Comparison of Calculation Procedures for Fault Analysis

Complex Network Methods (Ohms Law)

vs.

ANSI/IEEE Standards (ANSI C37.010, C37.5 and C37.13)

Prepared by SKM Systems Analysis, Inc. for the
Institute of Electrical and Electronics Engineers, Industry Application Society

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Introduction

There are three ANSI/IEEE standards which apply to the calculation of fault current values which are used for the ratings of equipment used in electrical power systems.

1.	ANSI C37.13	Applies to low voltage equipment.
2.	ANSI C37.5	Medium and High Voltage equipment total current rated.
3.	ANSI C37.010	Medium and High Voltage equipment symmetrical rated.

The current values calculated by these standards are described as currents for the rating of the equipment. This rating current is different from the prospective fault current which could flow through equipment during a faulted condition.

The prerequisites to understanding ANSI calculation procedures are (1) knowledge of the complex solution methodology (Ohms Law solution) and (2) use of per unit analysis techniques.

These notes include three phase analysis technique only. The standards require analysis of both the three phase and the single line to ground networks. Understanding of the three phase solution in this paper will fully demonstrate ANSI procedure.

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1.0 Per Unit Terminology

Per unit analysis is a method by which all of the system impedance values are normalized to a common base power usually expressed in kVA or in MVA. The system impedance values include the impedance of cables, overhead lines, transformers and sources of fault currents.

Network reduction methods are simplified by the use of per unit analysis, because (1) the transformer turns ratios may be ignored, (2) the impedance values of series circuits at different voltage levels can be added directly and (3) the admittance values of parallel circuits can likewise be added directly. Therefore, the Thevenin equivalent impedance at each point in the circuit can be determined more easily using per unit analysis (as opposed to using values in ohms).

It is assumed at this point that the engineer is familiar with per unit calculation procedures. The following Equations are presented as an aid in using per unit methods. Keep in mind that all impedance terms are in complex vector notation.

For utility contributions: $Z\ PU = (kVA_{base})/(kVA_{source})$

For motor contributions: $Z\ PU = Z_m \times (kVA_{base})/(kVA_{motor})$

For feeders: $Z\ PU = (Z_f \times kVA_{base})/[(KV_{ll})^2 \times 1000]$

where $Z_f = R + jX$ feeder impedance in ohms
and $Z_m = R_{machine} + X_d''$ (sub transient reactance)

For transformers: $Z\ PU = (Z_{tr\%} \times kVA_{base})/(100 \times kVA_{tr})$

where $Z_{tr\%}$ = Transformer % Z

To find fault current: $I_{fc} = (1\ PU\ Voltage/Z_{Thevenin}) * I_{base}$

where $I_{base} = (kVA_{base})/(kV_{ll} \times 1.732 \times 1000)$
and kV_{ll} = line to line voltage (in thousands)

These Equations permit the direct addition of series impedance values to find the total impedance at any fault location. Parallel impedance can be calculated by the direct addition of admittance (1/Z) of the parallel branches. By knowing the Thevenin impedance value at the fault location, the fault current can be calculated.

2.0 Three Phase Fault Calculations: Complex Network Solution Methods

Complex network solutions are best described as Ohms law solutions. The results of this solution present the best method of determination of the prospective symmetrical fault currents which may flow in the power system immediately after the fault. To solve for fault currents using this method, the use of complex numbers is required for analysis. A network reduction of the power system is required at each point in the system where fault current values are calculated.

Network reduction requires that a Thevenin equivalent circuit of the power system be generated which represents the series and parallel paths between the faulted bus location and the sources of the fault currents. Figure 1 illustrates a simple radial power system.

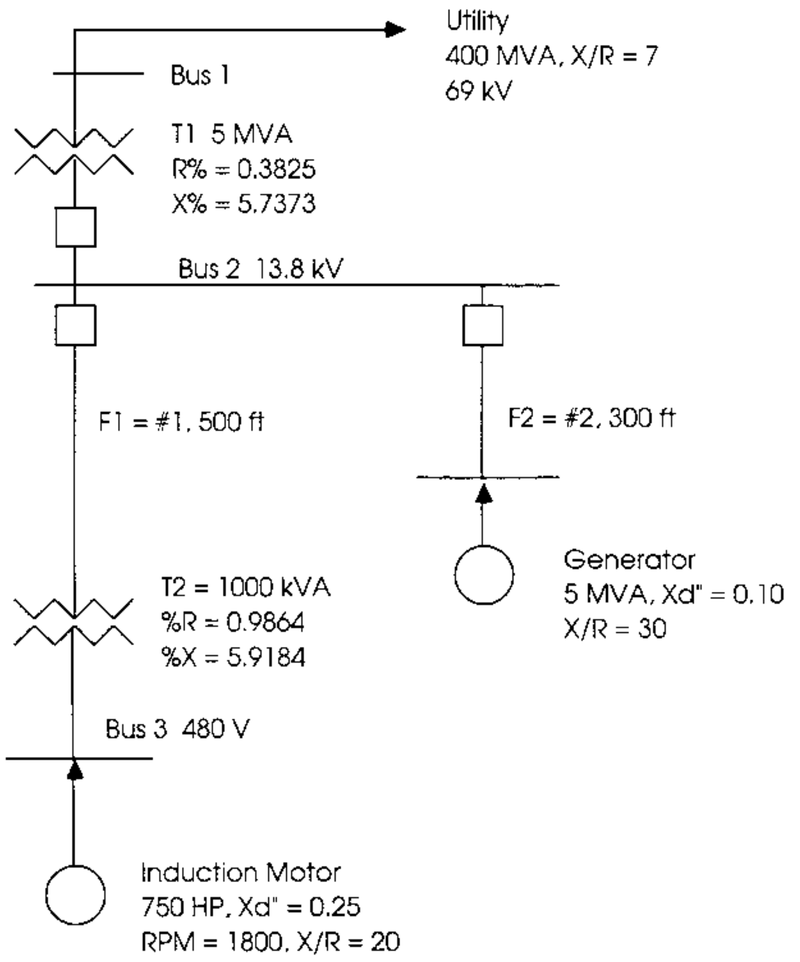


Figure 1. Sample one line diagram.

For faults at Bus 1, Bus 2 and Bus 3, the one line diagram reduces to the equivalent circuits shown in Figures 2, 3, and 4 respectively. Note that the equivalent circuits are considerably different for determination of the fault currents in each case.

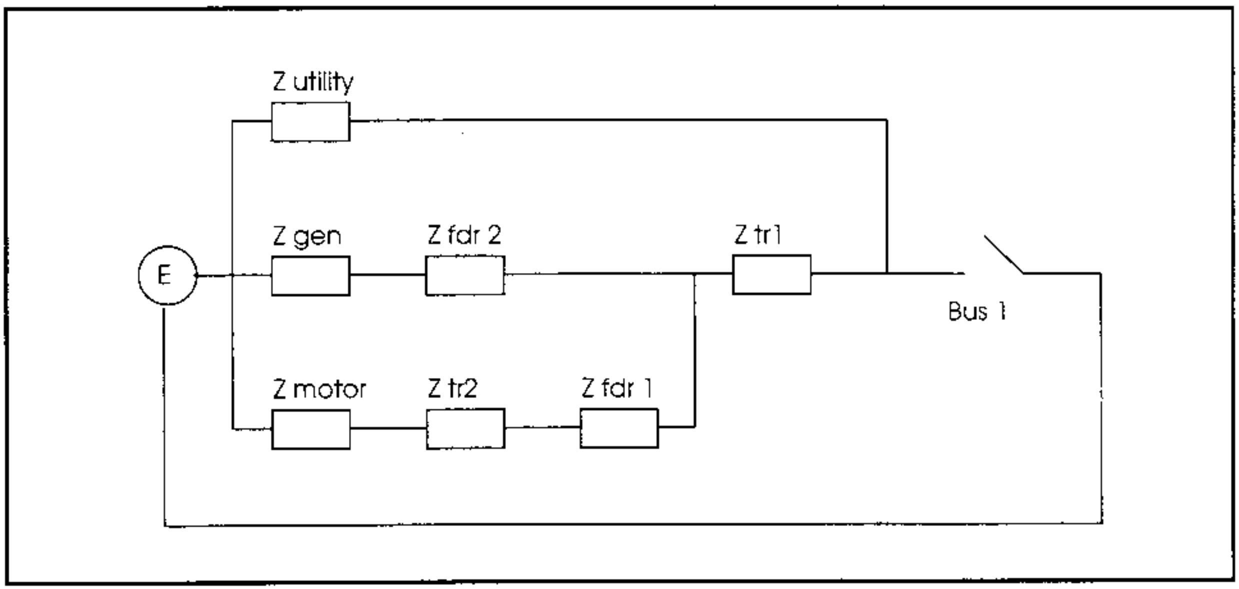


Figure 2. Equivalent network for a fault at Bus 1.

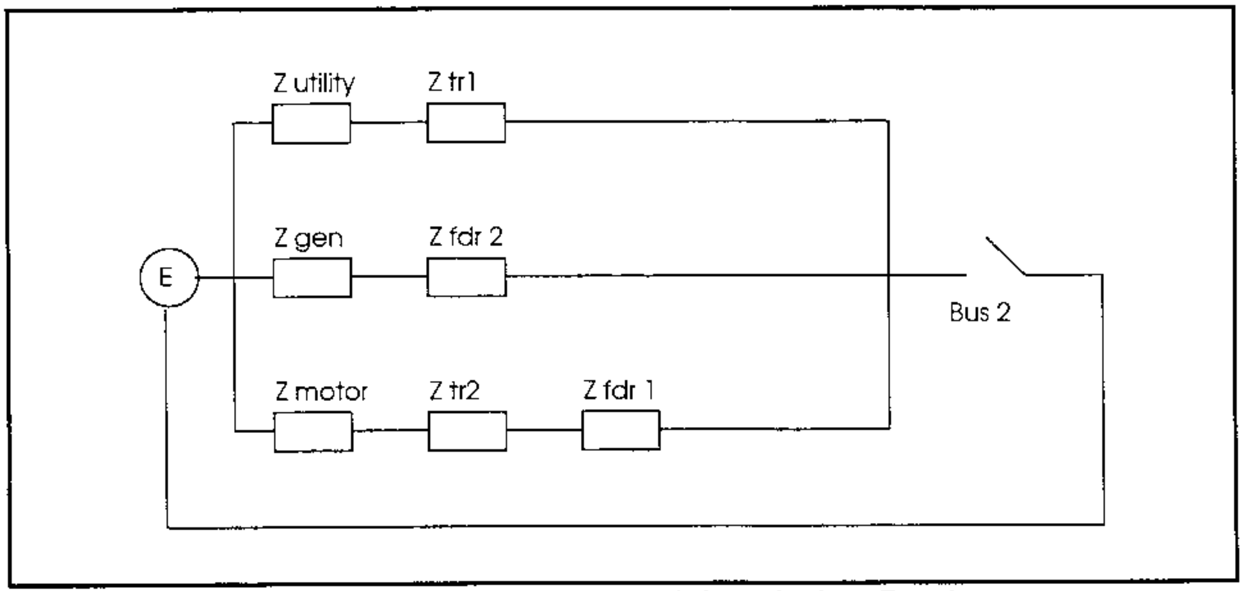


Figure 3. Equivalent network for a fault at Bus 2.

