FAULT FUNDAMENTALS

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Distribution Protection Track
Monday, August 4, 2025
Day 1 – Session 2

FAULT CALCULATION

- Nature of Short Circuit Currents
- Fault Types
- PU Normalization
- Symmetrical Components
- Example on a Power System Network
- Fault Contribution from DGs & IBRs

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IMPORTANCE OF SHORT CIRCUIT CALCULATIONS

Calculation of short circuit values is essential in Power system Analysis.
The results are used in a number of applications like:

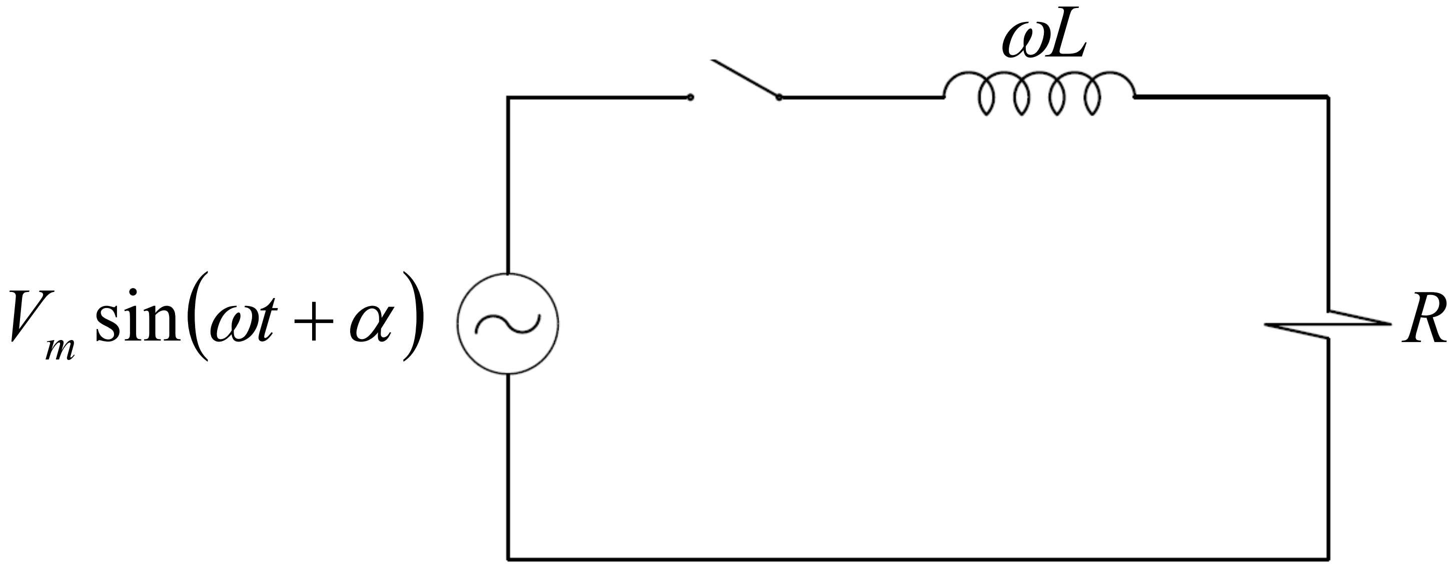
- Sizing of breakers and other elements
- Designing grounding grids
- Setting protective equipment
- Evaluating THD of harmonic currents
- Arc Flash Analysis

NATURE OF SHORT CIRCUIT CURRENTS

When calculating short circuit currents, it is necessary to take into account two factors which could result in the currents varying with time:

- The presence of the DC component
- The behavior of the generator under short circuit conditions

NATURE OF SHORT CIRCUIT CURRENTS



$$e(t) = L\frac{di(t)}{dt} + Ri(t)$$

NATURE OF SHORT CIRCUIT CURRENTS

The previous expression for the short circuit current is a differential equation, whose solution has two parts:

$$i(t) = i_h(t) + i_p(t)$$

Where:

$i_h(t)$ is the solution to the homogeneous equation corresponding to the transient period

$i_p\,(t)$ is the solution to the particular equation corresponding to the steady state period

NATURE OF SHORT CIRCUIT CURRENTS

By the use of differential equation theory, the complete solution can be expressed in the following form:

$$i(t) = \frac{V_m}{Z}\left[\sin(\omega t + \alpha - \theta) - \sin(\alpha - \theta)e^{-\left(\frac{R}{L}\right)t}\right]$$

$$Z = \sqrt{\left(R^2 + \omega^2 L^2\right)}$$

The first term varies sinusoidally and is called the AC component. The second term decreases exponentially and is called the DC component.

NATURE OF SHORT CIRCUIT CURRENTS

α is the closing angle which defines the point on which the fault occurs.

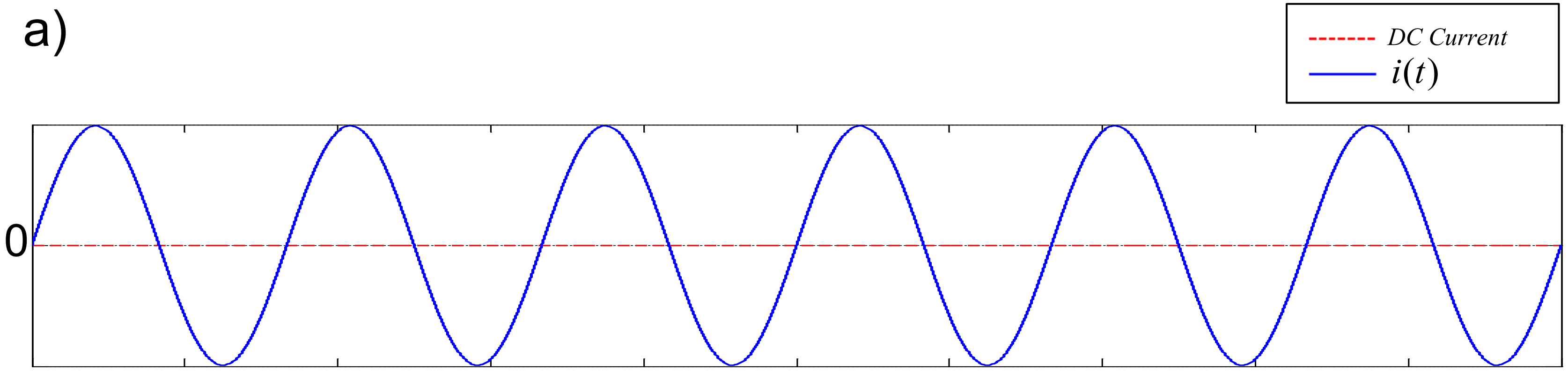
θ is defined as: $\tan^{-1}\left(\frac{\omega L}{R}\right)$

The effective value of the total asymmetric short circuit current can be obtained from the following expression:

$$I_{rms\ asym} = \sqrt{I_{rms}^{\ 2} + I_{DC}^{\ 2}}$$

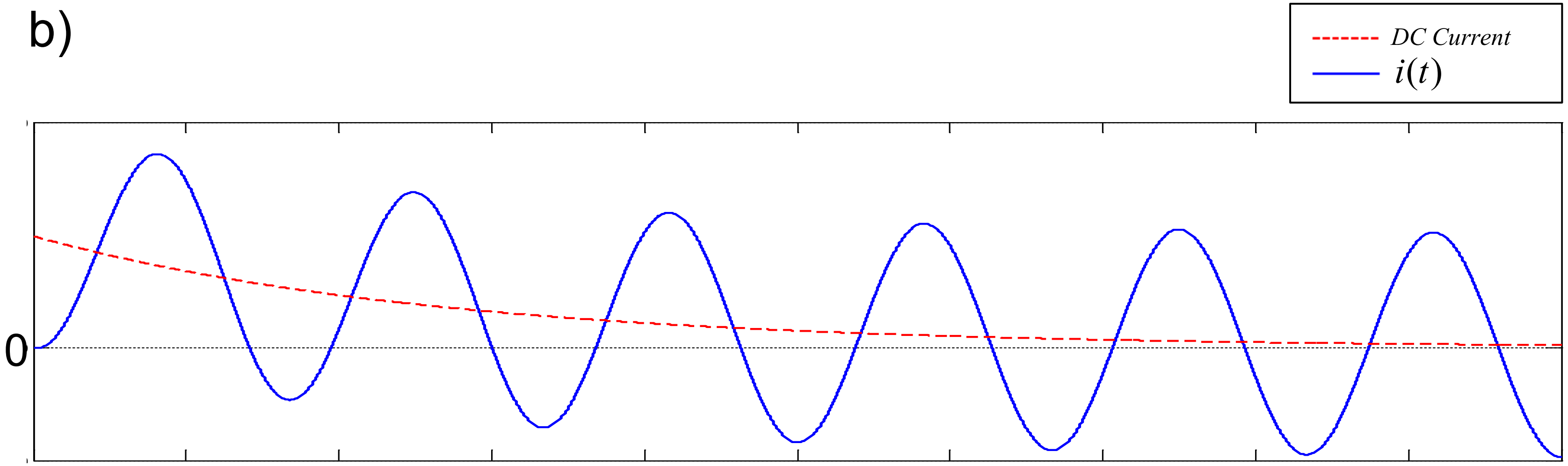
VARIATION OF FAULT CURRENT DUE TO THE DC COMPONENT

a)



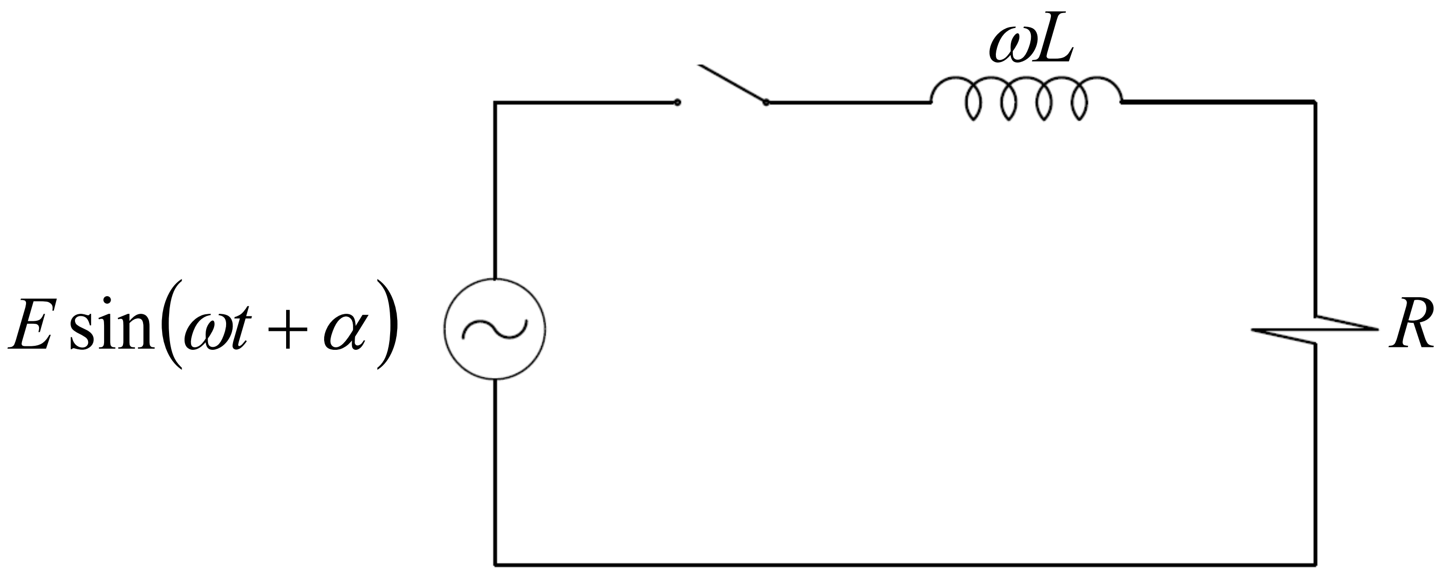
$$\alpha - \theta = 0$$

b)



$$\alpha - \theta = -\frac{\pi}{2}$$

EXAMPLE



$E = 7620$ V

$\omega = 377$ rad/s

$\alpha = 30° = 0.524$ rad

$R = 1.5$ Ohms

$L = 0.032$ H

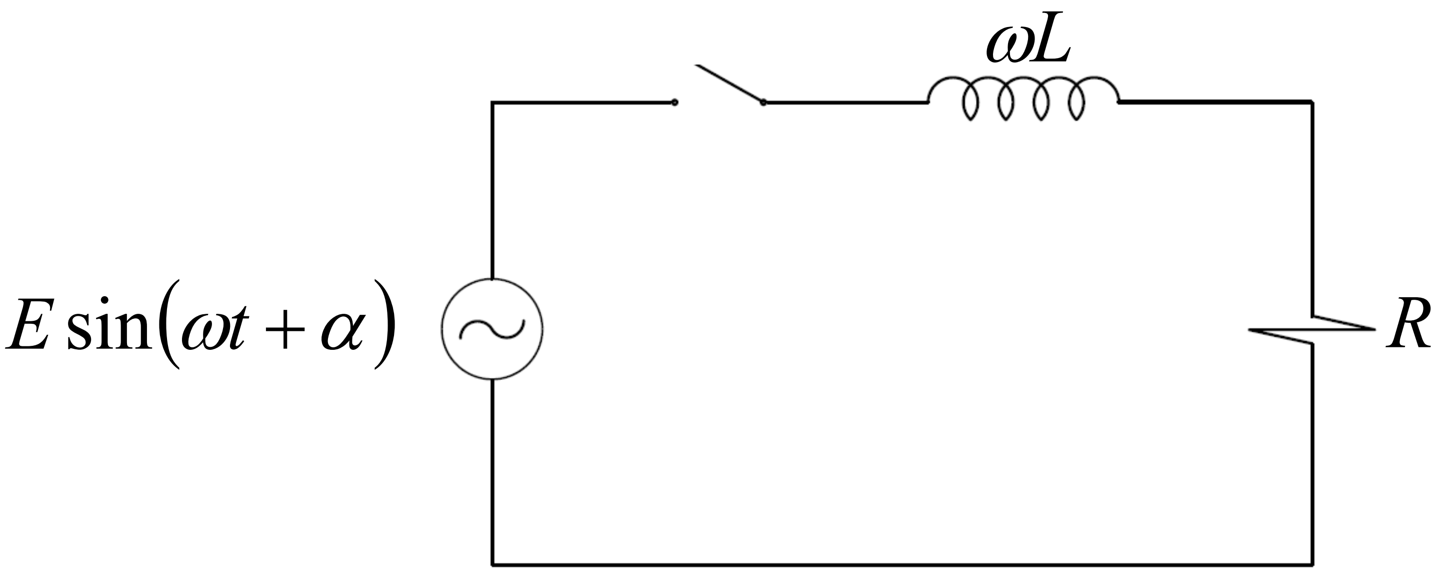
$\omega L = 12.064$ Ohms

$$\frac{\omega L}{R} = 8.043$$

$$|Z| = \sqrt{1.5^2 + 12.064^2}$$

$$\theta = \tan^{-1}(8.043) = 1.447$$

EXAMPLE



Substituting into equation of current short circuit:

$$i(t) = 626.8\sin(377t - 0.923) + 500e^{-46.86t}$$

NATURE OF SHORT CIRCUIT CURRENTS

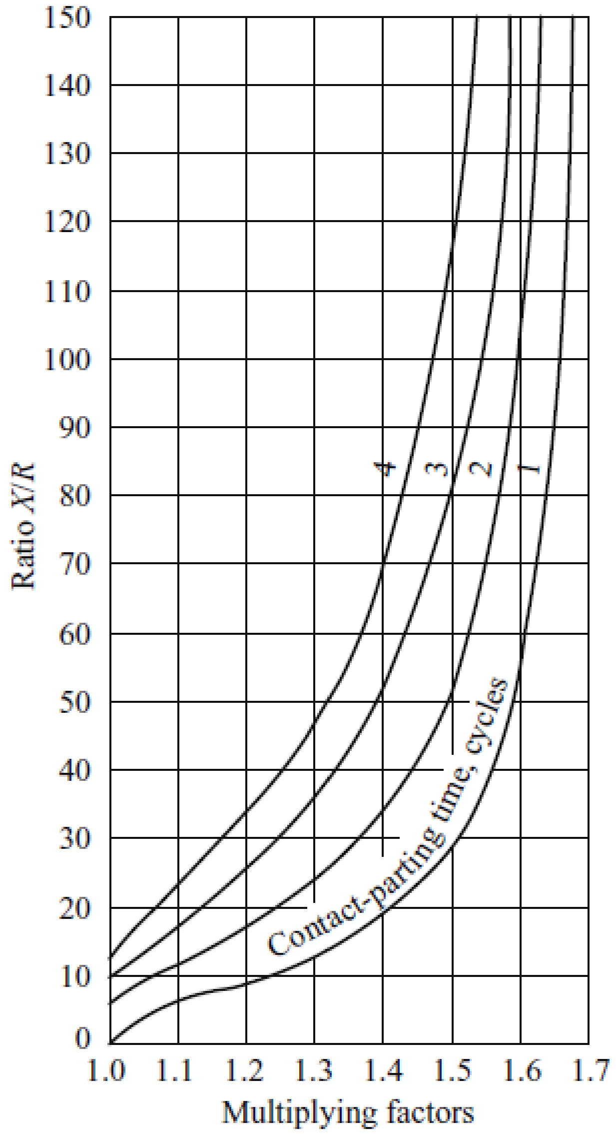
As an illustration of the validity of the curves for any situation, consider a circuit breaker with a total contact separation time of two cycles – one cycle due to the relay and one related to the operation of the circuit breaker mechanism.

If the frequency, *f*, is 60 Hz and the ratio *X*/*R* is given as 50, with *t* = 2 cycles = 0.033 s, then (*X/R*) = (*ωL/R*) = 50.

