Chapter 13 - Transmission

13.1 Introduction

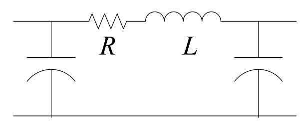
Power analysis looks at the energy conversion segment of electrical systems. Machines can be modeled as a Thevenin equivalent voltage and impedance with a magnetizing circuit consisting of an inductor with its resistance. Three types of problems are encountered.

1) Model parameters and losses require the complete model using circuit theory.
2) Transients and load flow use the Thevenin equivalent.
3) Steady state uses the terminal conditions with complex power.

The time domain signal representation contains all the components of the responses including DC, transient, and sinusoidal.

$$y(t) = F + (I - F)e^{-t/\tau} \cos(\omega t + \theta)$$

13.2 Transmission Lines



Power transmission is investigated by making a two-port network for the line. The components are distributed and are typically measured in Ohms/mile, Ohms/foot, or Ohms/km. Since impedance can only be measured use one-phase, work the problem as per- phase.

The normal representation is the conductor resistance in series with the magnetizing (inductive) reactance. The capacitance for the phase is split with half at the beginning and half at the end of the line. This is the same model as a low pass filter, where higher frequencies are shunted to ground.

13.3 Geometric Mean

The reactance of aerial cable depends on the spacing between wires. The effective distance between the wires is called the geometric mean radius (GMR).

Reactance of most cables is published by the manufacturer. The reactance in ohms per 1000 feet of aerial cables with one foot spacing can be found with the following formula.

$$X_L = 0.02298 * \ln\left(\frac{1}{GMR}\right)$$

GMR is the geometric mean radius in feet. It can be calculated by multiplying the wire O.D. in inches by .03245.

$$GMR \cong R * e^{-0.25} \cong 0.3894 * D \cong 0.03245 * d$$

R = wire radius in feet
D = wire diameter in feet
d = wire diameter in inches

Reactance at spacings other than one foot can be calculated with the following formula.

$$X_{new} = X_{old}\left[1 + \frac{\ln(spacing)}{\ln\left(\frac{1}{GMR}\right)}\right]$$

Cable operating temperature has an effect on the resistance of a cable. Most cables have a rated operating temperature of 90 °C. Aerial cable is rated 75 °C. Cables have higher resistances at their rated operating temperature ratings than at ambient temperature. The resistance at rated operating temperature can be calculated from the resistance at ambient temperature using the following formula.

$$R_2 = R_1\left[1 + \alpha\left(T_2 - T_1\right)\right]$$

R_2 = resistance at operating temperature

R_1 = resistance at ambient temperature

T_2 = rated operating temperature

T_1 = ambient temperature

α = temperature coefficient of resistivity corresponding to temperature T_1 (0.00393 for copper at 20 °C)

The current that causes the cable to reach its highest temperature may not be the maximum available current. The current depends on the cable's resistance and the resistance depends on the current. The maximum available current should be the current that causes maximum temperature.

13.4 Per Unit Notation

Per unit notation is used to reduce the complexity when working with circuits that have multiple voltage levels. Both Ohm's law and the power relationship permit a third term to be calculated from only two terms.

Two parameters are selected as the reference or base values. These are generally S and V. A different base V is used on each side of a transformer. The base current and base impedance can be determined from these two values

$$I_{base} = \frac{S_{base}}{V_{base}}$$

$$Z_{base} = \frac{V_{base}^{\ 2}}{S_{base}}$$

All the circuit equipment voltages and currents are then converted to per unit (percentage) values before normal circuit calculations are made

$$S_{pu} = \frac{S_{equip} * 100}{S_{base}}$$

$$V_{pu} = \frac{V_{equip} * 100}{V_{base}}$$

$$I_{pu} = \frac{I_{equip} * 100}{I_{base}}$$

$$Z_{pu} = \frac{Z_{equip} * 100}{Z_{base}}$$

As an example, transformer impedance is usually rated in per unit values. To find the actual impedance, combine the above equations

$$Z_{equip} = \left(\frac{Z_{pu}}{100}\right) Z_{base}$$

$$Z_{equip} = \left(\frac{Z_{pu}}{100}\right) \frac{V_{base}^{\ 2}}{S_{base}}$$

An example illustrates the relationship between per unit values and short circuit capability.

Transformer, S_{base}=10kVA, V_{base}=120, Z_{pu}=2%

$$Z_{equip} = \frac{\left(\frac{2}{100}\right) 120^2}{10000} = 0.0288\Omega$$

$$SCC = 10000\left(\frac{100}{2}\right) = 5000kVA = \frac{S_{base}}{Z_{pu}}$$

$$I_{sc} = \frac{V}{Z_{equip}} = \frac{SCC}{V_{base}} = \frac{V_{base}}{Z_{equip}} = 4167A \text{ (use pre-fault voltage)}$$

13.5 Short Circuit Considerations

13.5.1 Introduction

A short circuit condition differs from normal current operations only by virtue of an accidental decrease in the circuit impedance. The decrease in impedance is caused by a fault.