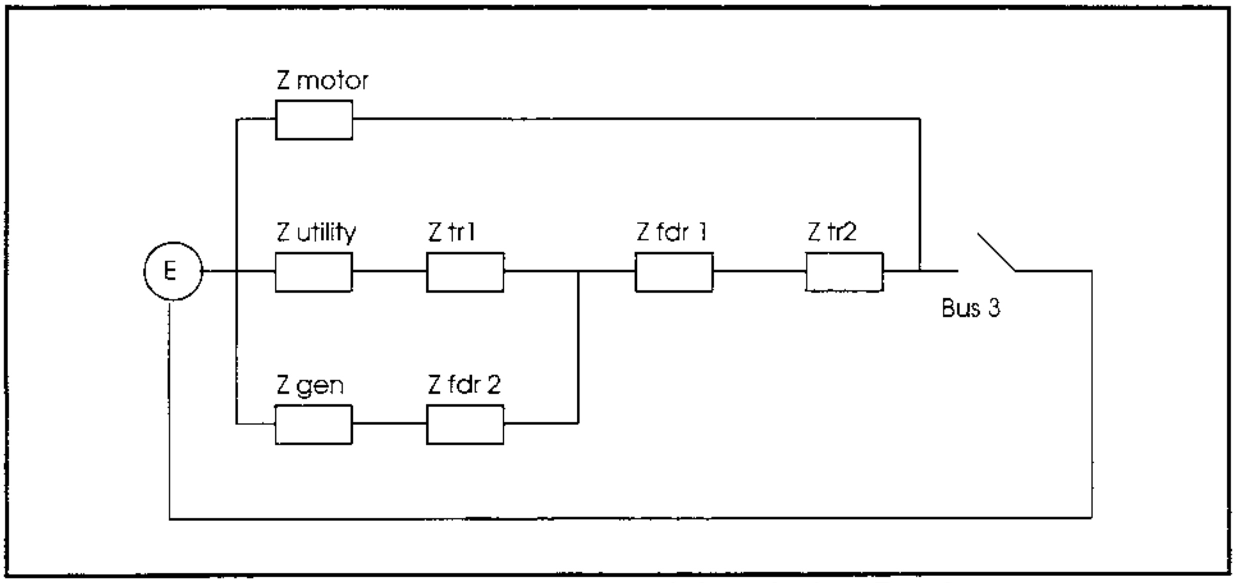


Figure 4. Equivalent network for a fault at Bus 3.

To calculate the fault currents in each case, the network is reduced by first combining the series branch elements and then combining the parallel branch elements to obtain a Thevenin equivalent circuit. Having calculated the Thevenin equivalent impedance of the power system at the faulted bus, the fault current is then calculated.

2.1 Sample Calculations for Complex Network Solutions

Step 1: Calculate the Per Unit Impedance Values

Calculate the per unit impedance of each element. Assume a 100 MVA base. Use the subtransient reactances of the motors and the generator to determine the maximum three phase symmetrical values.

Utility contribution

Z utility = $kVA_{base} / kVA_{source}$
= 100,000 / 400,000
= 0.25 per unit

Given: X/R = 7
then: θ = Arc Tan(X/R)

X per unit = Z utility * Sin θ
= 0.24749 per unit

R per unit = Z utility * Cos θ
= 0.03536 per unit

750 HP Induction Machine

Z machine = $Z_m * kVA_{base}/kVA_{motor}$

Assuming 1 hp = 1 kVA then

X per unit = $X_d'' * kVA_{base}/kVA_{motor}$
= 0.250 * (100,000/750)
= 33.3333 per unit

Since X/R = 20

R per unit = $X_d'' / (X/R) * kVA_{base}/kVA_{motor}$
= (0.25 / 20) * (100,000/750)
= 1.66666 per unit

5 MVA Generator

Z machine = $Z_m * kVA_{base}/kVA_{generator}$

X per unit = $X_d'' * kVA_{base}/kVA_{generator}$
= 0.100 * (100,000/5000)
= 2.00000 per unit

R per unit = $X_d'' / (X/R) * kVA_{base}/kVA_{generator}$
= (0.100 / 30) * (100,000/5000)
= 0.06667 per unit

5 MVA Transformer

Z PU = $(Z_{tr\%} \times kVA_{base})/(100 \times kVA_{tr})$

X per unit = 5.7373 * (100,000/(100 * 5000))
= 1.14745 per unit

R per unit = 0.3825 * (100,000/(100 * 5000))
= 0.07650 per unit

1000 kVA Transformer

Z PU = $(Z_{tr\%} \times kVA_{base})/(100 \times kVA_{tr})$

X per unit = 5.9184 * (100,000/(100 * 1000))
= 5.9184 per unit

R per unit = 0.9864 * (100,000/(100 * 1000))
= 0.9864 per unit

Feeder #1

Z PU = Z_f * $kVA_{base}/(kV_{ll}^2$ * 1000)

R Ohms/1000 ft = 0.1600 Ω
X Ohms/1000 ft = 0.0540 Ω

X per unit = (500 ft/1000) * 0.0540 * 100,000/ (13.8^2 * 1000)
= 0.01418 per unit
R per unit = (500 ft/1000) * 0.1600 * 100,000/ (13.8^2 * 1000)
= 0.04201 per unit

Feeder #2

Z PU = Z_f * $kVA_{base}/(kV_{ll}^2$ * 1000)

R Ohms/1000 ft = 0.2020 Ω
X Ohms/1000 ft = 0.0547 Ω

X per unit = (300 ft/1000) * 0.0547 * 100,000/ (13.8^2 * 1000)
= 0.00862 per unit
R per unit = (300 ft/1000) * 0.2020 * 100,000/ (13.8^2 * 1000)
= 0.03182 per unit

Summary of impedance values

Element	R per unit	X per unit
Z utility	0.03536	j 0.24749
Z motor	1.66666	j 33.3333
Z gen	0.06666	j 2.00000
Z TR 1	0.07650	j 1.14745
Z TR 2	0.98639	j 5.91836
Z Fdr 1	0.04201	j 0.01418
Z Fdr 2	0.03182	j 0.00862

Step 2: Network Reduction for Fault at Bus 2

Combine the series impedances shown in Figure 3. The equivalent circuit after combining the series impedances is shown in Figure 5.

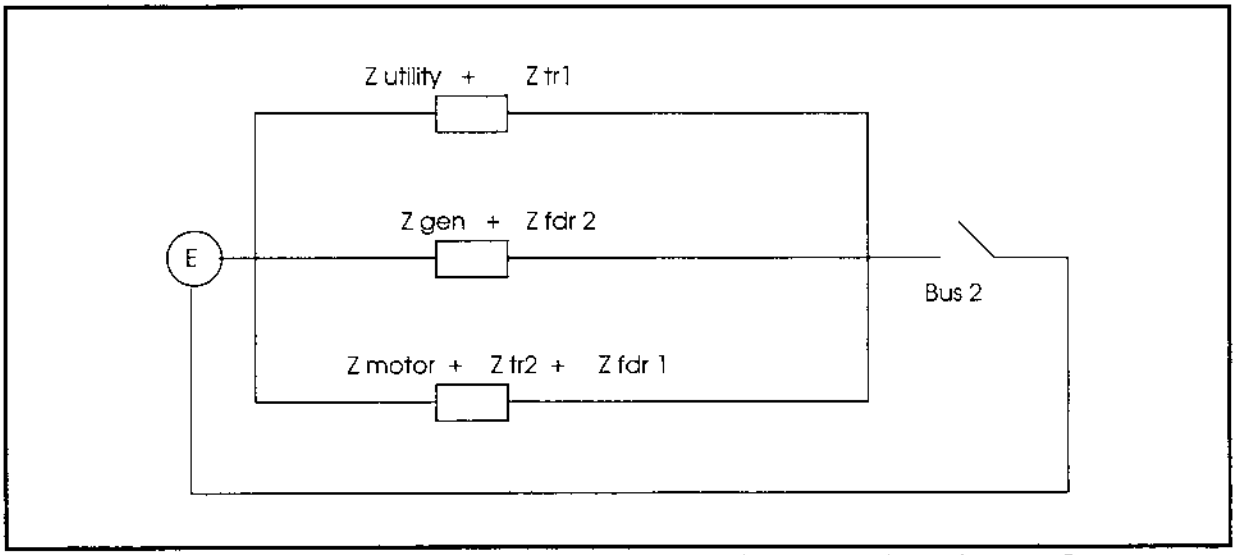


Figure 5. Combining the series impedances of Figure 3 for a fault at Bus 2.

Now combine the parallel impedances of Figure 5 to determine the Thevenin equivalent impedance illustrated in Figure 6. (The details of combining the parallel impedance values is left to the reader).

$Z_{Thevenin} = 0.05435 + j0.80650$ per unit

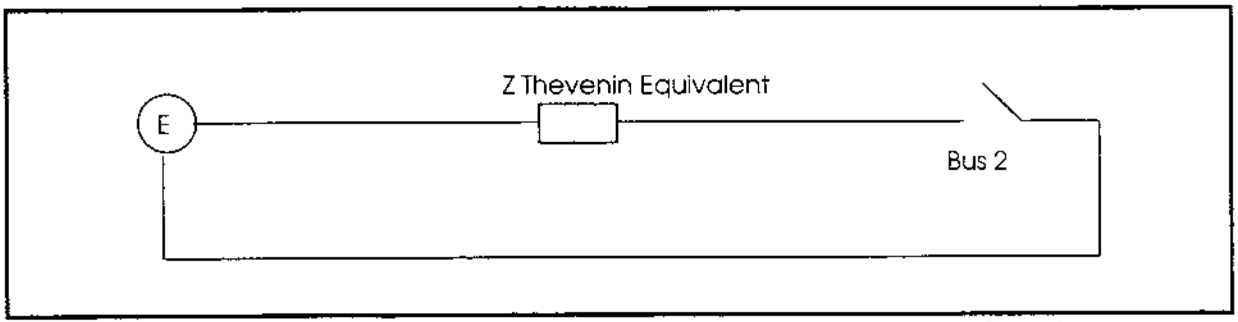


Figure 6. Thevenin equivalent circuit for power system at Bus 2.

Step 3: Calculate the Three Phase Fault Current

I_{base} = 100,000/ (13.8 * 1.732)
= 4183.8 Amps

I_{fc} = (1.0 / $Z_{Thevenin}$) * I_{base}
= 4183.8/0.8083
= 5176 Amps (at 1 PU driving voltage)

$$X/R = 0.8065/0.05435 = 14.84$$

The above values represent the three phase symmetrical fault current which flows in the power system at the time the fault is initiated.

Editors Note: A number of simplifying methods are often used to avoid the network reduction illustrated herein. The most common simplification is to simply lump all fault contributions into a single contribution at the point of the utility service and then to use a simple series circuit between the utility source and the faulted bus. It can be shown that this solution method can result in serious errors. A 20 percent error for a simple three bus problem is not uncommon.

