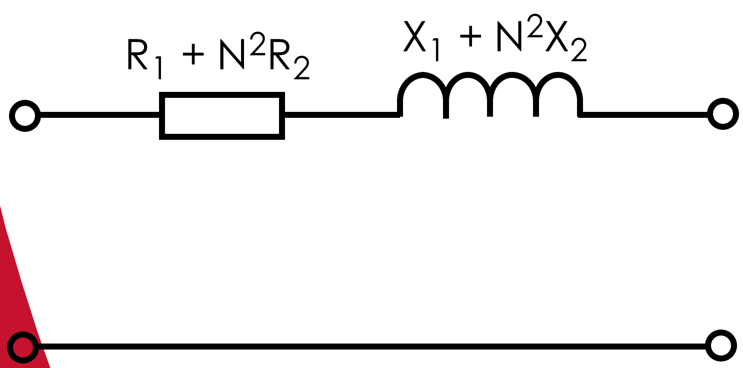


Referring Impedances

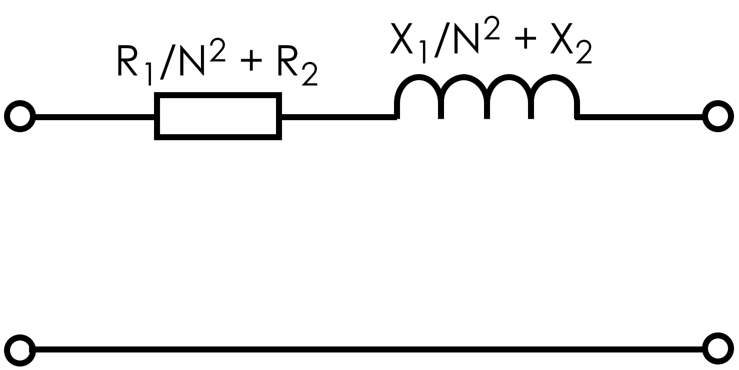


Consider the equivalent CCT referred to :-

Primary



Secondary

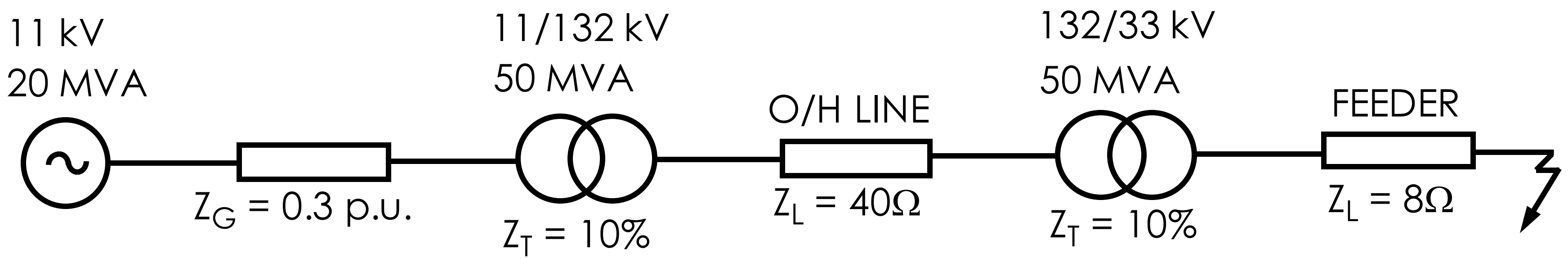


Used to simplify calculations on systems with more than 2 voltages.

Definition

$$\text{: P.U. Value of a Quantity} = \frac{\text{Actual Value}}{\text{Base Value in the Same Units}}$$

Base Quantities and Per Unit Values



- **Particularly useful when analysing large systems with several voltage levels**
- **All system parameters referred to common base quantities**
- **Base quantities fixed in one part of system**
- **Base quantities at other parts at different voltage levels depend on ratio of intervening transformers**

Base Quantities and Per Unit Values (1)

Base quantites normally used :-

BASE MVA = MVA_b = 3∅ MVA

Constant at all voltage levels

Value ~ MVA rating of largest item of plant or 100MVA

BASE VOLTAGE = KV_b = ∅/∅ voltage in kV

Fixed in one part of system

This value is referred through transformers to obtain base voltages on other parts of system.

Base voltages on each side of transformer are in same ratio as voltage ratio**.**

Other base quantites :-

$$\text{Base Impedance} = Z_b = \frac{(kV_b)^2}{MVA_b} \text{ in Ohms}$$

$$\text{Base Current} = I_b = \frac{MVA_b}{\sqrt{3}\,.\,kV_b} \text{ in kA}$$

Base Quantities and Per Unit Values (3)

Per Unit Values = $\dfrac{\textbf{Actual Value}}{\textbf{Base Value}}$

$$\text{Per Unit MVA} = MVA_{p.u.} = \frac{MVA_a}{MVA_b}$$

$$\text{Per Unit Voltage} = kV_{p.u.} = \frac{KV_a}{KV_b}$$

$$\text{Per Unit Impedance} = Z_{p.u.} = \frac{Z_a}{Z_b} = Z_a \cdot \frac{MVA_b}{(kV_b)^2}$$

$$\text{Per Unit Current} = I_{p.u.} = \frac{I_a}{I_b}$$

Transformer Percentage Impedance

- If $Z_T = 5\%$

  with Secondary S/C

  5% $V_{(RATED)}$ produces $I_{(RATED)}$ in Secondary.

  $\therefore V_{(RATED)}$ produces $\frac{100}{5} \times I_{(RATED)}$

  $= 20 \times I_{(RATED)}$

- If Source Impedance $Z_S = 0$

  Fault current $= 20 \times I_{(RATED)}$

  Fault Power $= 20 \times kVA_{(RATED)}$

- Z_T is based on $I_{(RATED)}$ & $V_{(RATED)}$

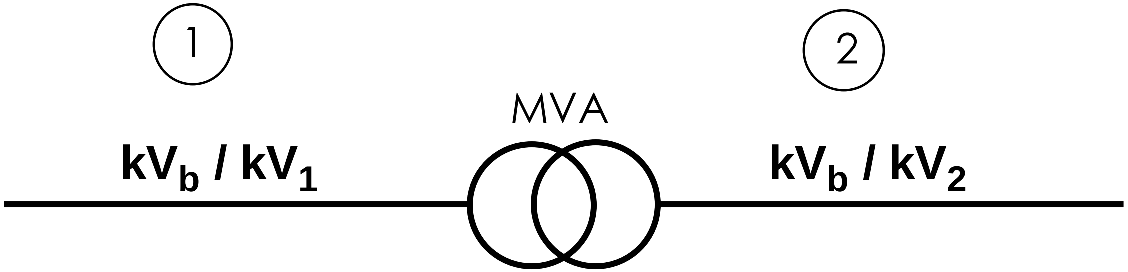
  i.e. Based on $MVA_{(RATED)}$ & $kV_{(RATED)}$

  $\therefore$ is same value viewed from either side of transformer.

Example (1)

Per unit impedance of transformer is same on each side of the transformer.

Consider transformer of ratio kV1 / kV2

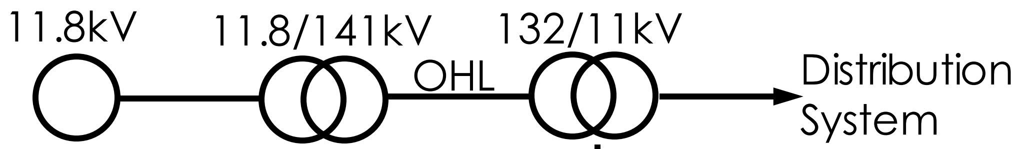


Actual impedance of transformer viewed from side 1 = Z_{a1}

Actual impedance of transformer viewed from side 2 = Z_{a2}

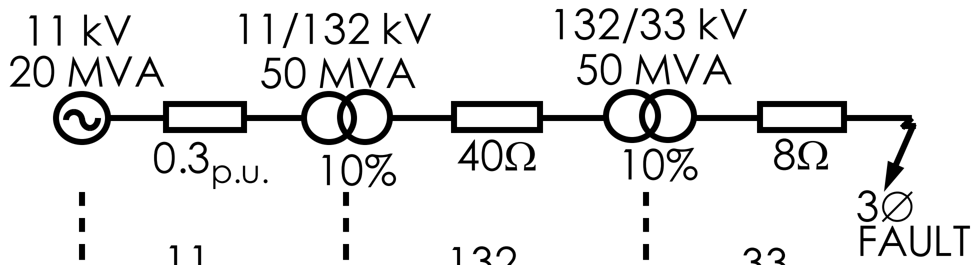
Example (2)

Base voltage on each side of a transformer must be in the same ratio as voltage ratio of transformer.



Incorrect selection of kVb	**11.8kV**	**132kV**	**11kV**
Correct selection of kVb	$\frac{132 \times 11.8}{141} = 11.05\text{kV}$	**132kV**	**11kV**
Alternative correct selection of kVb	**11.8kV**	**141kV**	$\frac{141 \times 11}{132} = 11.75\text{kV}$

Example

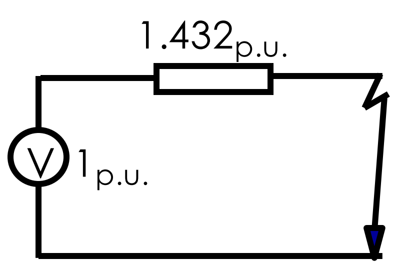


kV_b	11	132	33
MVA_b	50	50	50
$Z_b = \frac{kV_b^2}{MVA_b}$	2.42Ω	349 Ω	21.8 Ω
$I_b = \frac{MVA_b}{\sqrt{3}kV_b}$	2625 A	219 A	874 A
$Z_{p.u.}$	$0.3 \times \frac{50}{20} = 0.75_{p.u.}$; $0.1_{p.u.}$	$\frac{40}{349} = 0.115_{p.u.}$; $0.1_{p.u.}$	$\frac{8}{21.8} = 0.367_{p.u.}$

$\therefore\ I_{11}$ kV = 0.698 x I_b = 0.698 x 2625 = 1833A

I_{132} kV = 0.698 x 219 = 153A

I_{33} kV = 0.698 x 874 = 610A



$$I_F = \frac{1}{1.432} = 0.698\text{p.u.}$$

Fault Types

Line - Ground (65 - 70%)

Line - Line - Ground (10 - 20%)

Line - Line (10 - 15%)

Line - Line - Line (5%)

Statistics published in 1967 CEGB Report, but are similar today all over the world.

Unbalanced Faults

Unbalanced Faults (1)

In three phase fault calculations, a single phase representation is adopted.

3 phase faults are rare.

Majority of faults are unbalanced faults.

UNBALANCED FAULTS may be classified into SHUNT FAULTS and SERIES FAULTS.

SHUNT FAULTS:

- **Line to Ground**
- **Line to Line**
- **Line to Line to Ground**

SERIES FAULTS:

- **Single Phase Open Circuit**
- **Double Phase Open Circuit**

Unbalanced Faults (2)

LINE TO GROUND

LINE TO LINE

LINE TO LINE TO GROUND

Causes :

1) Insulation Breakdown
2) Lightning Discharges and other Overvoltages
3) Mechanical Damage

Unbalanced Faults (3)

OPEN CIRCUIT OR SERIES FAULTS

Causes :

1) **Broken Conductor**
2) **Operation of Fuses**
3) **Maloperation of Single Phase Circuit Breakers**

DURING UNBALANCED FAULTS, SYMMETRY OF SYSTEM IS LOST

$\therefore$ SINGLE PHASE REPRESENTATION IS NO LONGER VALID

Unbalanced Faults (4)

Analysed using :-

- **Symmetrical Components**
- **Equivalent Sequence Networks of Power System**
- **Connection of Sequence Networks appropriate to Type of Fault**

Symmetrical Components

Symmetrical Components

Fortescue discovered a property of unbalanced phasors 'n' phasors may be resolved into :-

- **(n-1) sets of balanced n-phase systems of phasors, each set having a different phase sequence**

plus

- **1 set of zero phase sequence or unidirectional phasors**

$$V_A = V_{A1} + V_{A2} + V_{A3} + V_{A4} \text{ - - - - - } V_{A(n-1)} + V_{An}$$
$$V_B = V_{B1} + V_{B2} + V_{B3} + V_{B4} \text{ - - - - - } V_{B(n-1)} + V_{Bn}$$
$$V_C = V_{C1} + V_{C2} + V_{C3} + V_{C4} \text{ - - - - - } V_{C(n-1)} + V_{Cn}$$
$$V_D = V_{D1} + V_{D2} + V_{D3} + V_{D4} \text{ - - - - - } V_{D(n-1)} + V_{Dn}$$

- -

$$V_n = V_{n1} + V_{n2} + V_{n3} + V_{n4} \text{ - - - - - } V_{n(n-1)} + V_{nn}$$

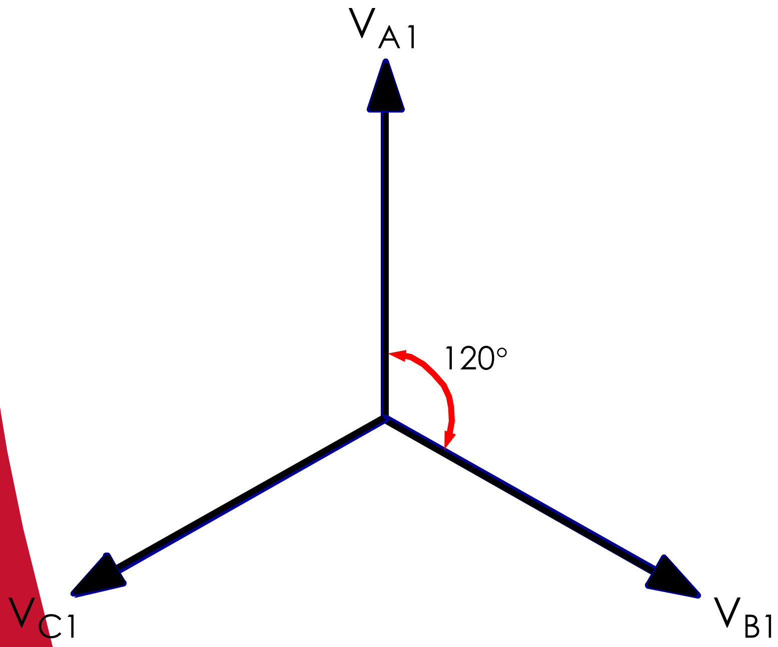
(n-1) x Balanced **1 x Zero Sequence**

Unbalanced 3-Phase System

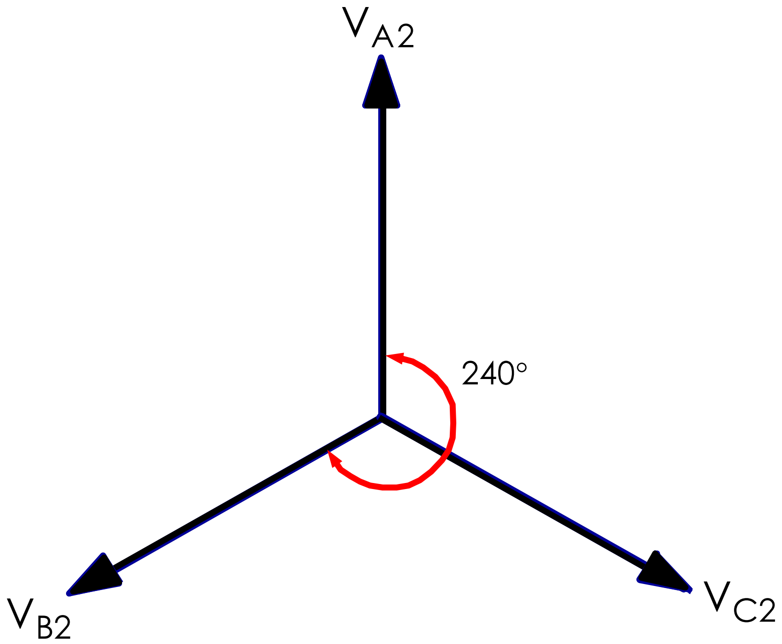
$$V_A = V_{A1} + V_{A2} + V_{A0}$$

$$V_B = V_{B1} + V_{B2} + V_{B0}$$

$$V_C = V_{C1} + V_{C2} + V_{C0}$$

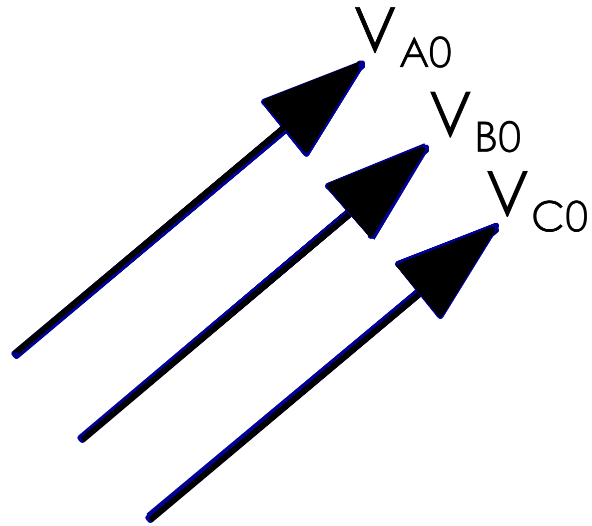


Positive Sequence



Negative Sequence

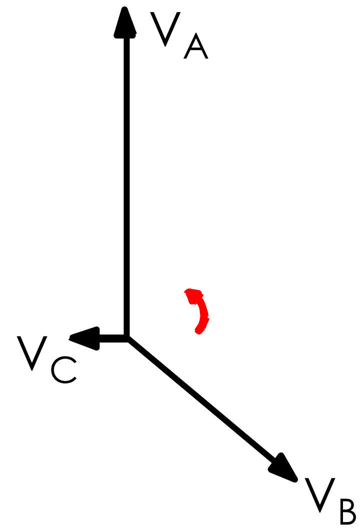
Unbalanced 3-Phase System



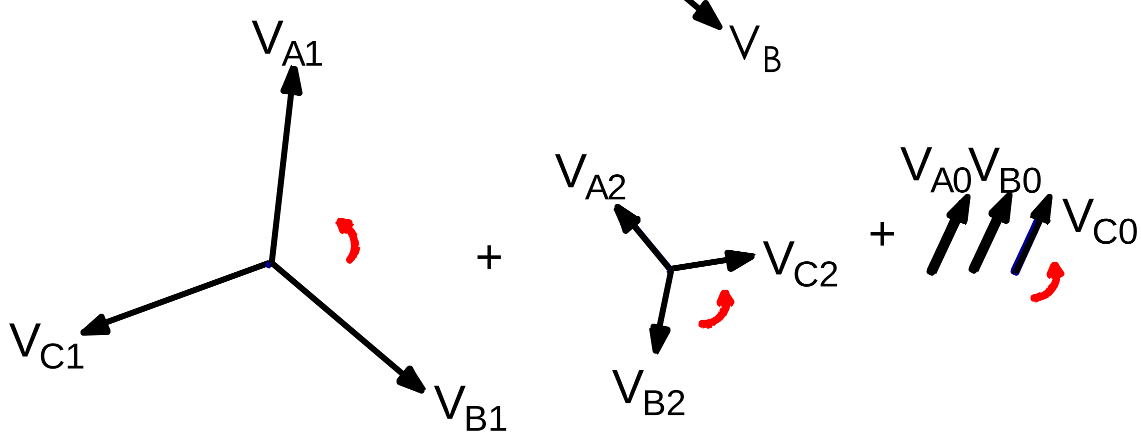
Zero Sequence

Symmetrical Components

Phase ≡ Positive + Negative + Zero



$$V_A = V_{A1} + V_{A2} + V_{A0}$$
$$V_B = V_{B1} + V_{B2} + V_{B0}$$
$$V_C = V_{C1} + V_{C2} + V_{C0}$$



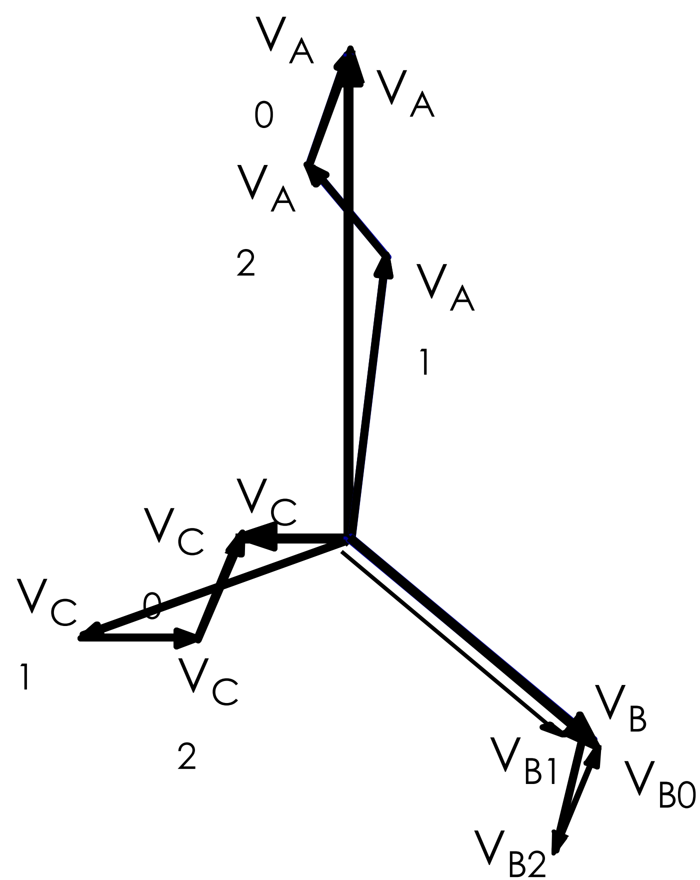
$$V_{B1} = a^2 V_{A1} \qquad V_{B2} = a\, V_{A2} \qquad V_{B0} = V_{A0}$$
$$V_{C1} = a\, V_{A1} \qquad V_{C2} = a^2 V_{A2} \qquad V_{C0} = V_{A0}$$