Thus (*L/R*) = (*50/ω*) = (*50/2f*) = 0.132. Therefore:

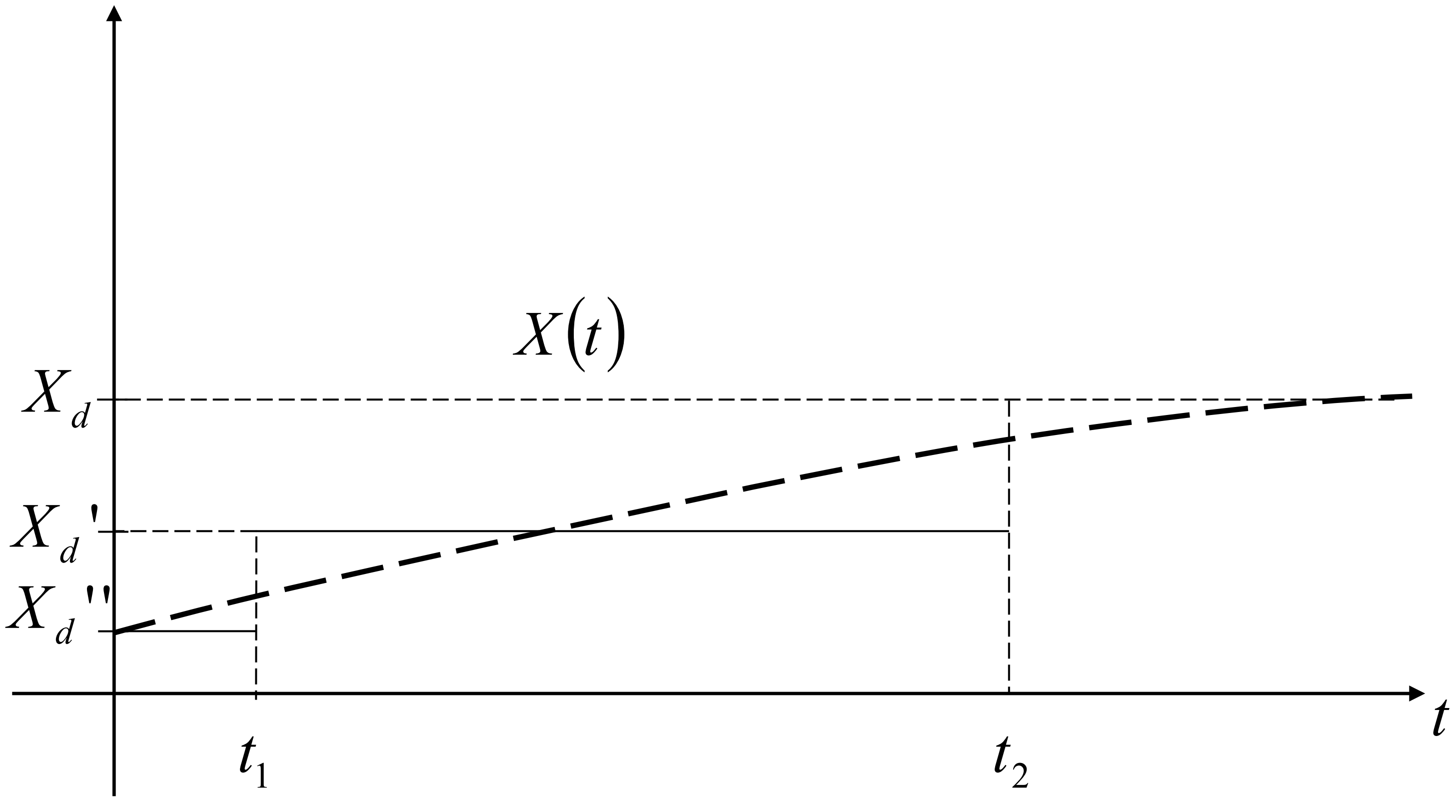
$$\frac{I_{asym}}{I_{sym}} = \sqrt{2e^{-2\left(\frac{R}{L}\right)t} + 1} = \sqrt{2e^{-2\left(\frac{0.033}{0.132}\right)} + 1} = 1.49$$

MULTIPLYING FACTORS

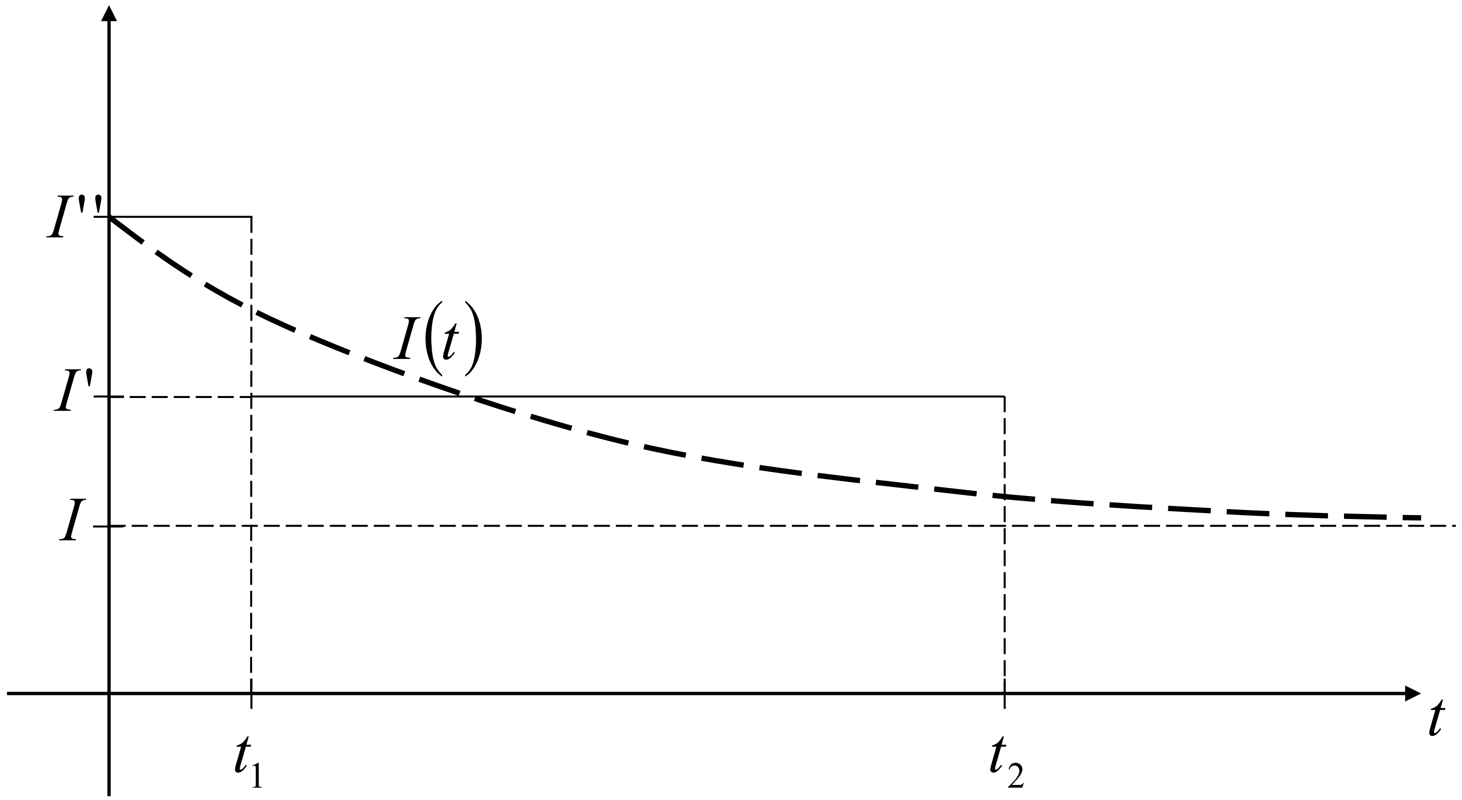


From IEEE Standard C37.5-1979; reproduced by permission of IEEE

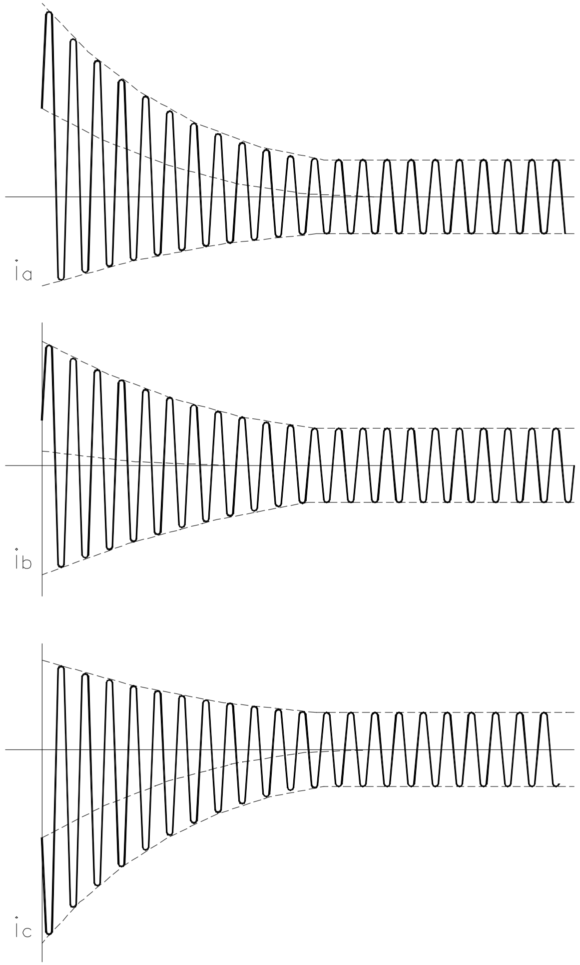
VARIATION OF GENERATOR REACTANCE DURING A FAULT



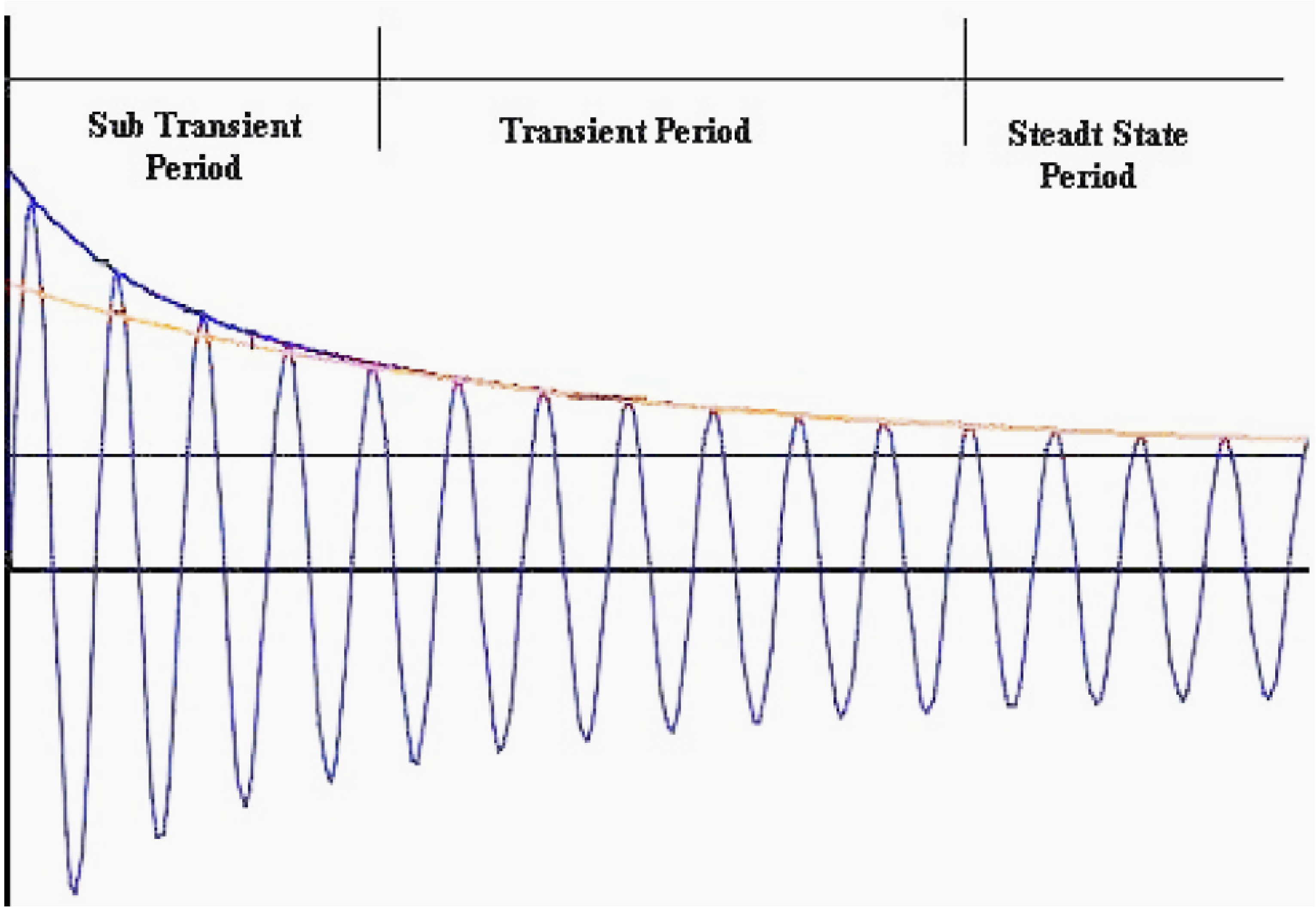
VARIATION OF GENERATOR CURRENT DURING A FAULT



TRANSIENT SC CURRENT AT GENERATOR TERMINALS



SYNCHRONOUS GENERATOR SHORT CIRCUIT CURRENT CONTRIBUTION



SYNCHRONOUS GENERATOR SHORT CIRCUIT CURRENT CONTRIBUTION

Reactance	Description	Symbol	Range per-unit	Period
Sub-transient reactance	Determines maximum instantaneous current and current at time Molded Case Circuit Breaker usually open	Xd˝	0.09 – 0.17	0 – 6 Cycles
Transient Reactance	Determines current at short time delay of circuit breakers	Xd´	0.13 – 0.20	6 cycles to 5 sec.
Synchronous reactance	Determine steady state current together with AVR	Xd	1.7 – 3.3	After 5 sec.
Zero sequence reactance	A factor in L-N short circuit current	X0	0.06 – 0.09	
Negative sequence reactance	A factor in single-phase short circuit current	X2	0.10 – 0.22	

ROTATING MACHINE REACTANCES

Subtransient reactances for use in fault current determination according to : IEEE Std C37.010™-2016

Type of rotating machine	Positive sequence reactances for calculating: Interrupting duty (per unit)	Positive sequence reactances for calculating: Closing and latching duty (per unit)
All turbo generators, all hydro-generators with am-ortisseur windings, and all condensers[a]	1.0 $X''d$	1.0 $X''d$
Hydro generators without amortisseur windings[a]	0.75 $X'd$	0.75 $X'd$
All synchronous motors[b,d,e]	1.5 $X''d$	1.0 $X''d$
Induction motors[c,d,e] Above 750 kW (1000 hp) at 1800 r/min or less Above 185 kW (250 hp) at 3600 r/min From 37.5 kW (50 hp) to 750 kW (1000 hp) at 1800 r/min or less From 37.5 kW (50 hp) to 185 kW (250 hp) at 3600 r/min	1.5 $X''d$ 3.0 $X''d$	1.0 $X''d$ 1.2 $X''d$
NOTE—Neglect all three-phase induction motors below 37.5kW (50 hp) and all single-phase motors.		