The power source is generally rated by a short circuit capacity (SCC) rating in volt-amps. This is the product of the pre-fault voltage and the post-fault current. Short circuit current is restricted only by the source impedance, since the load is greatly reduced.

$$VA_{scc1} = V_{pre} I_{sc}$$

$$VA_{scc3} \sqrt{3} V_{pre} I_{sc}$$

With the short circuit capability and the voltage rating, the source impedance can be determined. The impedance calculated is for each phase, if the system is three-phase.

$$Z_{source} = \frac{V_p^{\ 2}}{SCC}$$

The SCC of a magnetic device, such as a transformer or machine, can be found using the percent impedance (Z_{pu}) and the device rating

$$SCC = kVA\left(\frac{100}{Z_{pu}}\right) = \frac{kVA}{Z_{pu}}$$

The available fault current is also restricted by the SCC of the transformer

$$I_{SC_3} = \frac{SCC_3}{\sqrt{3} V_{line}}$$

$$I_{SC_1} = \frac{SCC_1}{V_{line}}$$

The available fault current is restricted by the source fault current and the transformer turns ratio.

$$N = \frac{V_{primary}}{V_{secondary}}$$

$$I_{SC_{secondary}} = I_{SC_{primary}} N$$

The available fault current is the smaller value that is calculated using the two methods above. Other impedance in the wiring will further restrict the fault current.

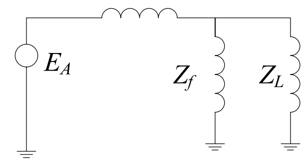
$$I_{SC} = \frac{V_{pre}}{Z_{fault}}$$

Short circuit contribution from induction machines continues after a fault. Inertia causes the machine to continue turning with a collapsing magnetic field. This results in approx 25% of the machine's capability contributing to the fault current.

13.5.2 Fault Analysis

Fault analysis is commonly called a short-circuit study. Fault current differs from normal current only by an accidental decrease in circuit Z.

Under fault conditions, the load (Z_L) may be 1 or more Ohm, while the fault is ~0.0001 ohm.



The resulting Z is a parallel combination.

$$\frac{1}{Z_T} = \frac{1}{0.0001} + \frac{1}{1} = 1\times10^4 + 1$$

The load is negligible compared to the fault.

$$I_{fault} = \frac{V_A}{Z_T} \approx \frac{V_A}{Z_f}$$

Realistically, the Z_T will provide a significant restriction on fault current. The first part of the process is to select the base values for the one-line diagram.

4) Need complete one-line diagram
5) Convert to per unit (percent)
6) Normally pick S_b & V_b, and then calculate I_b & S_b

$$I_b = \frac{S_b}{V_b}$$

$$Z_b = \frac{V_b}{I_b} = \frac{|V_b|^2}{S_b} = \frac{\left(\sqrt{3}V_b\right)^2}{3S_b}$$

Because to the three-phase characteristics, we can use either per phase values or line values for 3-phase current and voltage calculations

Do all calculations on single phase basis for Z. Impedance is a phase measurement only.

13.6 Symmetrical Components

Faults by definition indicate there is an imbalance in the system. This impacts the impedance and the resulting current and voltage drops. Because of the asymmetry, the interaction in the calculation would be very convoluted. A preferred method is to make a transform that converts the system to balanced, and separates the components by the 120° normally expected in three-phase power systems.

The transform is called symmetrical components. The operator is α

$$\alpha = -0.5 + j0.866 = 1\angle 120°$$

$$\alpha^2 = -0.5 - j0.866 = 1\angle -120°$$

Sequence Currents

Sequence currents are positive, negative, and zero sequence. These are found from the transform operating on the phase currents.

$$I_{A+} = \tfrac{1}{3}(I_A + \alpha I_B + \alpha^2 I_C) = I_1 = I_p$$

$$I_{A-} = \tfrac{1}{3}(I_A + \alpha^2 I_B + \alpha I_C) = I_2 = I_n$$

$$I_{A0} = \tfrac{1}{3}(I_A + I_B + I_C) = I_o = I_G$$

Line Currents

Phase currents can be obtained by taking the inverse transform on the sequence currents.

$$I_A = I_{A+} + I_{A-} + I_{A0}$$

$$I_B = I_{B+} + I_{B-} + I_{B0}$$

$$I_C = I_{C+} + I_{C-} + I_{C0}$$

Symmetrical components are used to take any unbalance combination of V & I and make them operate as balanced 3φ model.

The only use is to aid the algebra. Symmetrical components are not “real”.