Converting from Sequence Components to Phase Values

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

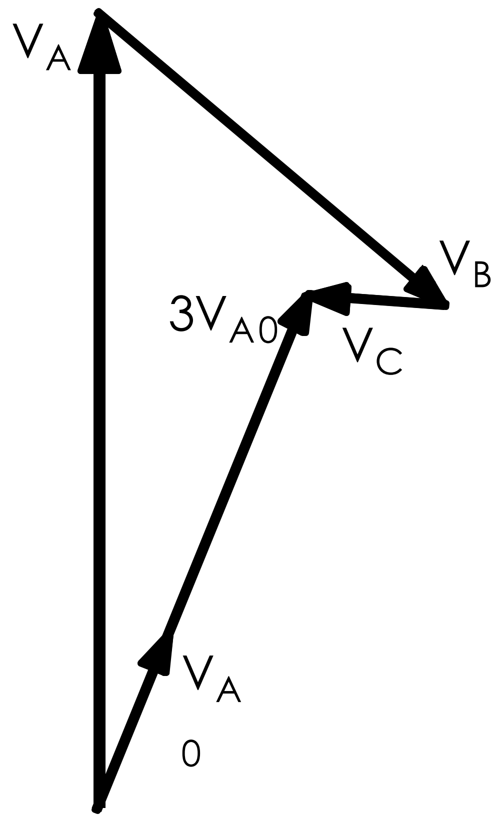
$$V_B = V_{B1} + V_{B2} + V_{B0} = a^2V_{A1} + a\,V_{A2} + V_{A0}$$

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



Converting from Phase Values to Sequence Components

$$V_{A1} = 1/3\ \{V_A + a\,V_B + a^2V_C\}$$
$$V_{A2} = 1/3\ \{V_A + a^2V_B + a\,V_C\}$$
$$V_{A0} = 1/3\ \{V_A + V_B + V_C\}$$



Summary

$$V_A = V_{A1} + V_{A2} + V_{A0}$$
$$V_B = \propto^2 V_{A1} + \propto V_{A2} + V_{A0}$$
$$V_C = \propto V_{A1} + \propto^2 V_{A2} + V_{A0}$$

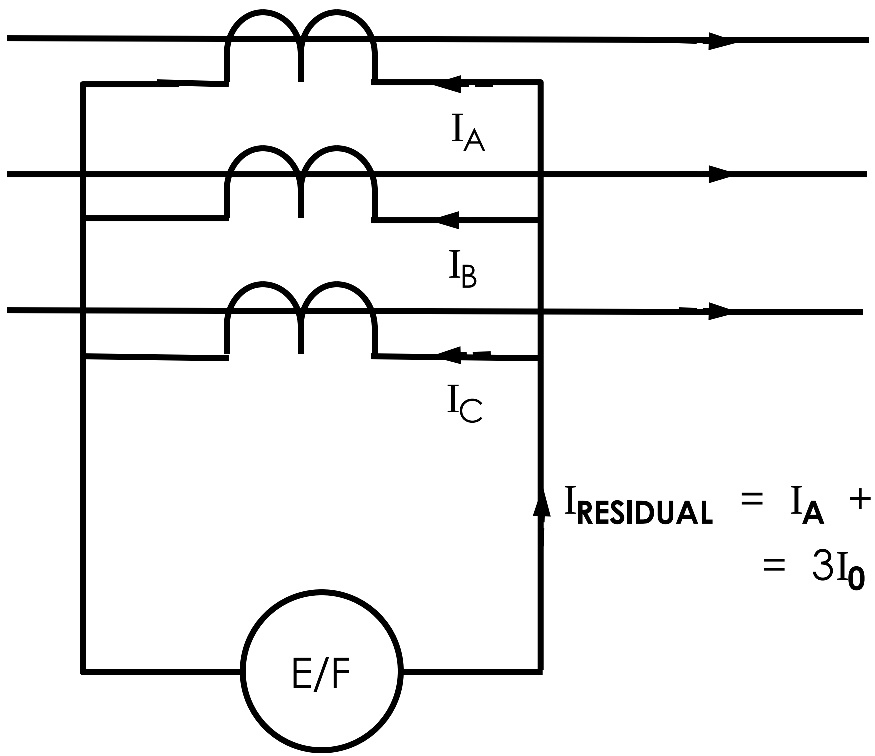
$$I_A = I_{A1} + I_{A2} + I_{A0}$$
$$I_B = \propto^2 I_{A1} + \propto_{A2} + I_{A0}$$
$$I_C = \propto I_{A1} + \propto^2 I_{A2} + I_{A0}$$

$$V_{A1} = 1/3\,\{V_A + \propto V_B + \propto^2 V_C\}$$
$$V_{A2} = 1/3\,\{V_A + \propto^2 V_B + \propto V_C\}$$
$$V_{A0} = 1/3\,\{V_A + V_B + V_C\}$$

$$I_{A1} = 1/3\,\{I_A + \propto I_B + \propto^2 I_C\}$$
$$I_{A2} = 1/3\,\{I_A + \propto^2 I_B + \propto I_C\}$$
$$I_{A0} + 1/3\,\{I_A + I_B + I_C\}$$

Residual Current

Used to detect earth faults

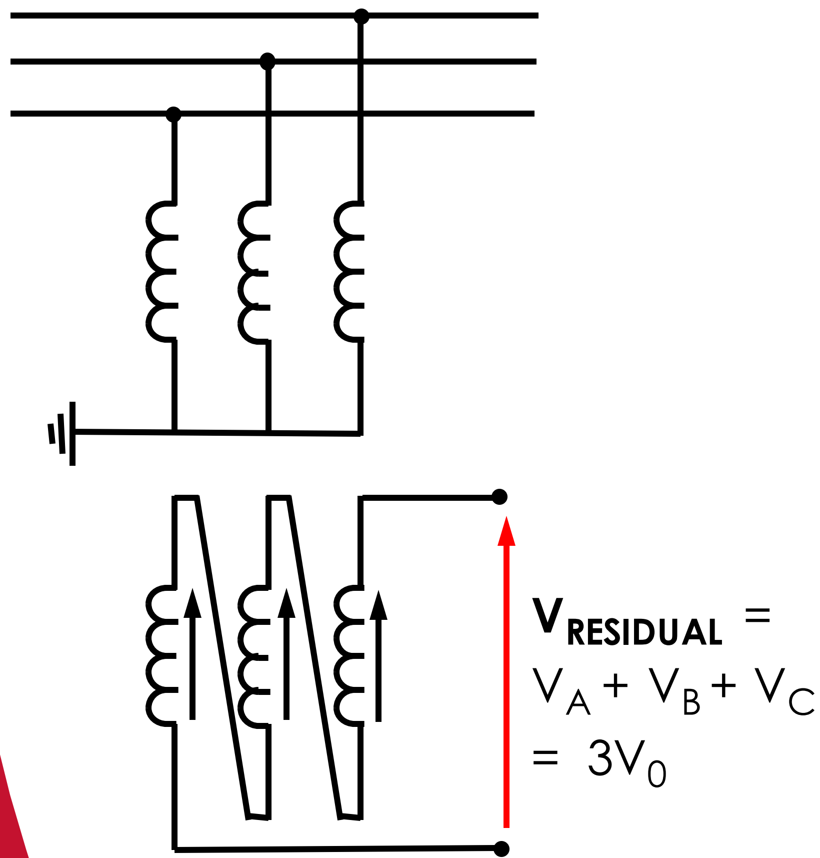


$$I_{RESIDUAL} = I_A + I_B + I_C$$
$$= 3I_0$$

$I_{RESIDUAL}$ **is zero for :-**	**Balanced Load** **3∅ Faults** **Ø/∅ Faults**	$I_{RESIDUAL}$ **is present for :-**	**∅/E Faults** **∅/Ø/E Faults** **Open circuits (with current in remaining phases)**

Residual Voltage

Used to detect earth faults



Residual voltage is measured from "Open Delta" or "Broken Delta" VT secondary windings.

$V_{RESIDUAL}$ **is zero for:-**

- **Healthy unfaulted systems**
- **3∅ Faults**
- **∅/∅ Faults**

$V_{RESIDUAL}$ **is present for:-**

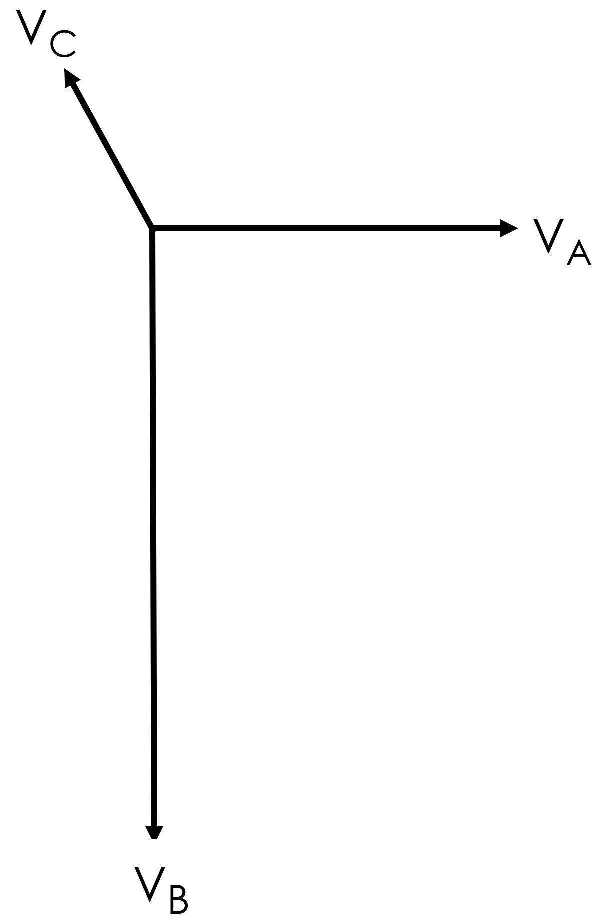
- **∅/E Faults**
- **∅/∅/E Faults**
- **Open Circuits (on supply side of VT)**

Evaluate the positive, negative and zero sequence components for the unbalanced phase vectors :