Source: IEEE Std C37.010™-2016

FAULT TYPES

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FAULT TYPES

Symmetrical or Faults

Three phase

Three phase to ground

Unsymmetrical Faults

Phase to ground

Phase to phase

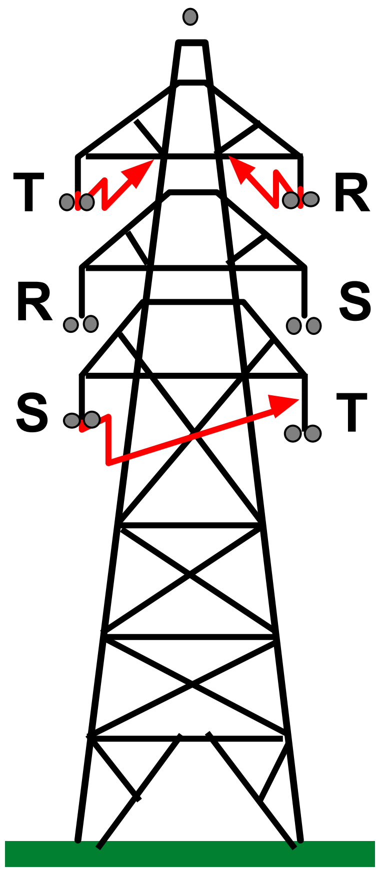
Phase to phase to ground

- Special faults: open conductor, faults between 2 voltage levels

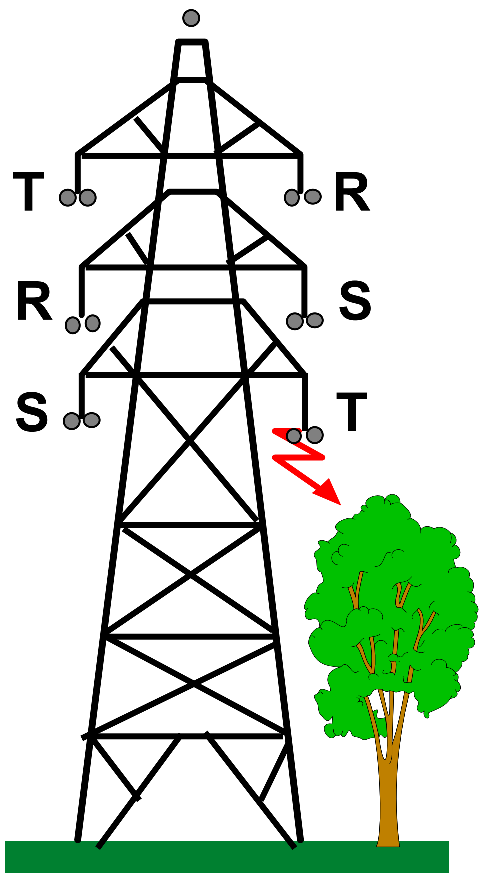
Calculation methods

- Standard ANSI/IEEE C37.10
- Standard IEC 909
- Superposition method from load flow calculation

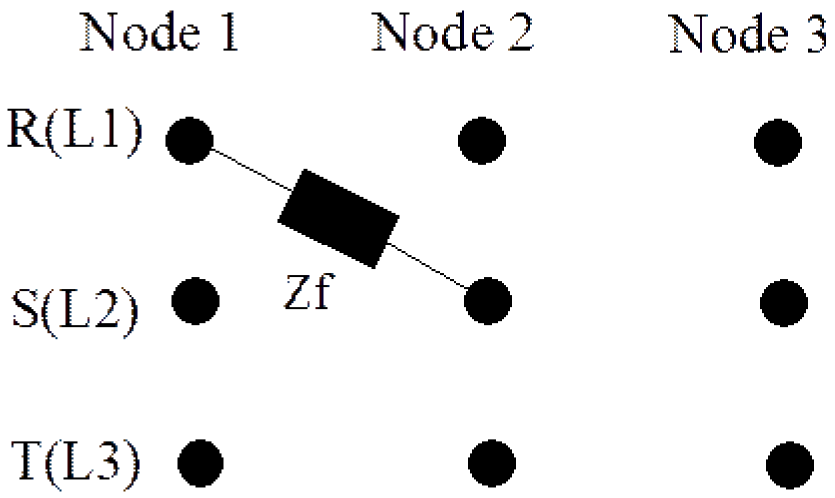
DEFINITION OF SPECIAL FAULTS



- Fault definition in phase system
- Any kind of fault definition possible (e.g. SC between different voltage levels)
- Connection of 3 definable nodes by fault impedances Zf



Special FAULTS (Fault between 2 phases)



1-L1 -> 2-L2 : Zf = 3.0 Ohm

TERMINOLOGY

ANSI	*English*	*IEC*
$I^1/_2c$	Subtransient short-circuit current/ Have cycle current	Ik”
$AI^1/_2c$	Angle of $I^1/_2c$	AIk”
$I^1/_2ctot$ = 1.6x $I^1/_2c$	Momentary Current	doesn’t exist
Icres = 2.7x $I^1/_2c$	Peak current	Ip
Iint	Interruption current	Ib
I30c	Steady state current	Ik
IDC	DC current component	IDC
Iint as	Asymmetrical interruption current	Iasy

PER UNIT NORMALIZATION

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PU NORMALIZATION

In power system calculations a normalization of variables called per unit normalization is almost always used. It is especially convenient if many transformers and voltage levels are involved.

The idea is to pick base values for quantities such as voltages, currents, impedances, power and so on, and to define the quantity in per unit as follows.

$$quantity\ in\ per\ unit = \frac{actual\ quantity}{base\ value\ of\ quantity}$$

PU NORMALIZATION

A vital points is that the base variables are picked to satisfy the same kind of relationship as the variables. For example, corresponding to the equation between actual variables (complex numbers),

$$V = Z \cdot I \qquad (1)$$

We have the equation for base quantities (real numbers),

$$V_B = Z_B \cdot I_B \qquad (2)$$

Dividing (1) by (2), we get

$$\frac{V}{V_B} = \frac{Z \cdot I}{Z_B \cdot I_B} \qquad (3)$$

PU NORMALIZATION

OR

$$V_{p.u} = Z_{p.u} \cdot I_{p.u}$$

Equation (3) has the same form as (2), which implies that we can do circuit analysis using (3) exactly as with (2). The p.u. subscript indicates per unit and is read "per unit".

What we have done for Ohm's law can also be done in the case of power calculations. For example, corresponding to

$$S = V \cdot I^* \qquad (4)$$

We have

$$S_B = V_B \cdot I_B \qquad (5)$$

And

$$S_{p.u} = V_{p.u} \cdot I^*_{p.u} \qquad (6)$$

PU NORMALIZATION

CHANGE OF BASE

With several items of equipment, with different ratings, it is not usually possible to pick base values so that they are always the same as the nameplate ratings. It is the necessary to recalculate the per unit values on the new basis. The key idea is that Z_{pu} depends on Z_B but, of course, Z_{actual} does not. We note the relationship between old and new values:

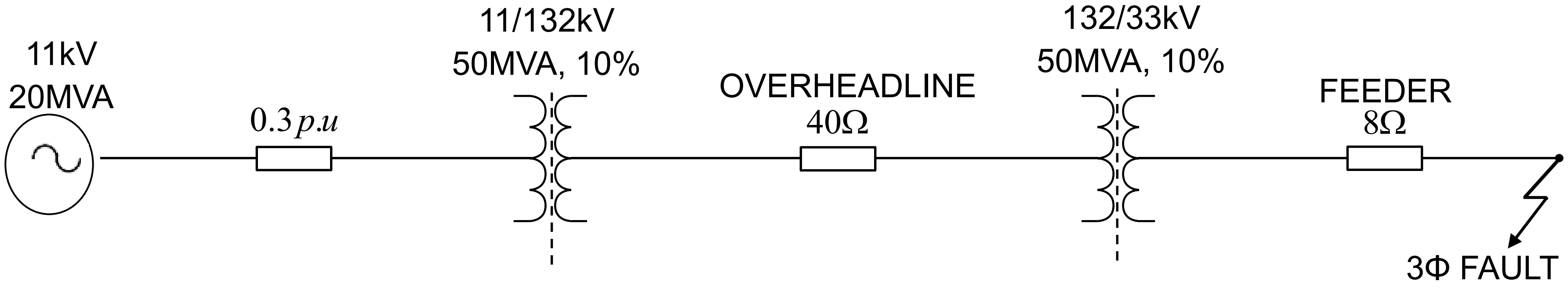
$$Z_{actual} = Z_{p.u}^{old} \cdot Z_B^{old} = Z_{p.u}^{new} \cdot Z_B^{new} \tag{7}$$

Then

$$\begin{aligned} Z_{p.u}^{new} &= Z_{p.u}^{old} \cdot \frac{Z_B^{old}}{Z_B^{new}} \\ &= Z_{p.u}^{old} \cdot \left[\frac{V_B^{old}}{V_B^{new}}\right]^2 \cdot \frac{S_B^{new}}{S_B^{old}} \end{aligned} \tag{8}$$

Note: In applying (8), we can substitute three-phase and/or line-line values.

EXAMPLE



At the Generator

Base kV_B = 11
Base MVA_B = 50

$$Z_B = \frac{(11kV)^2}{50MVA} = 2.42\Omega$$

$$I_B = \frac{50MVA}{\sqrt{3} \cdot 11kV} = 2624A$$

$Z_{GENp.u}$ on common base

$$Z_{GENp.u} = 0.3 \cdot \frac{50MVA}{20MVA} = 0.75\,p.u$$

At the Transf.

Base kV_B = 11
Base MVA_B = 50

$$0.1\,p.u$$

At the Line

Base kV_B = 132
Base MVA_B = 50

$$Z_B = \frac{(132kV)^2}{50MVA} = 348.5\Omega$$

$$I_B = \frac{50MVA}{\sqrt{3} \cdot 132kV} = 218.7A$$

$$Z_{OHLp.u} = \frac{40\Omega}{348.5\Omega} = 0.115\,p.u$$

At the Transf.

Base kV_B = 33
Base MVA_B = 50

$$0.1\,p.u$$

At the Feeder

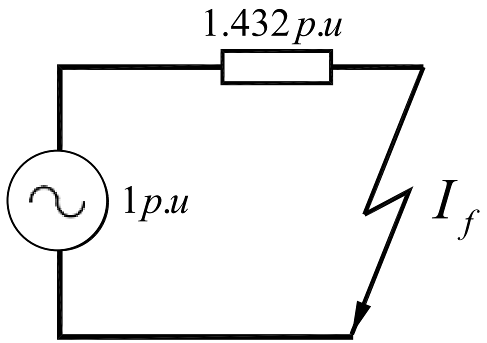
Base kV_B = 33
Base MVA_B = 50

$$Z_B = \frac{(33kV)^2}{50MVA} = 21.78\Omega$$

$$I_B = \frac{50MVA}{\sqrt{3} \cdot 33kV} = 874.77A$$

$$Z_{FEEDERp.u} = \frac{8\Omega}{21.78\Omega} = 0.367\,p.u$$

EXAMPLE



$$I_f = \frac{1}{1.432} = 0.698\,p.u$$

$$\therefore I_{11kV} = 0.698\,p.u \cdot 2624\,A = 1831.55\,A$$

$$I_{132kV} = 0.698\,p.u \cdot 218.7\,A = 152.65\,A$$

$$I_{33kV} = 0.698\,p.u \cdot 874.77\,A = 610.6\,A$$

SYMMETRICAL COMPONENTS

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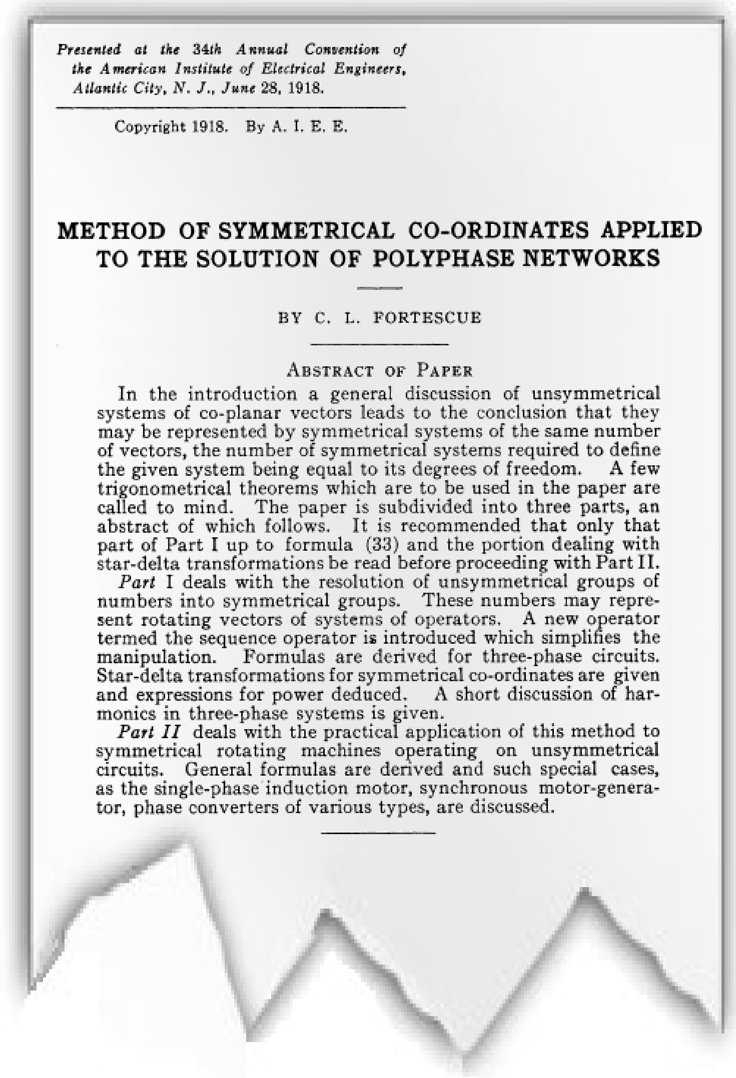
INTRODUCTION TO SYMMETRICAL COMPONENTS

On June 28, 1918, **Mr. Charles L. Fortescue** presented at the 34th Annual Convention of the AIEE, in Atlantic City, N.J. a very famous paper entitled “Method of Symmetrical Co-ordinates Applied to the Solution of Polyphase Networks”.

This method allowed the representation of any unbalanced system with n phases, into n systems of balanced networks. The method was later called Symmetrical Components.

The main use of this method was of course in the analysis of unbalanced three phase systems.


Presented at the 34th Annual Convention of the American Institute of Electrical Engineers, Atlantic City, N. J., June 28, 1918.

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METHOD OF SYMMETRICAL CO-ORDINATES APPLIED TO THE SOLUTION OF POLYPHASE NETWORKS

BY C. L. FORTESCUE

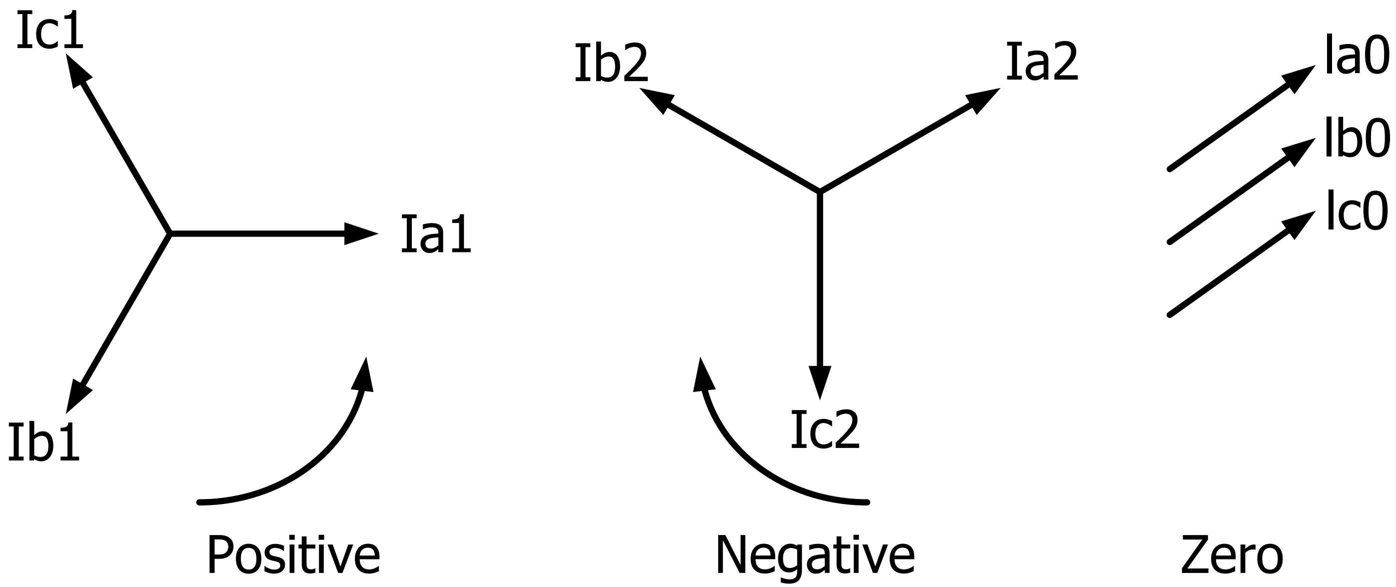
ABSTRACT OF PAPER

In the introduction a general discussion of unsymmetrical systems of co-planar vectors leads to the conclusion that they may be represented by symmetrical systems of the same number of vectors, the number of symmetrical systems required to define the given system being equal to its degrees of freedom. A few trigonometrical theorems which are to be used in the paper are called to mind. The paper is subdivided into three parts, an abstract of which follows. It is recommended that only that part of Part I up to formula (33) and the portion dealing with star-delta transformations be read before proceeding with Part II.

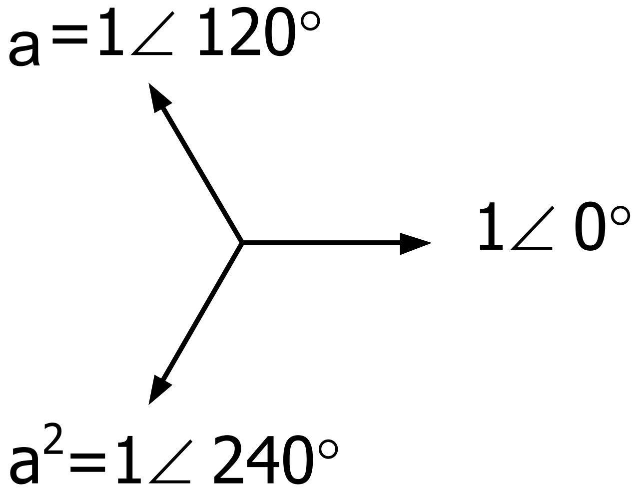
Part I deals with the resolution of unsymmetrical groups of numbers into symmetrical groups. These numbers may represent rotating vectors of systems of operators. A new operator termed the sequence operator is introduced which simplifies the manipulation. Formulas are derived for three-phase circuits. Star-delta transformations for symmetrical co-ordinates are given and expressions for power deduced. A short discussion of harmonics in three-phase systems is given.

Part II deals with the practical application of this method to symmetrical rotating machines operating on unsymmetrical circuits. General formulas are derived and such special cases, as the single-phase induction motor, synchronous motor-generator, phase converters of various types, are discussed.