Step 4: Calculate the Asymmetrical Fault Currents

Depending on the exact instant the fault occurs, the initial fault current can be offset from the symmetrical fault current waveshape. This offset is referred to as the asymmetrical fault current.

After the fault is initiated, the magnetic fields of the plant rotating machinery will begin to collapse and after a few cycles will result in the rotating machinery ceasing to contribute to the fault. On the other hand, it is assumed that the utility network contribution will continue to contribute for an indefinite period of time. In addition to the decay of the contributions to the fault associated with rotating machinery, the power system itself causes a decay due to the time constant (X/R) in the system impedances.

At one half cycle, the current that flows is called the momentary fault current. In the newer standards, this is also referred to as the closing and latching current. The momentary fault current is an asymmetrical fault current composed of both an ac decrement and a dc offset. The ac decrement is due to the collapsing magnetic field of local generation and motors. The dc offset is due to the dramatic change in X/R ratio (network time constant) pre- and post- fault time. At latter moments of time, say 3 cycles latter, the fault current is identified also as an asymmetrical fault current associated with protective device interruption. If all of the contributions are utility (or remote) type contributions, then the asymmetrical fault current reaches a steady state value equal to the symmetrical fault current calculated in Step 3.

A rigorous analysis to calculate the momentary and interrupting fault currents requires the use of transient analysis solution techniques to accurately determine the values. Transient analysis is beyond the realm of practical long hand solution techniques. There is hope however.

For power systems with an X/R ratio of less than 15, and where most of the fault contributions are from the utility source, it can be shown that the decay of rotating machinery can be neglected and the system decay (e.g. the dc offset) need only can be considered to calculate the momentary and interrupting fault currents. Using the equivalent circuit in Figure 6, the transient conditions are described by Equation 1.

$$i = e^{-(R/L)t} \; -V_{max}/Z \; \sin[\, \varphi - \tan\text{-}1(\omega L/R)] +$$

$$(V_{max}/Z) \; \sin[\, \omega t + \varphi \; - \tan\text{-}1(X/R)] \qquad \text{Eq. (1)}$$

where ω = $2\pi f$
φ = time in cycles
t = time in seconds
V_{max} = peak voltage

The first part of this Equation represents the transient or offset conditions that exist at the beginning of the fault. It can be seen that this term goes to zero in a very short time for low values of X/R. If

$$[\, \varphi \; - \tan^{-1}(X/R)] = (1 + 2n)\, /2 \text{ where } n = 0, 1, 2, \ldots,$$

the transient term will have a maximum value.

The second part of the Equation is the steady state solution; the current lags the voltage by:

$$\theta \; = \tan^{-1}(X/R)$$

The addition of the results of part one and part two of Equation 1, at a time of one-half cycle after the fault, is the momentary fault current; evaluating the Equation at 3, 5, and 8 hertz provides the asymmetrical current values.

Equation 1 reduces to Equation 2 for the worst case conditions (the sine terms have a maximum value of 1.0). Keep in mind, that the current here is the instantaneous current and not the rms (root mean square) current.

$$i = e^{-(R/L)t} \; -V_{max}/Z \; + V_{max}/Z \qquad \text{Eq.(2)}$$

Rewriting this equation in a different form further simplifies the solution.

$$\text{Asymmetrical rms Amps} \; = \text{rms symm Amps} * \; [\, 1 \; + \; 2e^{(-4\pi C/(X/R))}]^{0.5} \qquad \text{Eq. (3)}$$

where C = value in cycles.

For the momentary current, a value of C = 0.5 is used, for a three cycle value, C = 3.0 is used.

This solution method assumes that all of the impedance elements remain constant during the period which is used to calculate the transient conditions, and that the source voltage is a constant one per unit.

Computer analysis has shown that the use of Equation 3 provides conservative results when compared to the results of a transient analysis solution. The results of Equation 3 is very representative of the asymmetrical currents which flow in a power system with an X/R of less than 15. Most industrial and commercial power systems fall within this category. For power systems with large local generation, the system X/R may exceed this value close to the generation. Inasmuch as transformers have X/R ratios in the range of 6 to 15 and the X/R values of cabled conductors are less than 2 and often less than 1, the X/R of the industrial/commercial power system is normally less than 15.

At Bus 2, Equation 3 is solved to calculate the momentary and interrupting fault currents.

At Bus 2: Momentary fault current (1/2 cycle) = 7865 Amps
3 cycle asymmetrical current = 5568 Amps
5 cycle asymmetrical current = 5250 Amps
8 cycle asymmetrical current = 5182 Amps

The symmetrical rms fault current was calculated at 5176 Amps. Since instantaneous trip devices are subject to momentary currents, the aforementioned momentary value would be used for setting these devices.

Notice: Although these values are very representative of the theoretical momentary and asymmetrical fault current that flow during the fault, these are not the values use for comparison to the momentary and asymmetrical ratings of medium and high voltage equipment. The American National Standards Institute test procedures vary from the theoretical solution, and since the equipment *ratings* are established on these *test* standards, then these practical assumptions must be used when specifying electrical apparatus. To determine the equipment ratings, ANSI solution methods must be used.

3.0 ANSI Solution Methods

As shown in the previous sections, calculation of fault currents requires the extensive use of network reduction techniques and the use of complex numbers. Although ANSI standards reduce the amount of complex number calculations, other factors increase the complexity of solution. ANSI standards require separate network reductions for the R and the X networks. The calculation procedures require that calculation of the on-site (e.g. local) generation contributions and utility (e.g. remote) contributions be kept separate from the motor fault contributions. Additionally, ANSI requires that different impedance values be used for the low voltage, the momentary, and the asymmetrical analysis.

The IEEE Red Book offers some small degree of help. The Red Book permits the low voltage network impedances to be the same as the momentary or closing and latching network impedances.

3.1 Calculation of Fault Contribution Impedances for ANSI Analysis

The differences between the low voltage, the momentary and the interrupting networks are caused by the method by which the impedances of the fault contributions are calculated, and by the requirements of the low voltage standard to include all motor contributions, while the momentary and asymmetrical standards permit the exclusion of induction motors below 50 horsepower.

Table 1 illustrates fault source impedance multipliers by which fault contribution impedances for ANSI analysis

The results of using these fault source impedance multipliers in the sample problem (Figure 1) is illustrated in Table 2. The low voltage values in the table are the same values used in the complex network solution. The impedance values used for transformers and feeders are the same in all networks.

	Impedance Networks		
Contribution Type	LV Studies	Momentary	Asymmetrical
Utilities	$1.0\ X_d''$	$1.0\ X_d''$	$1.0\ X_d''$
Synchronous motors	$1.0\ X_d''$	$1.0\ X_d''$	$1.5\ X_d''$
Generators	$1.0\ X_d''$	$1.0\ X_d''$	$1.0\ X_d''$
Induction motors			
Above 1000 hp at 1800 rpm or less	$1.0\ X_d''$	$1.0\ X_d''$	$1.5\ X_d''$
Above 250 hp at 3600 rpm	$1.0\ X_d''$	$1.0\ X_d''$	$1.5\ X_d''$
From 50 -1000 hp at 1800 rpm or less	$1.0\ X_d''$	$1.2\ X_d''$	$3.0\ X_d''$
from 50 to 250 hp at 3600 rpm	$1.0\ X_d''$	$1.2\ X_d''$	$3.0\ X_d''$
Below 50 hp	$1.0\ X_d''$	excluded	excluded

Table 1. Fault source impedance multipliers.

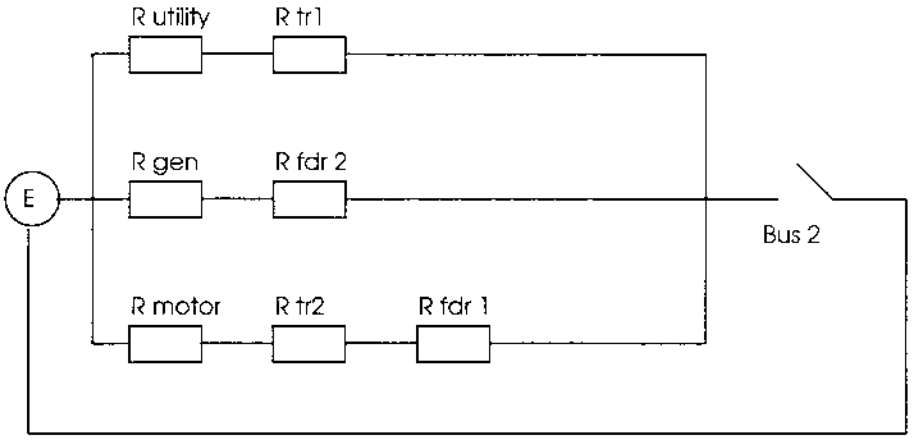
Element	Low Voltage Study		Momentary Study		Asymmetrical Study	
	R per unit	X per unit	R per unit	X per unit	R per unit	X per unit
Z utility	0.03536	j 0.24749	0.03536	j 0.24749	0.03536	j 0.24749
Z motor	1.66666	j 33.3333	2.00000	j 40.0000	5.00000	j 100.000
Z gen	0.06666	j 2.00000	0.06666	j 2.00000	0.06666	j 2.00000
Z TR 1	0.07650	j 1.14745	0.07650	j 1.14745	0.07650	j 1.14745
Z TR 2	0.98639	j 5.91836	0.98639	j 5.91836	0.98639	j 5.91836
Z Fdr 1	0.04201	j 0.01418	0.04201	j 0.01418	0.04201	j 0.01418
Z Fdr 2	0.03182	j 0.00862	0.03182	j 0.00862	0.03182	j 0.00862

Table 2. Impedance values for ANSI solution.

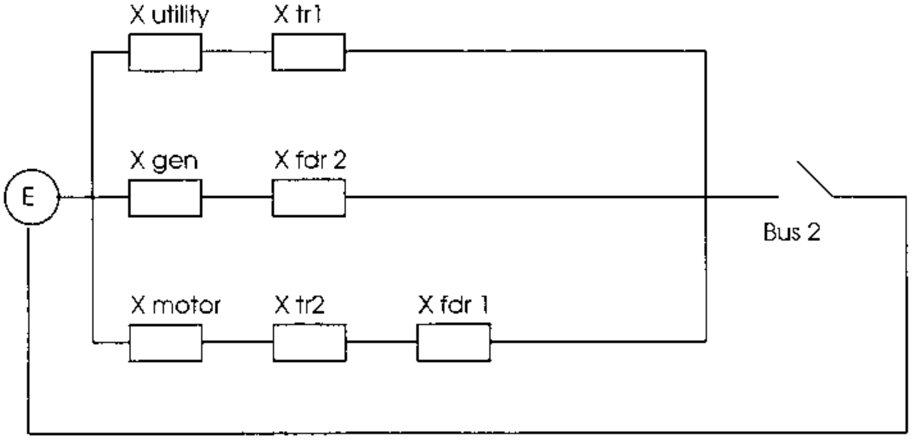
3.2 Separate Network Reduction

ANSI standards permit the engineer to calculate the momentary and interrupting fault currents based on the E/X solution (e.g., ignore resistance) method or the E/Z solution method. In both cases, the X/R ratio calculated at the fault location is determined by the separated reduction of the resistance and the reactance networks. Figure 7 illustrates the separate networks for a fault at Bus 2.