$V_A = 1 \angle 0°$

$V_B = 1.5 \angle -90°$

$V_C = 0.5 \angle 120°$



Solution

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

$$= 1/3\,[\,1 + (1\angle 120)(1.5\angle -90) + (1\angle 240)(0.5\angle 120)\,]$$

$$= 0.965\angle 15$$

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

$$= 1/3\,[\,1 + (1\angle 240)(1.5\angle -90) + (1\angle 120)(0.5\angle 120)\,]$$

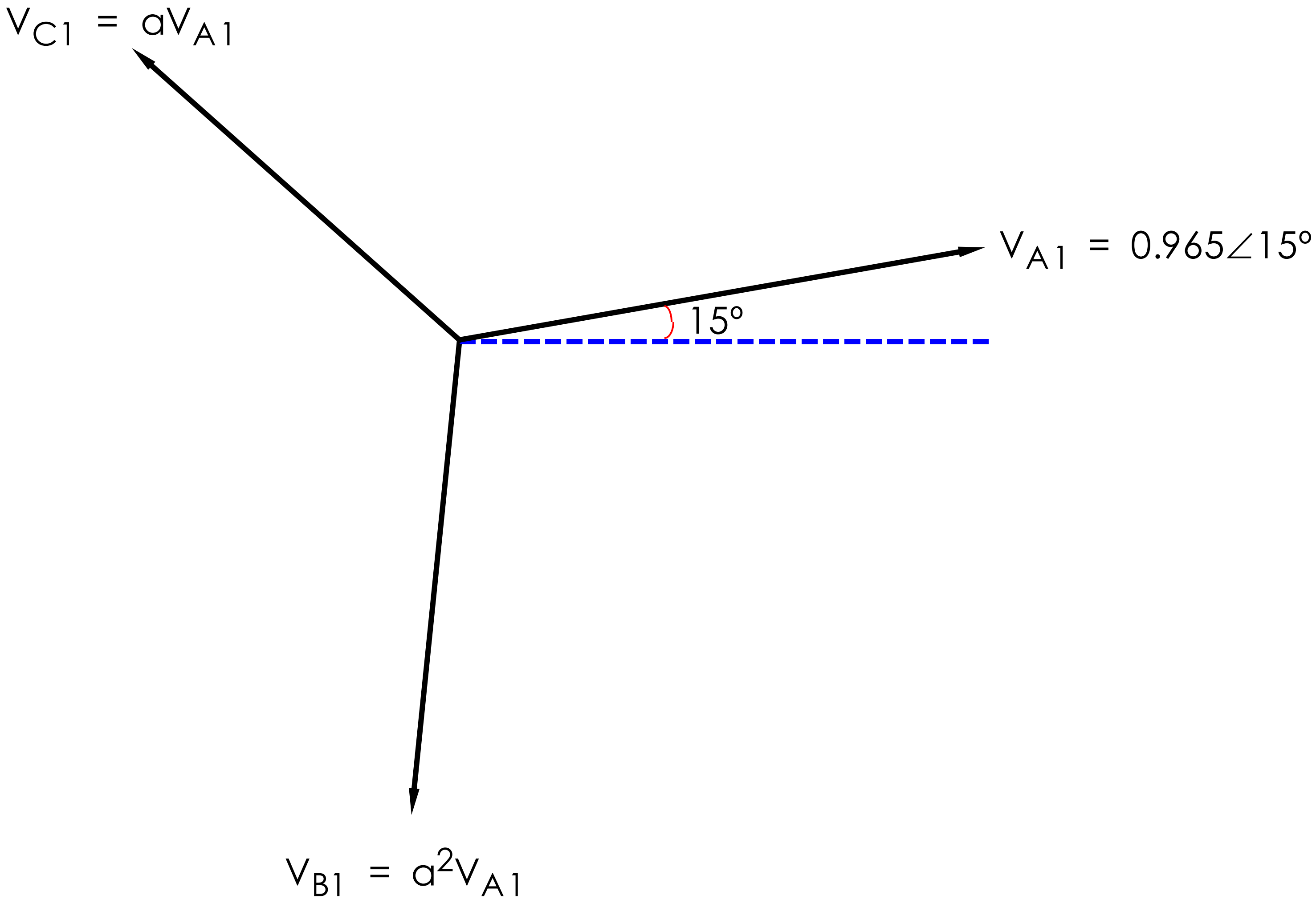
$$= 0.211\angle 150$$

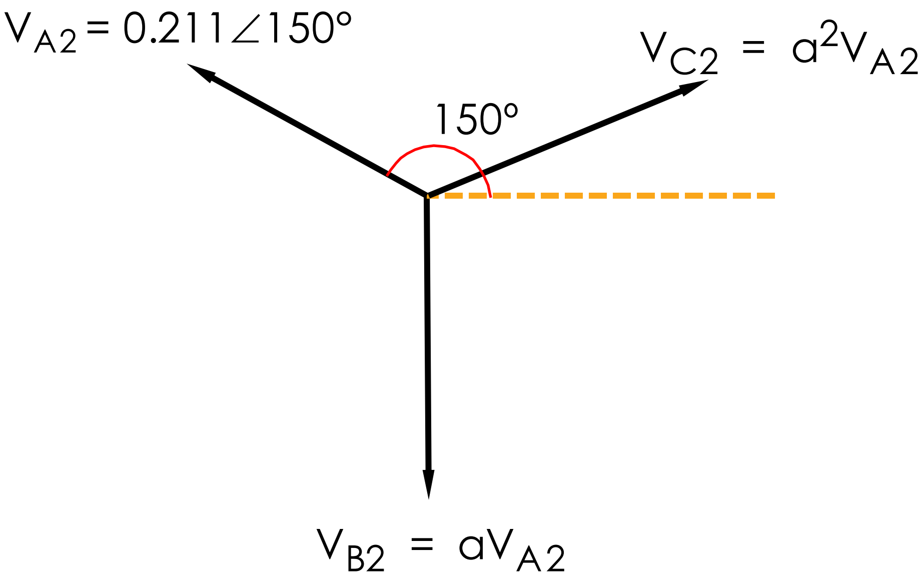
$$V_{A0} = 1/3\,(V_A + V_B + V_C)$$

$$= 1/3\,(1 + 1.5\angle -90 + 0.5\angle 120)$$

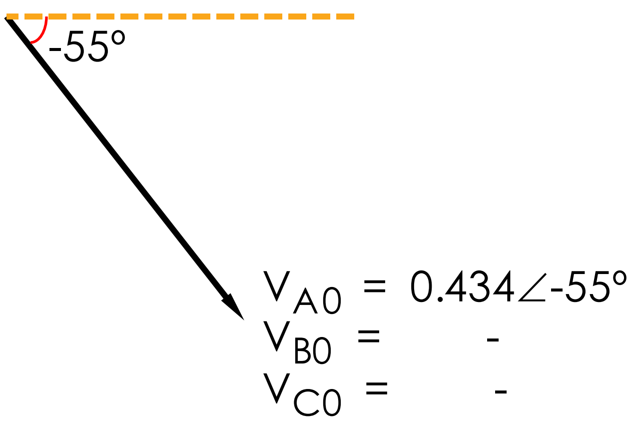
$$= 0.434\angle -55$$

Positive Sequence Voltages



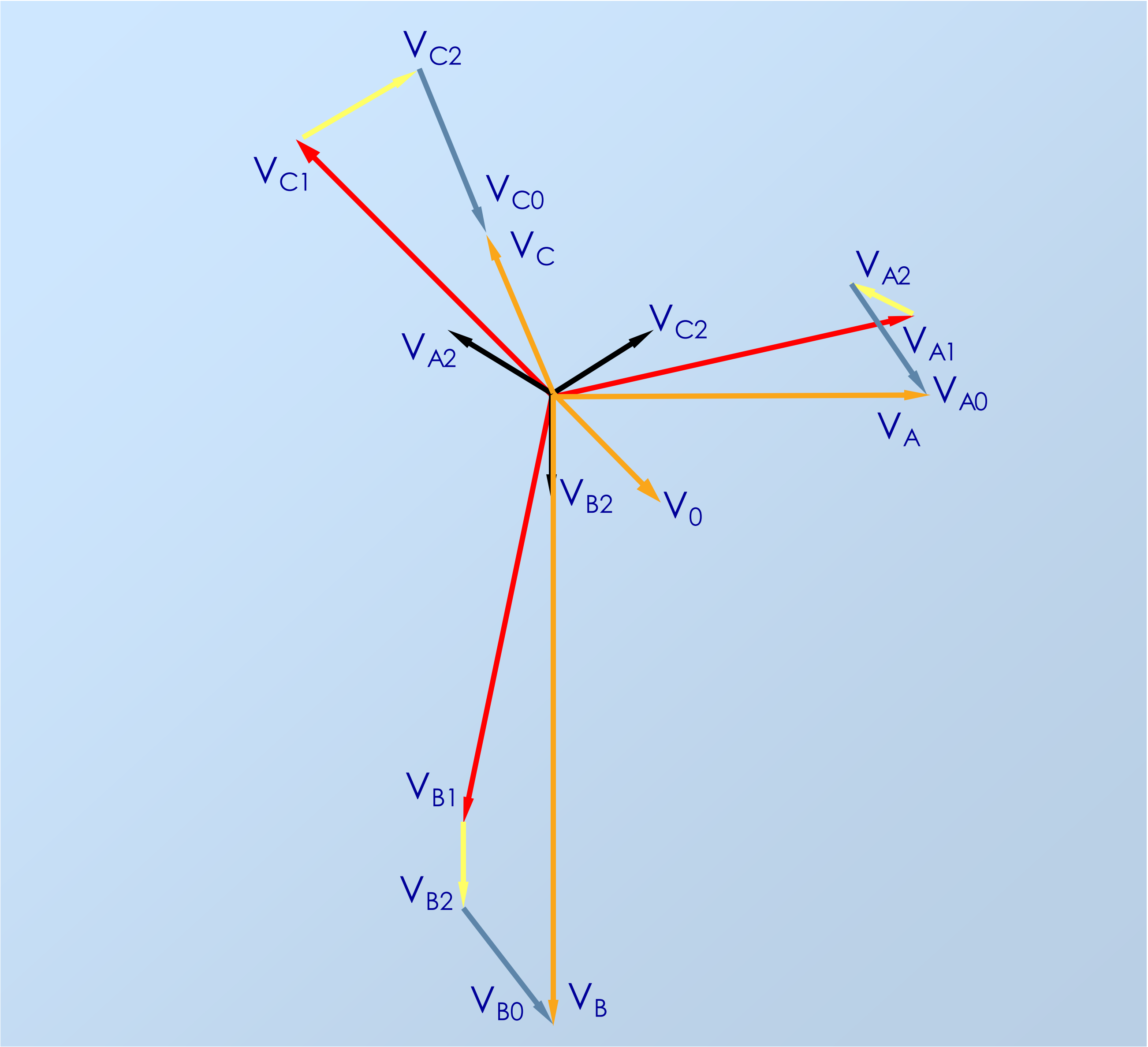


Negative Sequence Voltages



Zero Sequence Voltages

Symmetrical Components



Example

Evaluate the phase quantities I_a, I_b and I_c from the sequence components

$I_{A1} = 0.6 \angle 0$

$I_{A2} = -0.4 \angle 0$

$I_{A0} = -0.2 \angle 0$

Solution

$I_A = I_{A1} + I_{A2} + I_{A0} = 0$

$I_B = \propto^2 I_{A1} + \propto I_{A2} + I_{A0}$

$= 0.6\angle 240 - 0.4\angle 120 - 0.2\angle 0 = 0.91\angle -109$

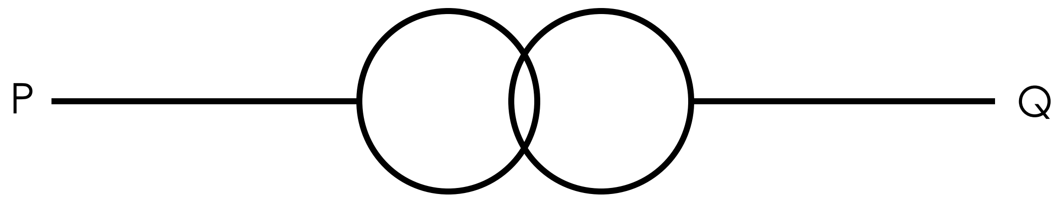
$I_C = \propto I_{A1} + \propto^2 I_{A2} + I_{A0}$

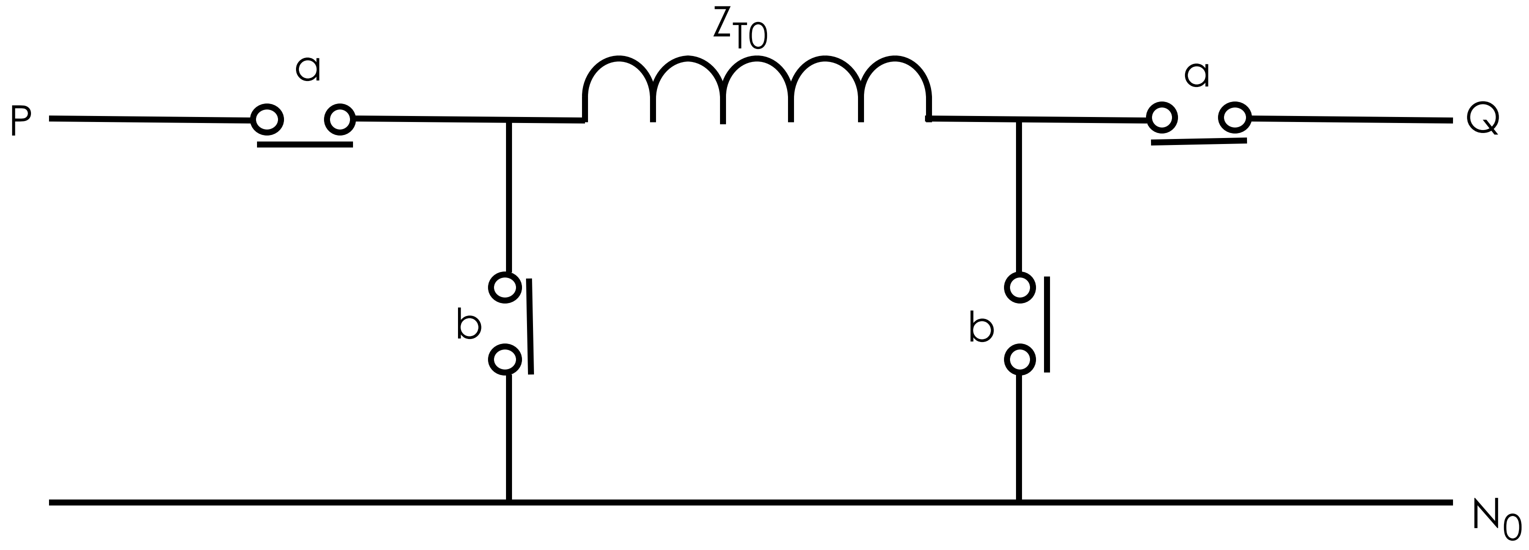
$= 0.6\angle 120 - 0.4\angle 240 - 0.2\angle 0 = 0.91\angle -109$

AREVA

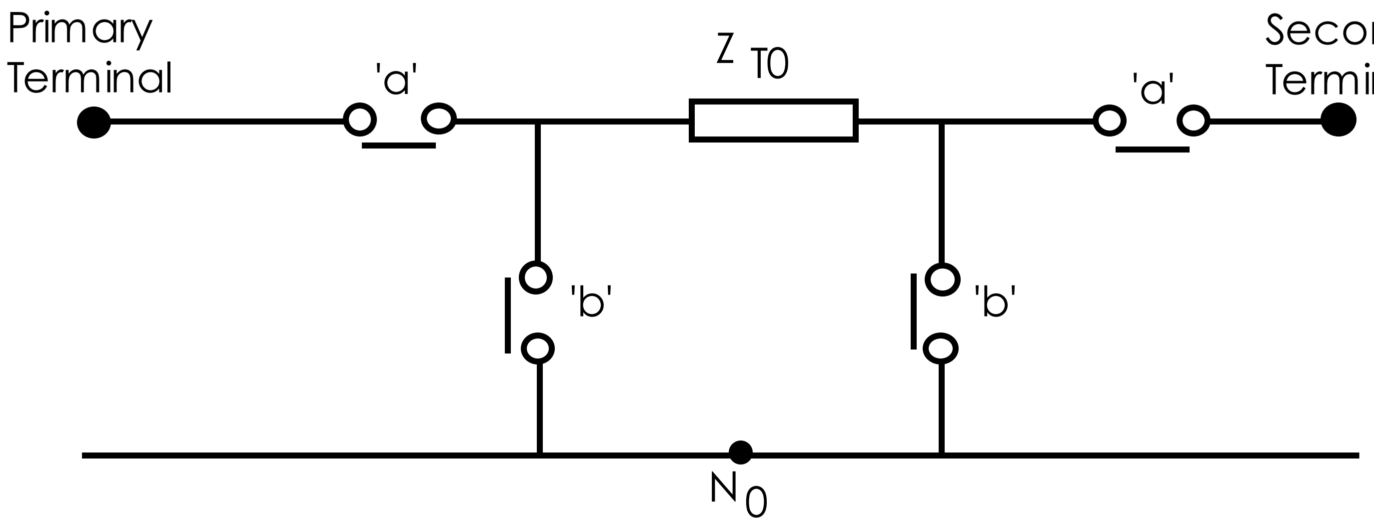
Representation of Plant Cont…

Transformer Zero Sequence Impedance





General Zero Sequence Equivalent Circuit for Two Winding Transformer



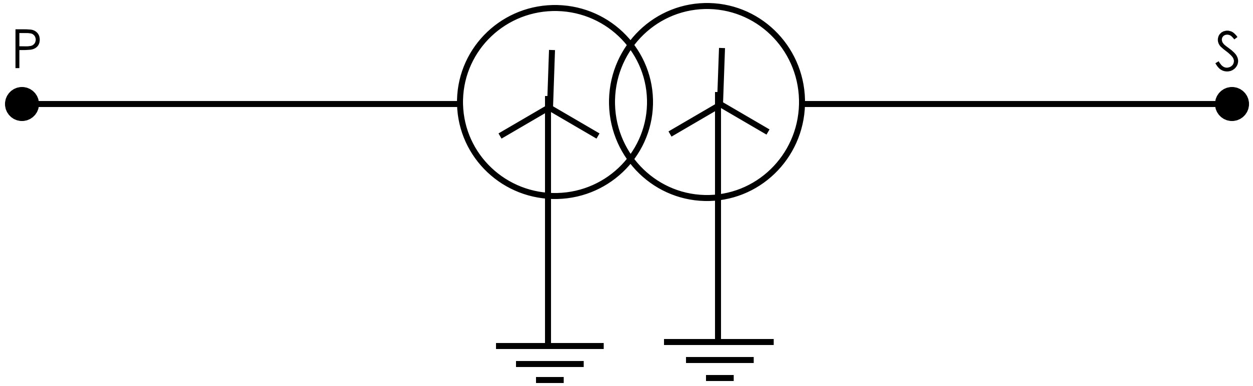
On appropriate side of transformer :

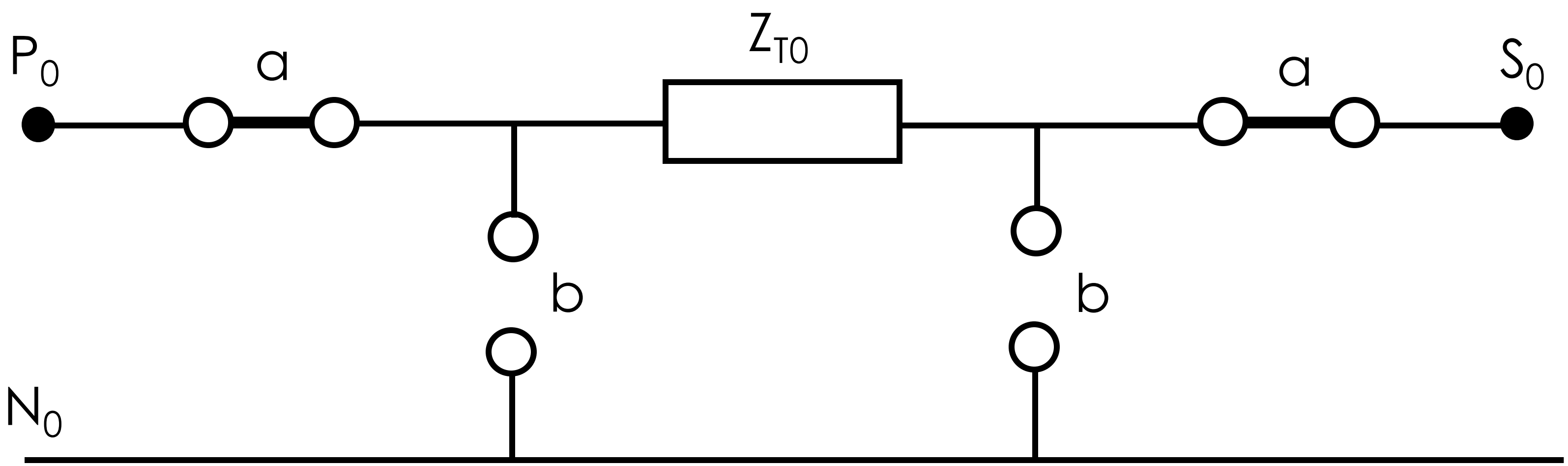
Earthed Star Winding - Close link 'a'
Open link 'b'

Delta Winding - Open link 'a'
Close link 'b'

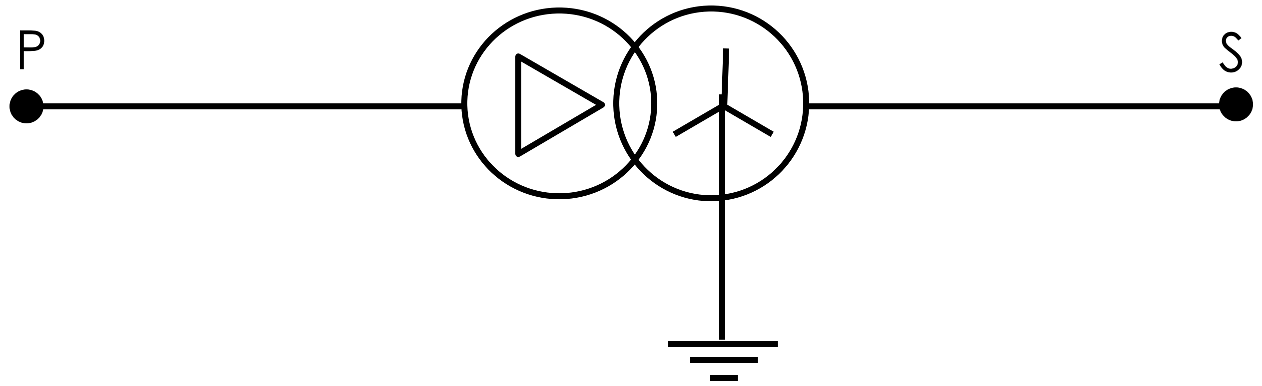
Unearthed Star Winding - Both links open

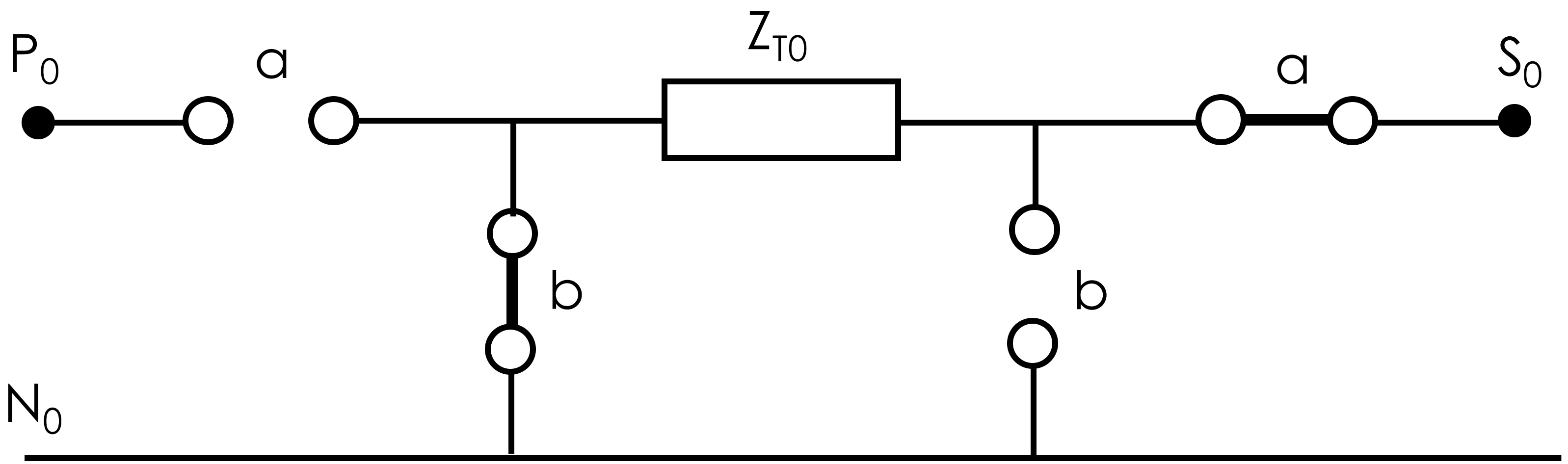
Zero Sequence Equivalent Circuits (1)



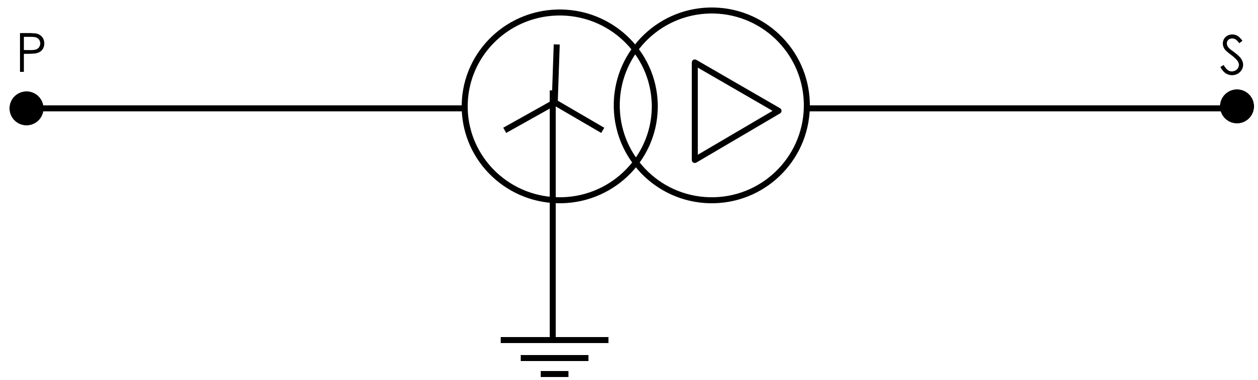


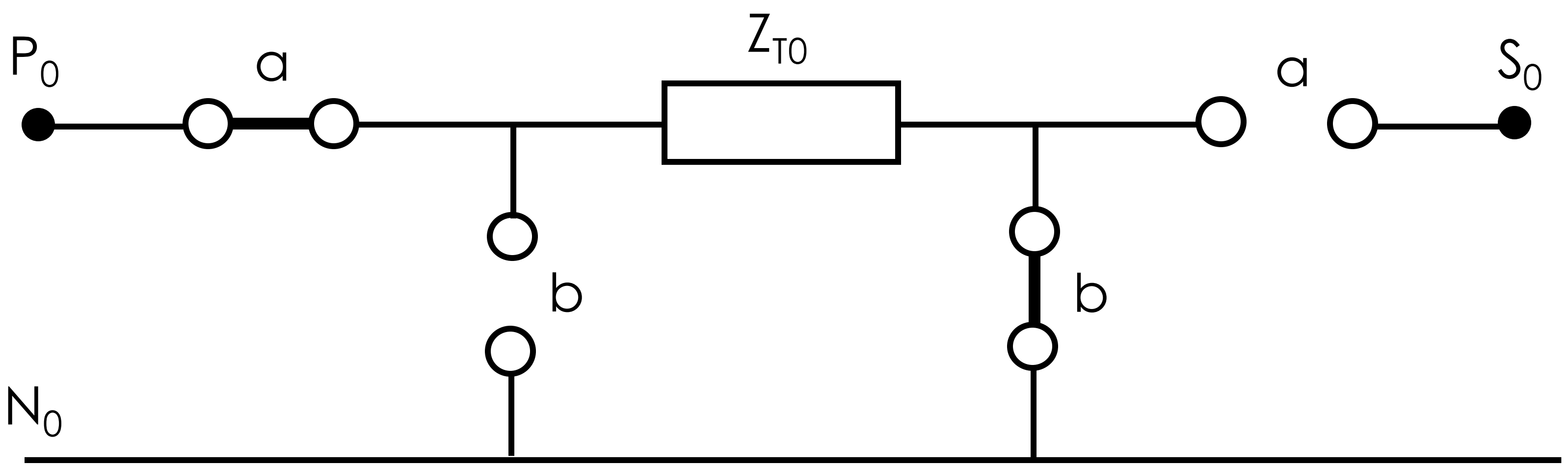
Zero Sequence Equivalent Circuits (2)