SYMMETRICAL COMPONENTS - SEQUENCE COMPONENTS



SYMMETRICAL COMPONENTS – "a" OPERATOR



$$I_{b1}=1_{a1}\angle 240 = a^2 I_{a1}$$

$$I_{c1}=1_{a1}\angle 120 = aI_{a1}$$

SYMMETRICAL COMPONENTS - NETWORK EQUATIONS

Current values of any three phase system, Ia, Ib, and Ic, can be represented as:

$$I_a = I_{a0} + I_{a1} + I_{a2}$$
$$I_b = I_{b0} + I_{b1} + I_{b2}$$
$$I_c = I_{c0} + I_{c1} + I_{c2}$$

Replacing the sequence component values, the following equations obtained:

$$I_a = I_{a0} + I_{a1} + I_{a2}$$
$$I_b = I_{a0} + a^2 I_{a1} + a I_{a2}$$
$$I_c = I_{a0} + a I_{a1} + a^2 I_{a2}$$

SYMMETRICAL COMPONENTS - NETWORK EQUATIONS

Therefore, the following matrix relationship can be established:

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \cdot \begin{bmatrix} I_{a0} \\ I_{a1} \\ I_{a2} \end{bmatrix}$$

Inverting the matrix of coefficients:

$$\begin{bmatrix} I_{a0} \\ I_{a1} \\ I_{a2} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \cdot \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}$$

SYMMETRICAL COMPONENTS - NETWORK EQUATIONS

Voltage values of any three phase system, Va, Vb, and Vc, can be represented as:

$$V_a = V_{a0} + V_{a1} + V_{a2}$$
$$V_b = V_{b0} + V_{b1} + V_{b2}$$
$$V_c = V_{c0} + V_{c1} + V_{c2}$$

Replacing the sequence component values, the following equations obtained:

$$V_a = V_{a0} + V_{a1} + V_{a2}$$
$$V_b = V_{a0} + a^2 V_{a1} + a V_{a2}$$
$$V_c = V_{a0} + a V_{a1} + a^2 V_{a2}$$

SYMMETRICAL COMPONENTS - NETWORK EQUATIONS

Therefore, the following matrix relationship can be established:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \cdot \begin{bmatrix} V_{a0} \\ V_{a1} \\ V_{a2} \end{bmatrix}$$

Inverting the matrix of coefficients:

$$\begin{bmatrix} V_{a0} \\ V_{a1} \\ V_{a2} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \cdot \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}$$

SYMMETRICAL COMPONENTS - NETWORK EQUATIONS

From the above matrix it can be deduced that:

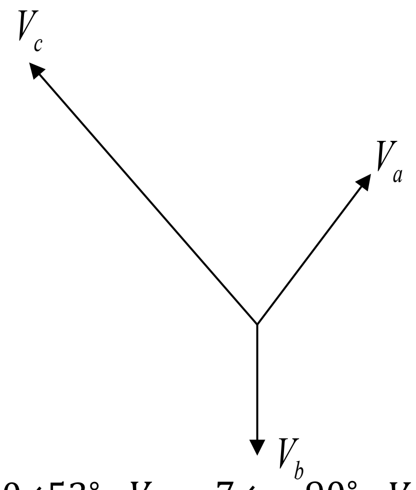
$$V_{a0} = \frac{1}{3}\left(V_a + V_b + V_c\right)$$

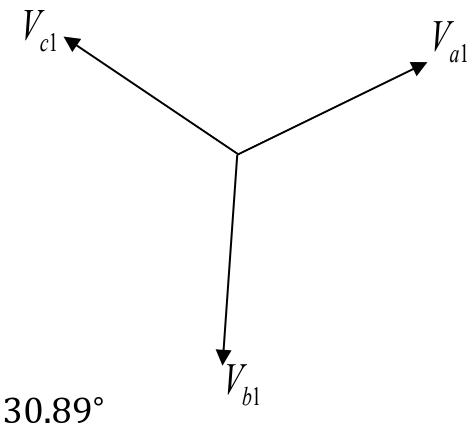
$$V_{a1} = \frac{1}{3}\left(V_a + aV_b + a^2V_c\right)$$

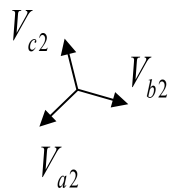
$$V_{a2} = \frac{1}{3}\left(V_a + a^2V_b + aV_c\right)$$

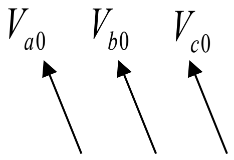
In three phase systems the neutral voltage is equal to $V_n = (V_{a0} + V_{b0} + V_{c0})$ and, therefore, $V_n = 3\ V_{a0}$.

ILLUSTRATION ON AN UNBALANCED SYSTEM

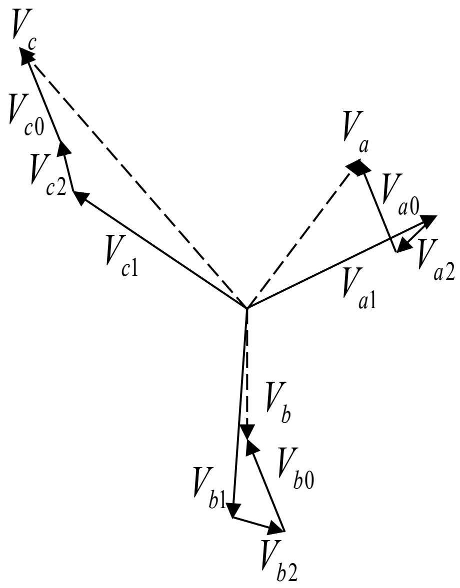








$V_a = 10\angle 53°$ $V_b = 7\angle -90°$ $V_c = 18.33\angle 130.89°$



$V_{a1} = 11.197\angle 26.43°$ $V_{a2} = 2.8\angle -136.02°$ $V_{a0} = 5.334\angle 111.95°$

$V_{b1} = 11.197\angle -93.57°$ $V_{b2} = 2.8\angle -16.02°$ $V_{b0} = 5.334\angle 111.95°$

$V_{c1} = 11.197\angle 146.43°$ $V_{c2} = 2.8\angle 103.98°$ $V_{c0} = 5.334\angle 111.95°$

ILLUSTRATION ON AN UNBALANCED SYSTEM WITH VOLTAGE INJECTIONS

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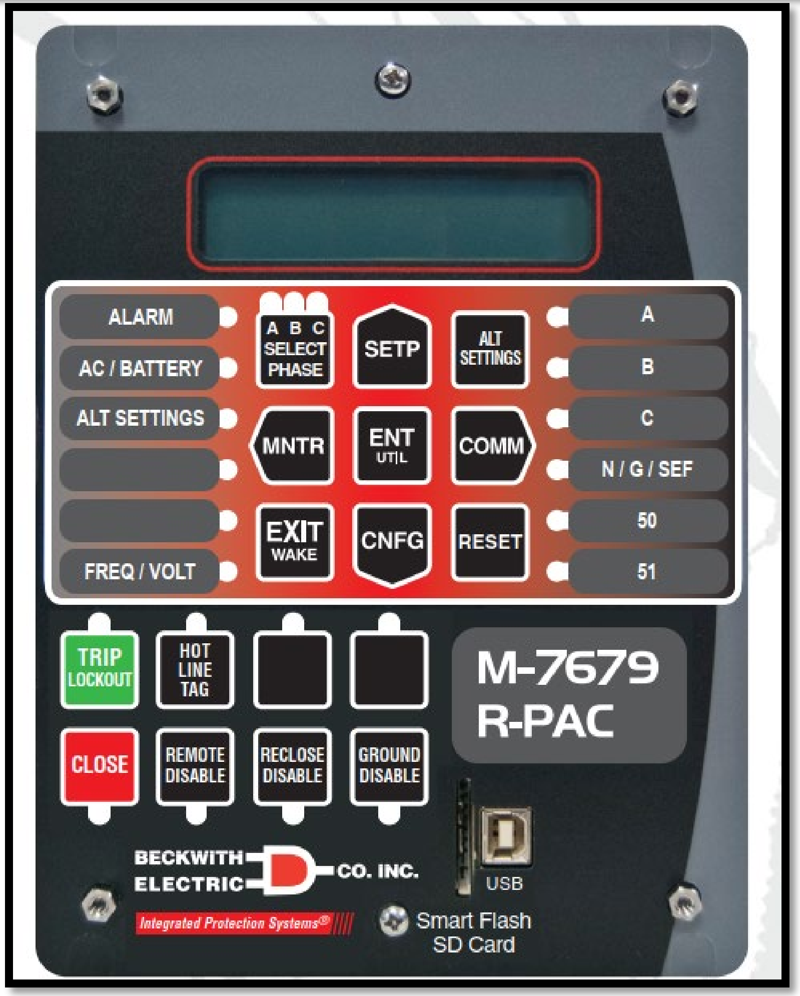
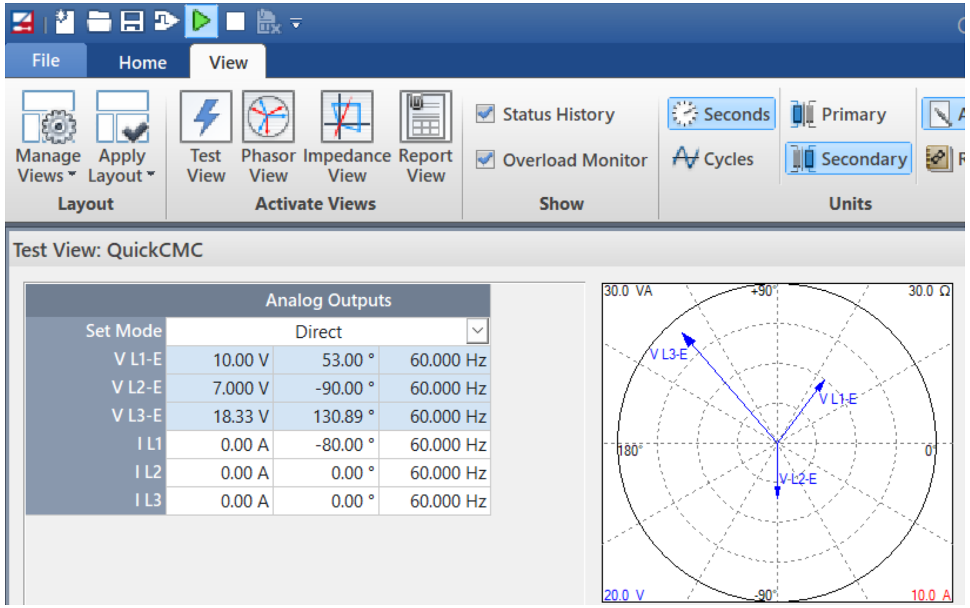
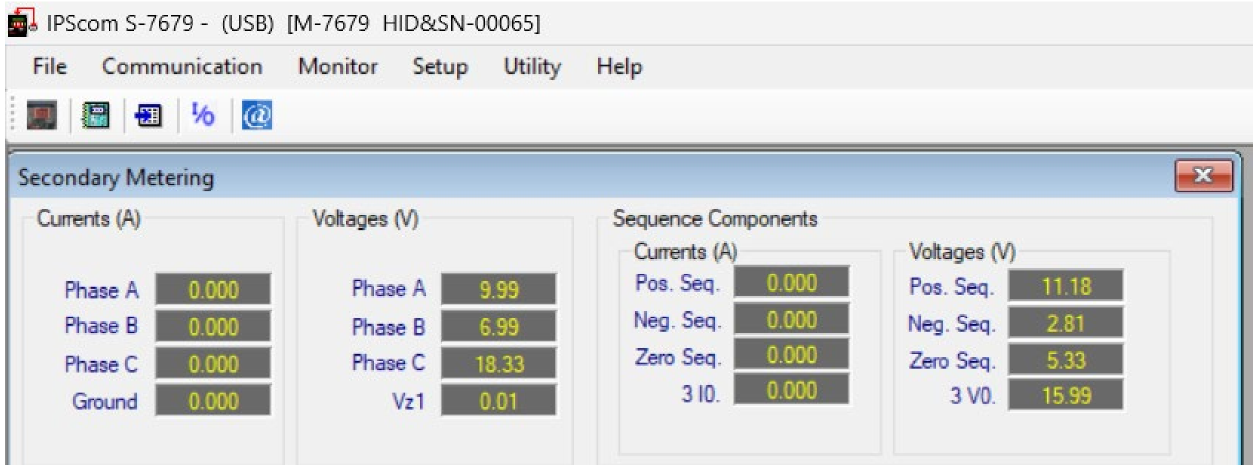
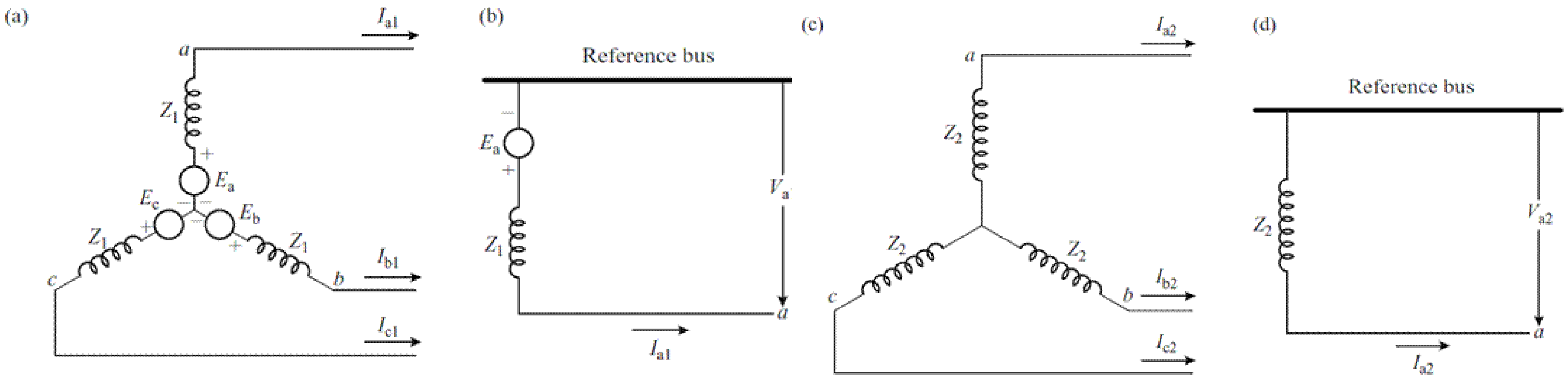