13.7 Ratings & Reactances

Under fault conditions, the power system waveform goes through a transient condition until it stabilizes. Three types of transient are used to describe the changes in state.

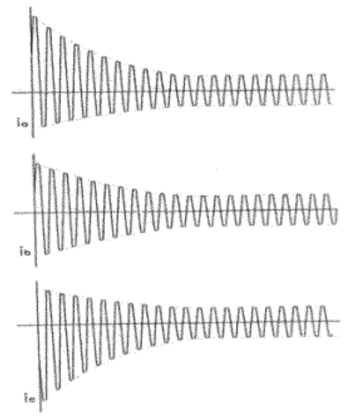
7) Momentary is the first cycle. Use all induction motors and subtransient (X_d'') reactances
8) Interrupting is for contact parting. Neglect branches w/ pure induction motors and use only transient (X_d') reactances, except below 600V
9) Assymetrical – use multiplier from tables (if not known, use 1.6)

Reactance values are dependent of frequency. Therefore, the reactance will change as the slope of the waveform varies. There are three conditions.

Sub-transient is during the first cycle to 0.1 seconds of the fault.

Transient is during 30 cycles to 2 seconds.

Synchronous is the steady state rating.



Rules of Thumb

$X_d \text{(steady state)} \approx 1.0$

$X_d' \text{(transient)} \approx 0.33$

$X_d'' \text{(subtransient)} \approx 0.25 \; for < 600V$

$X_d'' \text{(subtransient)} \approx 0.2 \; for > 600V$

13.8 Short Circuit Study

13.8.1 One-line diagram

A short circuit study is dependent on how the fault is connected within the one-line diagram.

1) Draw single line diagram w/ all sources of fault current, such as generators & motors, and utility connections.
2) Replace all components, including reactance, with resistors (impedance) symbol, and label with letters.
3) Show all transformer secondary feeding induction motors, whether motors are indicated or not.
4) Join all components by “infinite bus” (neutral)
5) The source is not the infinite bus, but is simply another reactance.
6) Rearrange impedances into series & parallel.
7) Reduce to single Z.
8) Convert Δ blocks to star to further reduce (Thevenin Z)

Example

The circuit in Figure 1 has a fault at X.

Calculate the Thevenin Z at the fault.

Use pre-fault V at the fault to find fault current, I.

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2)**Error! Not a valid link.**

3) **Error! Not a valid link.**

4)**Error! Not a valid link.**

5)**Error! Not a valid link.**

6)**Error! Not a valid link.**

13.8.2 Unbalanced Faults

The previous fault analysis development was for a 3-phase fault.

$$I_A + I_B + I_C = 0$$

Unbalanced conditions are redefined in terms of 3 components.

Positive sequence (+, p, 1)

System with sources rotating

"Normal" conditions

Negative sequence (-, n, 2)

The negative sequence is the same circuit as positive, but without sources.

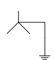
Z may have different value

Zero Sequence (0, Z, 0)

The zero sequence circuit is simply the ground path.

Δ has no ground

 has no Ground

 has a ground path

Draw three circuits, one for each sequence.

Leave sources in positive

Make negative w/o sources

Zero indicates ground paths

Connect each sequence with fault impedances for each component.

$3Z_f$ represents the fault impedance in pos, neg & zero sequences.

13.8.3 Faults with Rotating Machines

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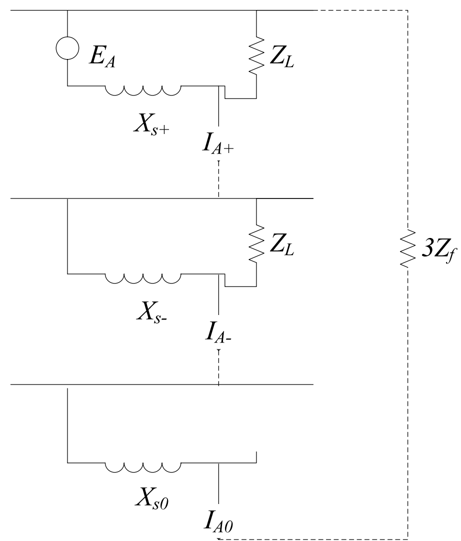
$$V_+ = E_A - Z_+ I_+$$

$$V_- = 0 - Z_- I_-$$

$$V_0 = 0 - Z_0 I_0$$



For 3φ faults, use the positive sequence only.

$$I_A + I_B + I_C = 0$$

$$I_A = I_{A+} + I_{A-} + I_{A0}$$

For one phase, calculate the symmetrical current..

$I_{A+} = \frac{1}{3} I_A$, since $I_{A+} = I_{A-} = I_{A0}$

The current is drawn at the fault.

The zero sequence is the path through ground. It will change depending on the wye or delta connection.