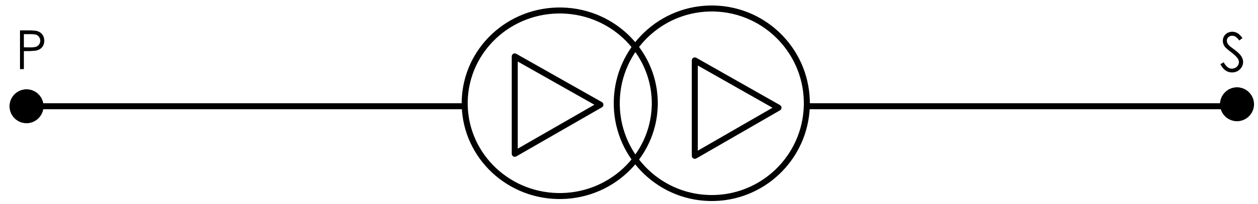


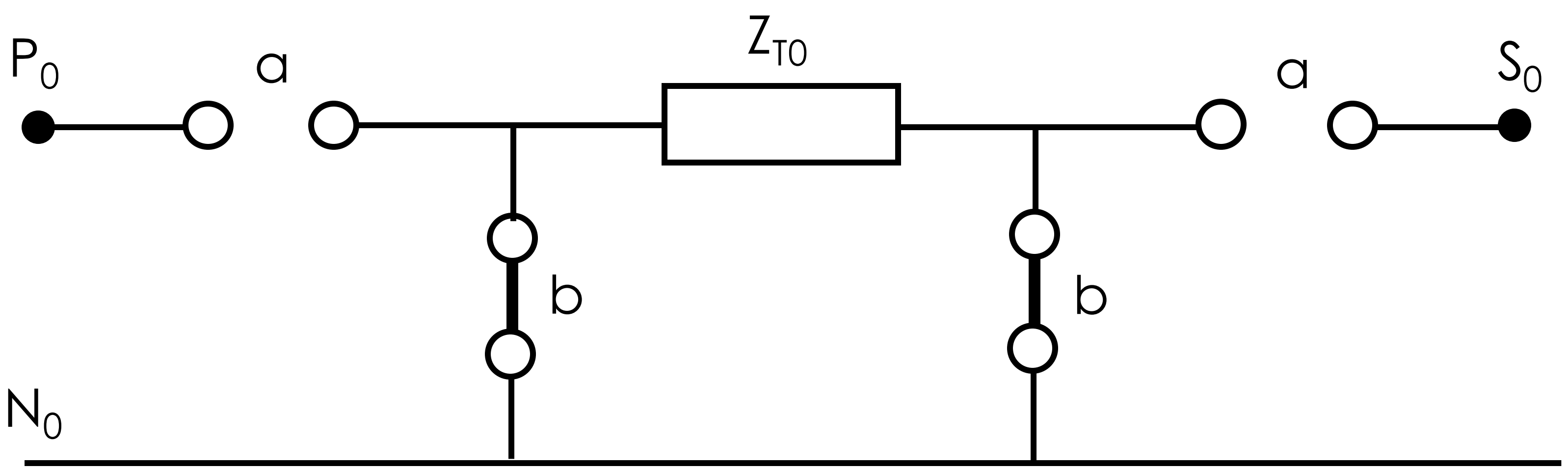
Zero Sequence Equivalent Circuits (3)



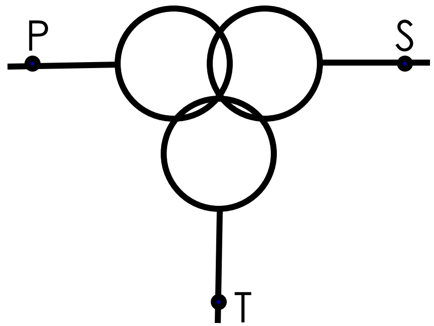


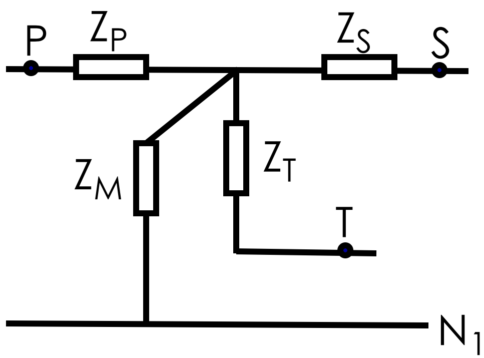
Zero Sequence Equivalent Circuits (4)





3 Winding Transformers

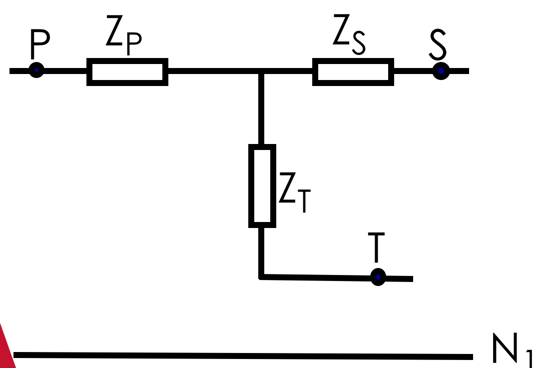




Z_P, Z_S, Z_T = **Leakage reactances of Primary, Secondary and Tertiary Windings**

Z_M = **Magnetising Impedance = Large**

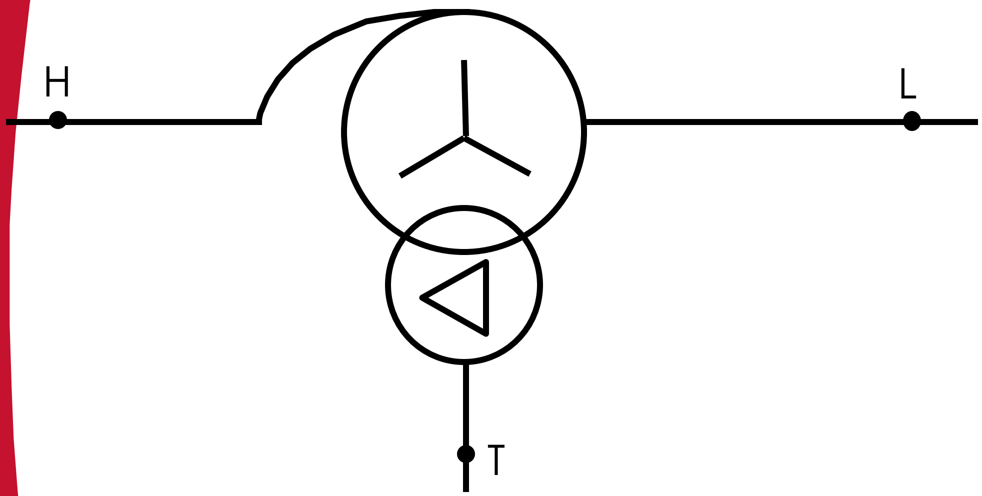
$\therefore$ **Ignored**

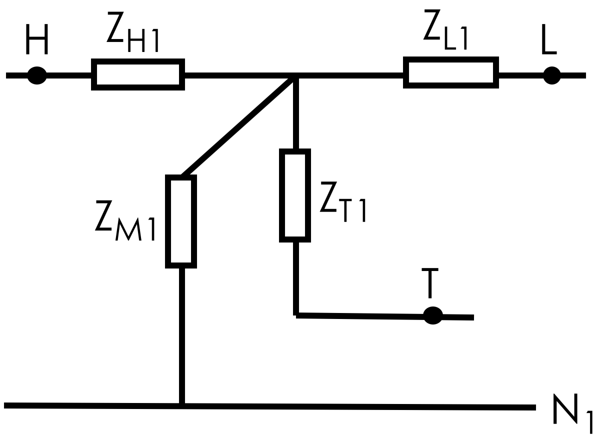


$Z_{P\text{-}S} = Z_P + Z_S$ = **Impedance between Primary (P) and Secondary (S) where Z_P & Z_S are both expressed on same voltage base**

Similarly $Z_{P\text{-}T} = Z_P + Z_T$ **and** $Z_{S\text{-}T} = Z_S + Z_T$

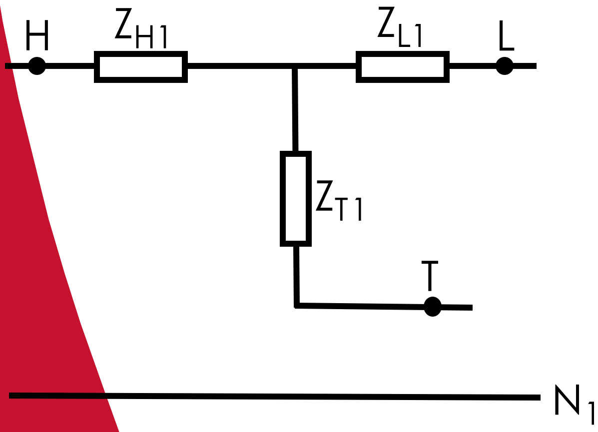
Auto Transformers





Equivalent circuit is similar to that of a 3 winding transformer.

Z_M = Magnetising Impedance = Large ∴ Ignored



$Z_{HL1} = Z_{H1} + Z_{L1}$ (both referred to same voltage base)

$Z_{HT1} = Z_{H1} + Z_{T1}$ (both referred to same voltage base)

$Z_{LT1} = Z_{L1} + Z_{T1}$ (both referred to same voltage base)

Sequence Networks

Sequence Networks (1)

It can be shown that providing the system impedances are balanced from the points of generation right up to the fault, each sequence current causes voltage drop of its own sequence only.

Regard each current flowing within own network thro' impedances of its own sequence only, with no interconnection between the sequence networks right up to the point of fault.

Sequence Networks (2)

- +ve, -ve and zero sequence networks are drawn for a 'reference' phase. This is usually taken as the 'A' phase.

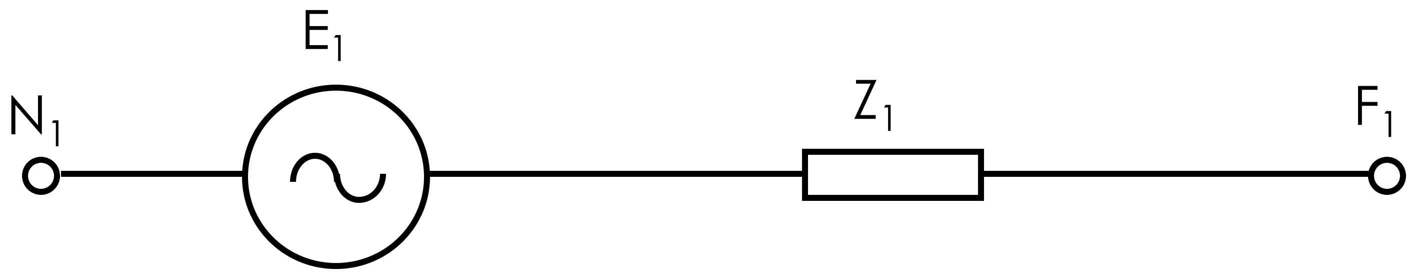
- Faults are selected to be 'balanced' relative to the reference 'A' phase.

e.g. For Ø/E faults consider an A-E fault

For Ø/Ø faults consider a B-C fault

- Sequence network interconnection is the simplest for the reference phase.

Positive Sequence Diagram



1. **Start with neutral point N_1**

- **All generator and load neutrals are connected to N_1**

2. **Include all source EMF's**

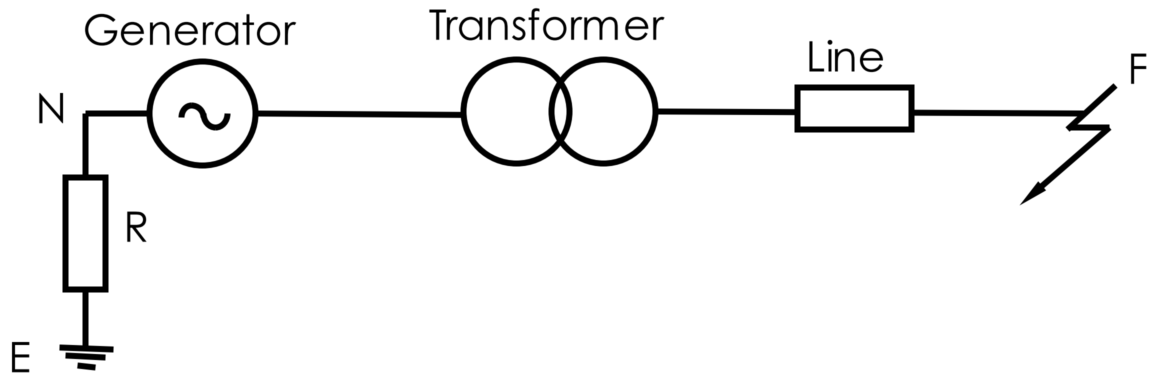
- **Phase-neutral voltage**

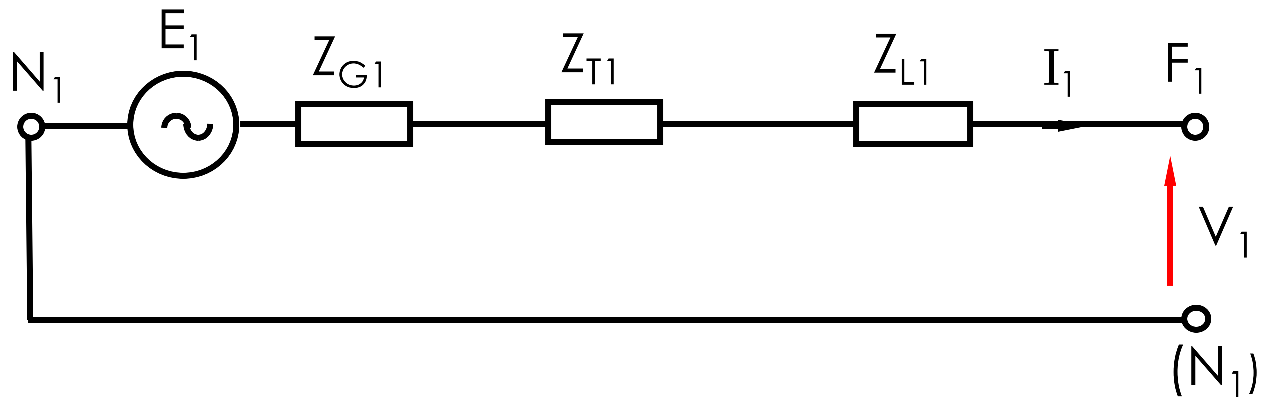
3. **Impedance network**

- **Positive sequence impedance per phase**

4. **Diagram finishes at fault point F_1**

Example





V_1 = Positive sequence PH-N voltage at fault point

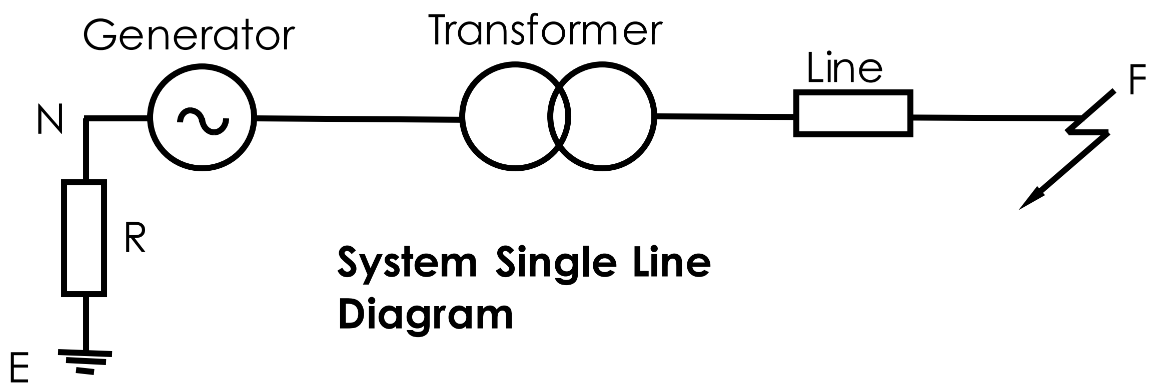
I_1 = Positive sequence phase current flowing into F_1

$V_1 = E_1 - I_1 (Z_{G1} + Z_{T1} + Z_{L1})$

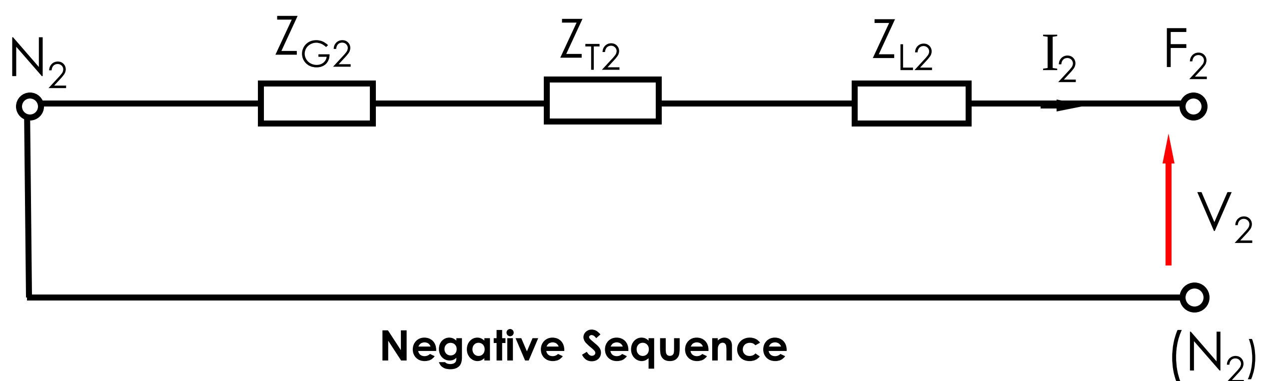
Negative Sequence Diagram

1. **Start with neutral point N_2**
- **All generator and load neutrals are connected to N_2**
2. **No EMF's included**
- **No negative sequence voltage is generated!**
3. **Impedance network**
- **Negative sequence impedance per phase**
4. **Diagram finishes at fault point F_2**