The circuits in Figure 7 are solved for the closing and latching (momentary) system impedances and for the interrupting duty impedances. (The low voltage solution is not required since the voltage at Bus 2 is greater than 1000 volts.) Although the standards permit the solution of the fault duty using E/X, the results will be very conservative since all of the resistance of the network is neglected. The following results are based on a more realistic E/Z solution.



The resistance network.



The reactance network.

Figure 7. Separate resistance and reactance networks.

3.3 Momentary Symmetrical Current

Using the momentary impedance values shown in Table 2, the impedance networks of Figure 7 are solved for a fault at Bus 2.
The initial symmetrical fault current: 5160 rms amperes
The Thevenin impedance: R: 0.05451 X: 0.80892 per unit
The X/R ratio: 15.71

Note that the symmetrical fault current calculated using the ANSI procedure is slightly less that the value calculated by the complex network solution, and that the X/R ratio is also different. In this case, the value of X/R calculated by the separate reduction is close to the value for the complex network (14.84). It would be incorrect to assume that this will always be true. In some cases, the separate network reduction will result in X/R values two times larger than the value calculated by complex network reduction methods.

3.4 Closing and Latching or Momentary Rating Calculation

ANSI permits the engineer to multiply the initial symmetrical rms current by a factor of 1.6 to determine a momentary rating value. This is an approximation however; the standards permit a more precise calculation procedure. Since the momentary current occurs at 0.5 cycles after the initiation of the fault, Equation 3 may be used to determine a more realistic value of the momentary current. The 1.6 factor comes from Equation 3 using C = 0.5 and X/R = 25.0.

Momentary Rating:	Symmetrical * 1.6	=	8256 amps
	Calculated (Eq. 3)	=	7895 amps

The lower of the two momentary values above may be used to specify the equipment. The momentary rating is the closing and latching value that the equipment must withstand if the breaker or switch is closed in on a fault.

IEEE Std 141-1993 cites C37.010 and C37.06 as requiring medium and high voltage protective devices to be rated not only in the closing and latching rms current, but also their peak or crest current. This is calculated to be no greater than $\sqrt{2}$ time the rms value at a system X/R ratio of 25. This peak or crest value is the preferred rating since 1987.

3.5 The Interrupting Symmetrical Current

Using the asymmetrical impedance values in Table 2, the interrupting fault current is calculated.

The total symmetrical fault current:	5109 rms amperes		
The Thevenin impedances:	R: 0.05498	X: 0.81706	per unit
The X/R ratio:	15.73		

3.6 Local and Remote Contributions for Asymmetrical Currents

Now the problem gets interesting. ANSI recognizes two types of decay in the power system: ac/dc decay and dc decay only.

The ac decay of motors have been accounted for by the changed values of impedance used for the asymmetrical network (Table 2) and it is assumed that the utility is not subject to ac decay. The net result is that the induction (and synchronous) motors and the utility are subject to dc decay only.

Local generation is a different issue. ANSI states that if there are two or more transformers between the generator and the faulted bus, or the reactance of the system is greater than 1.5 times the reactance (X_d") of the generator, then the generator is considered as a remote contribution and is not subject to ac decay. Under these conditions, the generator contribution is subject to dc only decay (Remote source).

But, if there is only one transformer between each generator faulted bus location, or the network reactance between each generator compared to each faulted bus location is less than 1.5 times the subtransient reactance of the generator, then the generator is subject to both ac and dc decay. Under these conditions, the generator is considered to be a local source. Only generators are classified as remote or local. Many computer algorithms use the 1.5 times the generator subtransient reactance criteria for determining the remote/local criteria.

In the sample problem, the branch current from the generator is easily calculated. In more complex systems it will be necessary to break the problem into multiple networks. The first network would consist of the contributions from the utility sources and the other non-generator sources. Then, for each of the generators in the system, a separate network would be constructed. Each of the networks would be solved to determine the magnitude of the currents from the generators and other sources. This can be a very time consuming process to complete long-hand, but is required for complete analysis.

Having calculated the total fault duty at the faulted bus, and the magnitude of the individual fault contributions, ANSI provides figures which are used to calculate the interrupting rating of equipment. Given an X/R ratio of separately reduced systems, and if the generator contribution is local or remote, a multiplying factor is determined; that factor is multiplied by the symmetrical current to determine the asymmetrical rating.

ANSI permits several options at this point. (1) Predominate sources, (2) All Remote sources and (3) Interpolated sources. These options refer to the determination of which of the ANSI look-up figures to be used for determining the multiplying factors used to calculate the asymmetrical currents.

Predominate Local or Remote Generation Method

This method requires that the magnitude of the generator fault contributions be evaluated based on the local or remote status. If more than 50 percent of the generator contribution is from local generation, then the ac/dc curves are used. If less than 50 percent of the generation contribution is local, then the dc only curve is used.

In the sample problem, the local generation is 2.080 kA and the remote generation is 2.990 kA. Using the predominate interpretation, the dc decay only curve is used for determination of the asymmetrical factors.

The C37.5 standard provides figures which will result in solutions for equipment based on the total current rating basis. Fig 3 of the C37.5 standard is used to determine the multiplying factors for equipment (breakers) operating at different speeds. This standard is used for protective devices made prior to 1965.

Using the X/R value = 15.73, the multiplying factors and the asymmetrical current ratings are as follows

Total rated equipment (C37.5)

	Total 2	Total 3	Total 5	Total 8
Mult. Factor:	1.347	1.169	1.076	1.027
Duty (kA)	6.883	5.974	5.498	5.248

The terms Total 2, Total 3, Total 5, and Total 8, refers to the speed of the breakers. Under this standard, as the breaker opening time increases, the rating of the breaker is decreasing. Since the fault current is decreasing as a function of time, this follows our intuitive logic about the decay of fault currents.

The C37.5 standard has been updated by C37.010. The C37.010 standard covers equipment ratings on a symmetrical basis. Equipment manufactured after 1964 is based on this updated standard.

Using the dc decay figure for three phase faults in the C37.010 standard (Fig 10), the multiplying factors are as follows:

	Sym 2	Sym 3	Sym 5	Sym 8
Mult. Factor:	1.000	1.000	1.007	1.050
Duty (kA):	5.109	5.109	5.145	5.367

Here, Sym 2, 3, 5, and 8 refer again to the operating time of the breaker. Since the X/R ratio is low, the multiplying factors for calculation of the asymmetrical currents are near the value of 1.0. But note, the multiplying factor for the five cycle breaker is greater than 1, and the factor for the eight cycle breaker is greater the factor for the five cycle breaker.

This increasing of the asymmetrical rating for slower rated breakers which open under lower values of asymmetrical current does not follow our intuitive understanding of asymmetrical decay. The C37.010 standard makes no justification for these values, but it can be speculated that the standard is attempting to account for the fact that the eight cycle breaker takes four cycles to clear the fault, while the five cycle breaker takes three cycles.

Note: The ANSI figures have been recreated, enlarged and are shown in the appendix of these notes.

Remote Only Method

A conservative approach to the standards is to consider all generation to be Remote. Under this method, the dc decay curves of the C37.5 and the C37.010 standard are used. This impacts the interrupting duty evaluations only, and will result in conservatively high results.

In the sample problem at Bus 2 there is no change in the results by treating all sources as remote, since the predominate source was remote in that case.

For three phase faults, Fig 3 of the C37.5 standard is used for all remote sources and Fig 10 in the C37.010 standard is used for remote sources.

Interpolated Sources Interpolation

An alternative to the use of the predominate or the all remote method is to use a combination of the local and remote figures for calculation of the asymmetrical ratings. Using this method, the ac/dc decay of generators is properly modeled, and the dc decay only of the utility sources is also properly modeled.

The ratio of the total remote source generation to the total fault duty is defined as the NACD (No ac Decay) ratio. To calculate the NACD ratio, the total amount of remote generation (including utility contributions) is first calculated and then divided by the total fault duty at the bus.

In the sample problem, the total utility remote generation is 2.990 kA which can be calculated as the fault duty in the branch from the utility source. The total fault duty at the faulted bus is 5.109 kA.

$$\begin{aligned} \text{NACD} &= 2990 / 5109 \\ &= 0.5852 \end{aligned}$$

Now using Fig 8 of the C37.010 standard for ac/dc decay and a value the total asymmetrical fault contribution from the local source can be estimated at 1.00; from Fig 10 of the C37.010 standard, the remote source contribution factor is 1.007. Although in power systems with large amounts of induction motor contributions, the actual asymmetrical current that flows at 5 and 8 cycles may be less than the calculated symmetrical current (thus a multiplier less than 1), the figures in the standards indicate the lowest multiplying factor that may be used is 1.0.

The interpolated value between the curves is equal to

MF = ac/dc factor + (dc factor - ac/dc factor) * NACD
= 1.000 + (1.007 - 1.000) * 0.5852
= 1.004

The five cycle breaker asymmetrical rating would then be:

Rating = Iasym sym fault current * MF
5109 * 1.004
= 5130 amps

A similar approach to interpolating between the ac/dc and dc only curves of the C37.5 standard may also be used. In this example, the value of the asymmetrical current is close to the symmetrical current. As the system X/R increases, a significant difference between the two values will be observed.

Item	Complex Solution	Momentary Both Standards	Asym C37.010 Sym. Rating		Asym C37.5 Total Rating	
			Pred.	Interp.	Pred	Interp.
Sym. Current	5176	5160	5109	5109	5109	5109
X/R	14.84	15.7	15.73	15.73	15.73	15.73
Momentary	7865	8256 (@1.6x) 7895 (Calc.)				
3 cycle	5568		5109	5109	5974	5898
5 cycle	5250		5145	5130	5498	5396
8 cycle	5182		5367	5260	5248	5192

Table 3. Comparison of solution methods.

Table 3 illustrates the differences between the solution methods. In the columns labeled C37.010 and C37.5, "Pred" refers to the use of the ANSI predominate method and "Interp" refers to the use of the ANSI interpolation method between the ac/dc and dc only curves.

It is dangerous to extrapolate general conclusions from this data. Due to the separate resistance and reactance network reduction techniques of ANSI, the X/R values of the complex network solution and the ANSI solutions may vary considerably. The final ANSI values for momentary and asymmetrical current ratings is highly dependent on the X/R values.

Inasmuch as ANSI requires interpretation and permits several solution methods to be used, which one is correct? The conservative approach is to use the method which results in the most conservative results. In all cases, the basis of the equipment rating tests determines which standard must be applied.

Note that the complex solution method calculates the current that flows at the each cycle noted above. A five cycle breaker begins to open at 3 cycles. Be careful not compare five cycles of a complex solution to the five cycle rating of ANSI.