Z_0 will be different since transformer & machine ground path may not be connected

Z_0 motor or gen = $3Z_n$

Z_0= 0 for connected neutrals

In zero sequence, include machine impedance to ground.

$3Z_n$=3 times impedance of any phase

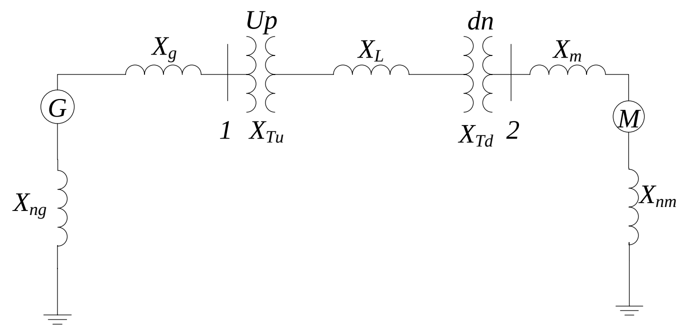
Use in place of source voltage

An assumption can be made for the sub-transient reactance.

$$Z''_{d0\,motor} = \frac{1}{2} Z''_{d0}$$

13.8.4 Fault Illustrations

A one-line diagram shows a generator, transformers, transmission line, and motor load. Convert the one-line into positive, negative, and zero sequences.



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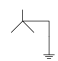
If the connection on a transformer to ground is  , then insert the connection and impedance. Else, leave the ground connection open.

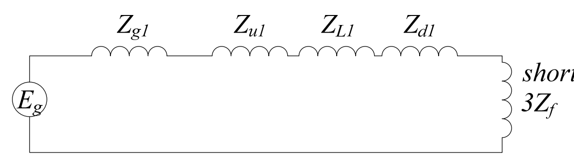
Illustrations are developed for four types of faults.

Three phase fault at 2, use positive sequence only.

$$V_0 = V_2 = 0$$

$$I_1 = \frac{V_f}{Z_{eqt}}$$

$$I_0 = I_2 = 0$$

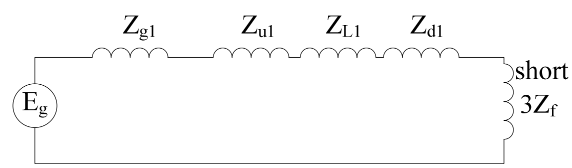


Single phase line to ground at 2, use positive, negative, and zero sequence in series.

$$V_0 + V_1 + V_2 = 3Z_f I_1$$

$$I_1 = \frac{V_{fault}}{Z_1 + Z_2 + Z_0 + 3Z_f}$$

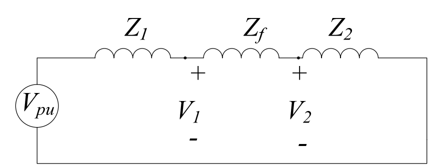
$$I_1 = I_2 = I_o$$



Line to line, use positive in series with negative and connect with Z_f.

$$I_1 = \frac{V_f}{Z_1 + Z_f + Z_2}$$

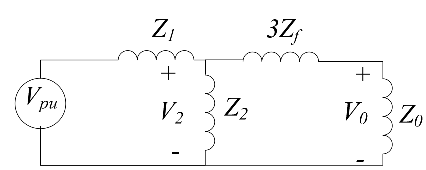
$$I_1 = -I_2$$



Double line to ground, use positive with negative in parallel with zero.