Example



System Single Line Diagram



Negative Sequence Diagram

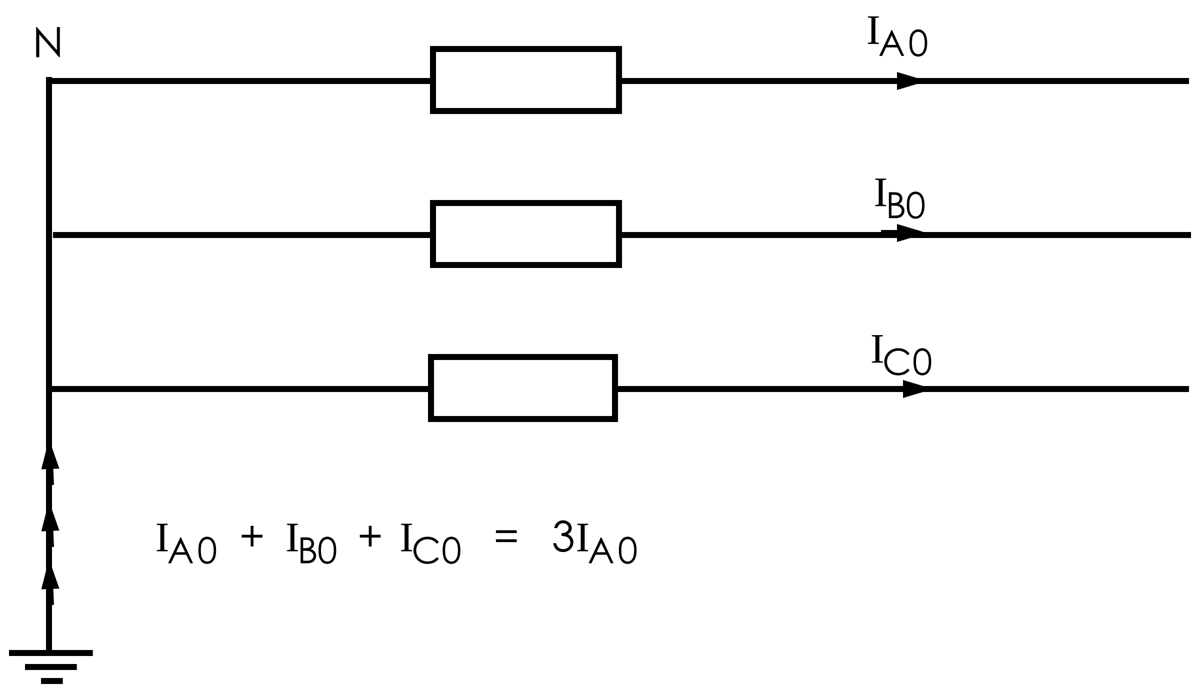
V_2 = Negative sequence PH-N voltage at fault point

I_2 = Negative sequence phase current flowing into F_2

$V_2 = -I_2 (Z_{G2} + Z_{T2} + Z_{L2})$

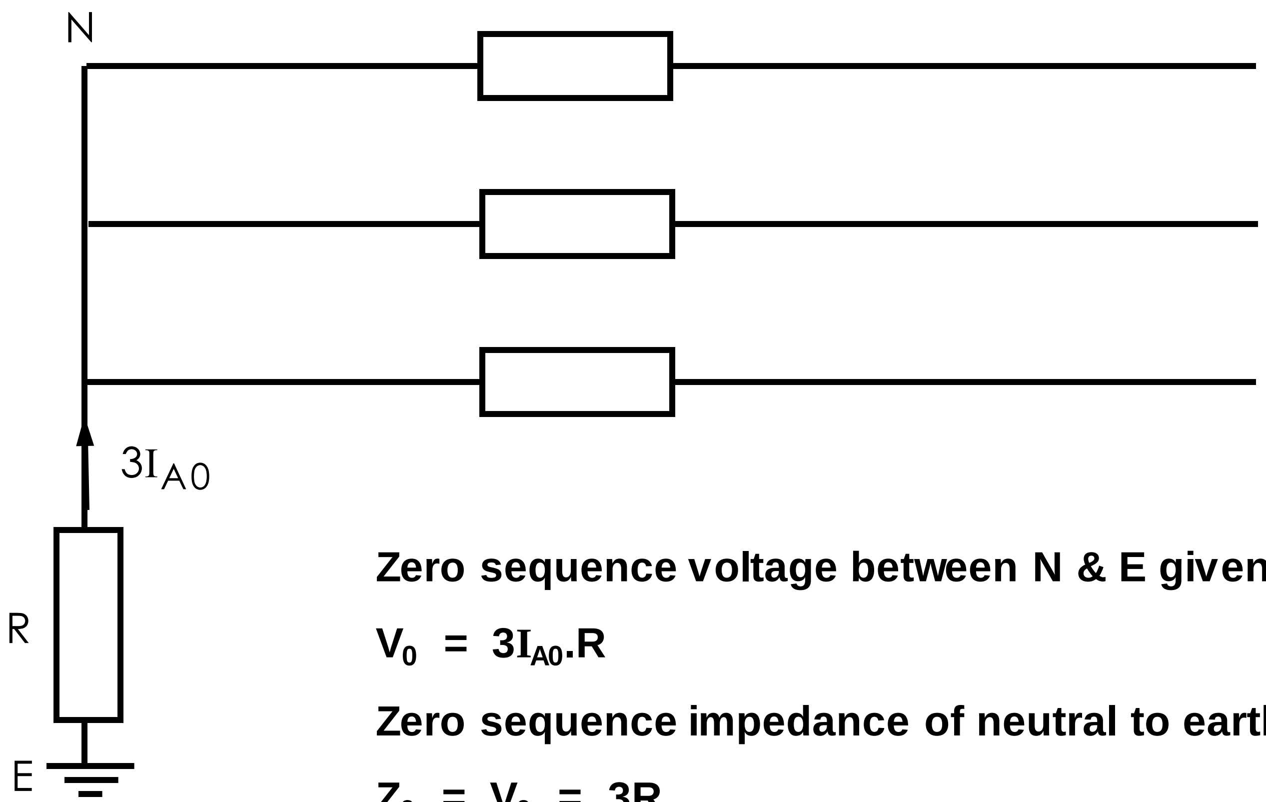
Zero Sequence Diagram (1)

For "In Phase" (Zero Phase Sequence) currents to flow in each phase of the system, there must be a fourth connection (this is typically the neutral or earth connection).



Zero Sequence Diagram (2)

Resistance Earthed System :-



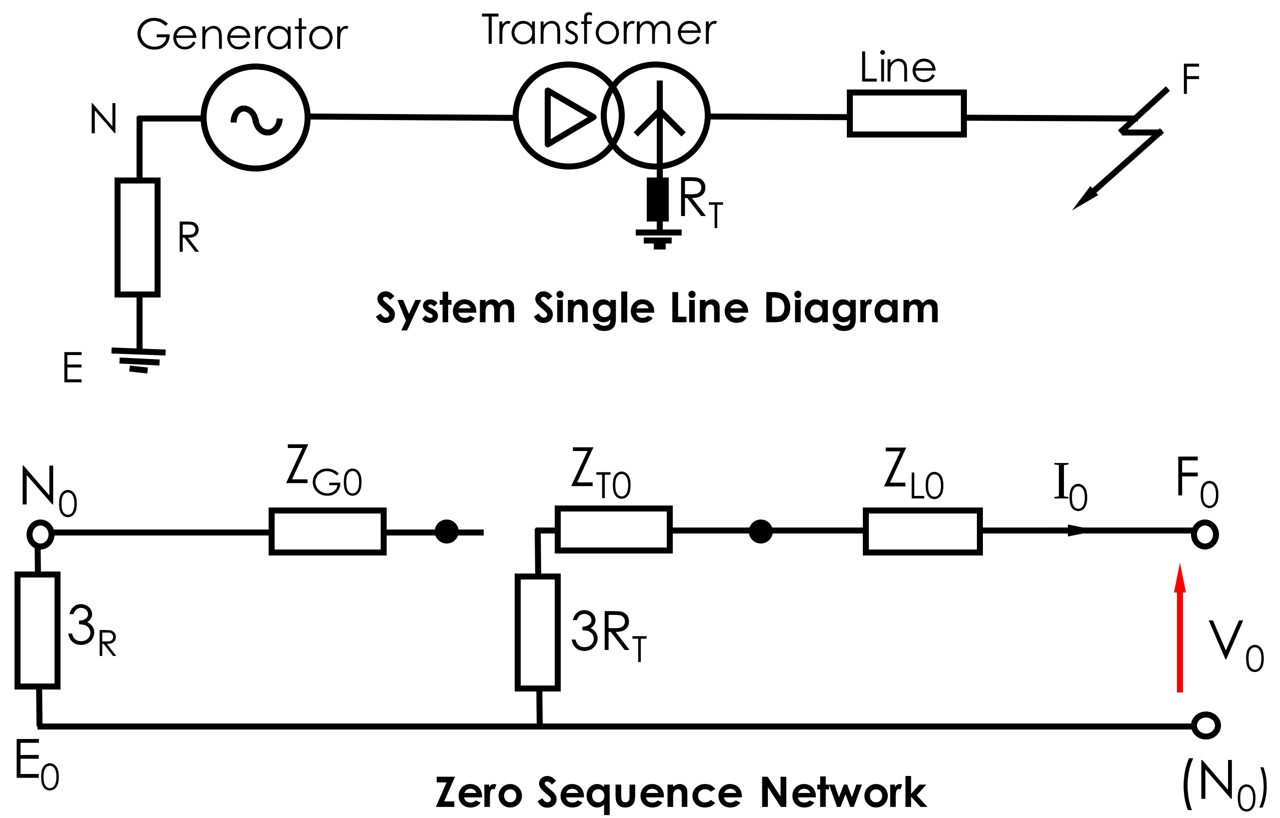
Zero sequence voltage between N & E given by

$$V_0 = 3I_{A0}.R$$

Zero sequence impedance of neutral to earth path

$$Z_0 = \frac{V_0}{I_{A0}} = 3R$$

Zero Sequence Diagram (3)



V_0 = Zero sequence PH-E voltage at fault point

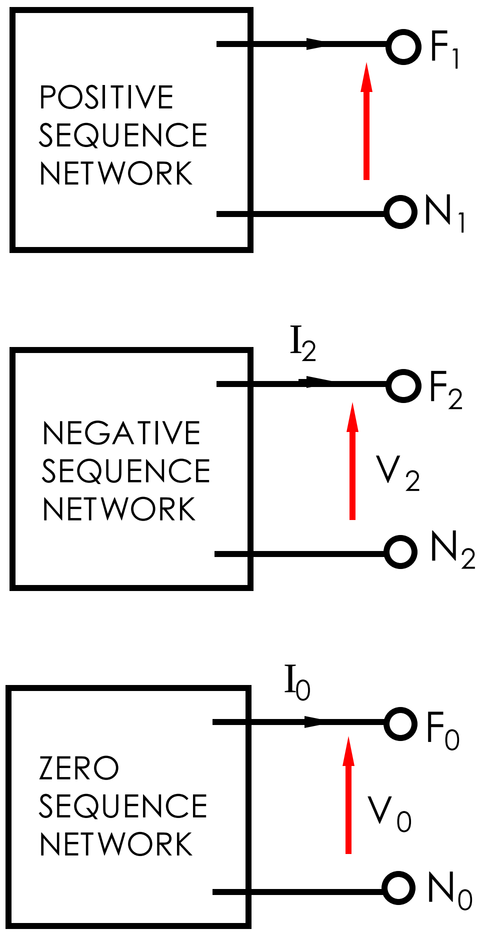
I_0 = Zero sequence current flowing into F_0

V_0 = $-I_0 (Z_{T0} + Z_{L0})$

Network Connections

Interconnection of Sequence Networks (1)

Consider sequence networks as blocks with fault terminals F & N for external connections.



Interconnection of Sequence Networks (2)

For any given fault there are 6 quantities to be considered at the fault point

i.e. V_A V_B V_C I_A I_B I_C

Relationships between these for any type of fault can be converted into an equivalent relationship between sequence components

V_1, V_2, V_0 and I_1, I_2, I_0

This is possible if :-

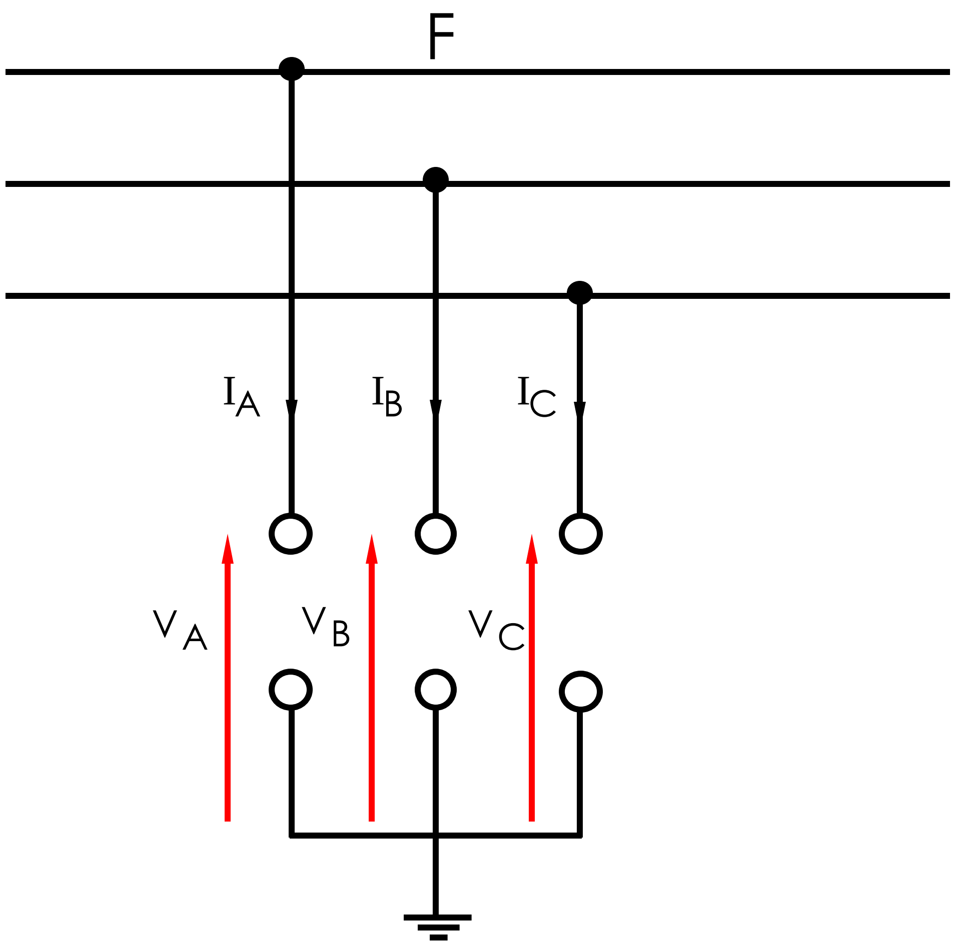
1) Any 3 phase quantities are known (provided they are not all voltages or all currents)

or 2) 2 are known and 2 others are known to have a specific relationship.

From the relationship between sequence V's and I's, the manner in which the isolation sequence networks are connected can be determined.

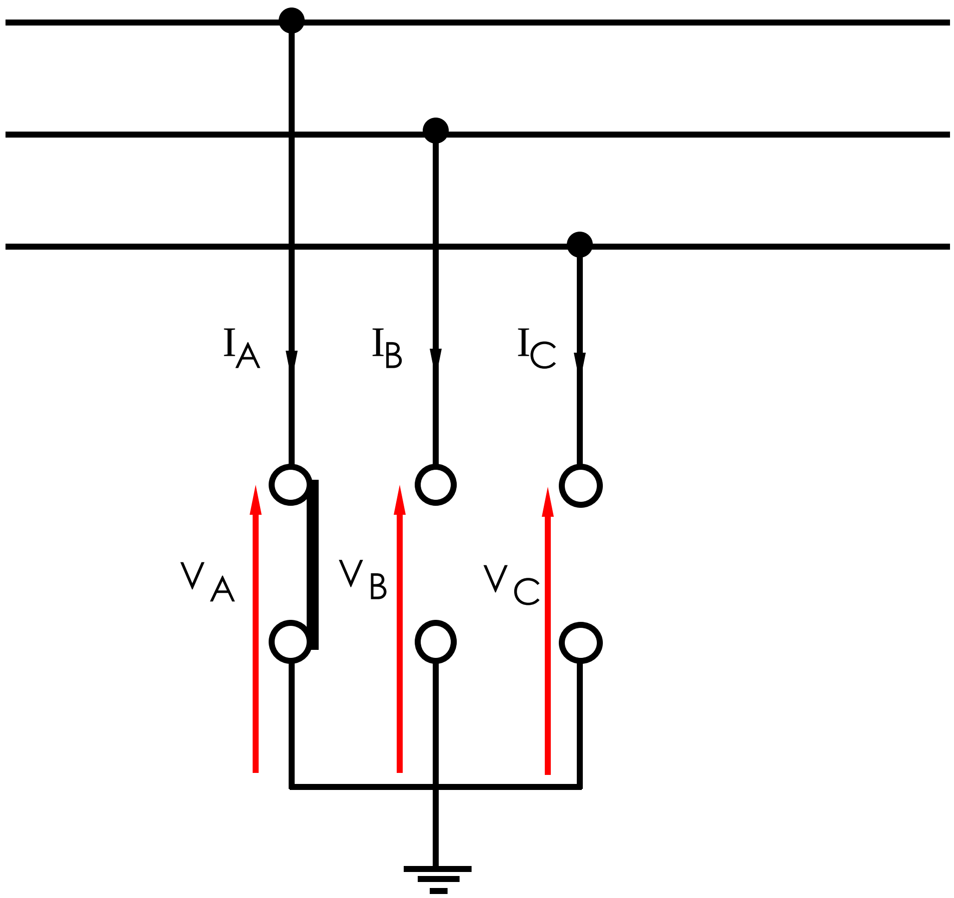
The connection of the sequence networks provides a single phase representation (in sequence terms) of the fault.

To derive the system constraints at the fault terminals :-



Terminals are connected to represent the fault.

Line to Ground Fault on Phase ‘A’



At fault point :-

V_A	=	0
V_B	=	?
V_C	=	?
I_A	=	?
I_B	=	0
I_C	=	0

Phase to Earth Fault on Phase 'A'

At fault point

$V_A \quad = \quad 0 \;;\quad I_B = 0 \;;\quad I_C = 0$

but $\quad V_A \quad = \quad V_1 + V_2 + V_0$

$\therefore \quad \boxed{V_1 + V_2 + V_0 = 0}$ ------------------------ (1)

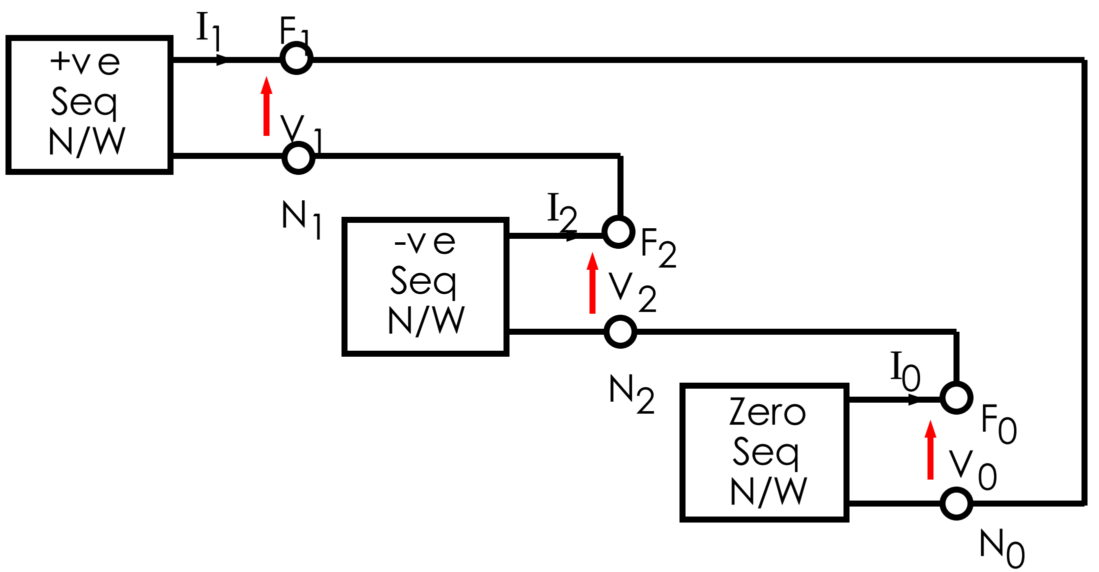
$I_0 \quad = \quad 1/3\,(I_A + I_B + I_C) = 1/3\, I_A$