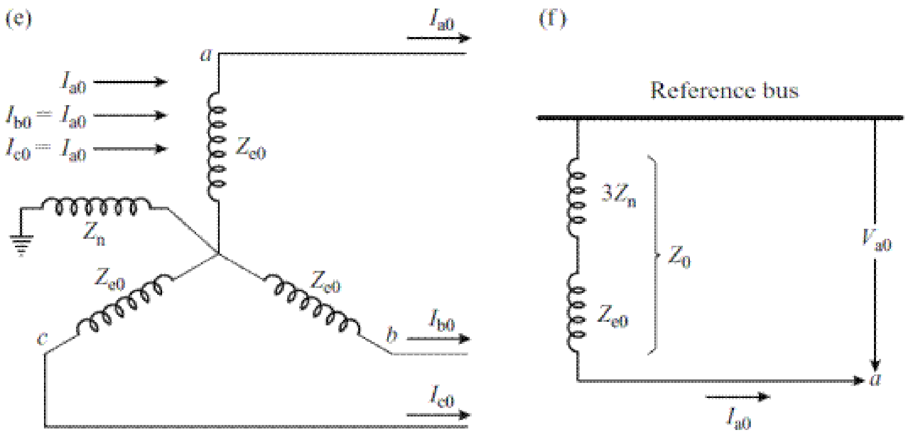
ILLUSTRATION ON AN UNBALANCED SYSTEM WITH VOLTAGE INJECTIONS





EQUIVALENT SEQUENCE NETWORKS OF A SYNCHRONOUS GENERATOR





a Positive sequence current

b Positive sequence network

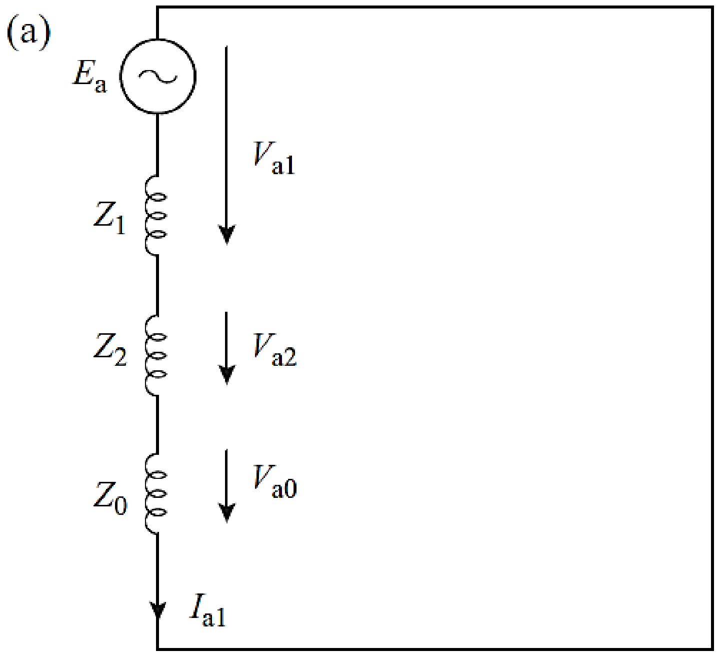
c Negative sequence current

d Negative sequence network

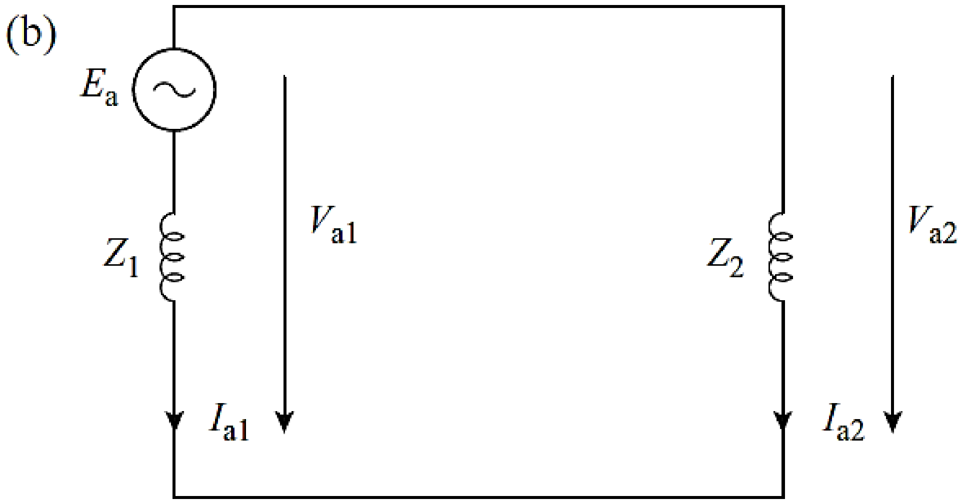
e Zero sequence current

f Zero sequence network

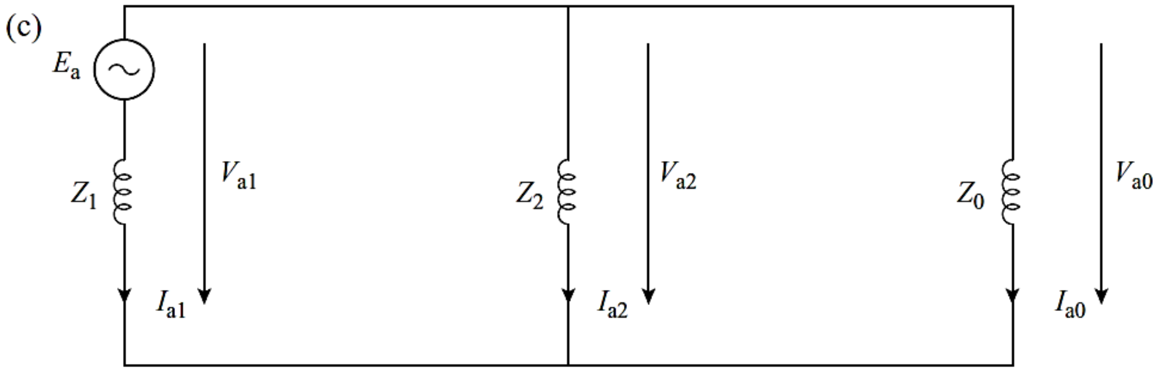
SEQUENCE NETWORK CONNECTION FOR FAULT CALCULATION



Phase to earth fault

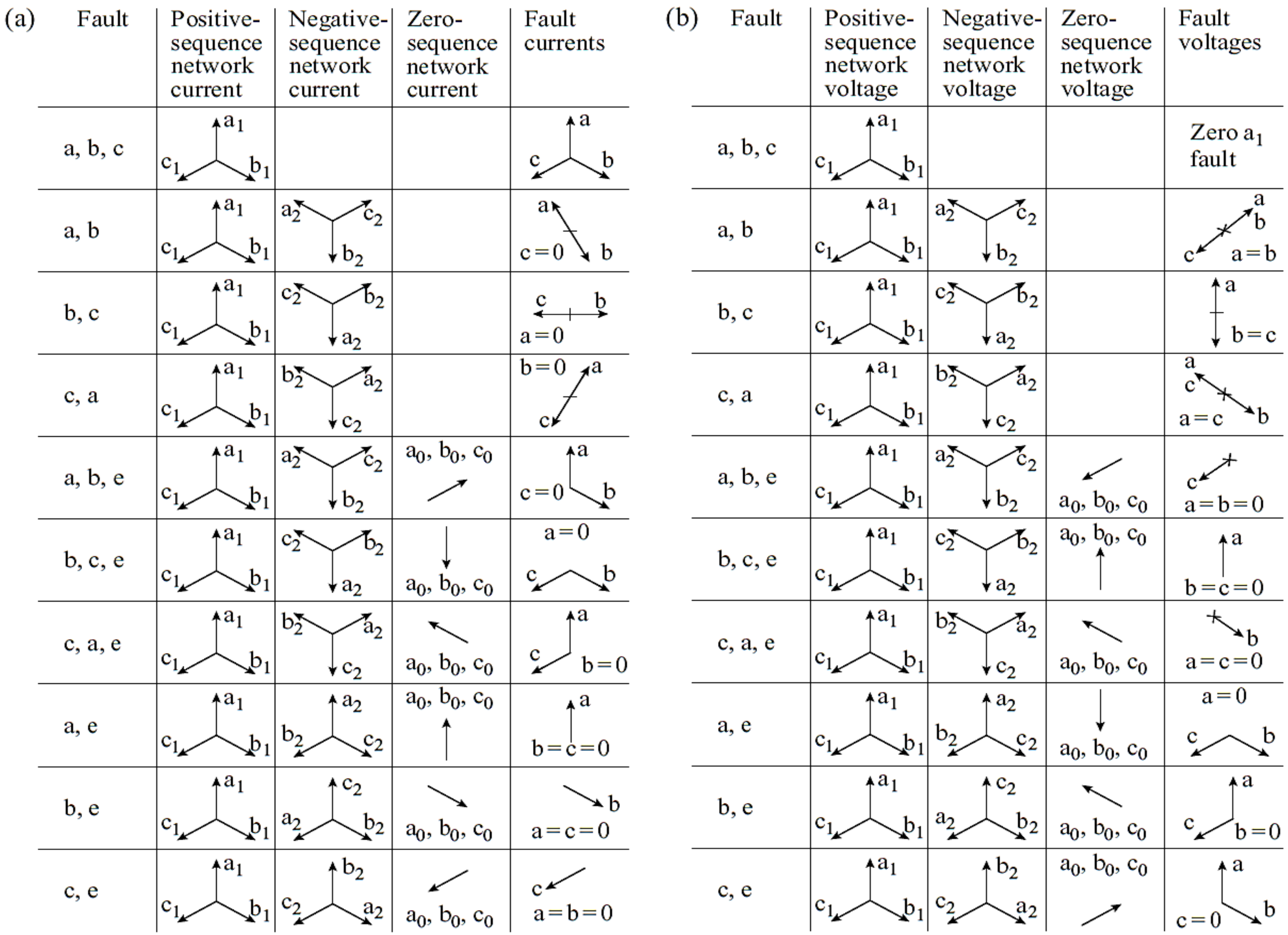


Phase to phase fault



Double phase to earth fault

I & V FOR VARIOUS TYPES OF FAULTS



EXAMPLE ON POWER SYSTEM NETWORK

- Nature of Short Circuit Currents
- Fault Types
- PU Normalization
- Symmetrical Components
- Example on a Power System Network
- Fault Contribution from DGs & IBRs

EXAMPLE

- Calculate the short circuit current for a three phase fault at busbar D.

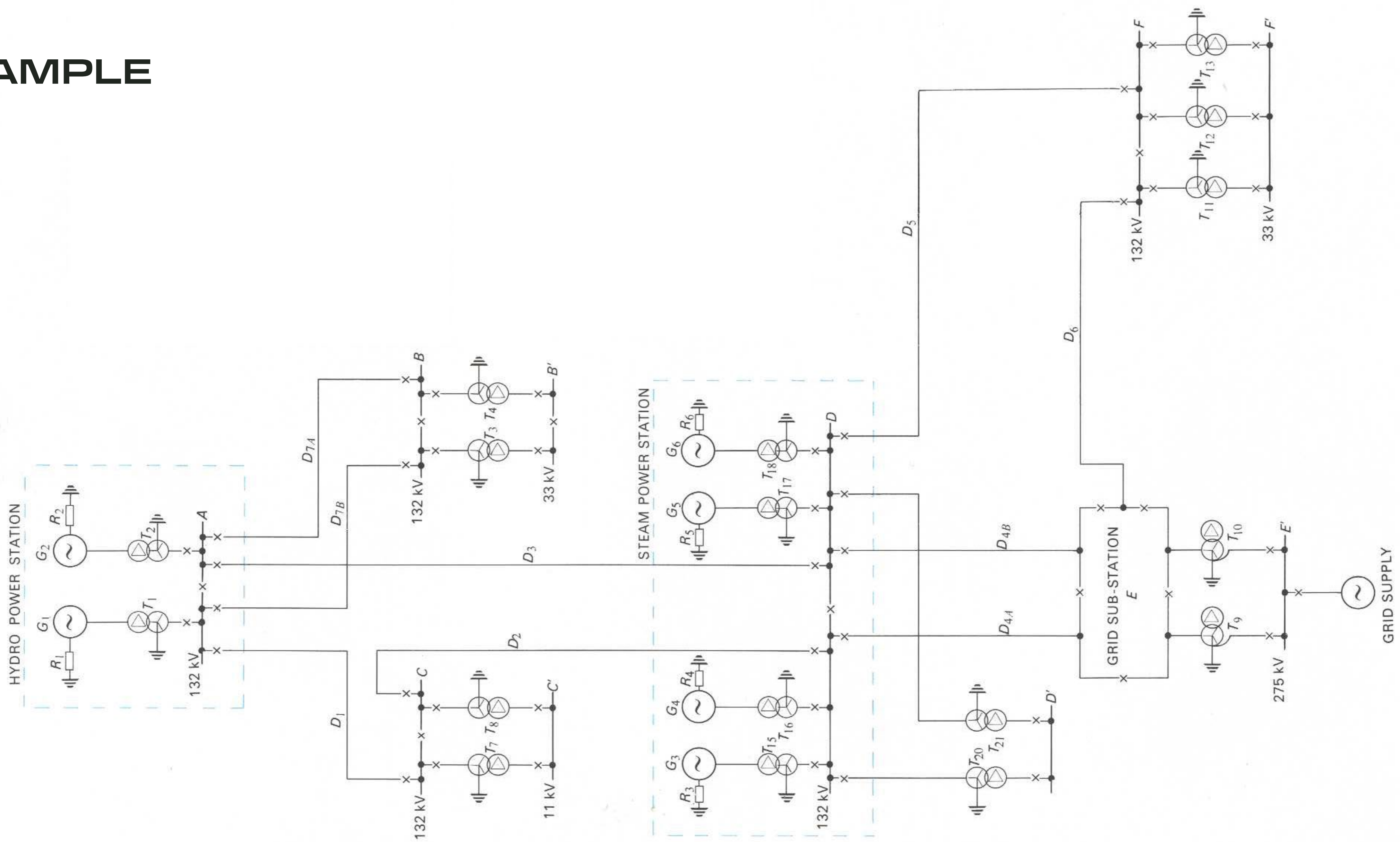
- Consider that the Hydro Power Station is under maintenance and therefore all the breakers associated are open.

- Let base MVA = 75 MVA

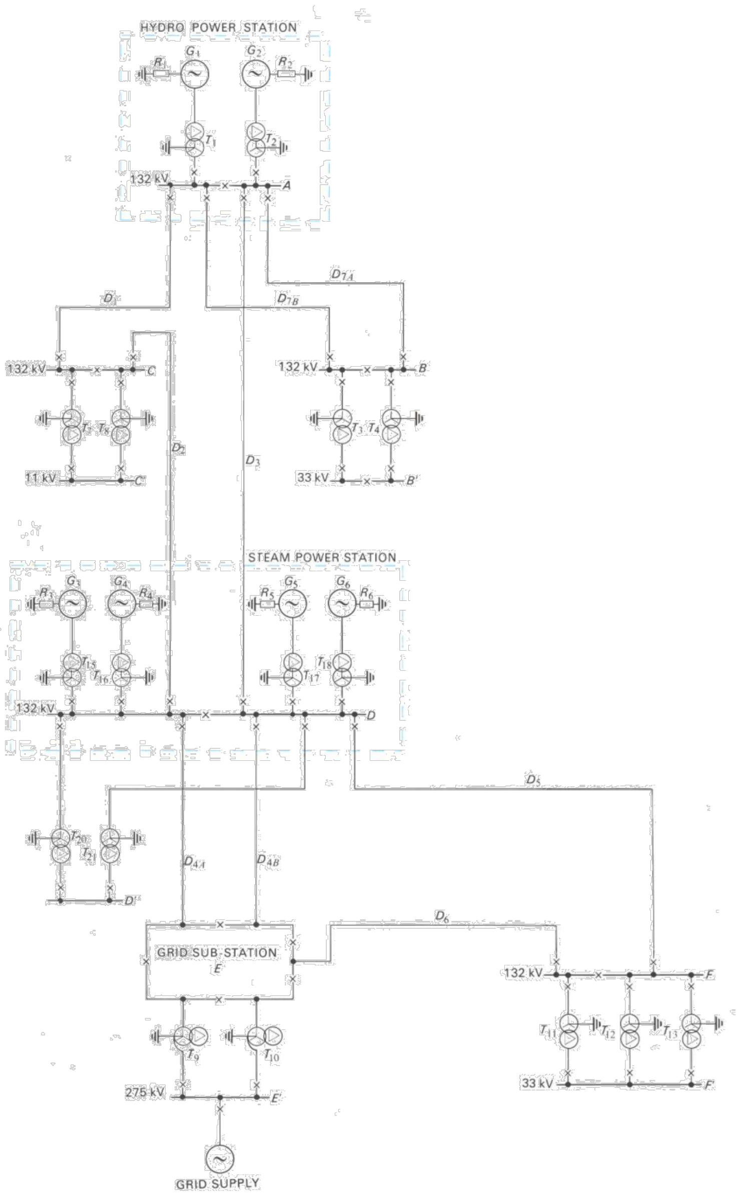
- Let base kV on 132 kV nominal part of system = 132 kV

- The base kV on other parts of the system is obtained by referring this voltage through the interconnecting transformers.

EXAMPLE


HYDRO POWER STATION
STEAM POWER STATION
GRID SUB-STATION
E
GRID SUPPLY
132 kV
33 kV
11 kV
275 kV
A
B
B′
C
C′
D
D′
E′
F
F′
D1
D2
D3
D4A
D4B
D5
D6
D7A
D7B

EXAMPLE



Hydro Power Station

G_1, G_2 — 66.6 MVA, 11kV; X_d =0.95 X_d' =0.325 X_d'' =0.26

T_1, T_2 — 75 MVA, 11/145kV ± 10%, X =0.125

Steam Power Station

G_3, G_4, G_5, G_6 — 75 MVA, 11.8kV; X_d =1.83 X_d' =0.615 X_d'' =0.111

T_{15}, T_{16}, T_{17}, T_{18} — 75 MVA, 11.8/145kV ± 10%, X =0.125

T_{11}, T_{12}, T_{13}, T_{20}, T_{21} — 60 MVA, 132/33kV, X =0.125

T_3, T_4 — 30 MVA, 132/33kV X =0.1

T_7, T_8 — 45 MVA, 132/11kV X =0.125

T_9, T_{10} — 120 MVA, 275/132/11kV; X_{HL} =0.15 X_{HT} =0.35 X_{LT} =0.25 on 120MVA

Grid Supply

Short circuit fault level 7500MVA on 275kV

Overhead Lines

All 132kV lines are 0.175 sq. In. except D_5, D_6 which are 0.4 sq. in.

0.175 sq. in.

R = 0.00146 per mile on 100MVA Base

X = 0.00385 per mile on 100MVA Base

0.4 sq. in.