$$I_1 = \frac{Vf}{(Z_1 + Z_2 \,||\, 3Z_f + Z_0)}$$

$$I_1 = I_2 + I_0$$



13.8.5 Symmetrical RMS Fault Currents / Voltages in Terms of Sequence Impedances				
	Three-phase fault through three-phase fault impedance Z_f	Line-to-Line fault. Phase b and c shorted through fault impedance Z_f	Line-to-line fault. Phase a grounded through fault impedance Z_f	Double line-to-ground fault. Phases b and c shorted, then grounded through fault impedance Z_f
I_a	$\frac{V_f}{Z_1+Z_f}$	0	$\frac{3V_f}{Z_0+Z_1+Z_2+3Z_f}$	0
I_b	$\frac{a^2V_f}{Z_1+Z_f}$	$-j\sqrt{3}\frac{V_f}{Z_1+Z_2+Z_f}$	0	$-j\sqrt{3}V_f\frac{Z_0+3Z_f-aZ_2}{Z_1Z_2+(Z_1+Z_2)(Z_0+3Z_f)}$
I_c	$\frac{aV_f}{Z_1+Z_f}$	$j\sqrt{3}\frac{V_f}{Z_1+Z_2+Z_f}$	0	$j\sqrt{3}V_f\frac{Z_0+3Z_f-a^2Z_2}{Z_1Z_2+(Z_1+Z_2)(Z_0+3Z_f)}$
V_a	$V_f\frac{Z_f}{Z_1+Z_f}$	$V_f\frac{2Z_2+Z_f}{Z_1+Z_2+Z_f}$	$V_f\frac{3Z_f}{Z_0+Z_1+Z_2+3Z_f}$	$V_f\frac{3Z_2(Z_0+2Z_f)}{Z_1Z_2+(Z_1+Z_2)(Z_0+3Z_f)}$
V_b	$V_f\frac{a^2Z_f}{Z_1+Z_f}$	$V_f\frac{a^2Z_f-Z_2}{Z_1+Z_2+Z_f}$	$V_f\frac{3a^2Z_f-j\sqrt{3}(Z_2-aZ_0)}{Z_0+Z_1+Z_2+3Z_f}$	$V_f\frac{-3Z_fZ_2}{Z_1Z_2+(Z_1+Z_2)(Z_0+3Z_f)}$
V_c	$V_f\frac{aZ_f}{Z_1+Z_f}$	$V_f\frac{aZ_f-Z_2}{Z_1+Z_2+Z_f}$	$V_f\frac{3aZ_f+j\sqrt{3}(Z_2-a^2Z_0)}{Z_0+Z_1+Z_2+3Z_f}$	$V_f\frac{-3Z_fZ_2}{Z_1Z_2+(Z_1+Z_2)(Z_0+3Z_f)}$
V_{bc}	$j\sqrt{3}V_f\frac{Z_f}{Z_1+Z_f}$	$j\sqrt{3}V_f\frac{Z_f}{Z_1+Z_2+Z_f}$	$j\sqrt{3}V_f\frac{3Z_f+Z_0+2Z_2}{Z_0+Z_1+Z_2+3Z_f}$	0
V_{ca}	$j\sqrt{3}V_f\frac{a^2Z_f}{Z_1+Z_f}$	$j\sqrt{3}V_f\frac{a^2Z_f-j\sqrt{3}Z_2}{Z_1+Z_2+Z_f}$	$j\sqrt{3}V_f\frac{a^2(3Z_f+Z_0)-Z_2}{Z_0+Z_1+Z_2+3Z_f}$	$\sqrt{3}V_f\frac{\sqrt{3}Z_2(Z_0+3Z_f)}{Z_1Z_2+(Z_1+Z_2)(Z_0+3Z_f)}$
V_{ab}	$j\sqrt{3}V_f\frac{aZ_f}{Z_1+Z_f}$	$j\sqrt{3}V_f\frac{aZ_f+j\sqrt{3}Z_2}{Z_1+Z_2+Z_f}$	$j\sqrt{3}V_f\frac{a(3Z_f+Z_0)-Z_2}{Z_0+Z_1+Z_2+3Z_f}$	$-\sqrt{3}V_f\frac{\sqrt{3}Z_2(Z_0+3Z_f)}{Z_1Z_2+(Z_1+Z_2)(Z_0+3Z_f)}$

13.9 Interrupting Capability

Voltage ratings

Rated maximum voltage: Designated the maximum rms line-to-line operating voltage. The breaker should be used in systems with an operating voltage less than or equal to this rating.

Rated low frequency withstand voltage: The maximum 60-Hz rms line-to-line voltage that the circuit breaker can withstand without insulation damage.

Rated impulse withstand voltage: The maximum crest voltage of a voltage pulse with standard rise and delay times that the breaker insulation can withstand.

Rated voltage range factor K: The range of voltage for which the symmetrical interrupting capability times the operating voltage is constant.

Current ratings

Rated continuous current: The maximum 60-Hz rms current that the breaker can carry continuously while it is in the closed position without overheating.

Rated short-circuit current: The maximum rms symmetrical current that the breaker can safely interrupt at rated maximum voltage.

Rated momentary current: The maximum rms asymmetrical current that the breaker can withstand while in the closed position without damage. Rated momentary current for standard breakers is 1.6 times the symmetrical interrupting capability.

Rated interrupting time: The time in cycles on a 60-Hz basis from the instant the trip coil is energized to the instant the fault current is cleared.

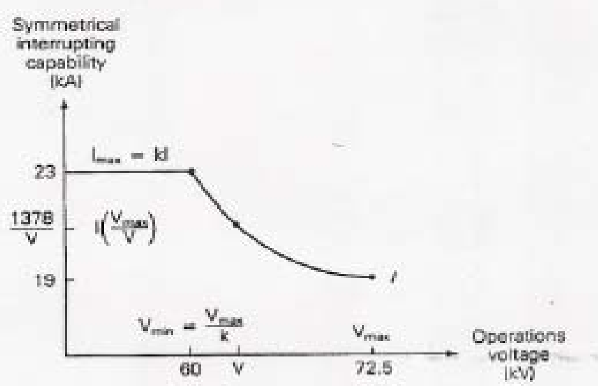
Rated interrupting MVA: For a three-phase circuit breaker, this is $\sqrt{3}$ times the rated maximum voltage in kV times the rated short-circuit current in kA. It is more common to work with current and voltage ratings than with MVA rating.