$I_1 \quad = \quad 1/3\,(I_A + aI_B + a^2I_C) = 1/3\, I_A$

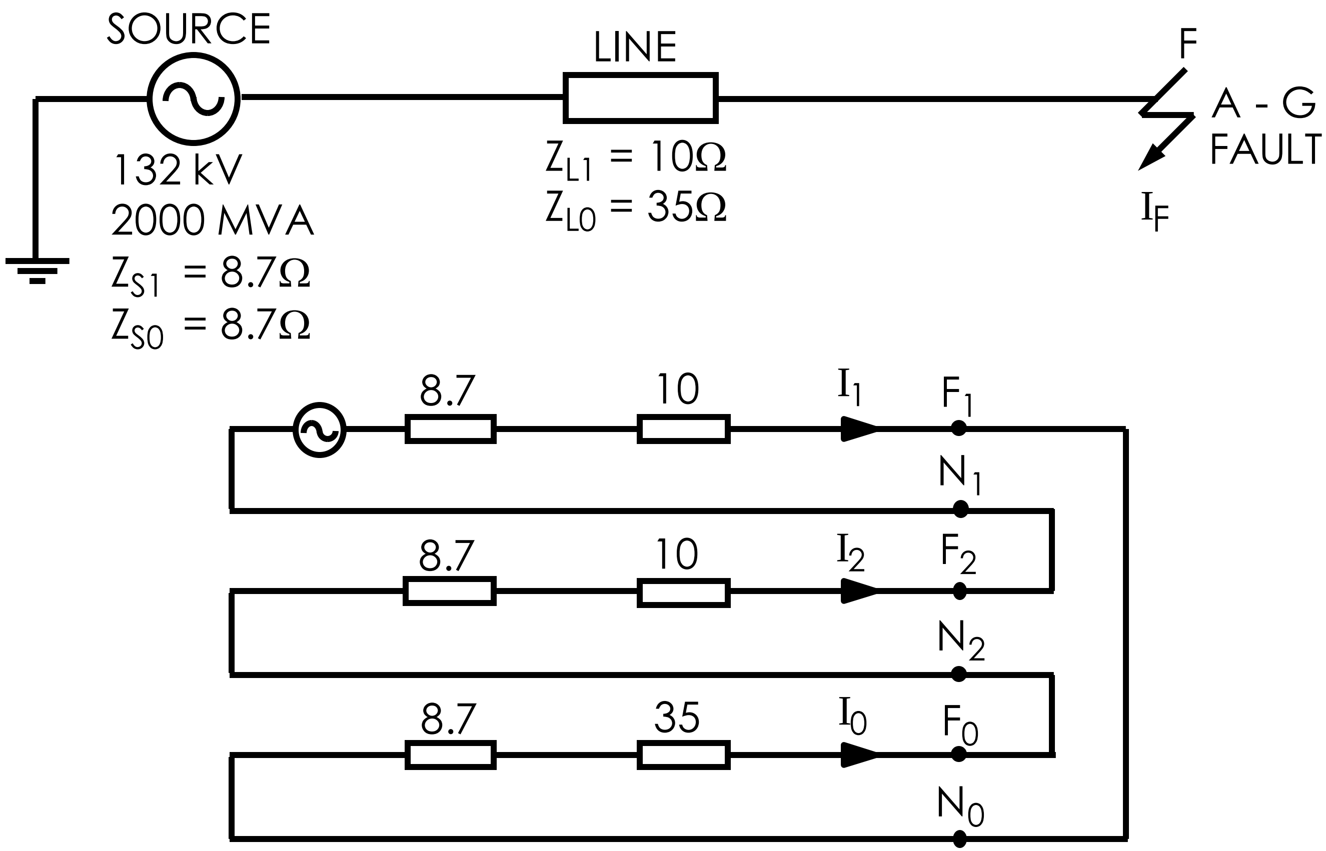
$I_2 \quad = \quad 1/3\,(I_A + a^2I_B + aI_C) = 1/3\, I_A$

$\therefore \quad \boxed{I_1 = I_2 = I_0 = 1/3\, I_A}$ ------------------------ (2)

To comply with (1) & (2) the sequence networks must be connected in series :-



Example : Phase to Earth Fault



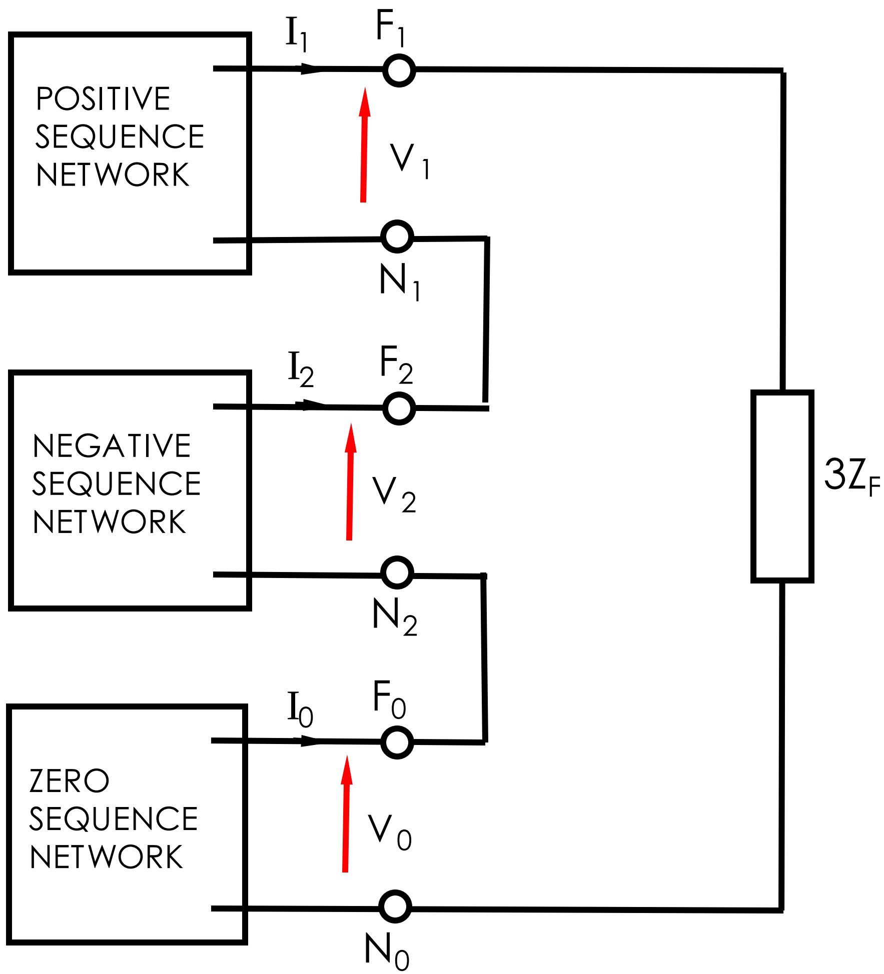
Total impedance = 81.1Ω

$$I_1 = I_2 = I_0 = \frac{132000}{\sqrt{3} \times 81.1} = 940 \text{ Amps}$$

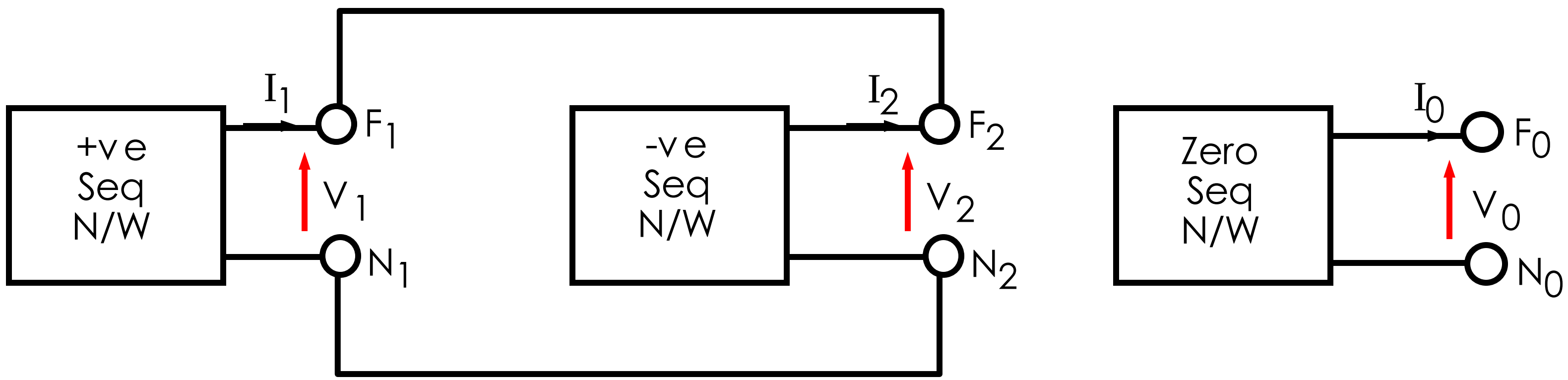
$$I_F = I_A = I_1 + I_2 + I_0 = 3I_0$$

$$= 2820 \text{ Amps}$$

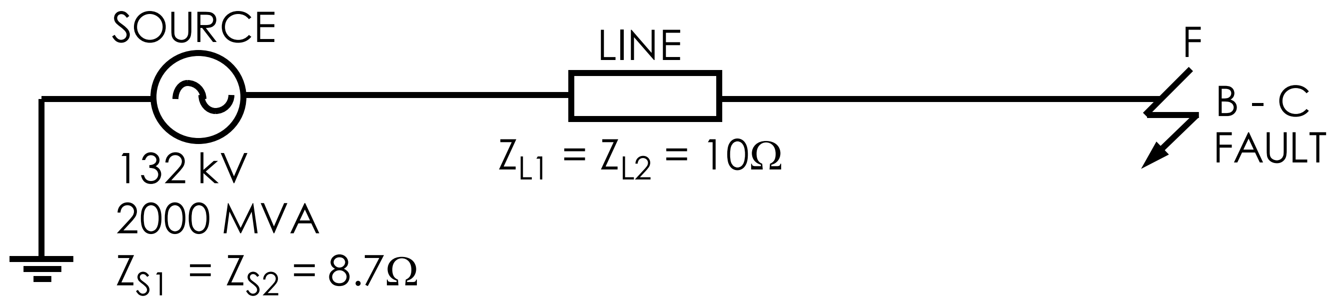
Earth Fault with Fault Resistance

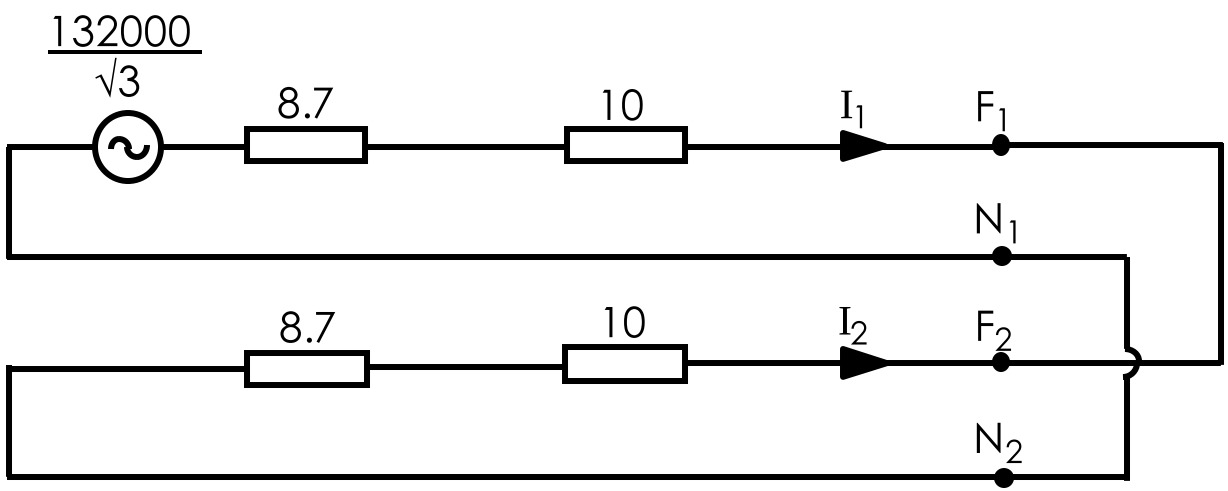


Phase to Phase Fault:- B-C Phase



Example : Phase to Phase Fault





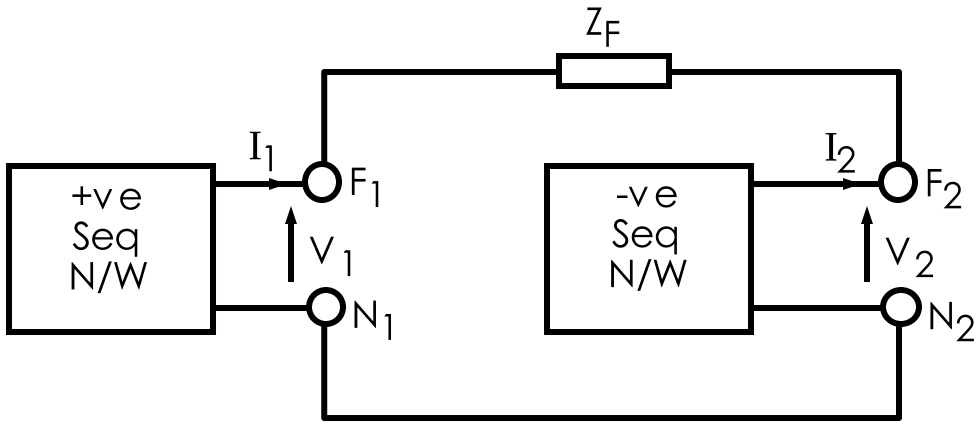
Total impedance = 37.4Ω

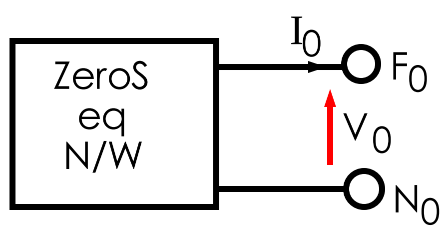
$$I_1 = \frac{132000}{\sqrt{3} \times 37.4} = 2037 \text{ Amps}$$

$$I_2 = -2037 \text{ Amps}$$

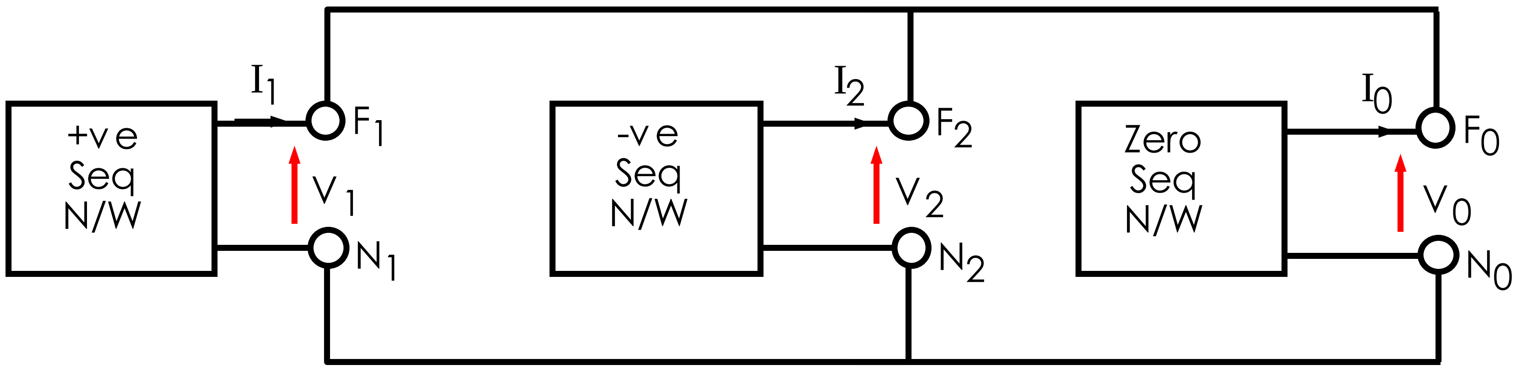
$$\begin{aligned} I_B &= a^2 I_1 + a I_2 \\ &= a^2 I_1 - a I_1 \\ &= (a^2 - a) I_1 \\ &= (-j) \cdot \sqrt{3} \times 2037 \\ &= 3529 \text{ Amps.} \end{aligned}$$

Phase to Phase Fault with Resistance

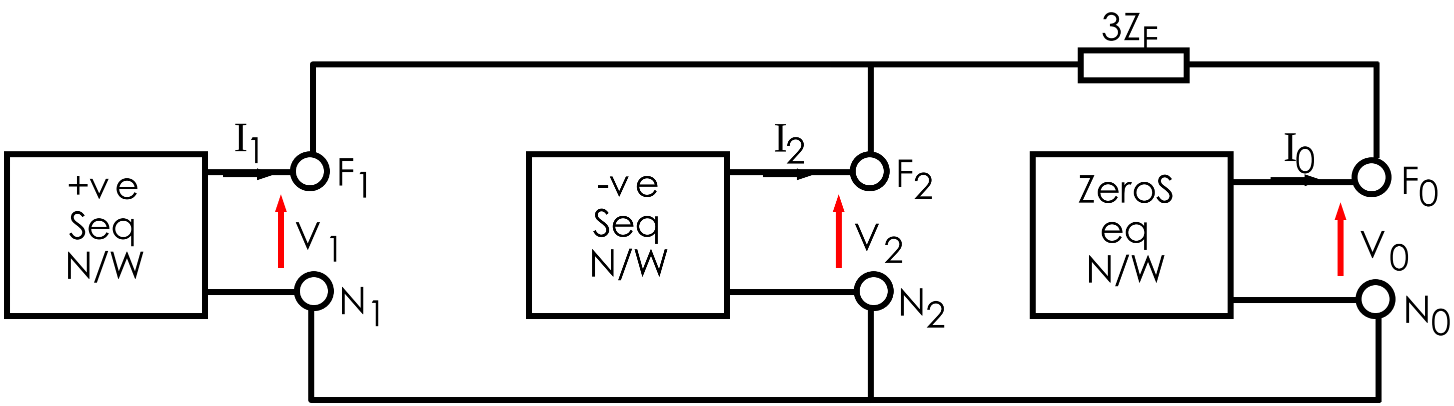




Phase to Phase to Earth Fault:- B-C-E



Phase to Phase to Earth Fault:- B-C-E with Resistance



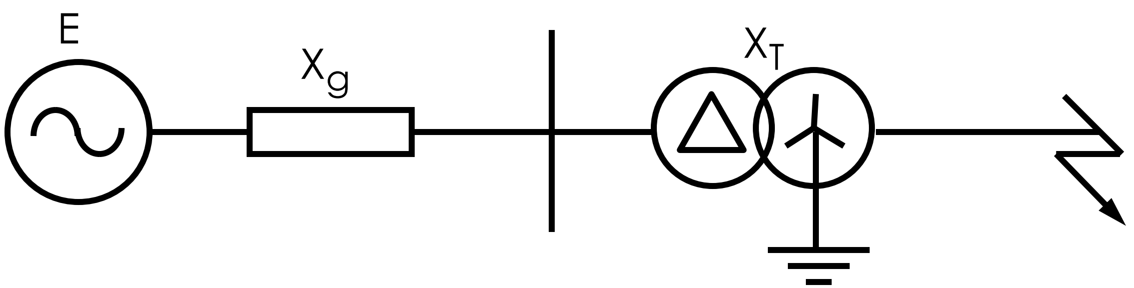
Maximum Fault Level

Single Phase Fault Level :

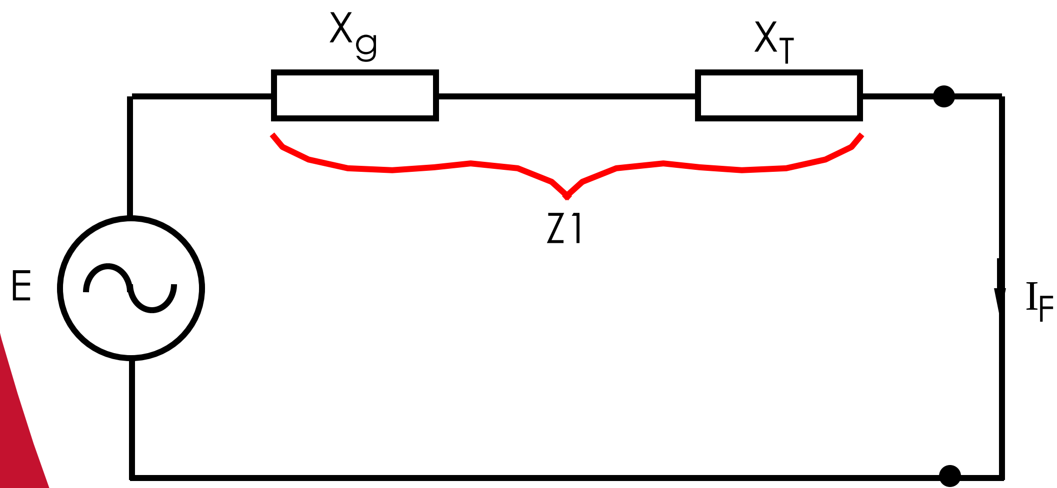
- **Can be higher than 3Φ fault level on solidly-earthed systems**

Check that switchgear breaking capacity > maximum fault level for all fault types.