R = 0.000627 per mile on 100MVA Base

X = 0.00356 per mile on 100MVA Base

$$\frac{Z_0}{Z_1} = 2.5$$

Lengths

D_1 50 miles — D_5 20 miles

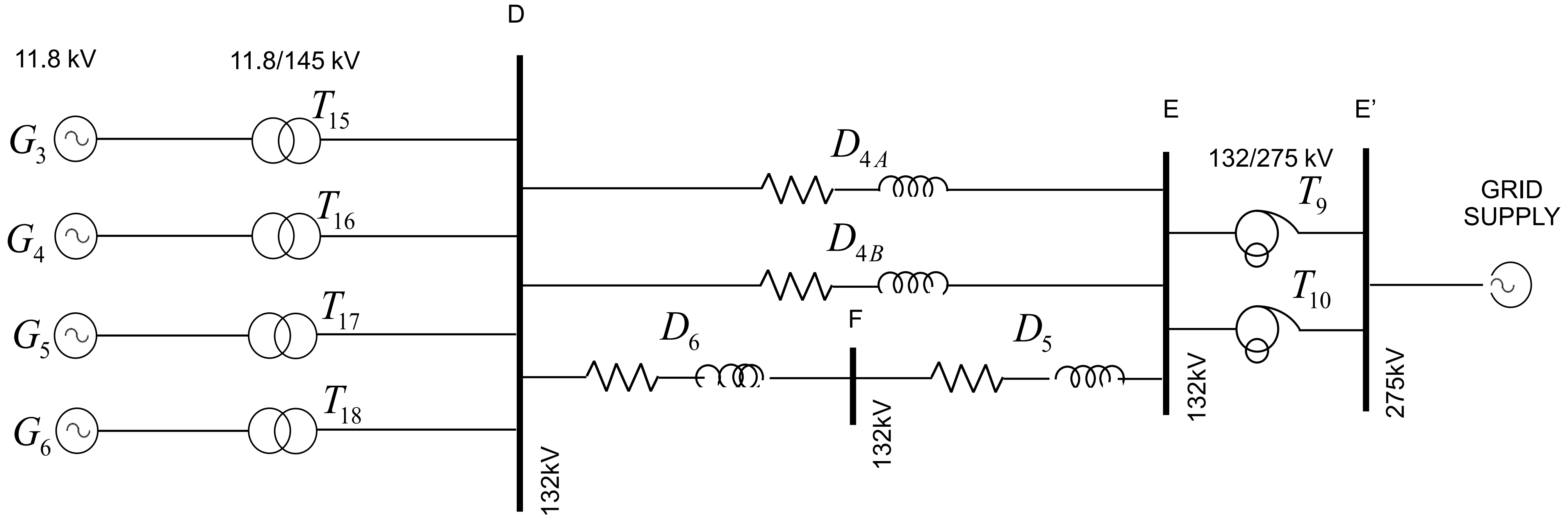
D_2 60 miles — D_6 30 miles

D_3 100 miles — D_{7A}, D_{7B} 15 miles

D_{4A}, D_{4B} 30 miles

All impedances are per unit

EXAMPLE - SOLUTION

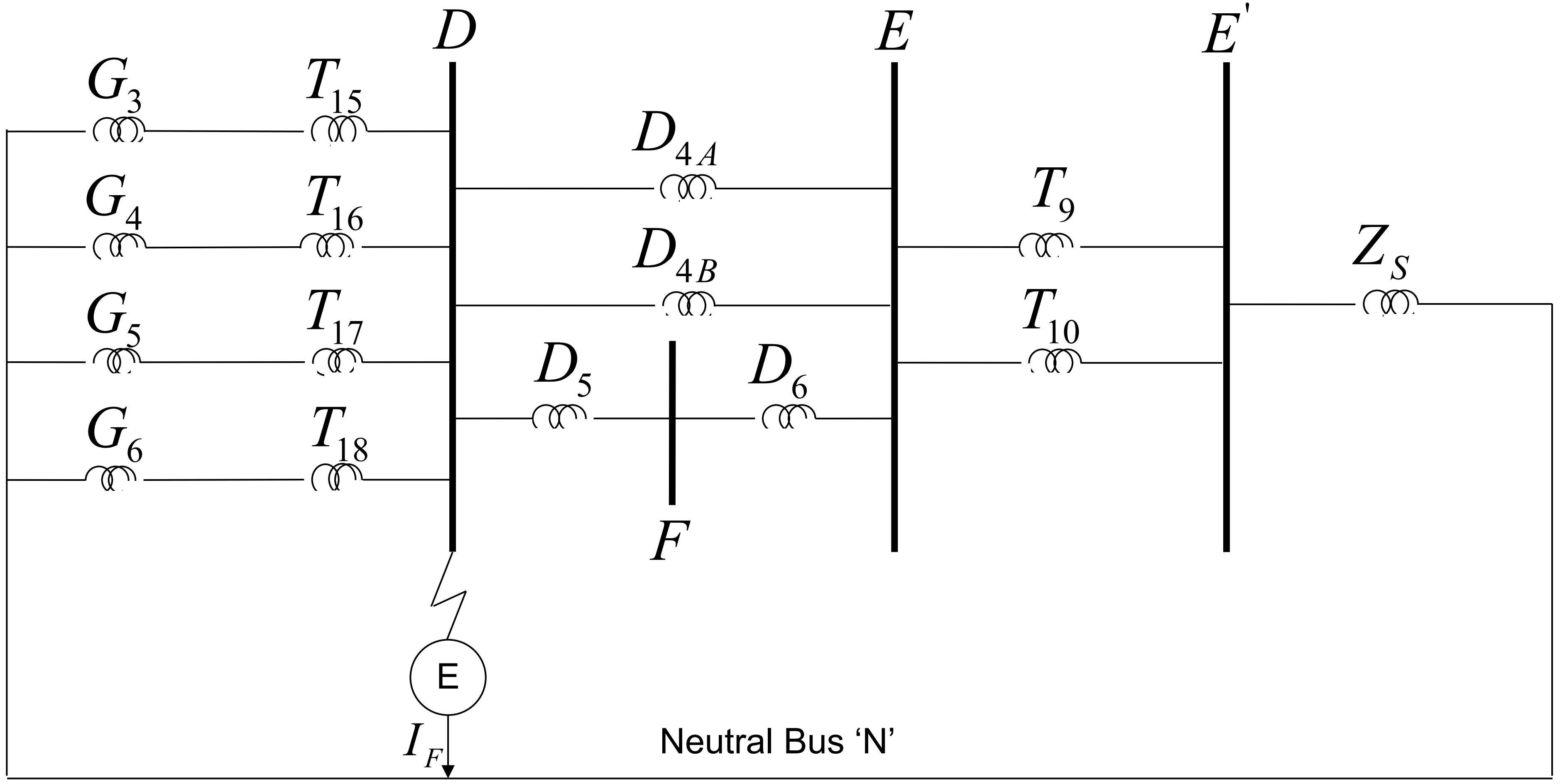


POSITIVE SECUENCE DIAGRAM FOR FAULT AT BUSBAR D

In order to calculate the short circuit currents for a three phase fault at busbar D, only those busbars having sources that contribute to the fault are considered. Lines in the path of the short circuit currents are also considered.

That is why for a three phase fault at busbar D, only buses D, E, E’ and F are left as shown in the equivalent diagram.

POSITIVE SECUENCE DIAGRAM FOR FAULT AT BUSBAR D



POSITIVE SEQUENCE NETWORK

- Generator Impedances Calculation

Since the initial value of fault current is required, the generator subtransient reactance Xd'' should be considered.

The value of $Xd'' = 0.111\ p.u.$ based on $75\ MVA\ \&\ 11.8\ kV$

Old base $MVA = MVA1 = 75\ MVA$

Old base $kV = kV1 = 11.8\ kV$

Old base impedance $= Z1base = \frac{kV_1^2}{MVA_1} = \frac{11.8^2}{75}$

Actual value of

$$Xd'' = Xd''act = 0.111\ x\ Z1base = 0.111\ x\ \frac{11.8^2}{75}$$

POSITIVE SEQUENCE NETWORK

Actual value of

$$Xd'' = Xd''\,act = 0.111\ x\ Z_1 base = 0.111\ x\ \frac{11.8^2}{75}$$

For the purpose of calculation:

New base $MVA = MVA_2 = 75\ MVA$

New base $kV = kV_2 = 132\ x\ \frac{11.8}{145} = 10.74\ kV$

New base impedance $= Z_2\ base = \frac{kV_2^2}{MVA_2} = \frac{10.74^2}{75}$

New per unit impedance $= \frac{Xd''act}{Z_2 base} = 0.111\ x\ \frac{11.8^2}{75}\ x\ \frac{75}{10.74^2} = 0.134\ p.u.$

$$\therefore Xd''_{G3} = Xd''_{G4} = Xd''_{G5} = Xd''_{G6} = 0.1340\ p.u.$$

POSITIVE SEQUENCE NETWORK

- Transformer Impedances Calculation

Generator transformers T15, T16, T17 and T18 ratio $\frac{11.8}{145kV}$

The value of $X_T = 0.125\ p.u.$ base on $75\ MVA$ and $145\ kV$ on H.V. side
Or base on $75\ MVA$ and $11.8\ kV$ on L.V. side

Old base $MVA_1 = 75\ MVA$

Old base $kV_1 = 145\ kV$ on H.V. side or $11.8\ kV$ on L.V. side.

New base $MVA_2 = 75\ MVA$
New base $kV_2 = 132\ kV$ on H.V. side or

$\frac{132\ x\ 11.8}{145} = 10.74\ kV$ on L.V. side

Consider H.V. side.
New p.u. reactance $= 0.125\ x\ \frac{75}{75} x\ \frac{(145)^2}{(132)^2} = 0.151\ p.u.$

Consider L.V. side.
New p.u. reactance $= 0.125\ x\ \frac{75}{75} x\ \frac{(11.8)^2}{(10.74)^2} = 0.151\ p.u.$

POSITIVE SEQUENCE NETWORK

i.e. the p.u. reactance of the transformer is the same on both sides of the transformers.

$$\therefore X_{T15} = X_{T16} = X_{T17} = X_{T18} = 0.151\ p.u.$$

Transformers T9, T10, ratio $275/132\ kV$

New p.u. reactance $= 0.15\ x\ \dfrac{75}{120}\ x\ \dfrac{(132)^2}{(132)^2} = 0.094\ p.u.$

$$\therefore X_{T9} = X_{T10} = 0.094\ p.u.$$

Transformers T7, T8, ratio $132/11\ kV$

New p.u. reactance $= 0.125\ x\ \dfrac{75}{45}\ x\ \dfrac{(132)^2}{(132)^2} = 0.208\ p.u.$

$$\therefore X_{T7} = X_{T8} = 0.208\ p.u.$$

POSITIVE SEQUENCE NETWORK

- Transmission Line impedances

Neglecting resistance

$$Z_{D2} = 60\,x\,0.00385\,x\,\frac{75}{100}\,x\,\frac{(132)^2}{(132)^2} = 0.1732\ p.u.$$

$$Z_{D4A} = Z_{D4B} = 30\,x\,0.00385\,x\,\frac{75}{100}\,x\,\frac{(132)^2}{(132)^2} = 0.0866\ p.u.$$

$$Z_{D5} = 20\,x\,0.00356\,x\,\frac{75}{100}\,x\,\frac{(132)^2}{(132)^2} = 0.0534\ p.u.$$

$$Z_{D6} = 30\,x\,0.00356\,x\,\frac{75}{100}\,x\,\frac{(132)^2}{(132)^2} = 0.0801\ p.u.$$

POSITIVE SEQUENCE NETWORK

- Grid Source Impedance

Fault level $= 7500\ MVA$ on the $275\ kV$ busbar E'.

Actual source impedance $= Zs\ act = \dfrac{kV^2}{MVA} = \dfrac{275^2}{7500}$

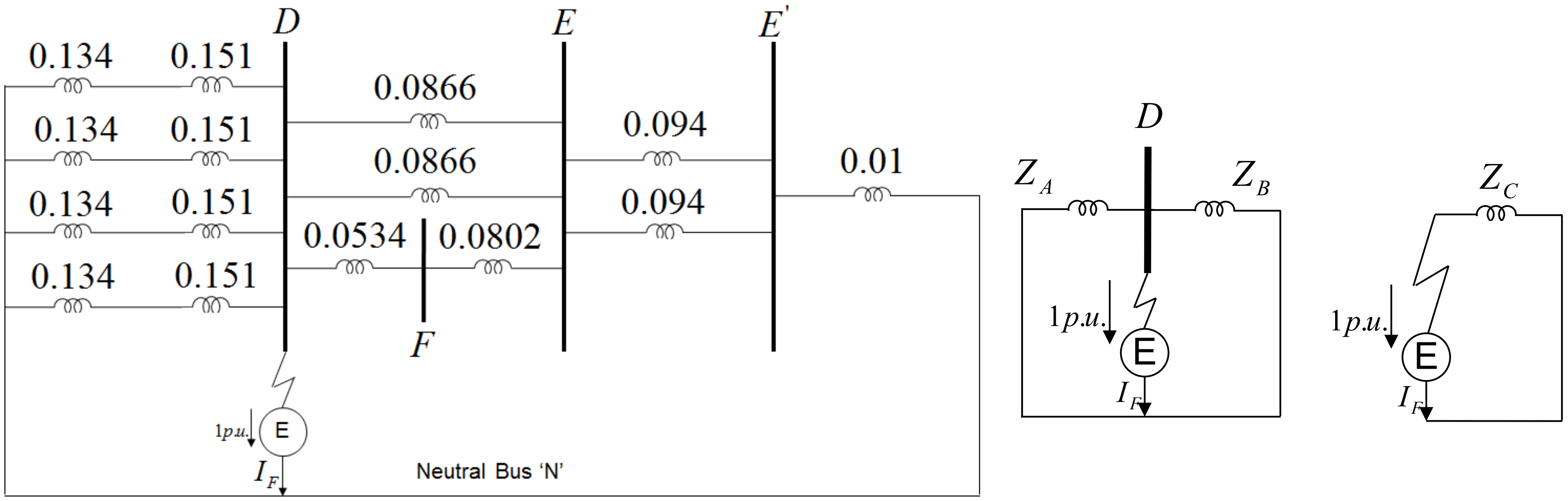
Base $kV = 275\ kV$

Base $MVA = 75\ MVA$

Base impedance $= Zbase = \dfrac{275^2}{75}$

$$\therefore Zs\ p.u. = \frac{Z_{s\ act}}{Z_{base}} = \frac{275^2}{7500} x \frac{75}{275^2} = 0.01\ p.u.$$

POSITIVE SEQUENCE NETWORK



EQUIVALENT IMPEDANCES

The resulting positive sequence diagram is shown below:

$$Z_A = \frac{0.134 + 0.151}{4} = \frac{0.285}{4} = 0.0712\, p.u.$$

$$Z_B = 0.01 + \frac{0.094}{2} + \frac{0.0433\, x\, 0.1335}{0.1768} = 0.01 + 0.047 + 0.0327 = 0.0897\, p.u.$$

$$Z_C = \frac{0.0712 + 0.0897}{0.1607} = 0.0397\, p.u.$$

$$\therefore\ I_F = \frac{E}{Z_c} = \frac{1}{0.0397} = 25.19\, p.u.$$

$$Base\, current\, (1\, p.u.) = \frac{75\, x 10^6}{\sqrt{3}\, x 132\, x 10^3} = 328\, A$$