As an example, the symmetrical interrupting capability of the 69-kV class breaker listed in Table 8.10 is plotted versus operating voltage in Figure 8.12. As shown, the symmetrical interrupting capability increases from its rated short-circuit current $I = 19$ kA at rated maximum voltage $V_{max} = 72.5$ kV up to $I_{max} = KI = (1.21)(19) = 23$ kA at an operating voltage $V_{min} = V_{max}/K = 72.5/1.21 = 60$ kV. At operating voltages V between V_{min} and V_{max}, the symmetrical interrupting capability is $I \times V_{max}/V = 1378/V$ kA. At operating voltages below V_{min}, the symmetrical interrupting capability remains at $I_{max} = 23$ kA.

Breakers of the 115-kV class and higher have a voltage range factor $K = 1.0$; that is, their symmetrical interrupting current capability remains constant.

Figure 8.12

Symmetrical interrupting capability of a 69-kV class breaker



EXAMPLE 8.9 **Circuit breaker selection**

The calculated symmetrical fault current is 17 kA at a three-phase bus where the operating voltage is 64 kV. The X/R ratio at the bus is unknown. Select a circuit breaker from Table 8.10 for this bus.

Solution The 69-kV-class breaker has a symmetrical interrupting capability $I\left(\frac{V_{max}}{V}\right) = 19\left(\frac{72.5}{64}\right) = 21.5$ kA at the operating voltage $V = 64$ kV. The calculated symmetrical fault current, 17 kA, is less than 80% of this capability (less than $0.80 \times 21.5 = 17.2$ kA), which is a requirement when X/R is unknown. Therefore, we select the 69-kV-class breaker from Table 8.10. ■

Table 8.10 Preferred ratings for outdoor circuit breakers (symmetrical current basis of rating) [10]

IDENTIFICATION		RATED VALUES									RELATED REQUIRED CAPABILITIES		
		VOLTAGE		INSULATION LEVEL		CURRENT					CURRENT VALUES		
				RATED WITHSTAND TEST VOLTAGE									
NOMINAL VOLTAGE CLASS kV, rms	NOMINAL 3-PHASE MVA CLASS	RATED MAX VOLTAGE kV, rms	RATED VOLTAGE RANGE FACTOR K	LOW FREQUENCY kV, rms	IMPULSE kV, CREST	RATED CONTINUOUS CURRENT AT 60 Hz AMPERES, rms	RATED SHORT-CIRCUIT CURRENT (AT RATED MAX kV) kA, rms	RATED INTERRUPTING TIME CYCLES	RATED PERMISSIBLE TRIPPING DELAY SECONDS	RATED MAX VOLTAGE DIVIDED BY K kV, rms	MAX SYMMETRICAL INTERRUPTING CAPABILITY (K TIMES RATED SHORT-CIRCUIT CURRENT) kA, rms	3-SECOND SHORT-TIME CURRENT CARRYING CAPABILITY (K TIMES RATED SHORT-CIRCUIT CURRENT) kA, rms	CLOSING AND LATCHING CAPABILITY 1.6K TIMES RATED SHORT-CIRCUIT CURRENT kA, rms
COL 1	COL 2	COL 3	COL 4	COL 5	COL 6	COL 7	COL 8	COL 9	COL 10	COL 11	COL 12	COL 13	COL 14
14.4	250	15.5	2.67			600	8.9	5	2	5.8	24	24	38
14.4	500	15.5	1.29			1200	18	5	2	12	23	23	37
23	500	25.8	2.15			1200	11	5	2	12	24	24	38
34.5	1500	38	1.65			1200	22	5	2	23	36	36	58
46	1500	48.3	1.21			1200	17	5	2	40	21	21	33
69	2500	72.5	1.21			1200	19	5	2	60	23	23	37
115		121	1.0			1200	20	3	1	121	20	20	32
115		121	1.0			1600	40	3	1	121	40	40	64
115		121	1.0			2000	40	3	1	121	40	40	64
115		121	1.0			2000	63	3	1	121	63	63	101
115		121	1.0			3000	40	3	1	121	40	40	64
115		121	1.0			3000	63	3	1	121	63	63	101
138		145	1.0			1200	20	3	1	145	20	20	32
138	Not	145	1.0			1600	40	3	1	145	40	40	64
138		145	1.0			2000	40	3	1	145	40	40	64
138		145	1.0			2000	63	3	1	145	63	63	101
138		145	1.0			2000	80	3	1	145	80	80	128
138	Applica-	145	1.0			3000	40	3	1	145	40	40	64
138		145	1.0			3000	63	3	1	145	63	63	101
138		145	1.0			3000	80	3	1	145	80	80	128
161	ble	169	1.0			1200	16	3	1	169	16	16	26
161		169	1.0			1600	31.5	3	1	169	31.5	31.5	50
161		169	1.0			2000	40	3	1	169	40	40	64
161		169	1.0			2000	50	3	1	169	50	50	80
230		242	1.0			1600	31.5	3	1	242	31.5	31.5	50
230		242	1.0			2000	31.5	3	1	242	31.5	31.5	50
230		242	1.0			3000	31.5	3	1	242	31.5	31.5	50
230		242	1.0			2000	40	3	1	242	40	40	64
230		242	1.0			3000	40	3	1	242	40	40	64
230		242	1.0			3000	63	3	1	242	63	63	101
345		362	1.0			2000	40	3	1	362	40	40	64
345		362	1.0			3000	40	3	1	362	40	40	64
500		550	1.0			2000	40	2	1	550	40	40	64
500		550	1.0			3000	40	2	1	550	40	40	64
700		765	1.0			2000	40	2	1	765	40	40	64
700		765	1.0			3000	40	2	1	765	40	40	64