3Ø Versus 1Ø Fault Level (1)

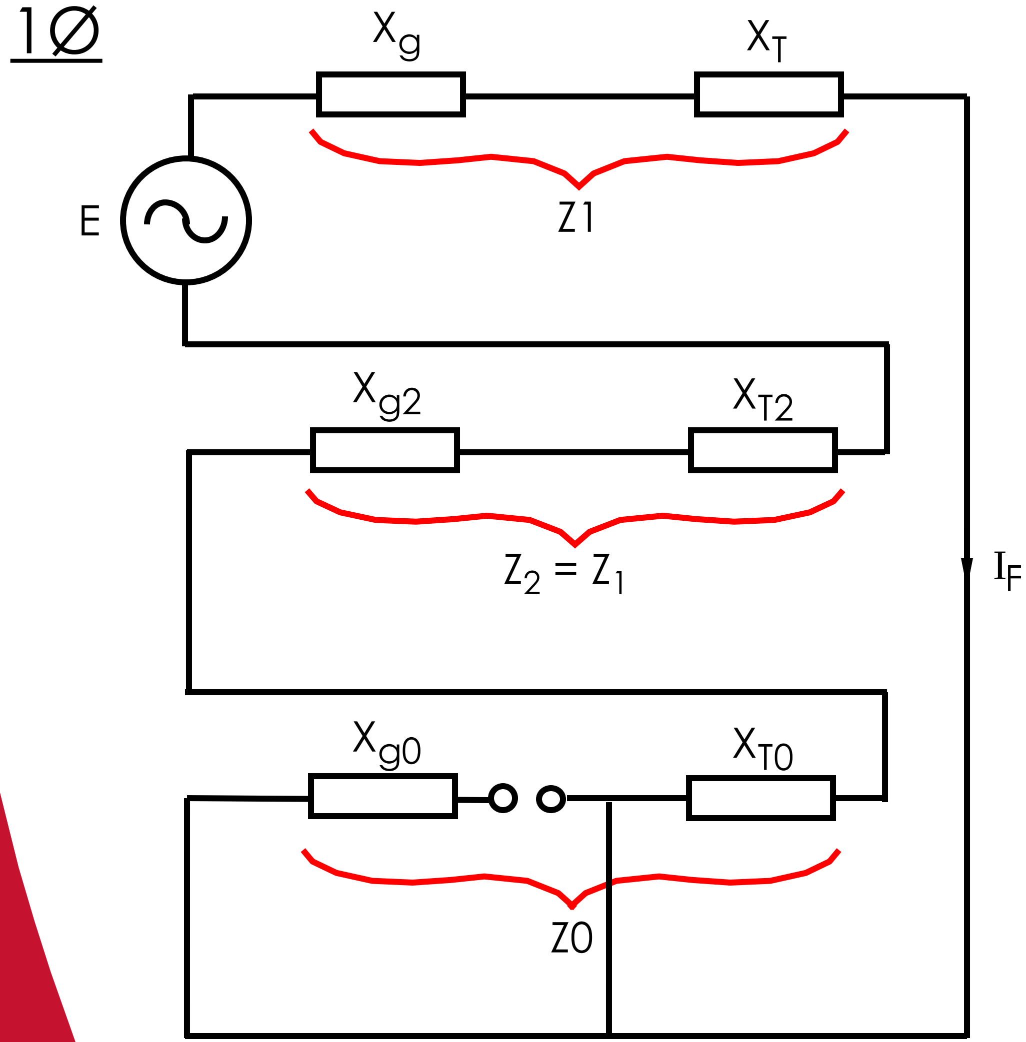


3Ø



$$I_F = \frac{E}{X_g + X_T} \equiv \frac{E}{Z_1}$$

3Ø Versus 1Ø Fault Level (2)



$$I_F = \frac{3E}{2Z_1 + Z_0}$$

3Ø Versus 1Ø Fault Level (3)

$$3\varnothing_{FAULTLEVEL} = \frac{E}{Z_1} = \frac{3E}{3Z_1} = \frac{3E}{2Z_1 + Z_1}$$

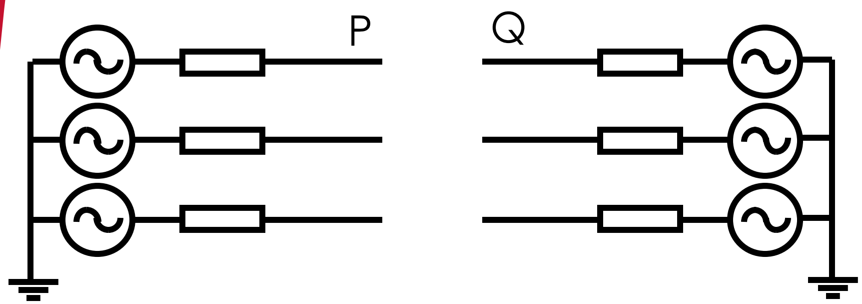
$$1\varnothing_{FAULTLEVEL} = \frac{3E}{2Z_1 + Z_0}$$

$$\therefore \text{ IF } Z_0 < Z_1$$

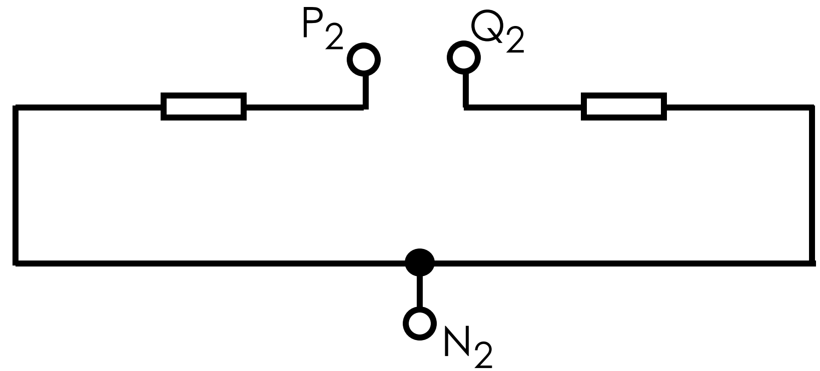
$$1\varnothing_{FAULTLEVEL} > 3\varnothing_{FAULTLEVEL}$$

Open Circuit & Double Faults

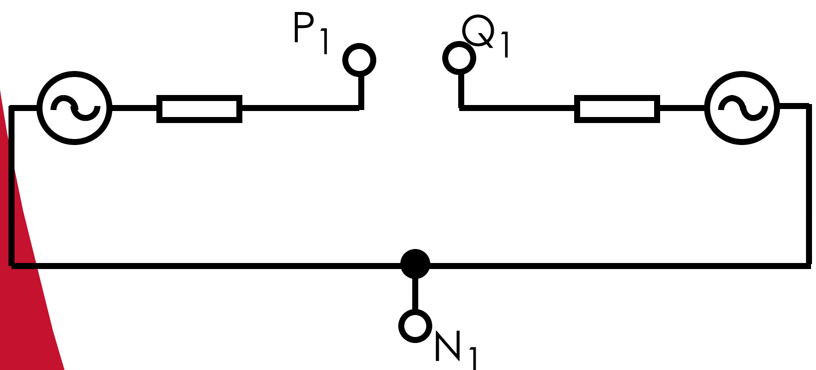
Series Faults (or Open Circuit Faults)



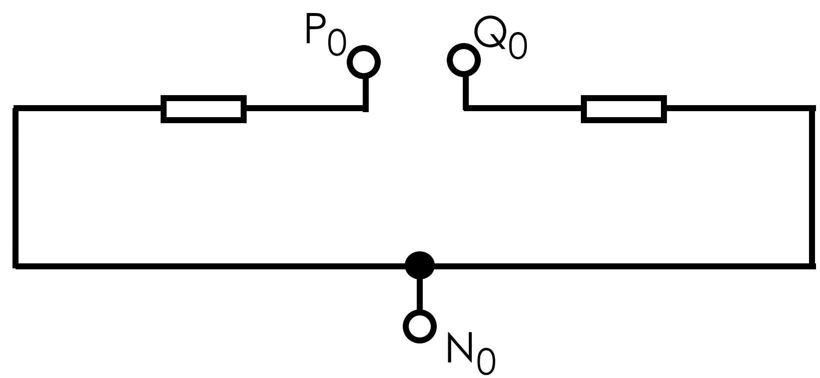
OPEN CIRCUIT FAULT ACROSS PQ



NEGATIVE SEQUENCE NETWORK



POSITIVE SEQUENCE NETWORK

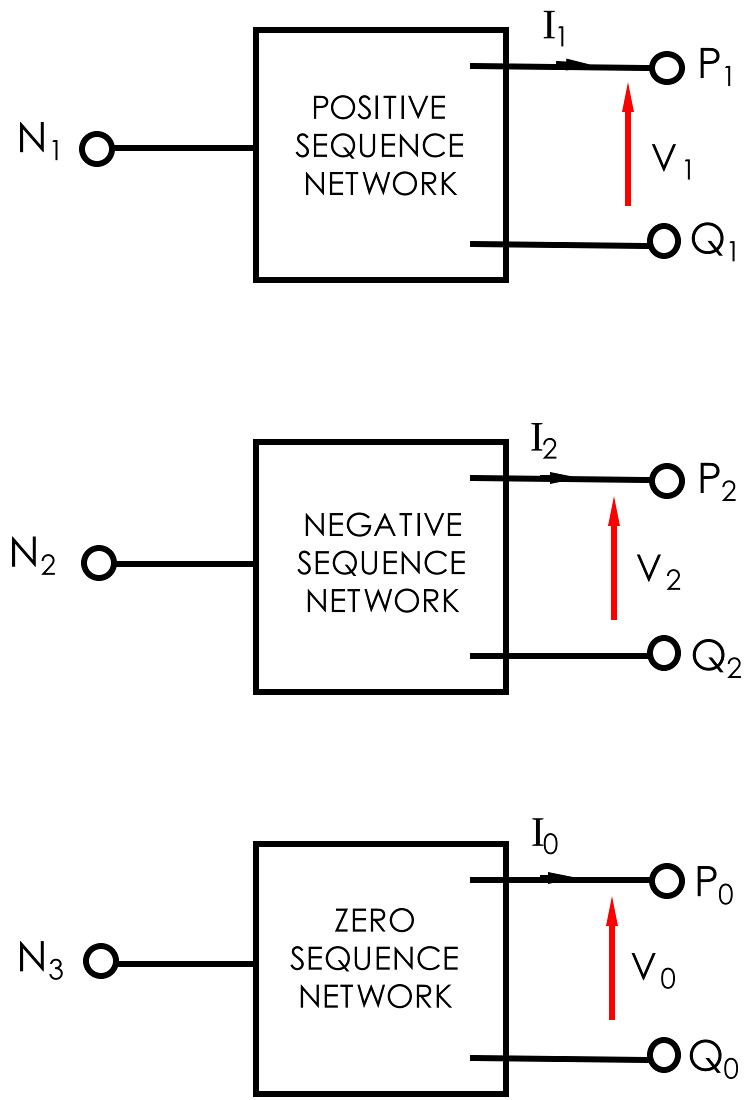


ZERO SEQUENCE NETWORK

Interconnection of Sequence Networks

Consider sequence networks as blocks with fault terminals P & Q for interconnections.

Unlike shunt faults, terminal N is not used for interconnections.

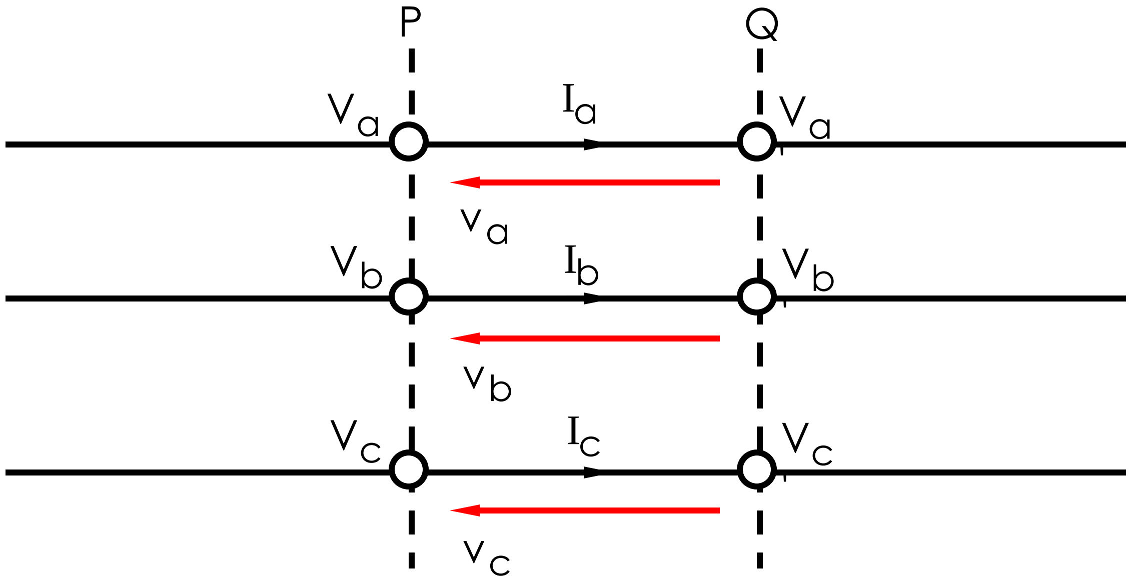


Derive System Constraints at the Fault Terminals

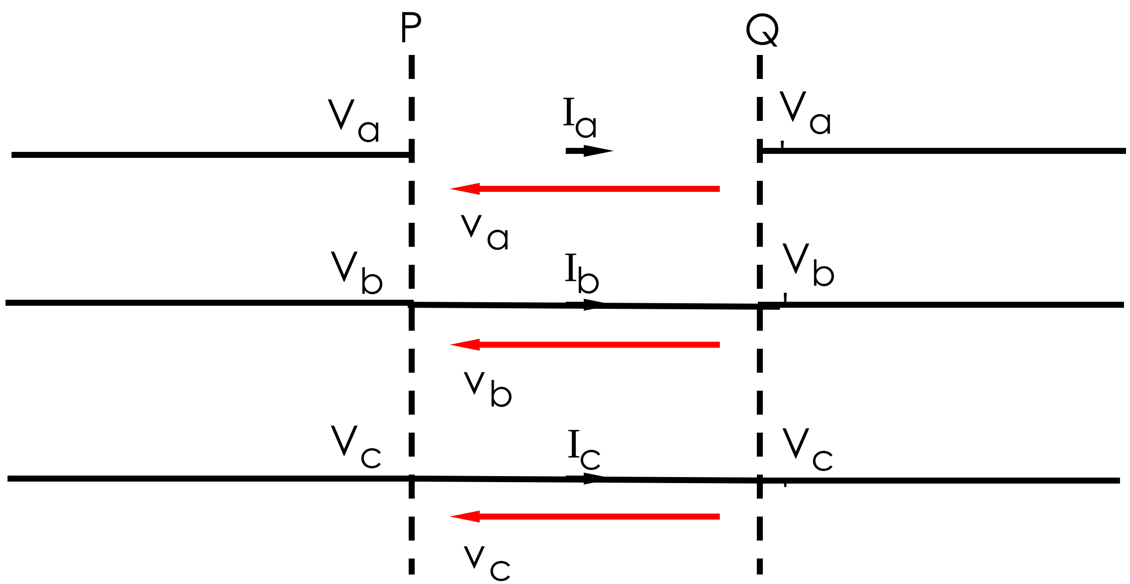
The terminal conditions imposed by different open circuit faults will be applied across points P & Q on the 3 line conductors.

Fault terminal currents I_a, I_b, I_c flow from P to Q.

Fault terminal potentials V_a, V_b, V_c will be across P and Q.



Open Circuit Fault On Phase A (1)



At fault point :-

$v_a = ?$

$v_b = 0$

$v_c = 0$

$I_a = 0$

$I_b = ?$

$I_c = ?$

Open Circuit Fault On Phase A (2)

At fault point

$v_b = 0 \; ; \; v_c = 0 \; ; \; I_a = 0$

$v_0 = 1/3\,(v_a + v_b + v_c) = 1/3\,v_a$

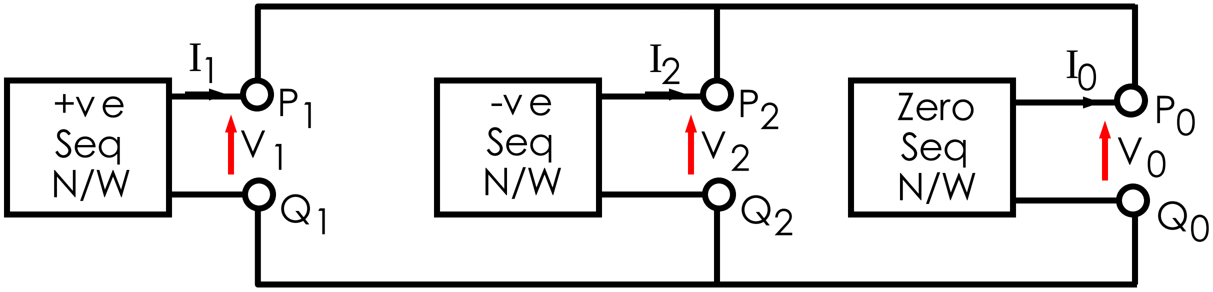
$v_1 = 1/3\,(v_a + \propto v_b + \propto^2 v_c) = 1/3\,v_a$

$v_2 = 1/3\,(v_a + \propto^2 v_b + \propto v_c) = 1/3\,v_a$

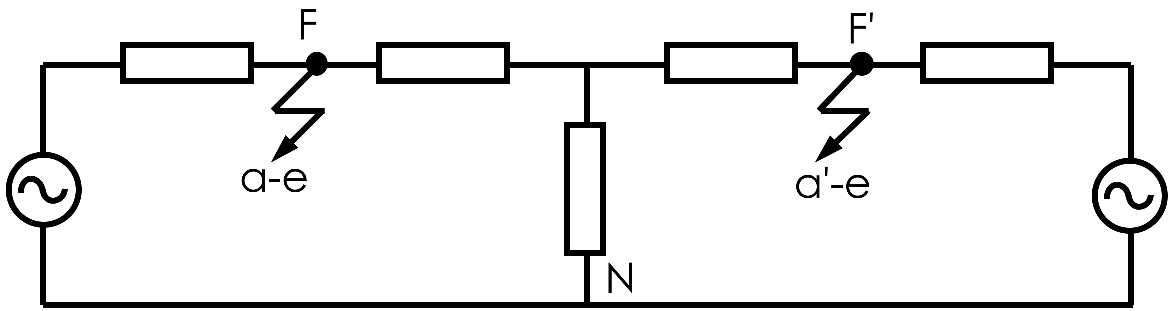
$\therefore \boxed{v_1 = v_2 = v_0 = 1/3\,v_a}$ --------------------- (1)

$I_a = I_1 + I_2 + \boxed{I_0 = 0}$ -------------------------- (2)

From equations (1) & (2) the sequence networks are connected in parallel.