3.7 Low Voltage Solution Methodology

ANSI C37.13 applies to low voltage protective devices. This standard uses the same impedance network as the complex network solution method. The source contributions are based on 100 percent of all sources contributing to the fault. The induction machines are not decremented. This standard requires that all contributions, regardless of the size be included. Under this standard, motors less than 50 horsepower are included.

The standard does not specifically require the separate reduction of the resistance and reactance networks. If the application engineer elects, the complex network solution method or the separate network reduction method may be used.

For a fault at Bus 3 in the sample problem the equivalent circuit of Figure 4 is solved. If the circuit is reduced using the separate network reduction method, then the results of the study will indicate the following:

Available symmetrical fault current = 21165 rms amperes
System X/R ratio = 8.57
Thevenin Equivalent Circuit = .0018 + j0.013 Ohms

The standard requires that the fault values should be modified for power factor considerations.

For un-fused circuit breakers, if the X/R ratio is greater than 6.6 then the breaker must be derated. For fused circuit breakers, if the X/R ratio is greater than 4.9 then the fused breakers must be derated. In addition, for fused circuit breakers, if the available short circuit rating approaches 80% of the breaker short circuit current rating, there may be other considerations.

For fused breakers within 80% of their ratings the engineer should derate the breakers if (1) there is local generation at circuit breaker voltages in unit sizes greater than 500 kVA, (2) if there are gas-filled and dry transformers in sizes 1000 kVA and above or 2500 kVA and above for all types of transformers, (3) network systems, (4) transformer impedances higher than those specified in ANSI C57 standard, (5) current limiting reactors at the circuit breaker voltage in the source circuits and (6) current limiting busway at circuit breaker source circuits. Under these conditions, the breaker should be derated by use of the multiplying factor in Table 3 of the C37.13 standard. The factors of this table are illustrated in Table 4 below.

System Short Circuit Power Factor Percent	*System X/R Ratio*	*Multiplying Factor for Calculated Short Circuit Current*	
		(1)	*(2)*
20	4.9	1.00	1.00
15	6.6	1.00	1.07
12	8.27	1.04	1.11
10	9.95	1.07	1.15
8.5	11.72	1.09	1.18
7	14.25	1.11	1.21
5	20.0	1.15	1.25

(1) Factors for un-fused circuit breakers.
(2) Factor for fused circuit breakers.

Table 4. Selection of low voltage multiplying factors (ANSI C37.13; Table 3)

Technical papers on application of this standard have taken this table further. Depending on the test power factor of the breaker (usually determined by the type of breaker and size), a value of interrupting current can be calculated directly from the symmetrical fault current and the system X/R ratio.

Breaker Type	*Test PF*
Power circuit breaker	15 %
Molded case circuit breaker of 20 kA	20 %
Molded case circuit breaker, 10 - 20 kA	30 %
Molded case circuit breaker, 0 - 10 kA	50 %

Table 5. Low voltage circuit breaker design power factors.

The low voltage factor is calculated by the following equation:

$$LVF = [\,1 + e^{(-\pi/(X/R))}\,] \;/\; [\,1 + e^{(-\pi/K)}\,]$$

where $K = \mathrm{Tan}\,(\mathrm{Cos}^{-1}\,(PF))$

Solving these equations for the breaker ratings at Bus 3, we find that the value of symmetrical current does not provide sufficient results to compare to the breaker rating.

Calculated symmetrical current		=	21165 amps
For Power circuit breakers	LVF	=	1.0445
	Required rating	=	22107 amps
For Molded Case breakers > 20 kA	LVF	=	1.1090
	Required rating	=	23472 amps

Clearly, the application of standard 22,000 amp rated breakers will not be sufficient to meet the requirements of the standard.

Many other factors may affect the specification of the low voltage breakers. Some of these factors include the altitude correction, service conditions, and repetitive duty operations.

4.0 Applicable Standards

Additional Standards which may apply to the specification of low voltage, medium and high voltage equipment include:

C37.43
C37.44
C37.45
C37.46
C37.47
C37.48
C37.48a
C37.50
C37.51
C37.52
C37.60
C37.61
C37.63
C37.66
C37.85
C37.90
C37.90a
C37.91
C37.93
C37.95
C37.96
C37.97
C37.98
C37.99
C37.100

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A.1 Modeling the ANSI Decrement Curves

The published ANSI figures used for determining the decrement factors are, at best, difficult to read. To create the following information, the published curves were photographically enlarged and data points interpolated. These data points were then entered into a graphic utility program and the interpolated points plotted. The graphic utility program permitted the output curves to be scaled to the same size as the enlarged curves taken from the standard. The interpolated curves were then compared directly with the published curves. The interpolated results agreed with the published curves. This method was used to certify the program decrement curves with the standard.

Figure A-1, Figure A-2, and Figure A-3 represent the decrement curves used by the C37.5 standard. Figure A-4 through Figure A-15 represent the decrement curves used by the C37.010 standard. In Figure A-4 through Figure A-15, the decrements curves corresponding to the breaker contact parting time are shown. The decrement curves for contact parting at other than 1.5, 2, 3, and 4 cycles are not shown as they are not required for solution.

It should be noted that the ac/dc decrement curves published by ANSI C37.010 occasionally result in multiplying factors which do not always follow the engineer's intuitive understanding of decrement factors and asymmetrical current flow. For example, careful examination of the symmetrical standard for three phase faults with local effects indicates multiplying factors for a five cycle breaker (3 cycle parting time) at a value of X/R = 60 will result in a multiplying factor of 1.167. With the same X/R value, an eight cycle breaker (4 cycle parting time) will have a multiplying factor of 1.180. Although the eight cycle breaker opens under a lower asymmetrical current, the breaker takes longer for contact parting, thus a higher asymmetrical rating requirement.

Examination of the dc decrement curves (remote sources) further illustrates that the intuitive understanding of asymmetrical current values does not correspond to asymmetrical ratings calculated by the C37.010 standard. For example, examination of a system with a X/R ratio of 30, the multiplying factors increase for slower operating breakers.

Engineering judgment must be used at all times in application of the results of A_FAULT solutions and DAPPER solutions (Ohms Law) in specification of equipment.

For all of the following drawings, the horizontal axis is the X/R ratio based on the separate reduction of the R and X networks. The vertical axis represent the ANSI multiplying factors.

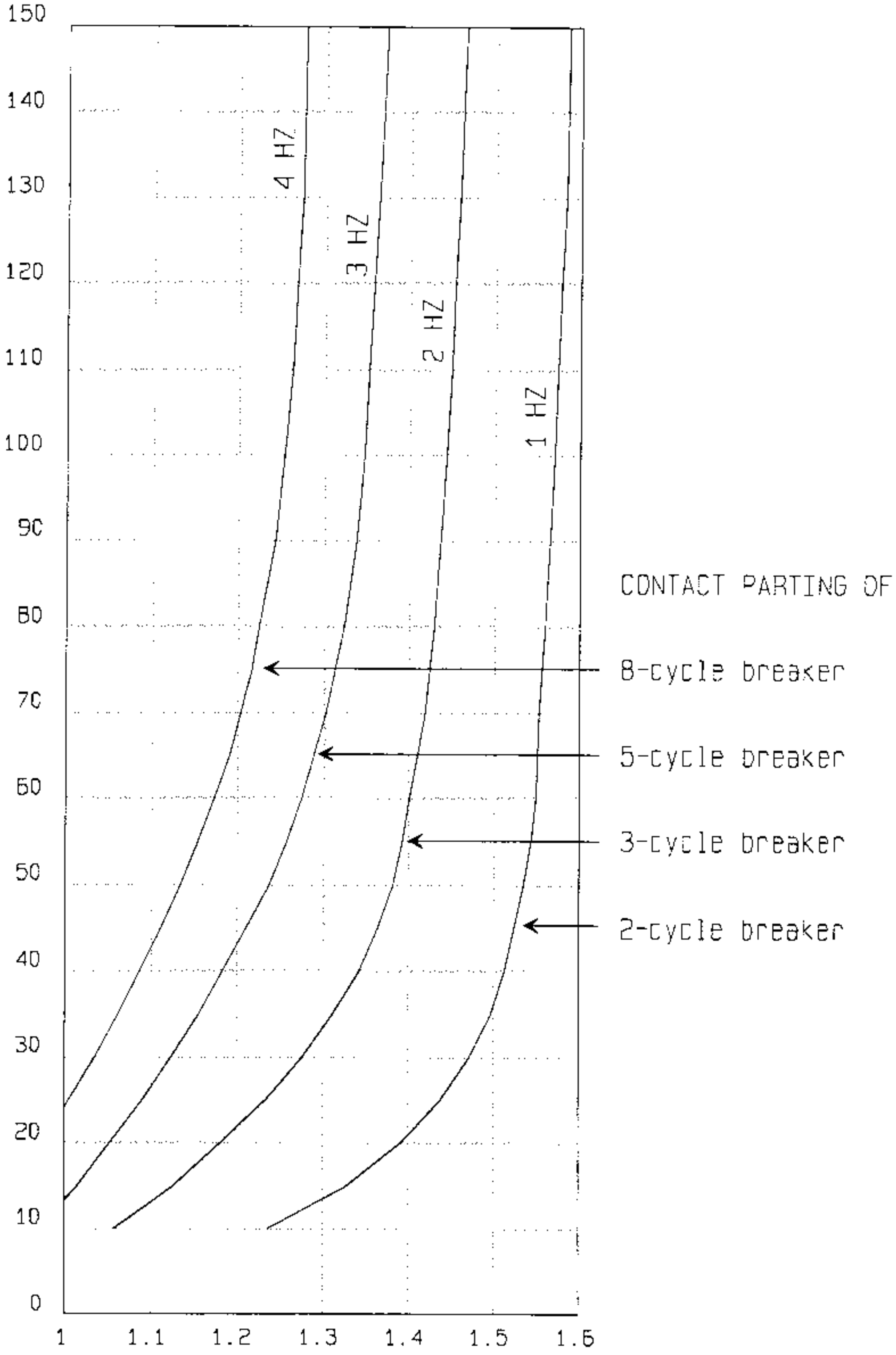

Figure A-1. C37.5 Three phase ac/dc decrement curves.