Table 8.10 (continued)

13.10 Exemplars

An exemplar is typical or representative of a system. These examples are representative of real world situations.

Practice Problem 13-1 (old style – similar to new style)

SITUATION:

In order to accommodate the needs of larger plant power systems, a switchgear manufacturer is offering a new line of vacuum circuit breakers rated in accordance with ANSI C 37.04 "Rating Structure for A-C High Voltage Circuit Breakers.

The following data apply:

Nominal voltage:	7.2kV
Nominal 3-phase MVA class:	700 MVA
Rated maximum voltage:	8.25kV
Rated voltage range factor (k):	1.3
Rated insulation level – low frequency:	36kV
Rated continuous current:	3000 A
Rated short circuit current:	46kA
Rated interrupting time:	5 cycles

REQUIREMENTS:

Determine the following related required capabilities (to three significant figures)

a) The symmetrical interrupting capability with the prefault voltage @ 7.2kV

b) The symmetrical interrupting capability with the prefault voltage @ 6.1kV

c) The symmetrical interrupting capability with the prefault voltage @ 8.5kV

d) Closing and latching capability operating voltage at 7.2kV

e) Closing and latching capability operating voltage at 6.1kV

f) Closing and latching capability operating voltage at 8.5kV

g) Three-second short time current carrying capability operating @ 7.2kV

h) If the circuit breaker is applied at a point where the system impedance is 0.08Ω/phase, what is the change in margin of symmetrical interrupting capability over short circuit current available when the operating voltage is changed from 7.2kV to 7.4kV?

SOLUTION:

i) Symmetrical interrupting capability at 7.2kV
Max kVA remains the same, so, as voltage goes down, current goes up, as long as voltage is within voltage range (1.3)

$$\frac{8.25}{7.2} = 1.15$$, so keep constant kVA

$$I_{SC} = I_{rated}\frac{V_{\max}}{V_{nom}} = 46\times 10^3\,\frac{8.25}{7.2} = 52.71\times 10^3\,Amp$$

- Symmetrical interrupting capability at 6.1kV
Max kVA remains the same, so, as voltage goes down, current goes up, as long as voltage is within voltage range (1.3)

$\frac{8.25}{6.1} = 1.35$, so limit voltage ratio to 1.3

$I_{SC} = I_{rated} * 1.3 = 46 \times 10^3 * 1.3 = 59.8 \times 10^3 \, Amp$

- Equipment is rated at 8.25kV, do not use at 8.5kV

  Max interrupting current: $I_m = 1.3 * 46 \times 10^3 = 59.8 \times 10^3 \, Amp$

  Refer to ANSY C 37.04 standards

- Closing & latching is 1.6 times the max current (at any voltage below rated)

  $I_{c\&l} = I_m * 1.6 = 95.68 \times 10^3 \, Amp$

- Closing & latching is 1.6 times the max current (at any voltage below rated)

  $I_{c\&l} = I_m * 1.6 = 95.68 \times 10^3 \, Amp$

- Equipment is rated at 8.25kV, do not use at 8.5k
- Three second current capability = max interrupting current (3s < 5s rating)

  $I_m = 1.3 * 46 \times 10^3 = 59.8 \times 10^3 \, Amp$

- 7.2kV is L-L voltage, need L-N (phase) voltage

  $V_{LN} = \frac{V_{LL}}{\sqrt{3}} = \frac{7200}{\sqrt{3}} = 4156.9V$

  System Z is 0.08,

  $I_{sc=} \frac{7200}{\sqrt{3} * 0.08} = 51.96 \times 10^3 \, Amp$

  From a) above, Max interrupting current at 7.2kV is 52.71x10^3 Amp, so margin is 748 Amp

- at 7.4kV, short circuit current is

  $I_{sc=} \frac{7400}{\sqrt{3} * 0.08} = 53.406 \times 10^3 \, Amp$

  Max short circuit current is

  $I_{SC\max} = I_{rated} \frac{V_{\max}}{V_{nom}} = 46 \times 10^3 \frac{8.25}{7.4} = 51.283 \times 10^3 \, Amp$

  So, equipment is overrated by 2,122 Amps. Change in margin is 2,870 Amps.