Two Earth Faults on Phase 'A' at Different Locations



(1) At fault point F

$V_a = 0\ ;\ I_b = 0\ ;\ I_c = 0$

It can be shown that

$$I_{a1} = \boxed{= I_{a2} = I_{a0}}$$

$$V_{a1} + \boxed{V_{a2} + V_{a0} = 0}$$

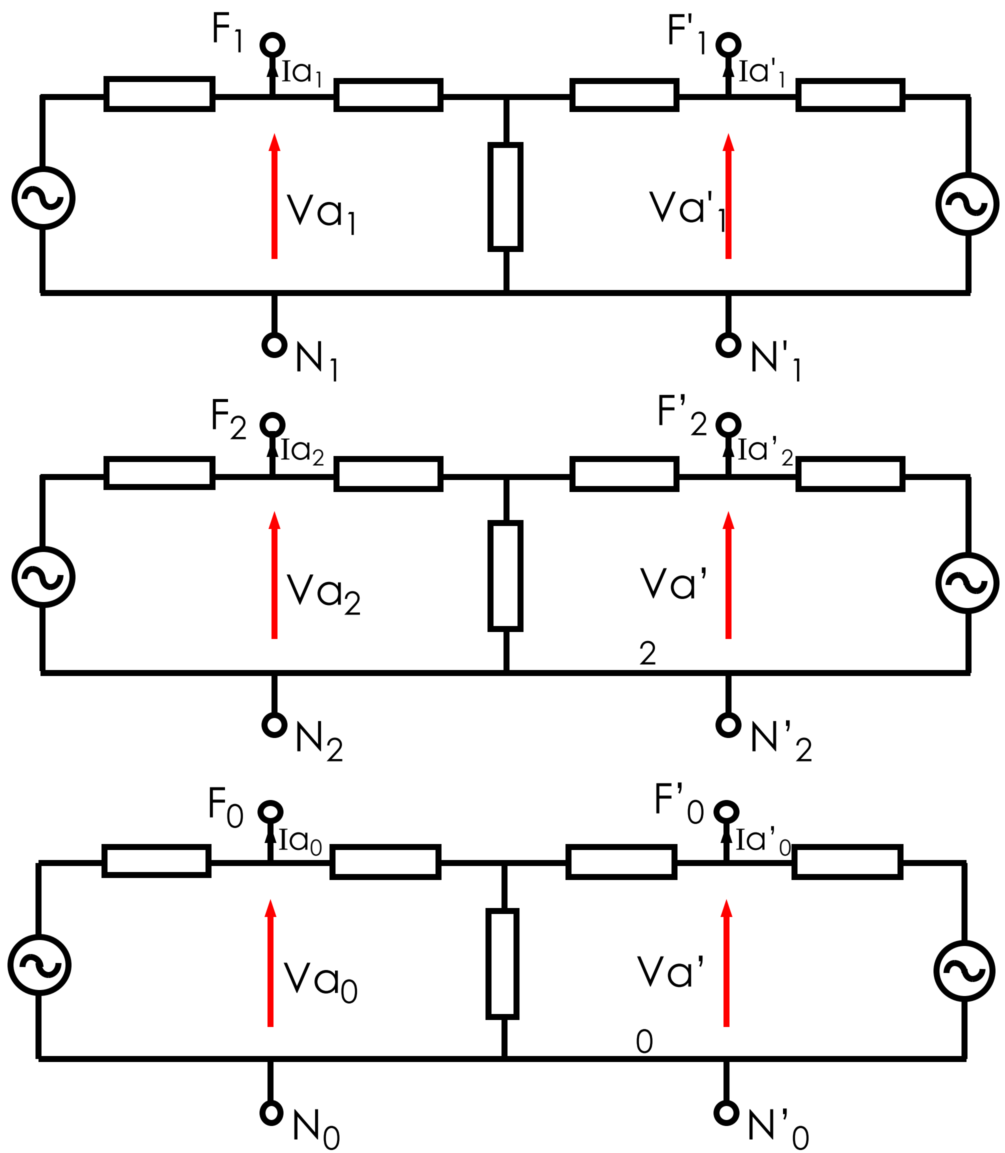
(2) At fault point F'

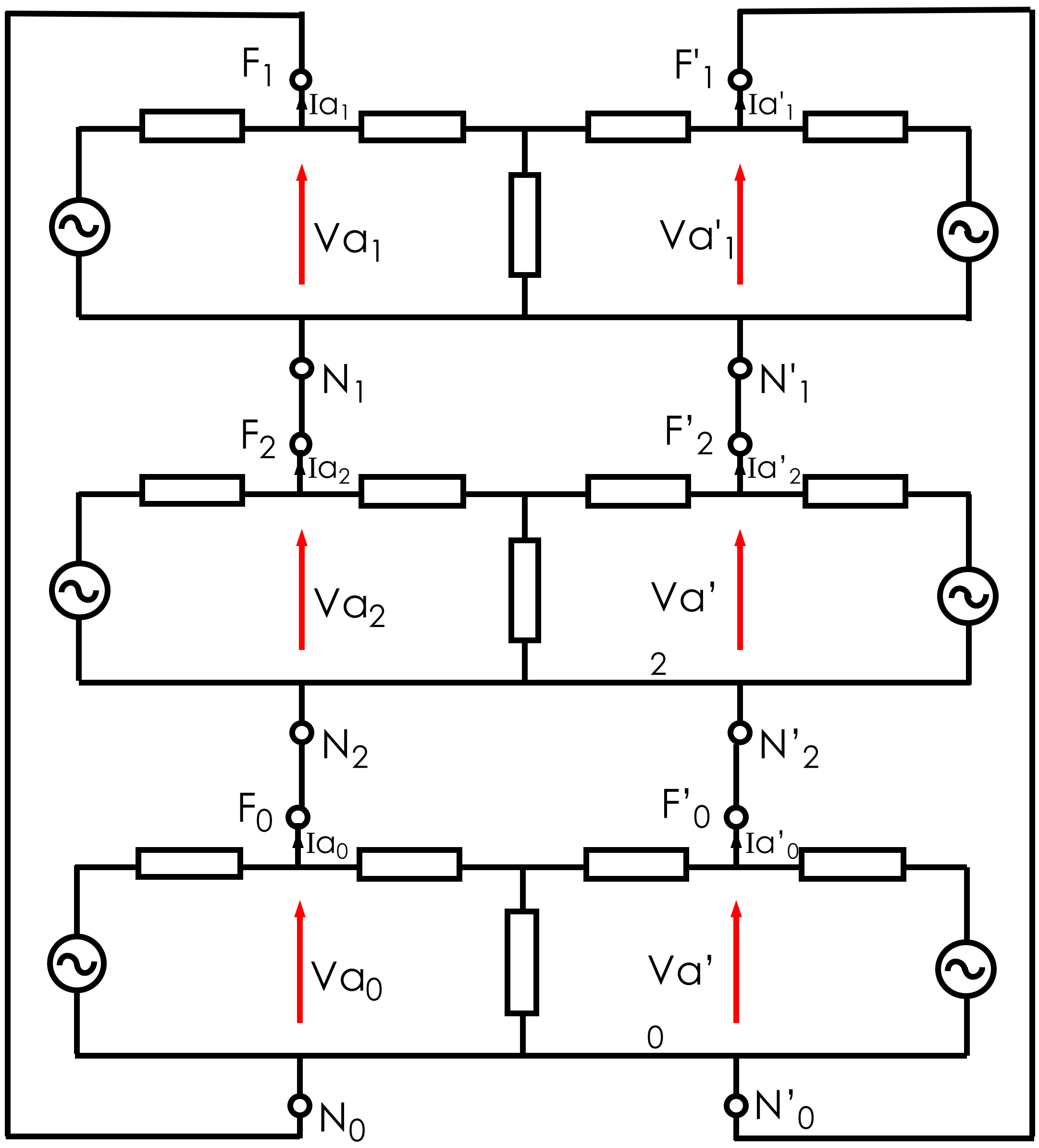
$V_a' = 0\ ;\ I_b' = 0\ ;\ I_c' = 0$

It can be shown that

$$I_a'_1 \boxed{= I_a'_2 = I_a'_0}$$

$$V_a'_1 + \boxed{V_a'_2 + V_a'_0 = 0}$$


F1
Ia1
F'1
Ia'1
Va1
Va'1
N1
N'1
F2
Ia2
F'2
Ia'2
Va2
Va'2
N2
N'2
F0
Ia0
F'0
Ia'0
Va0
Va'0
N0
N'0

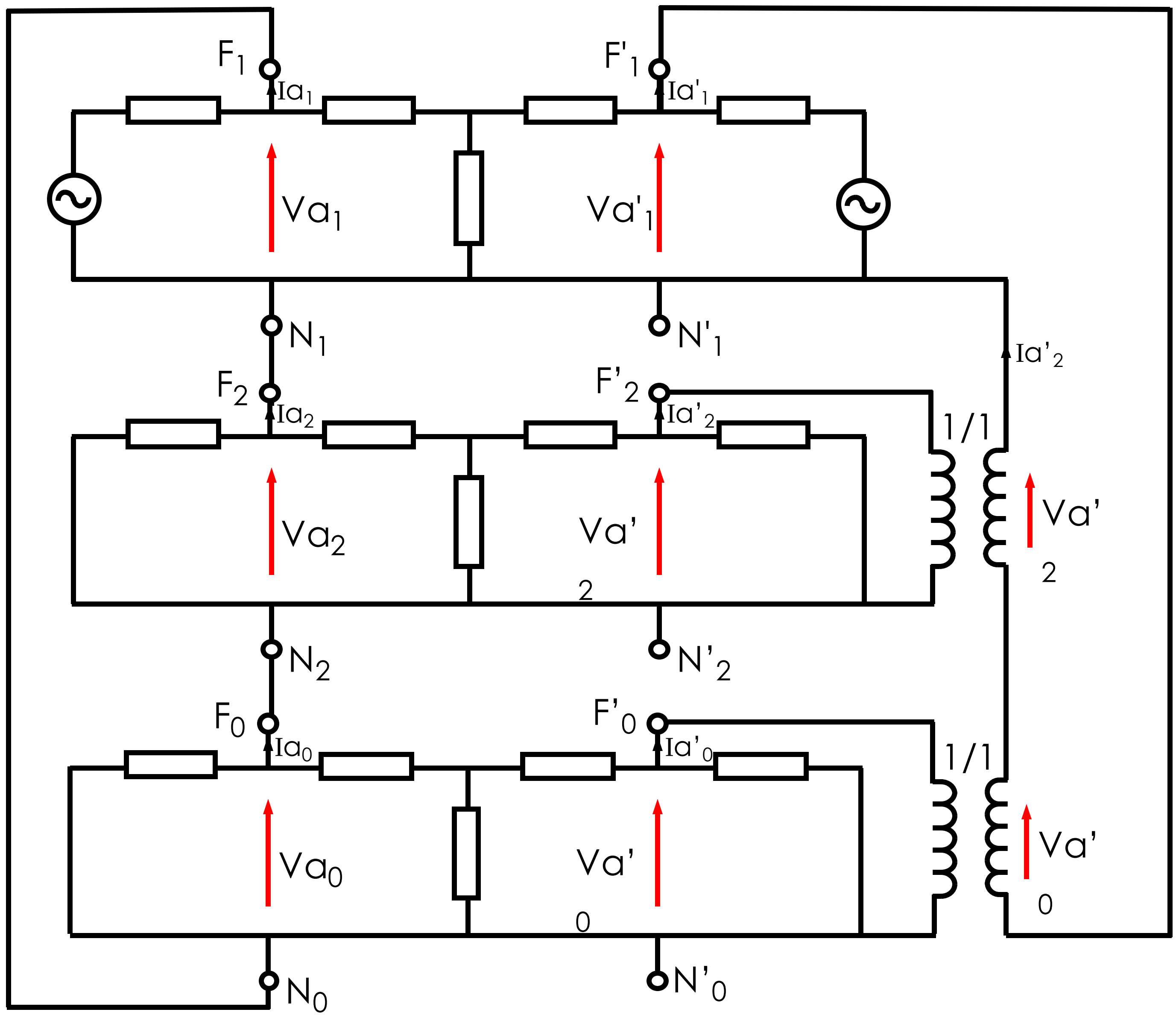


INCORRECT CONNECTIONS

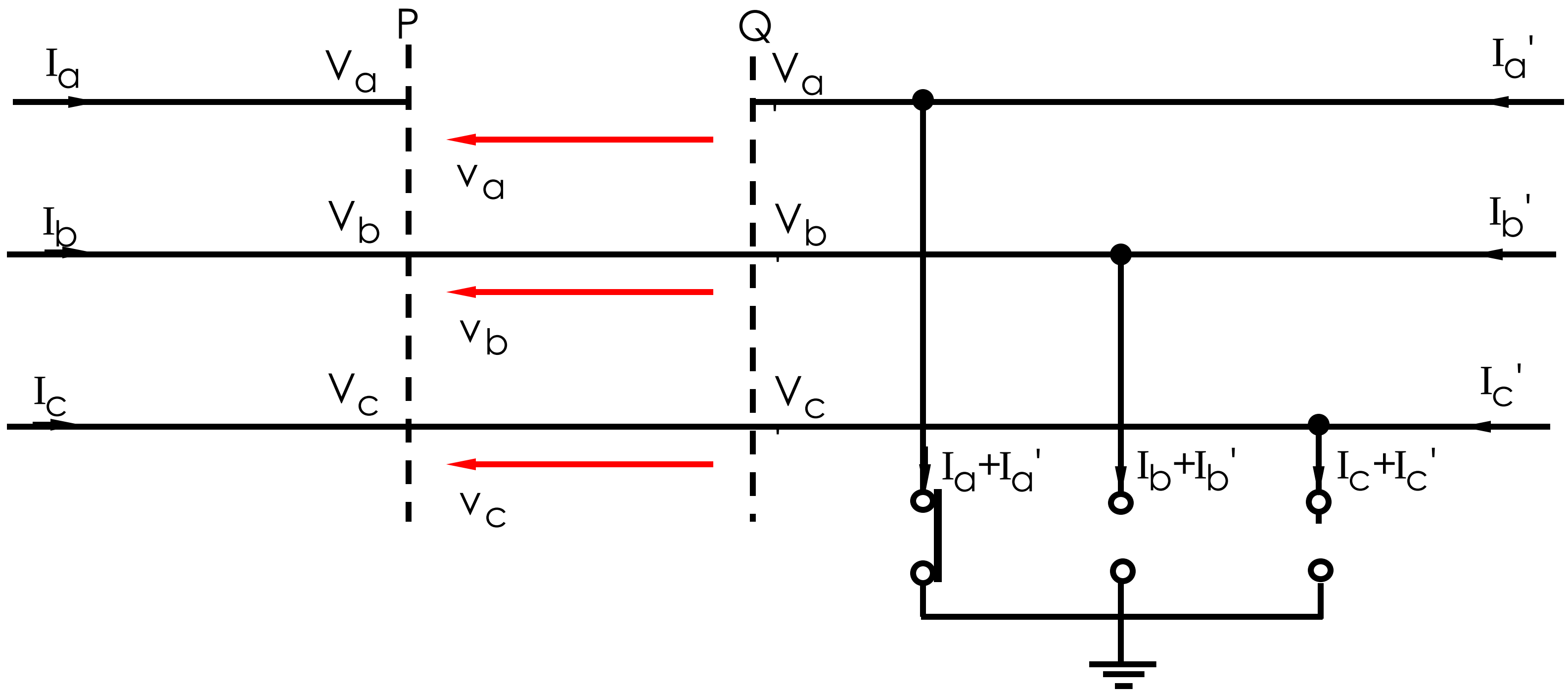
As :- $V_{a0} \neq V_{a0}'$

$V_{a2} \neq V_{a2}'$

$V_{a1} \neq V_{a1}'$

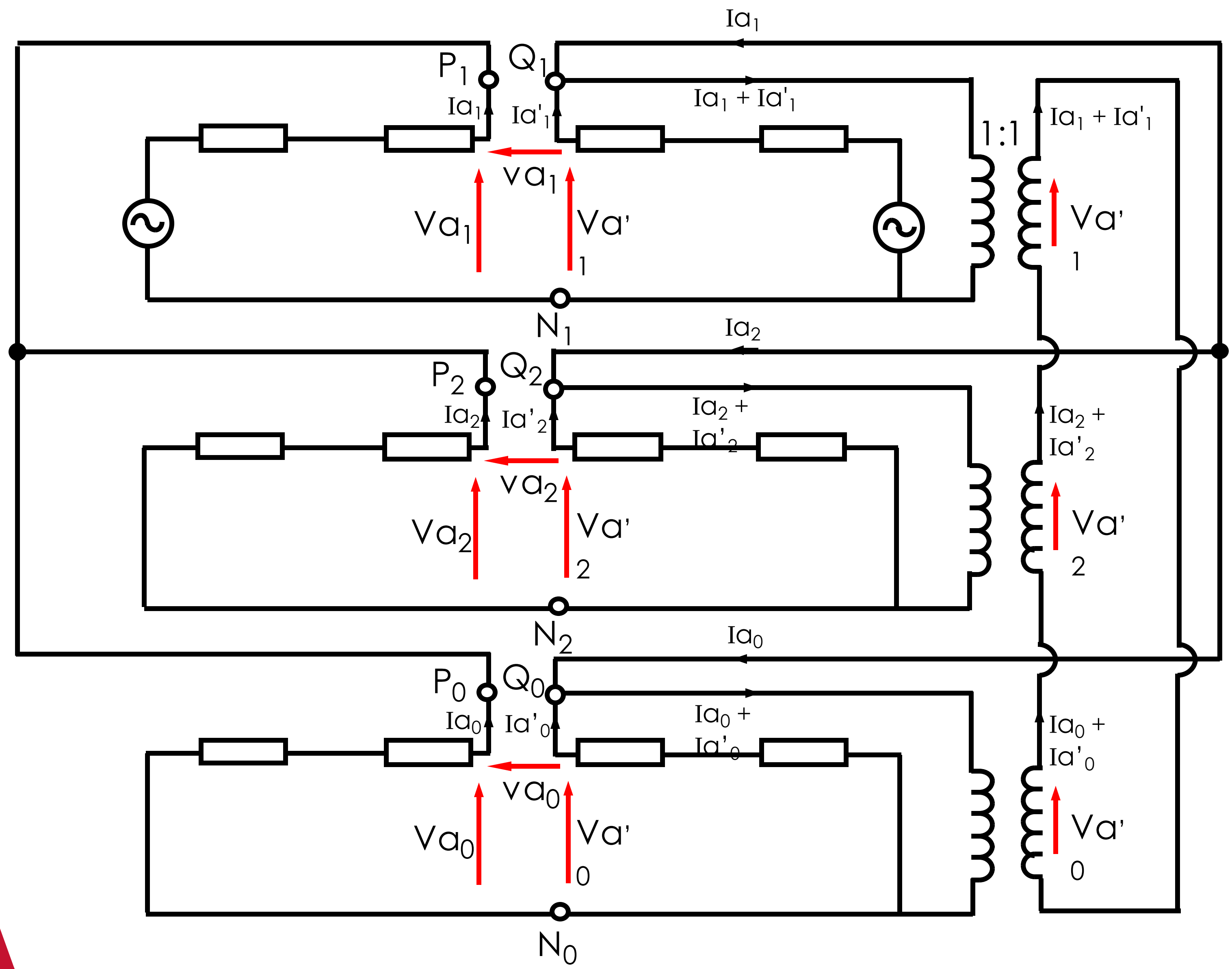

F1
Ia1
F'1
Ia'1
Va1
Va'1
N1
N'1
Ia'2
F2
Ia2
F'2
Ia'2
1/1
Va2
Va'
2
Va'
2
N2
N'2
F0
Ia0
F'0
Ia'0
1/1
Va0
Va'
0
Va'
0
N0
N'0

Open Circuit & Ground Fault



Open Circuit Fault	**At fault point :-**	
v_a	=	?
v_b	=	0
v_c	=	0
I_a	=	0
I_b	=	?
I_c	=	?

Line to Ground Fault	**At fault point :-**	
Va'	=	0
Vb'	=	?
Vc'	=	?
$I_a + I'_a$	=	?
$I_b + I'_b$	=	0
$I_c + I'_c$	=	0



Ia1
P1
Q1
Ia1 + Ia'1
Ia1
Ia'1
1:1
Ia1 + Ia'1
va1
Va1
Va'1
Va'1
N1
Ia2
P2
Q2
Ia2 + Ia'2
Ia2
Ia'2
Ia2 + Ia'2
va2
Va2
Va'2
Va'2
N2
Ia0
P0
Q0
Ia0 + Ia'0
Ia0
Ia'0
Ia0 + Ia'0
va0
Va0
Va'0
Va'0
N0

AREVA