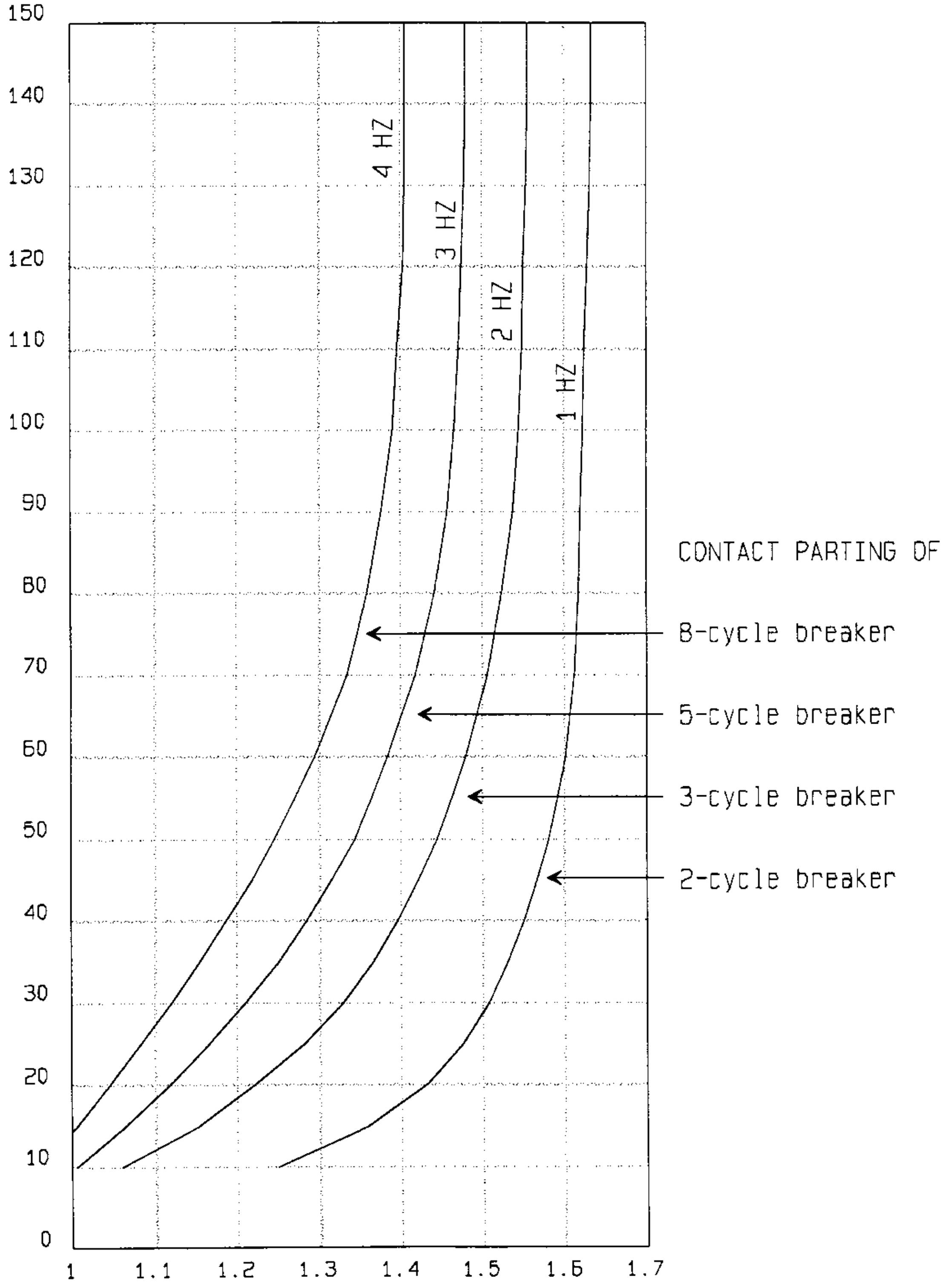

Figure A-2. C37.5 Single line to ground ac/dc decrement curves.

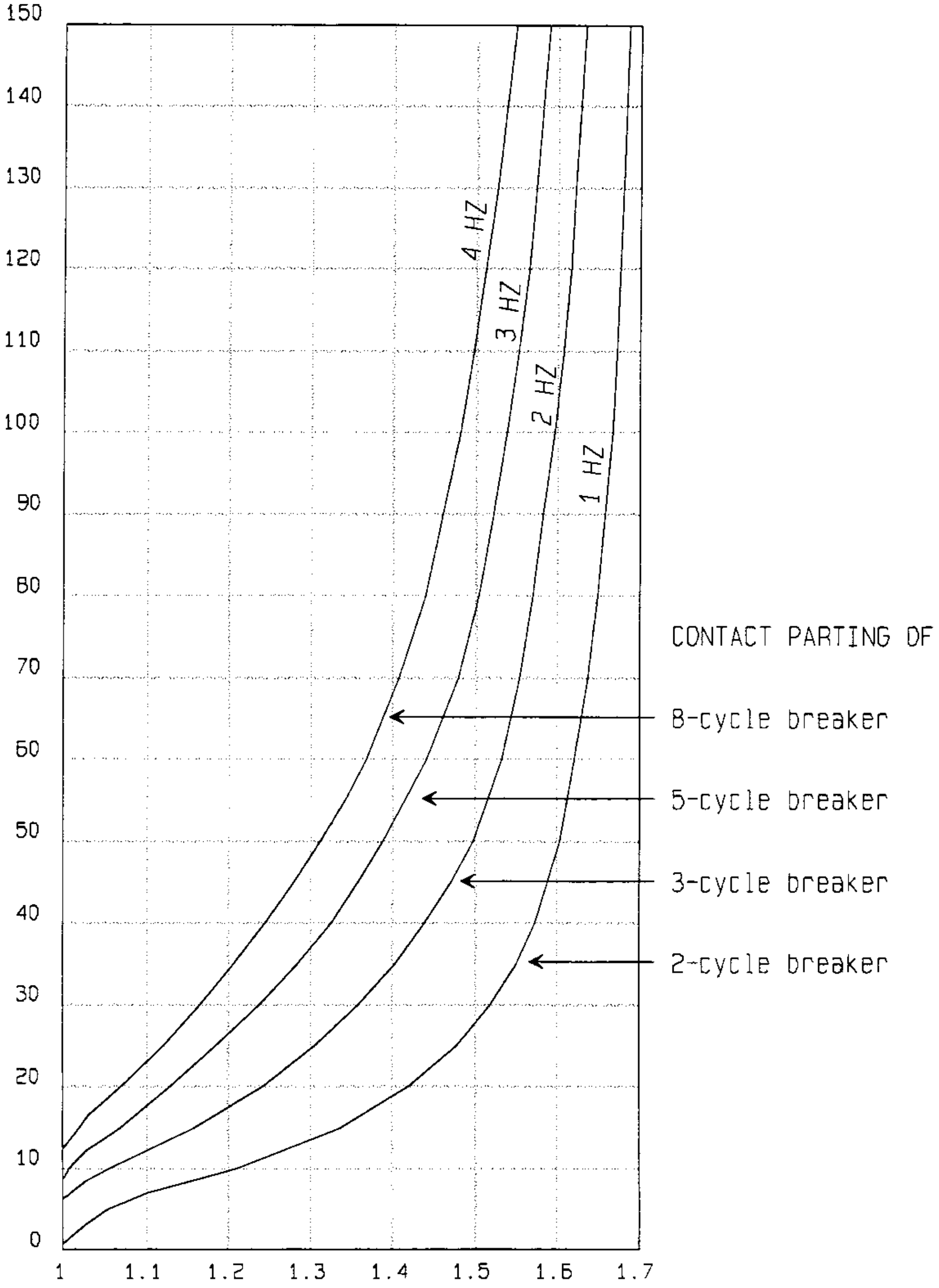

Figure A-3. C37.5 Three phase and single line to ground dc decrement curves.

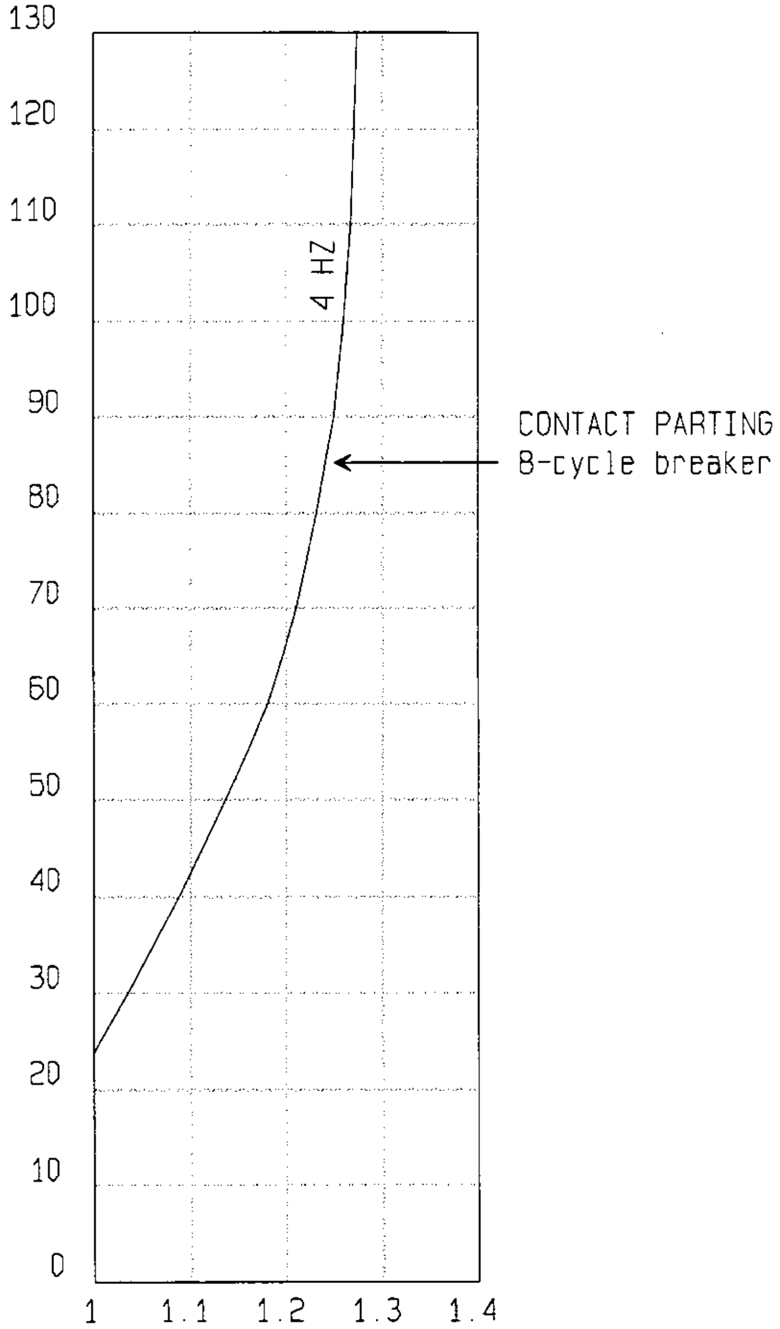

Figure A-4. C37.010 Three phase ac/dc decrement curve for 8 cycle breakers.