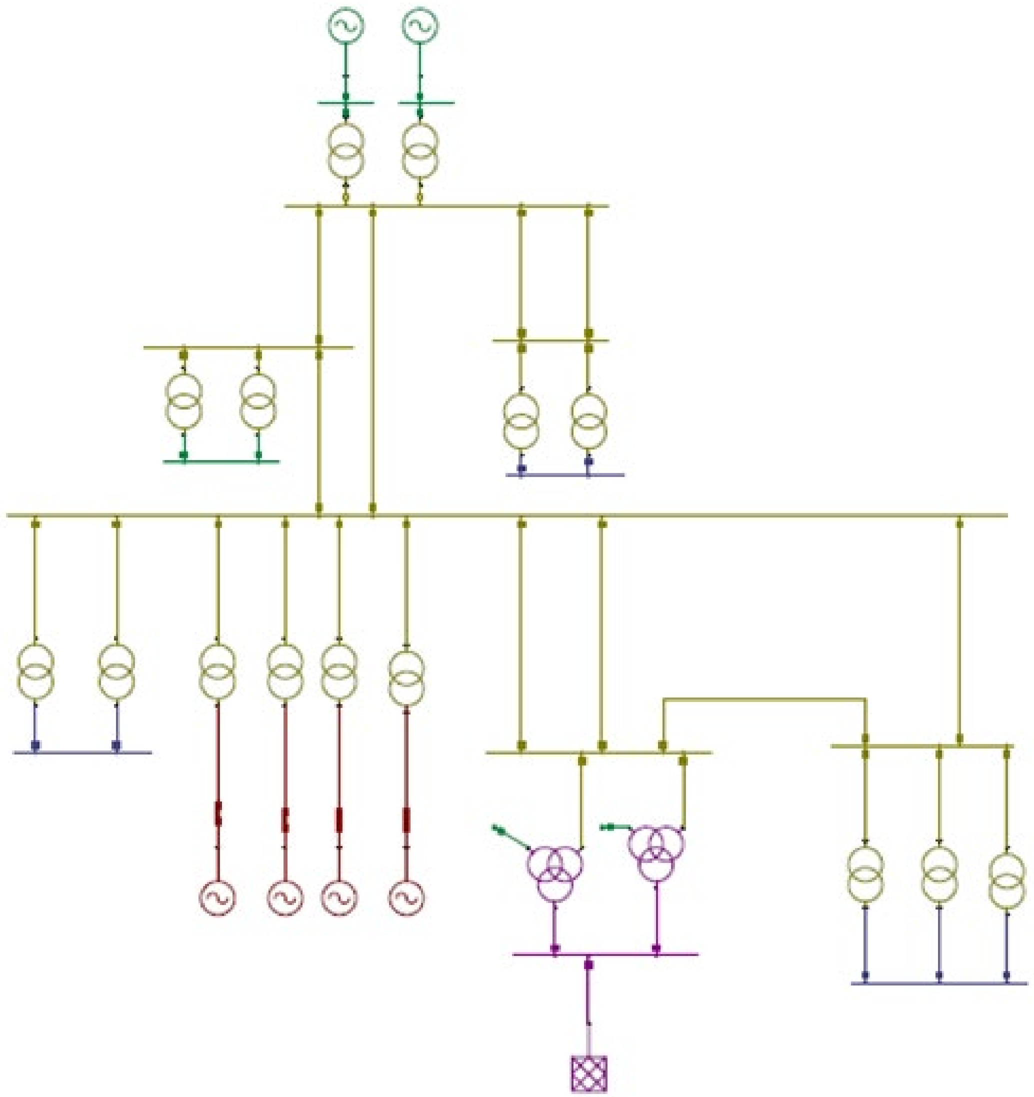
CASE EXAMPLE

$$\therefore\ I_F = 25.19x328 = 8262A$$

Fault MVA = $\sqrt{3}x132x103x8262 = 1889MVA$

Alternatively Fault MVA = $\dfrac{75}{0.0397} = 1889\,MVA$

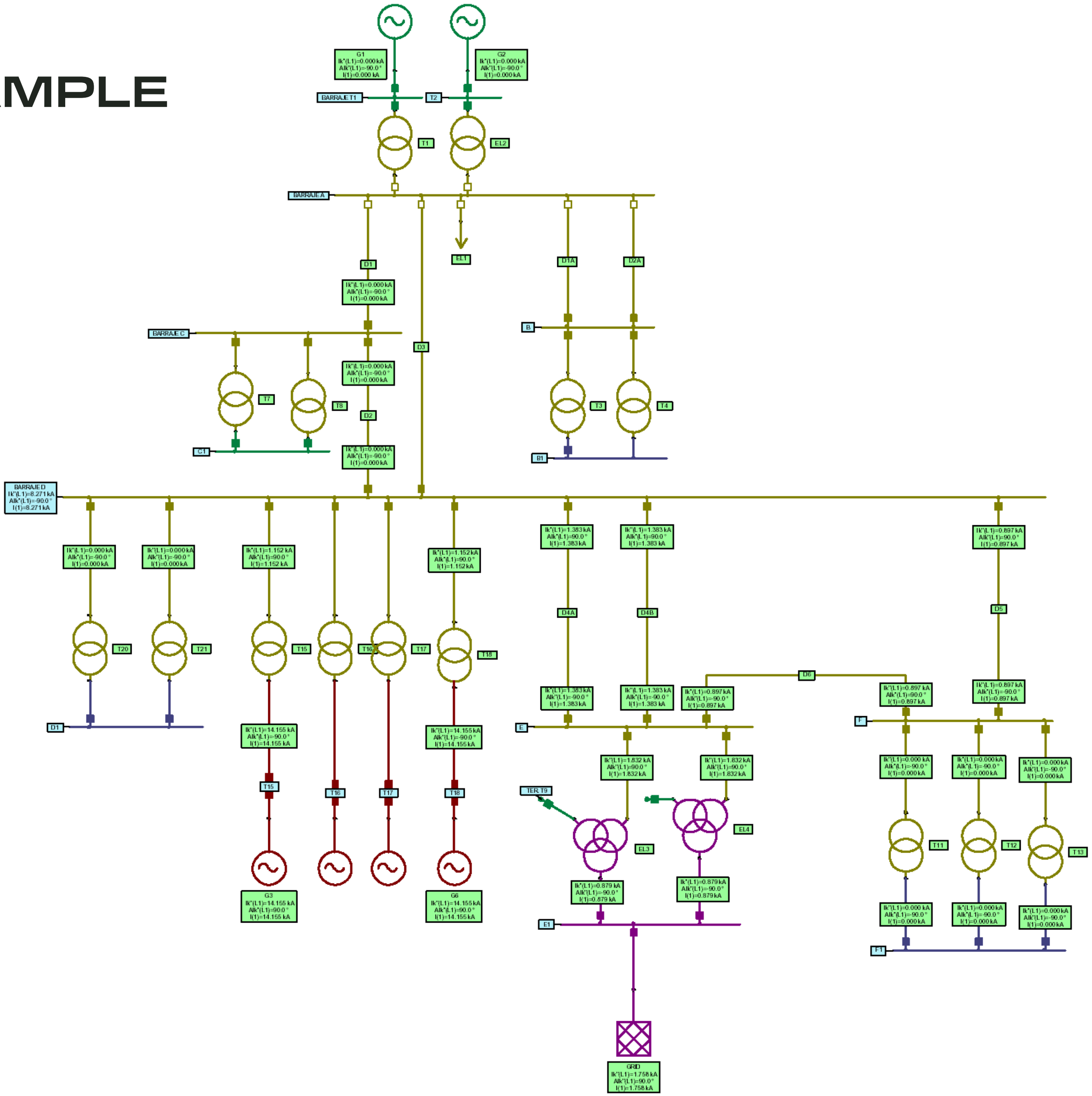
SOLUTION OF CASE EXAMPLE WITH SOFTWARE



Equivalent Network

SOLUTION OF CASE EXAMPLE WITH SOFTWARE

Results for Fault at Busbar D



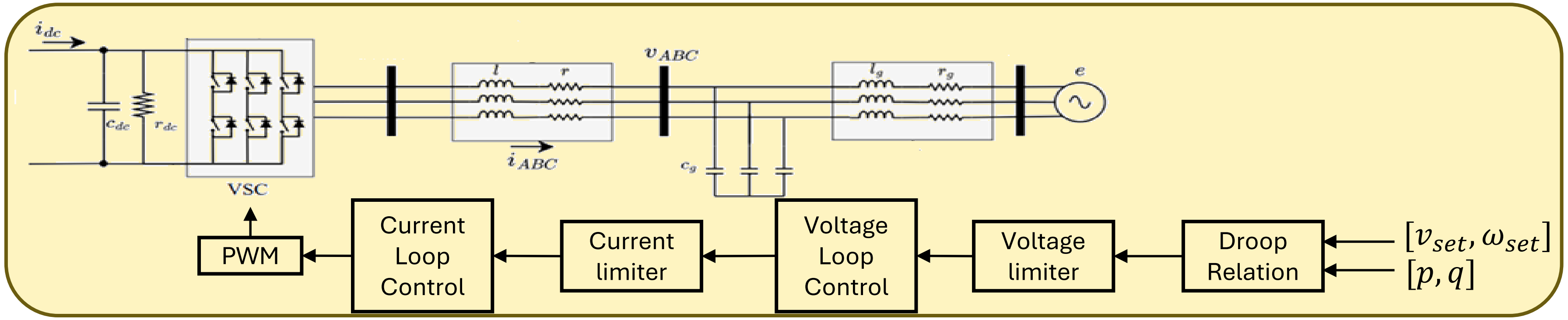
FAULT CONTRIBUTION FROM DG & IBR

- Nature of Short Circuit Currents
- Fault Types
- PU Normalization
- Symmetrical Components
- Example on a Power System Network
- Fault Contribution from DGs & IBRs

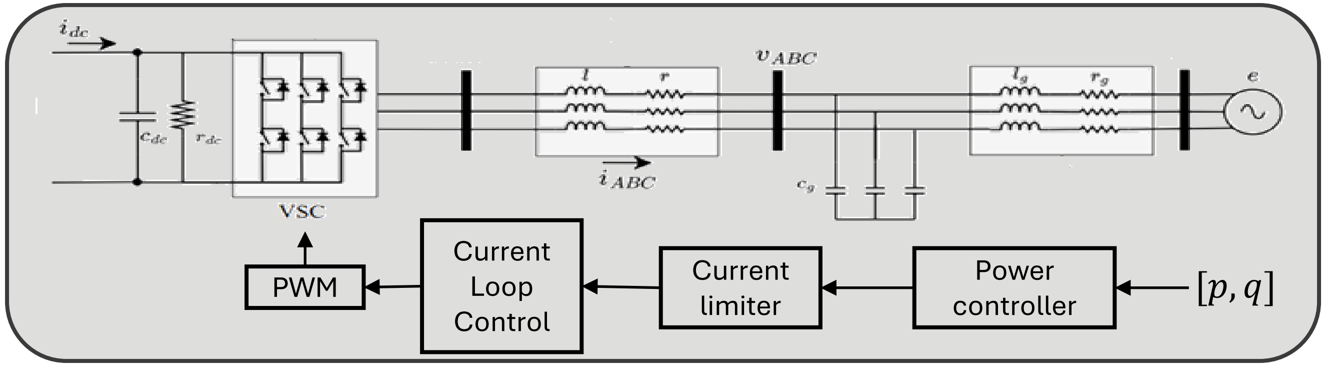
FAULT LEVEL WITH IBRS

Steady-state response to faults:

GFM:



GFL:



PWM = Pulse Width Modulation

$I_{SC} = kI_r$ where $k = [1.1 - 1.5]$

This is enforced by:

- Saturation of current references
- Protection functions like desaturation or overcurrent trip
- DC-link voltage control and active switching algorithms

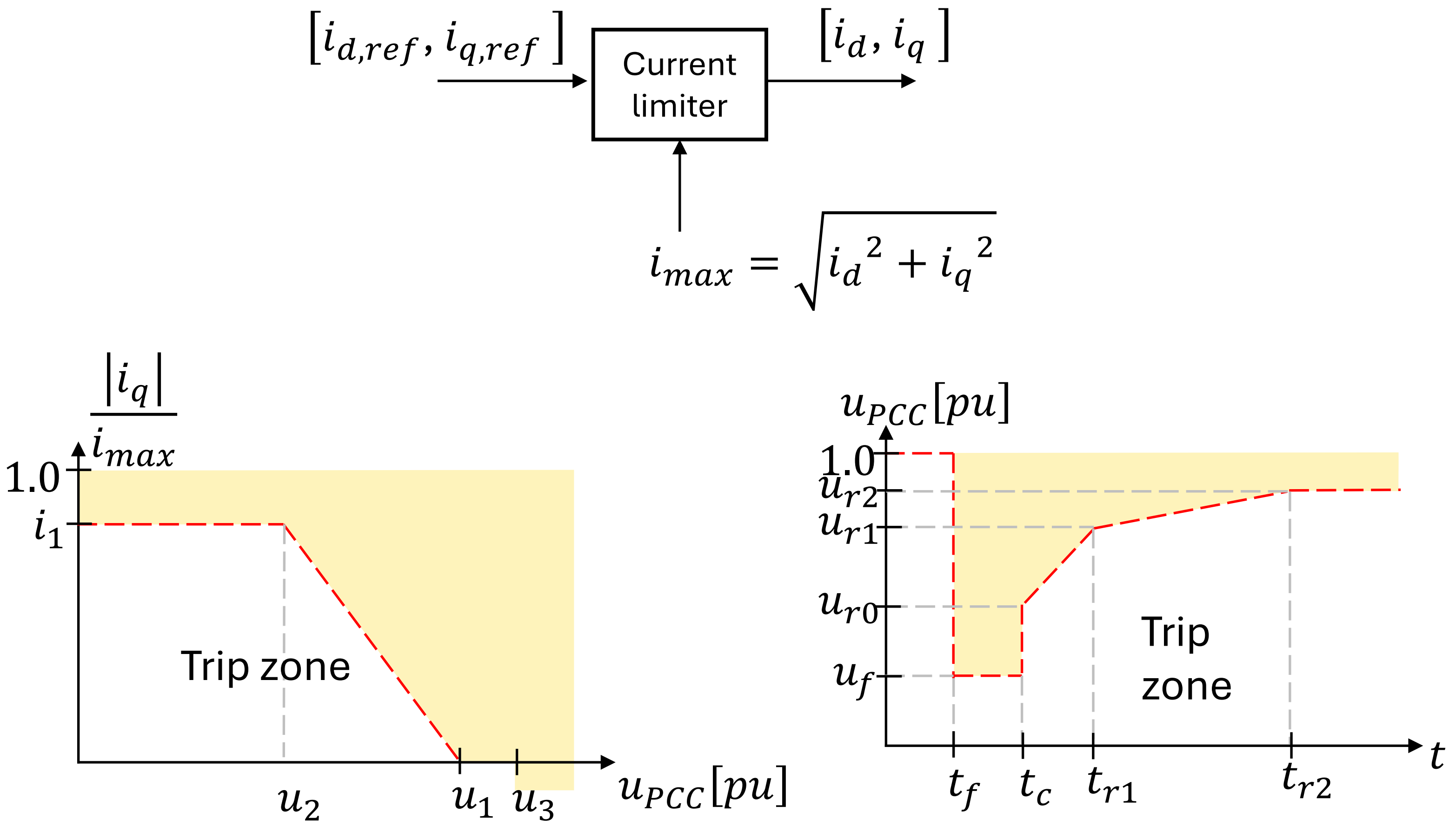
SYNCHRONOUS AND IBRs SHORT CIRCUIT VALUES

	Synchronous Generator	IBRs
Magnitude	Up to 5 - 10 p.u	1.2 - 1.5 p.u
Duration	Until fault is cleared by CB	Depending on FRT requirement
Sequence network	Can be modeled based on symmetrical component	No model
+ sequence	Yes	Yes
- sequence	Yes	No, unless designed to inject
0 sequence	Yes	No
DC offset	1.5 – 1.6 AC component	No
Negative current	Serval time-rated current depending on the negative sequence impedance of the network	Limited to VA capacity and inverter requirement
Symmetrical component	+, -, 0	No

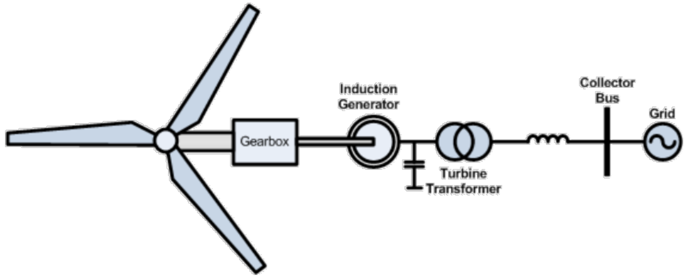
Sources:
Impact of Inverter Based Resources on Power System Protective Relaying,
Fault Calculation and Protection Setting: A Systematic Literature Review

FAULT LEVEL WITH IBRS

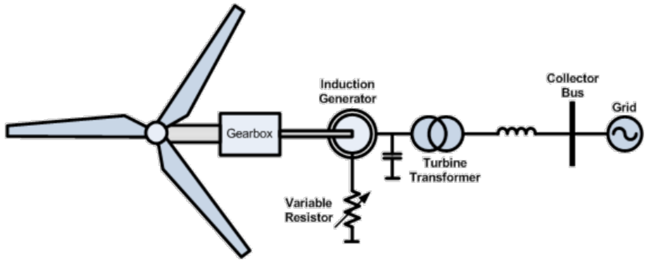
Dynamic response to faults: Fault Ride Through functions



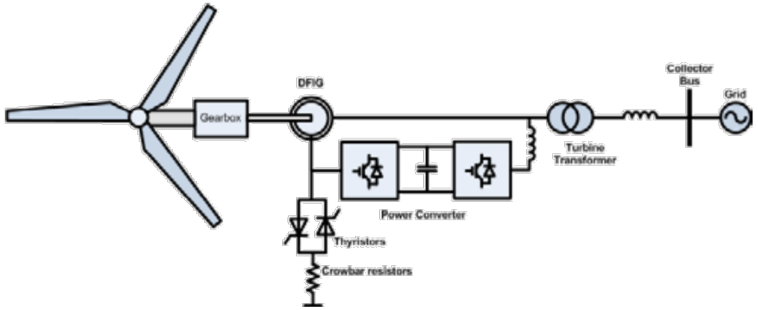
FAULT LEVEL WITH WIND TURBINES



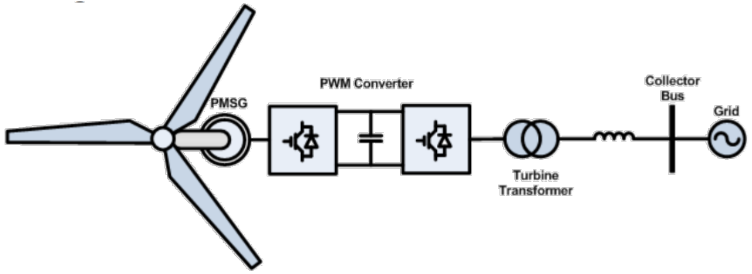
Type 1 WTG: Squirrel Cage Induction Generator-SCIG



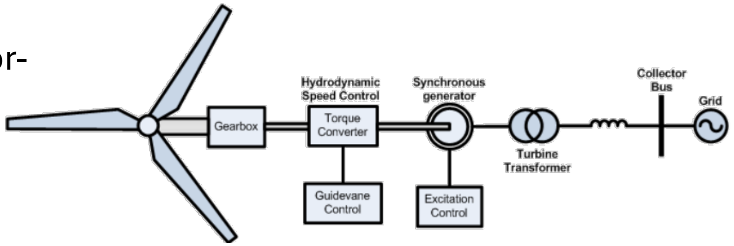
Type 2 WTG: Wound-Rotor Induction Generator with Variable External Rotor Resistance



Type 3 WTG: Double-Fed Induction Generator-DFIG



Type 4 WTG: Full-Converter Wind Turbine Generator

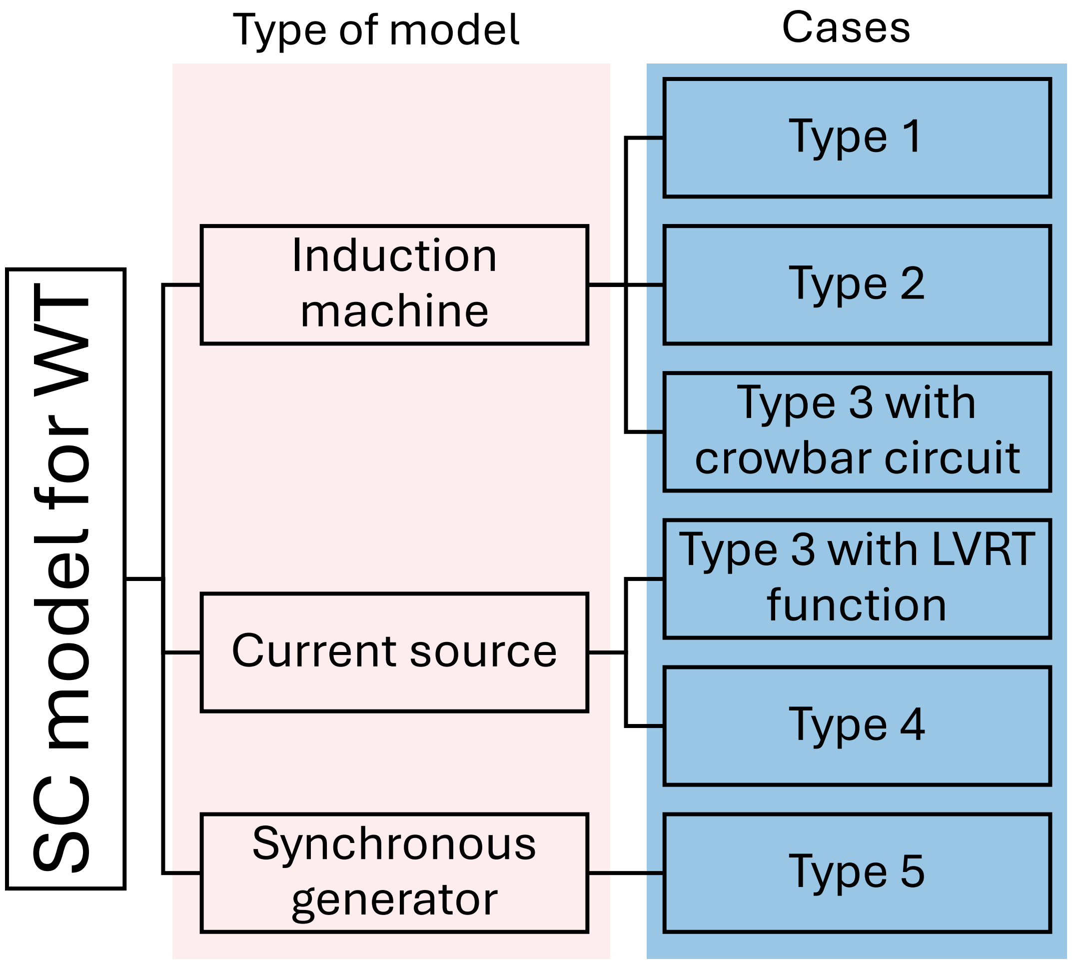


Type 5 WTG: Synchronous Generator mechanically connected through a torque converter