Practice Problem 13-2(old style)

SITUATION:

An industrial plant has four generators connected to a 13.8kV bus as shown in Figure 433 below. The neutral of each generator is connected through a neutral circuit breaker to a common neutral bus. This bus is connected through a neutral resistor to ground.

Individual generator reactances in pu:

$$X_d'' = j0.16$$
$$X_2 = j0.16$$
$$X_0 = j0.08$$

REQUIREMENTS:

j) Determine the value of the neutral resistor required to limit a line-to-ground fault to that of a three-phase fault when only one of the units is operating.

k) If a 0.1 pu neutral resistor is used, determine the ground fault current in pu when all units are operating, but with only one neutral circuit breaker closed.

l) Same as b., except all neutral circuit breakers closed.

SOLUTION:

Estimate positive, negative and zero sequence impedances from data given.

$$Z_1 \approx X_d'' = j0.16$$
$$Z_2 \approx X_2 = j0.16$$
$$Z_0 \approx X_0 = j0.08$$

a) $Z_f = Z_{resistor}$

$$I_{3ph} = \frac{v_f}{z_1 + z_f} \qquad I_{1ph} = \frac{3v_f}{Z_0 + Z_1 + Z_2 + 3Z_f}$$

Operating at 100% voltage (1.0 pu)

$$I_{3ph} = \frac{1.0}{j0.16 + 0} = -j6.25$$

$$I_{1ph} = \frac{3*1.0}{j0.16 + j0.08 + j0.16 + 3Z_{resistor}} = \frac{3}{j0.4 + 3Z_{resistor}}$$

Set $I_{1ph} = I_{3ph}$ and solve for $Z_{resistor}$

$$-j6.25 = \frac{3}{j0.4 + 3Z_{resistor}}$$

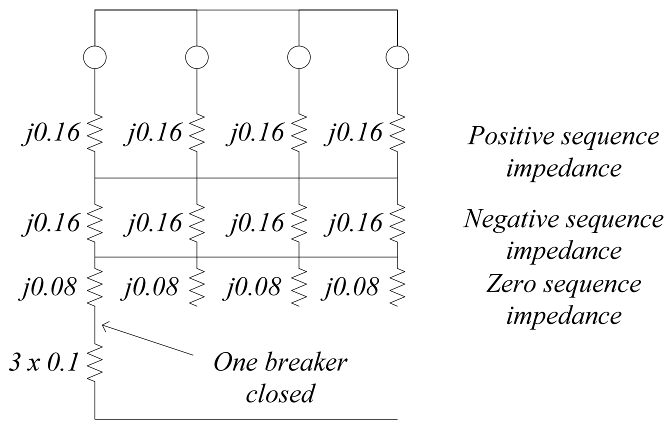
$$j0.4 + 3Z_r = \frac{3}{-j6.25}$$

$$\left(j0.4 + 3Z_r\right)^2 = \left(\frac{3}{-j6.25}\right)^2$$

$$0.16 + 9Z_r^{\ 2} = 0.2304$$

$$Z_r = \sqrt{\frac{0.2304 - 0.16}{9}}$$

$$= 0.08844$$



b)

$$I_{1ph} = \frac{3v_f}{Z_0 + Z_1 + Z_2 + 3Z_f} = \frac{3*1}{j0.08 + j0.04 + j0.04 + 3*j0.1}$$

$$I_{1ph} = \frac{3}{\sqrt{(j0.16)^2 + (0.3)^2}} = \frac{3}{\sqrt{X^2 + R^2}}$$

$$= 8.8235\,pu$$

c) With all breakers closed, Z_o=0.02j

$$I_{1ph} = \frac{3v_f}{Z_0 + Z_1 + Z_2 + 3Z_f} = \frac{3*1}{j0.08 + j0.04 + j0.02 + 3*j0.1}$$

$$I_{1ph} = \frac{3}{\sqrt{(j0.1)^2 + (0.3)^2}} = \frac{3}{\sqrt{X^2 + R^2}}$$

$$= 9.487\,pu$$

13.11 Applications

Applications are an opportunity to demonstrate familiarity, comfort, and comprehension of the topics.