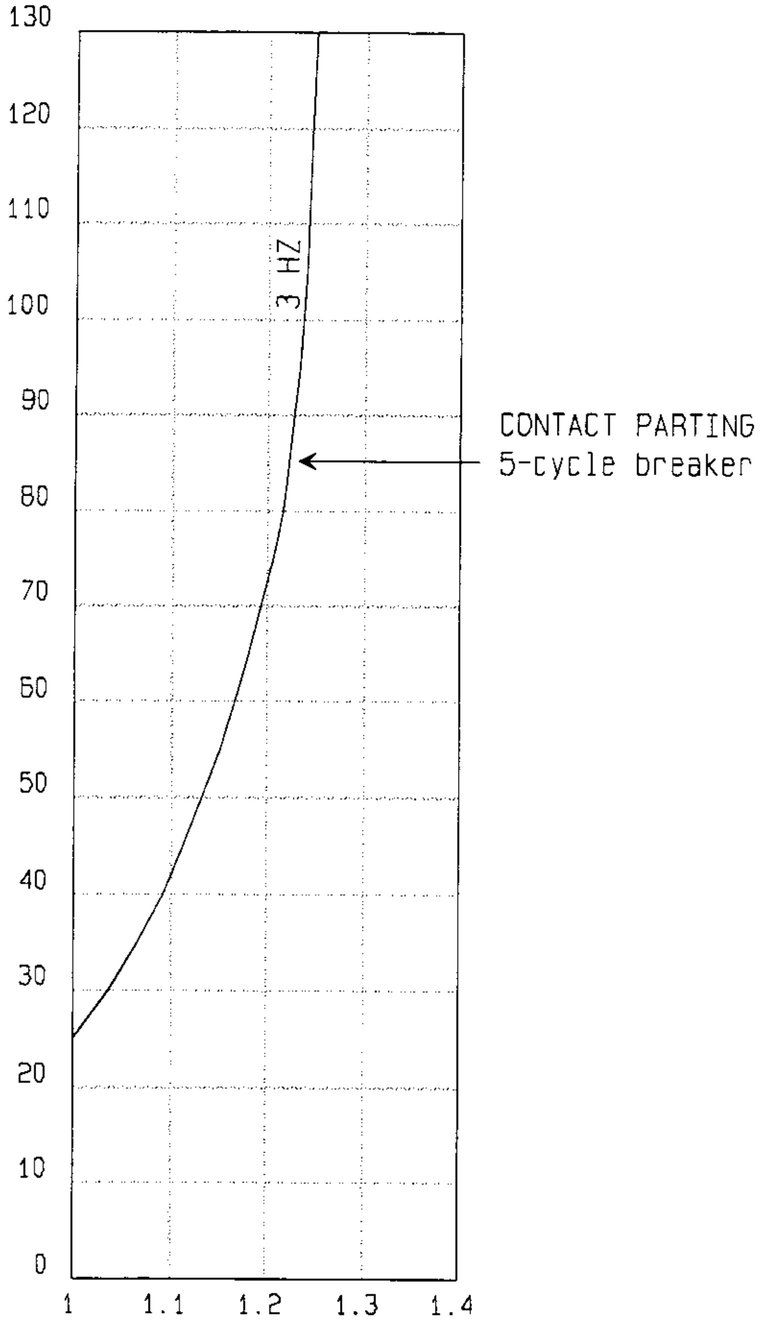

Figure A-5. C37.010 Three phase ac/dc decrement curve for 5 cycle breakers.

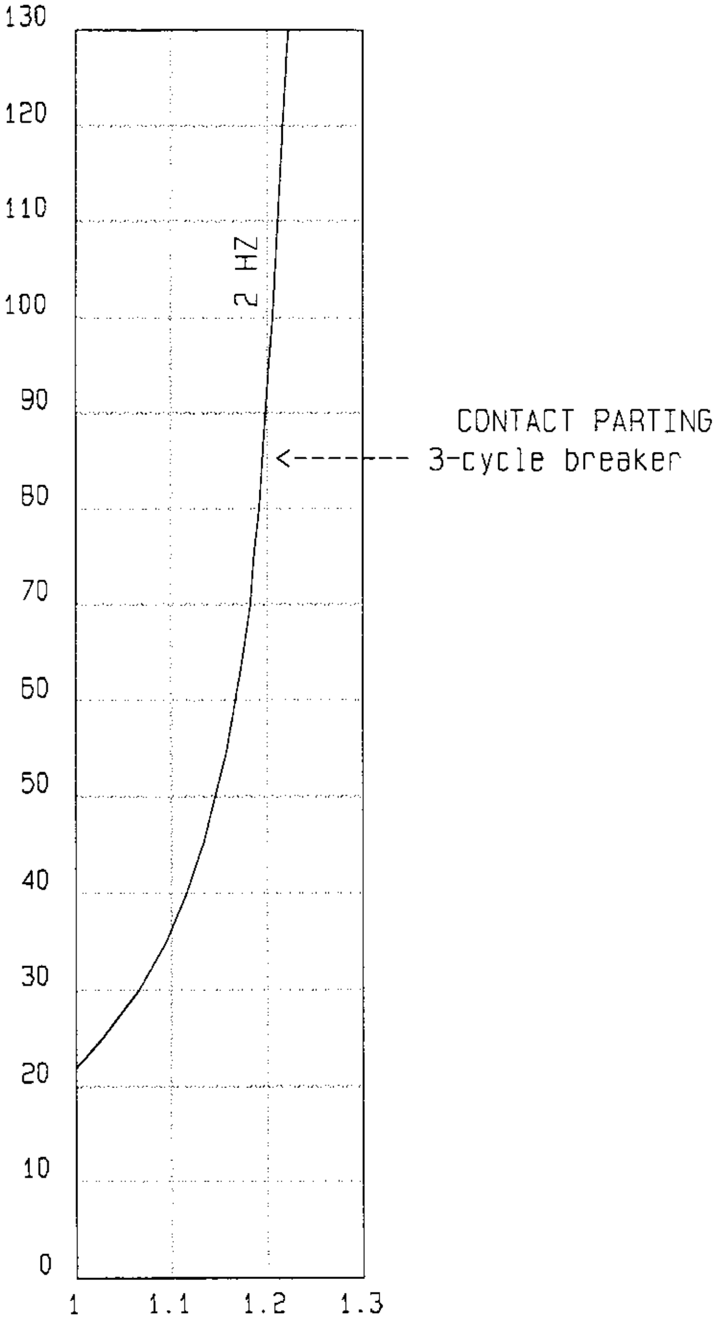

Figure A-6. C37.010 Three phase ac/dc decrement curve for 3 cycle breakers.

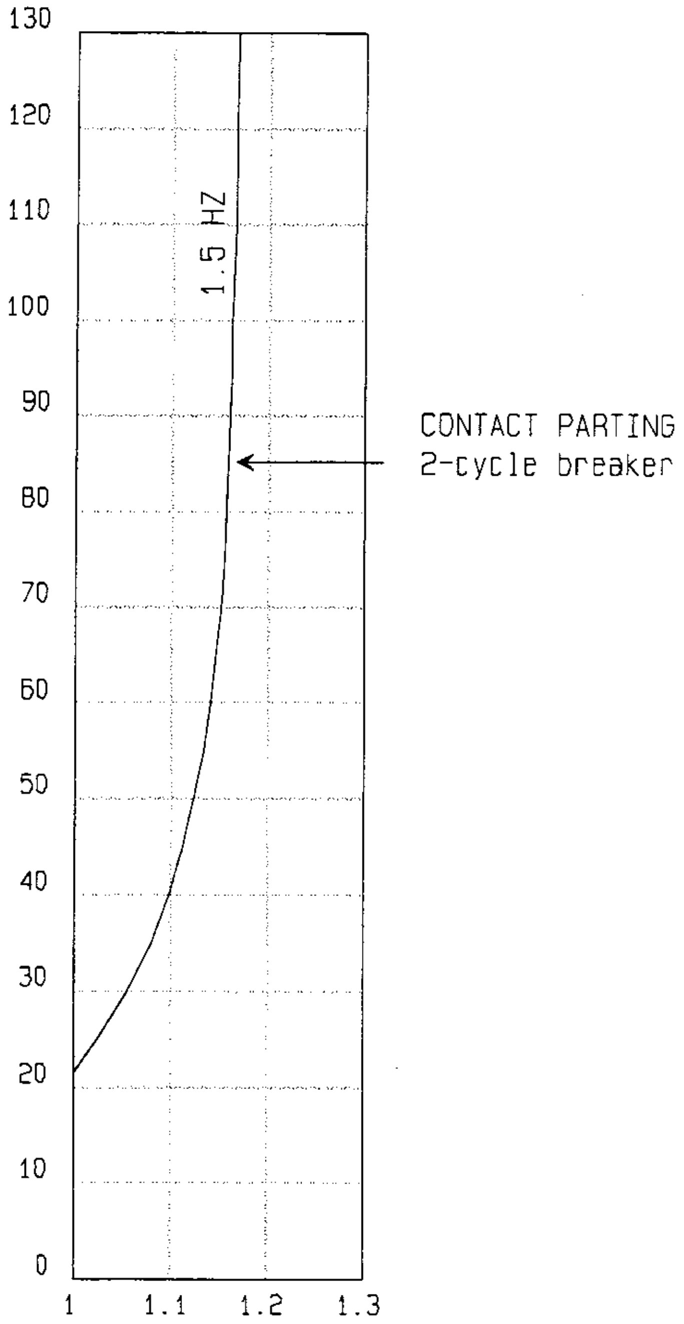

Figure A-7. C37.010 Three phase ac/dc decrement curve for 2 cycle breakers.

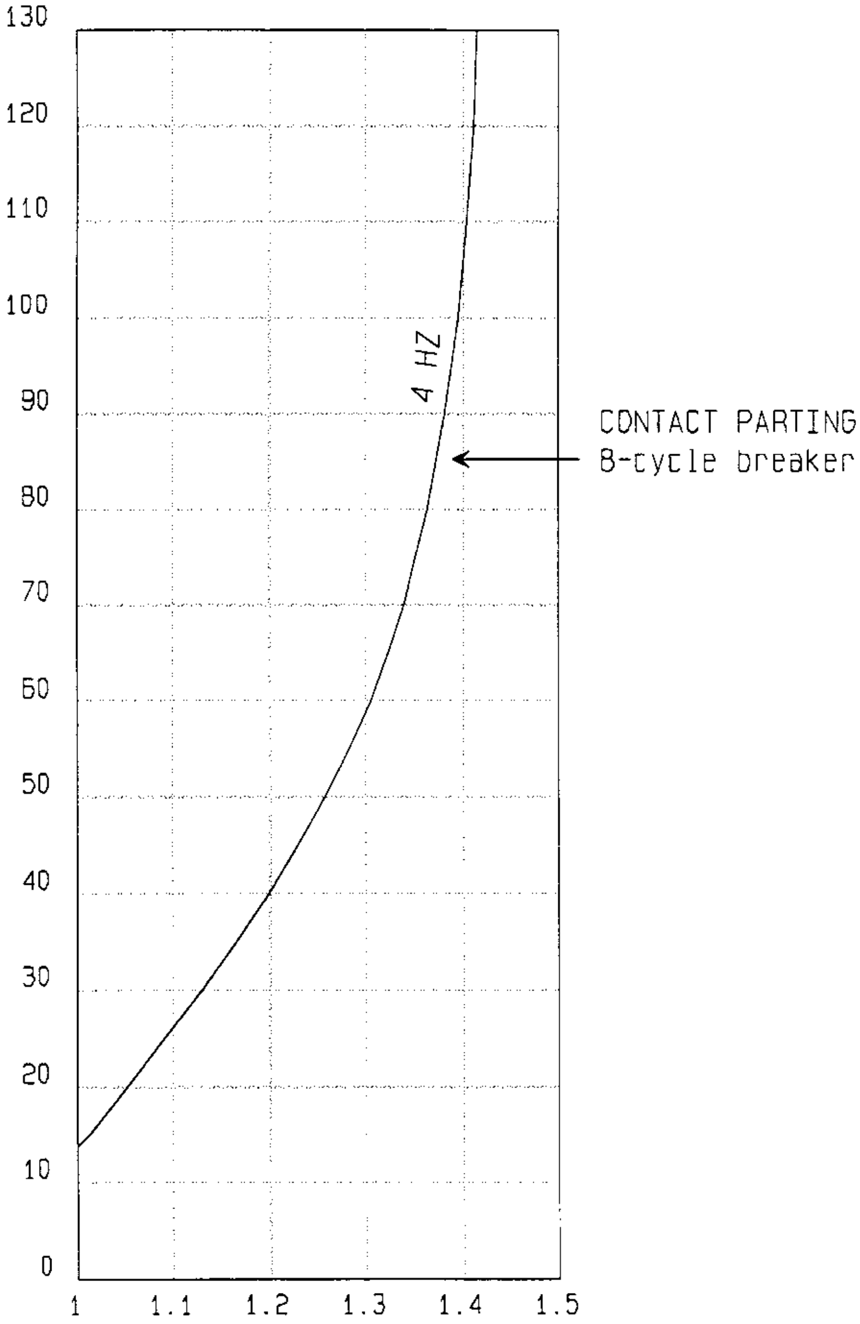

Figure A-8. C37.010 Single line to ground ac/dc decrement curve for 8 cycle breakers.