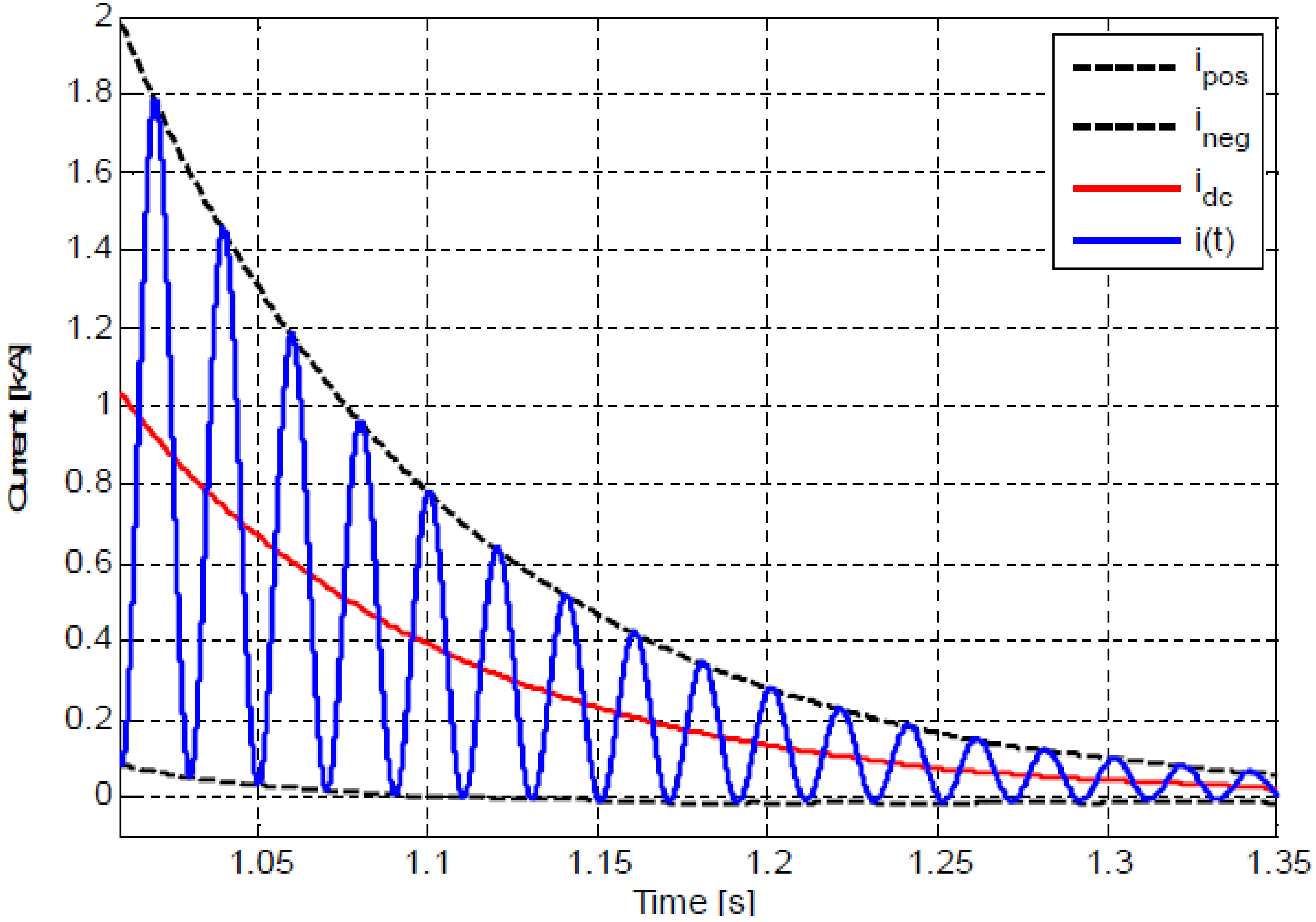
Source: Gevorgian, V.; Muljadi, E. “Wind Power Plant Short Circuit Current Contribution for Different Fault and Wind Turbine Topologies”. The 9th Annual International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants, Québec, Canada. October 18-19, 2010

FAULT LEVEL WITH WIND TURBINES

How to model SC contributions of wind turbines ?

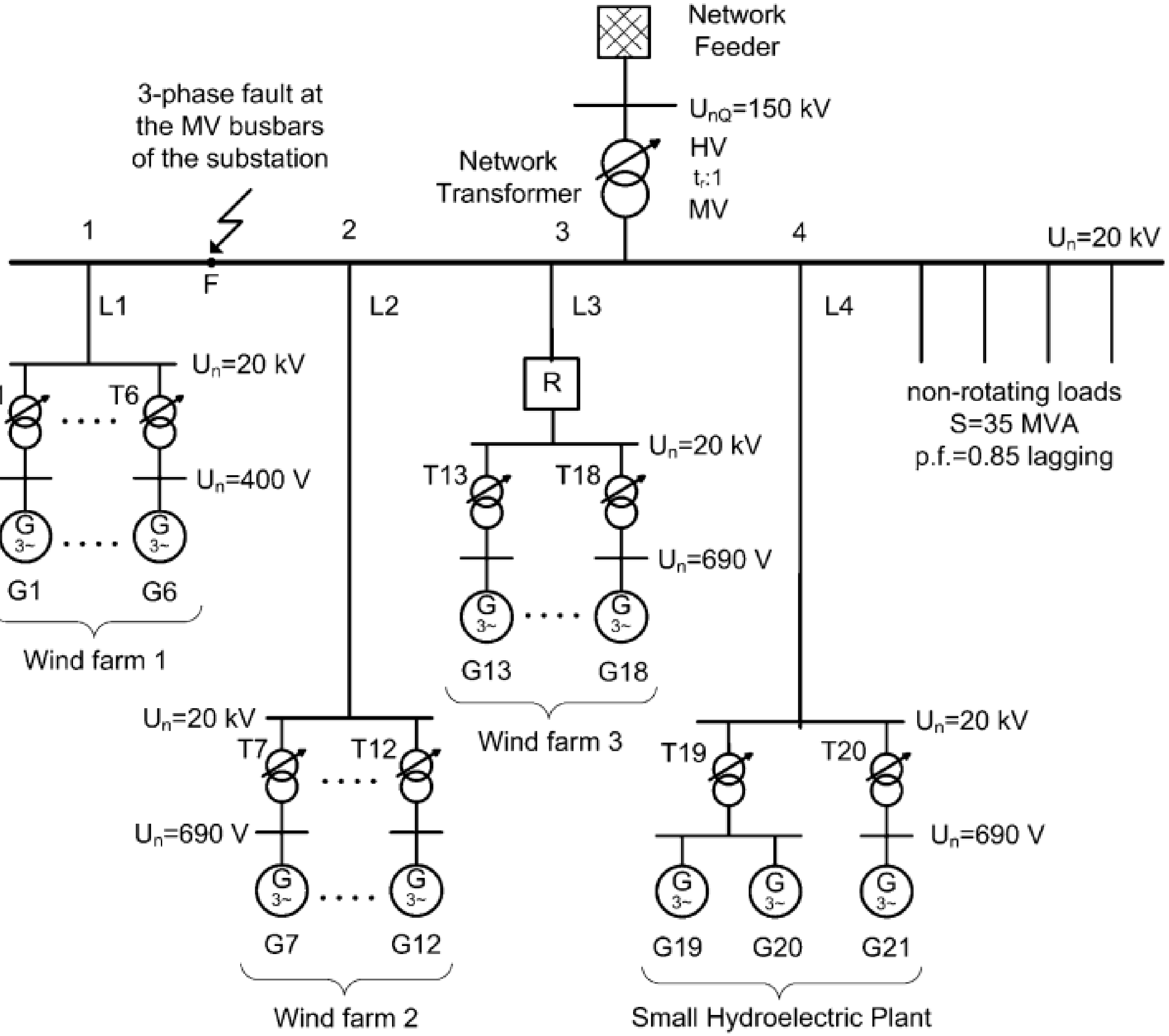


ASYNCHRONOUS GENERATOR SHORT CIRCUIT CURRENT CONTRIBUTION



EXAMPLE

MV distribution network:



Source: Boutsika, T.N.; Papathanassiou, S.A. “Short-circuit calculations in networks with distributed generation”. Electric Power Systems Research 78, 2008. pp: 1181–1191

EXAMPLE

MV distribution network:

Fault level calculation procedure and results

Network feeder	$U_{nQ} = 150\,kV$, $S''_{kQ} = 3000\,MVA$, $R_Q/Z_Q = 0.1$
System transformer	$S_{rT} = 50\,MVA$, $u_{kr} = 20.5\%$ ($u_{k-} = 19.5\%$, $u_{k+} = 22\%$), $P_{krT} = 160\,kW$, $t_r = 150 \begin{pmatrix} +12.5\% \\ -17.5\% \end{pmatrix} /21\,kV$
Wind farm 1	6 × 600 kW (G1–G6)
Generator (G1–G6)	Synchronous with converter (Type IV): $P_{rG} = 600\,kW$, $U_{rG} = 400\,V$, $I_{rG} = 866\,A$, $k = 1.5$
Unit transformer (T1–T6)	$S_{rT} = 630\,kVA$, $t_{rT} = 20(\pm 5\%)/0.4\,kV$, $u_{krT} = 4\%$, $u_{RrT} = 1.2\%$
Line L1	Overhead line: $R_L = 0.215\,\Omega/km$, $X_L = 0.334\,\Omega/km$, $l_1 = 10\,km$ Underground cable: $R_L = 0.162\,\Omega/km$, $X_L = 0.115\,\Omega/km$, $l_1 = 0.5\,km$
Wind farm 2	6 × 660 kW (G7–G12)
Generator (G7–G12)	DFIG (Type III): $P_{rG} = 660\,kW$, $U_{rG} = 690\,V$, $I_{rG} = 560\,A$
Unit transformer (T7–T12)	$S_{rT} = 700\,kVA$, $t_{rT} = 20(\pm 5\%)/0.69\,kV$, $u_{krT} = 5\%$, $u_{RrT} = 1.2\%$
Line L2	Overhead line: $R_L = 0.215\,\Omega/km$, $X_L = 0.334\,\Omega/km$, $l_2 = 10\,km$ Underground cable: $R_L = 0.162\,\Omega/km$, $X_L = 0.115\,\Omega/km$, $l_2 = 0.5\,km$
Wind farm 3	6 × 850 kW (G13–G18)
Generator (G13–G18)	Asynchronous (Type II): $P_{rG} = 850\,kW$, $U_{rG} = 690\,V$, $I_{rG} = 710\,A$, $I_{LR} = 5.5\,kA$, $R_G/X_G = 0.1$
Unit transformer (T13–T18)	$S_{rT} = 1000\,kVA$, $t_{rT} = 20(\pm 5\%)/0.69\,kV$, $u_{krT} = 6\%$, $u_{RrT} = 1.1\%$
Reactor	$S_{rR} = 6\,MVA$, $U_{rR} = 20\,kV$, $u_{kr} = 14\%$, $u_{Rr} = 0\%$
Line L3	Overhead line: $R_L = 0.215\,\Omega/km$, $X_L = 0.334\,\Omega/km$, $l_3 = 10\,km$ Underground cable: $R_L = 0.162\,\Omega/km$, $X_L = 0.115\,\Omega/km$, $l_3 = 1\,km$
SHEP	3 × 1500 kW (G19–G21)
Generator (G19–G21)	Synchronous (Type I): $S_{rG} = 1650\,kVA$, $U_{rG} = 690\,V$, $x''_d = 0.18\,p.u.$, $R_G/X''_d = 0.15$, $\cos\varphi_{rG} = 0.9$(lag) (operating p.f.=0.95 lag. to 0.95 lead.)
Unit transformer (T19, T20)	T19: $S_{rT} = 3.5\,MVA$, $t_{rT} = 20(\pm 5\%)/0.69\,kV$, $u_{krT} = 8\%$, $u_{RrT} = 1\%$ T20: $S_{rT} = 2\,MVA$, $t_{rT} = 20(\pm 5\%)/0.69\,kV$, $u_{krT} = 6\%$, $u_{RrT} = 1\%$
Line L4	Overhead line: $R_L = 0.215\,\Omega/km$, $X_L = 0.334\,\Omega/km$, $l_4 = 7.5\,km$

Source: Boutsika, T.N.; Papathanassiou, S.A. “Short-circuit calculations in networks with distributed generation”. Electric Power Systems Research 78, 2008. pp: 1181–1191

EXAMPLE

MV distribution network:

Fault level calculation procedure and results

Contribution of upstream grid

Network feeder

$(10) \Rightarrow Z_Q = 8.25\,\Omega$

$\underline{Z}_{Qt} = \underline{Z}_Q / t_r^2 = 0.016 + j0.161\,(\Omega)$

System transformer

$(11) \Rightarrow Z_T = 1.81\,\Omega, \quad (12) \Rightarrow R_T = 0.028\,\Omega$

$(13) \Rightarrow X_T = 1.808\,\Omega, \quad (17) \Rightarrow K_T = 0.930556$

$\underline{Z}_T = 0.026 + j1.682\,(\Omega)$

Contribution of the grid

$(22) \Rightarrow I_k'' = 6.889\,\text{kA} \quad (S_k'' = 238.65\,\text{MVA}, \varphi_k = 88.684^\circ)$

Contribution of wind farm 1 (Type IV)

Single generator

$(24) \Rightarrow I_{ki}'' = 1.5\,I_{rG} = 1.299\,\text{kA}$

Wind farm contribution

$(24) \Rightarrow I_k'' = 6 \cdot (I_{ki}''/t_r) = 0.156\,\text{kA} \quad (S_k'' = 5.4\,\text{MVA}, \varphi_k = 90^\circ)$

Contribution of wind farm 2 (Type III)

Single generator

$(16) \Rightarrow Z_G = 0.089\,\Omega$

$\underline{Z}_{Gt} = \underline{Z}_G \cdot t_r^2 = 7.434 + j74.338\,(\Omega)$

Unit transformer

$(11) \Rightarrow Z_T = 28.57\,\Omega, \quad (12) \Rightarrow R_T = 6.857\,\Omega$

$(13) \Rightarrow X_T = 27.736\,\Omega, \quad (17) \Rightarrow K_T = 1.015428$

$\underline{Z}_T = 6.963 + j28.164\,(\Omega)$

Line L2

$$\underline{Z}_L = \sum_i R_i \cdot l_i + \sum_i X_i \cdot l_i$$

$\underline{Z}_{L2} = 2.231 + j3.398\,(\Omega)$

Wind farm contribution

$(23) \Rightarrow I_k'' = \frac{cU_n}{\sqrt{3}(\underline{Z}_{Gt}/6 + \underline{Z}_T/6 + \underline{Z}_{L2})} \Rightarrow I_k'' = 0.605\,\text{kA} \quad (S_k'' = 20.95\,\text{MVA}, \varphi_k = 77.261^\circ)$

Contribution of wind farm 3 (Type II):

Single generator

$(16) \Rightarrow Z_G = 0.072\,\Omega$

$\underline{Z}_{Gt} = \underline{Z}_G \cdot t_r^2 = 6.055 + j60.552\,(\Omega)$

Unit transformer

$(11) \Rightarrow Z_T = 24\,\Omega, \quad (12) \Rightarrow R_T = 4.4\,\Omega$

$(13) \Rightarrow X_T = 23.593\,\Omega, \quad (17) \Rightarrow K_T = 1.009282$

$\underline{Z}_T = 4.441 + j23.812\,(\Omega)$

Reactor

$(11) \Rightarrow Z_R = X_R = 9.333\,\Omega$

Line L3

$$\underline{Z}_L = \sum_i R_i \cdot l_i + \sum_i X_i \cdot l_i$$

$\underline{Z}_{L3} = 2.312 + j3.455\,(\Omega)$

Wind farm contribution

$(23) \Rightarrow I_k'' = \frac{cU_n}{\sqrt{3}(\underline{Z}_{Gt}/6 + \underline{Z}_T/6 + \underline{Z}_R + \underline{Z}_{L3})} \Rightarrow I_k'' = 0.468\,\text{kA}$

$(S_k'' = 16.2\,\text{MVA}, \varphi_k = 81.398^\circ)$

Please note: according to IEC 60909

$$I_k'' = \frac{cU_n}{\sqrt{3}Z_k}$$

I_k: initial symmetrical SCC

U_n: line-to-line voltage

Z_k: Thevenin impedance of the grid

c: scaling factor.

- c =1.05 for MV/HV
- c =1.10 for LV

Source: Boutsika, T.N.; Papathanassiou, S.A. “Short-circuit calculations in networks with distributed generation”. Electric Power Systems Research 78, 2008. pp: 1181–1191

EXAMPLE

Example case - MV distribution network:

Fault level calculation procedure and results

Contribution of SHEP (Type I)	
Single generator	$R_G = (R_G/X''_d) \cdot x''_d \cdot (U^2_{rG}/S_{rG}) = 0.008\,\Omega$
	$(14) \Rightarrow \underline{Z}_G = 0.008 + 0.052\,(\Omega)$
Unit transformer	$(11)–(13) \Rightarrow \underline{Z}_{T19(HV)} = 1.143 + j9.071\,(\Omega)$
	$(11)–(13) \Rightarrow \underline{Z}_{T20(HV)} = 2 + j11.832\,(\Omega)$
	$(17) \Rightarrow K_{T19} = 0.997496$
Correction factors	$(19) \Rightarrow K_G = 1.041465(\sin\varphi = 0.312)$
	$(21) \Rightarrow K_{SO} = 1.041465\,(p_G, p_T = 0, \sin\varphi = 0.312)$
(G19//G20 + T19)	$\underline{Z}_I = \frac{K_G \underline{Z}_G}{2} \cdot t_r^2 + K_{T19}\underline{Z}_{T19} = 4.548 + j31.771\,(\Omega)$
(G21 + T21)	$\underline{Z}_{II} = K_{SO}(\underline{Z}_G \cdot t_r^2 + \underline{Z}_{T20}) = 8.9 + j57.769\,(\Omega)$
Line L4	$\underline{Z}_{L4} = 1.613 + j2.505\,(\Omega)$
SHEP contribution	$(27) \Rightarrow \underline{I}''_k = \frac{cU_n}{\sqrt{3}(\underline{Z}_1 // \underline{Z}_2 + \underline{Z}_{L4})} \Rightarrow I''_k = 0.541\,\text{kA} \quad (S''_k = 18.75\,\text{MVA}, \varphi_k = 78.629^\circ)$
Resulting fault level at the MV busbars	
$S''_k = 299.96$ MVA	Algebraic sum
$S''_k = 299.28$ MVA	Phasor sum with contribution of WF1 added algebraically

Please note: according to IEC 60909

$$I_k'' = \frac{cU_n}{\sqrt{3}Z_k}$$

I_k: initial symmetrical SCC

U_n: line-to-line voltage

Z_k: Thevenin impedance of the grid

c: scaling factor.

- c =1.05 for MV/HV
- c =1.10 for LV

Source: Boutsika, T.N.; Papathanassiou, S.A. “Short-circuit calculations in networks with distributed generation”. Electric Power Systems Research 78, 2008. pp: 1181–1191