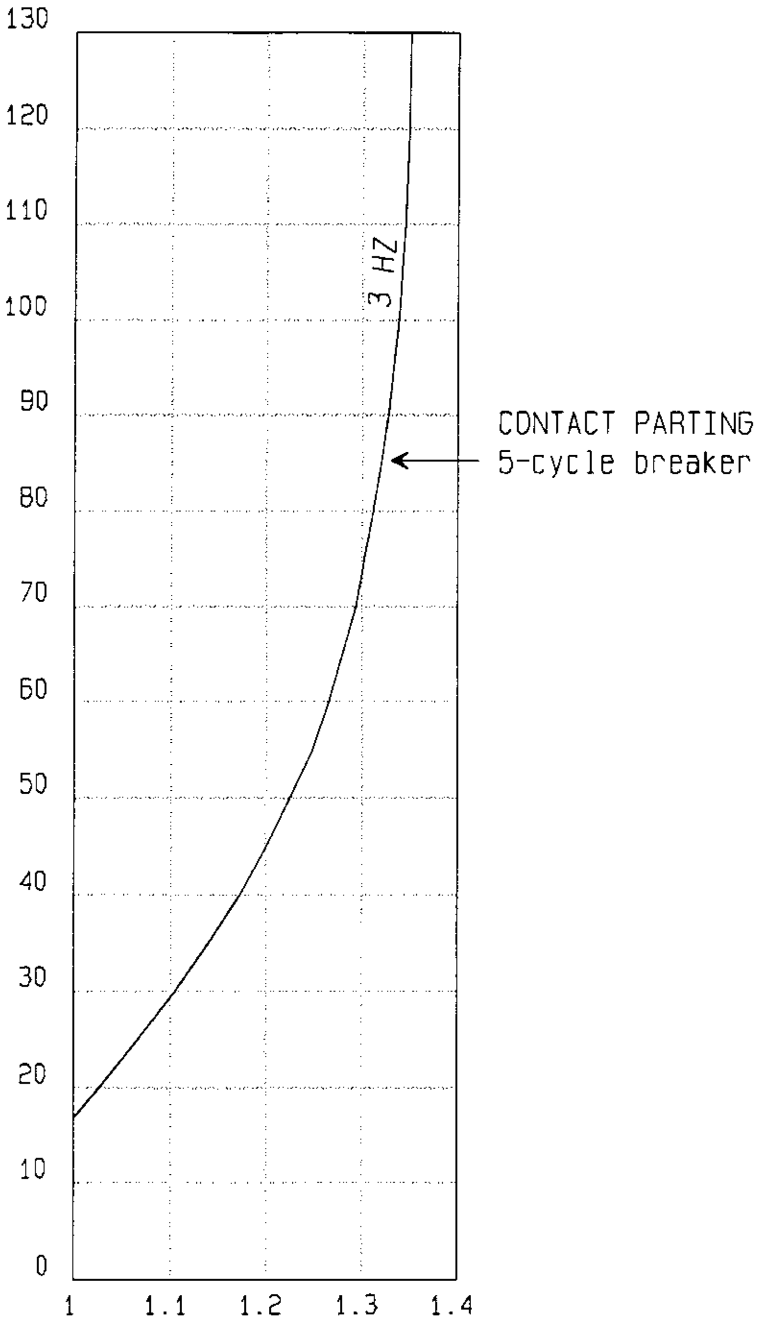

Figure A-9. C37.010 Single line to ground ac/dc decrement curve for 5 cycle breakers.

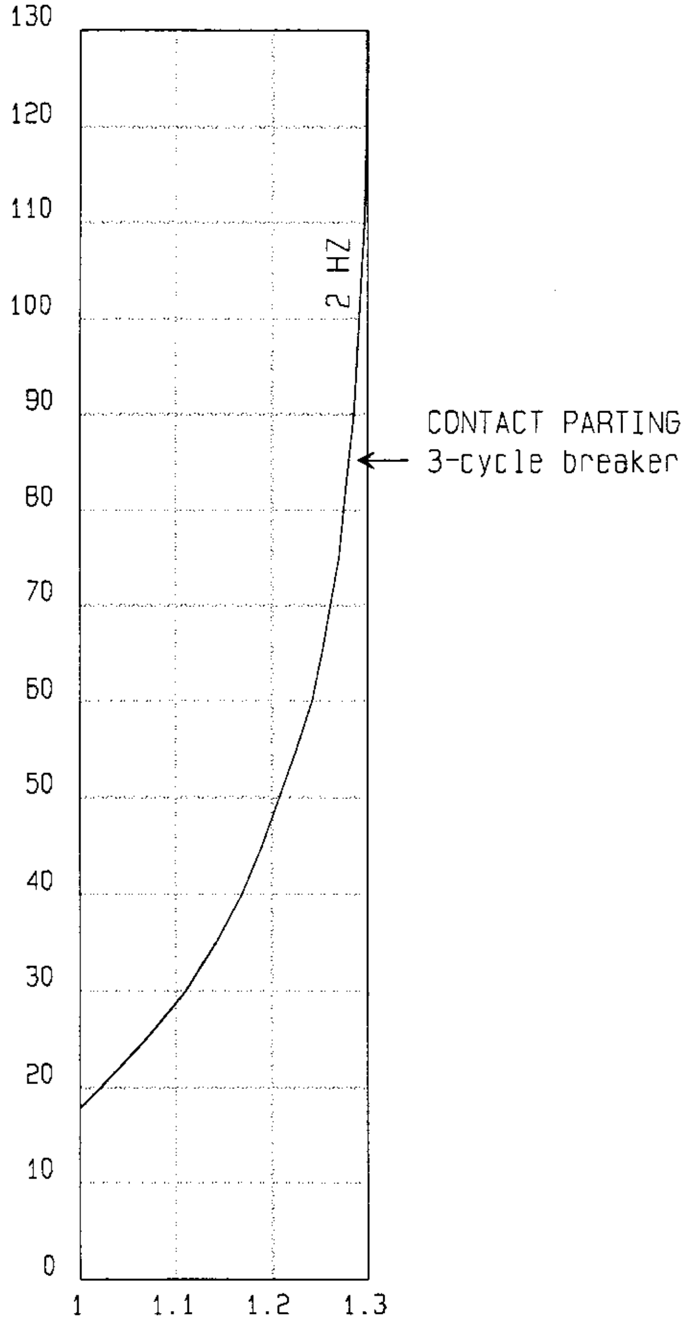

Figure A-10. C37.010 Single line to ground ac/dc decrement curve for 3 cycle breakers.

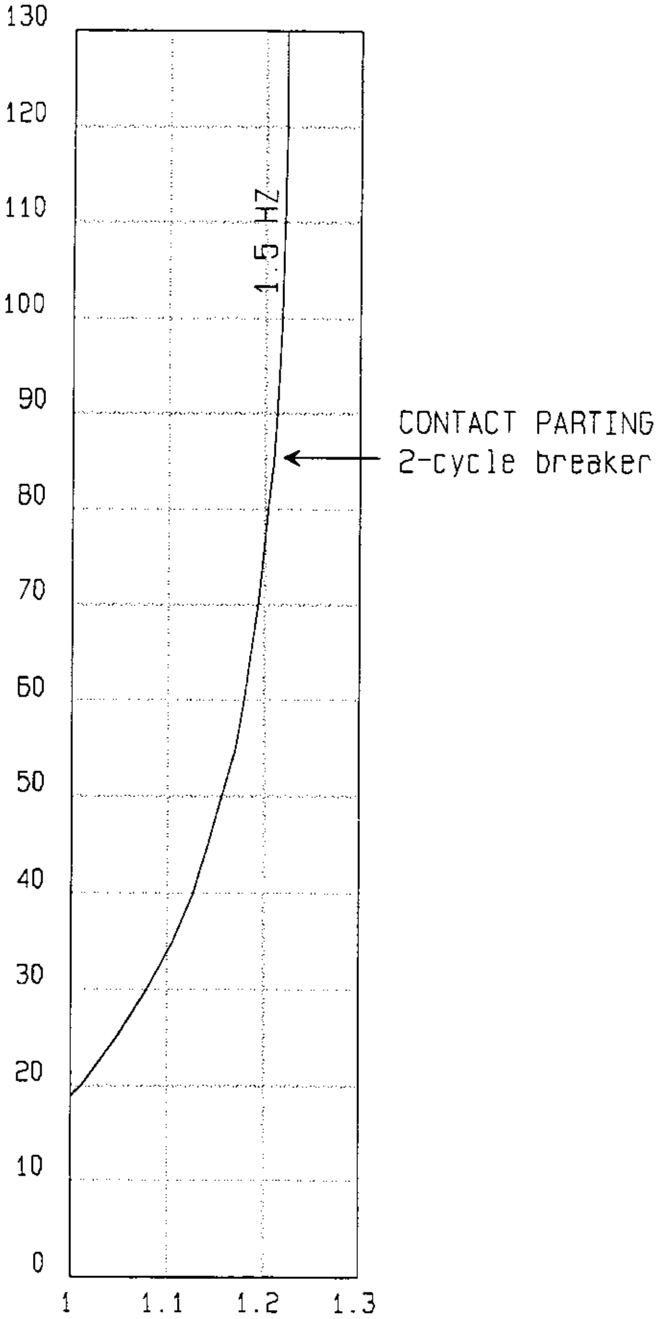

Figure A-11. C37.010 Single line to ground ac/dc decrement curve for 2 cycle breakers.

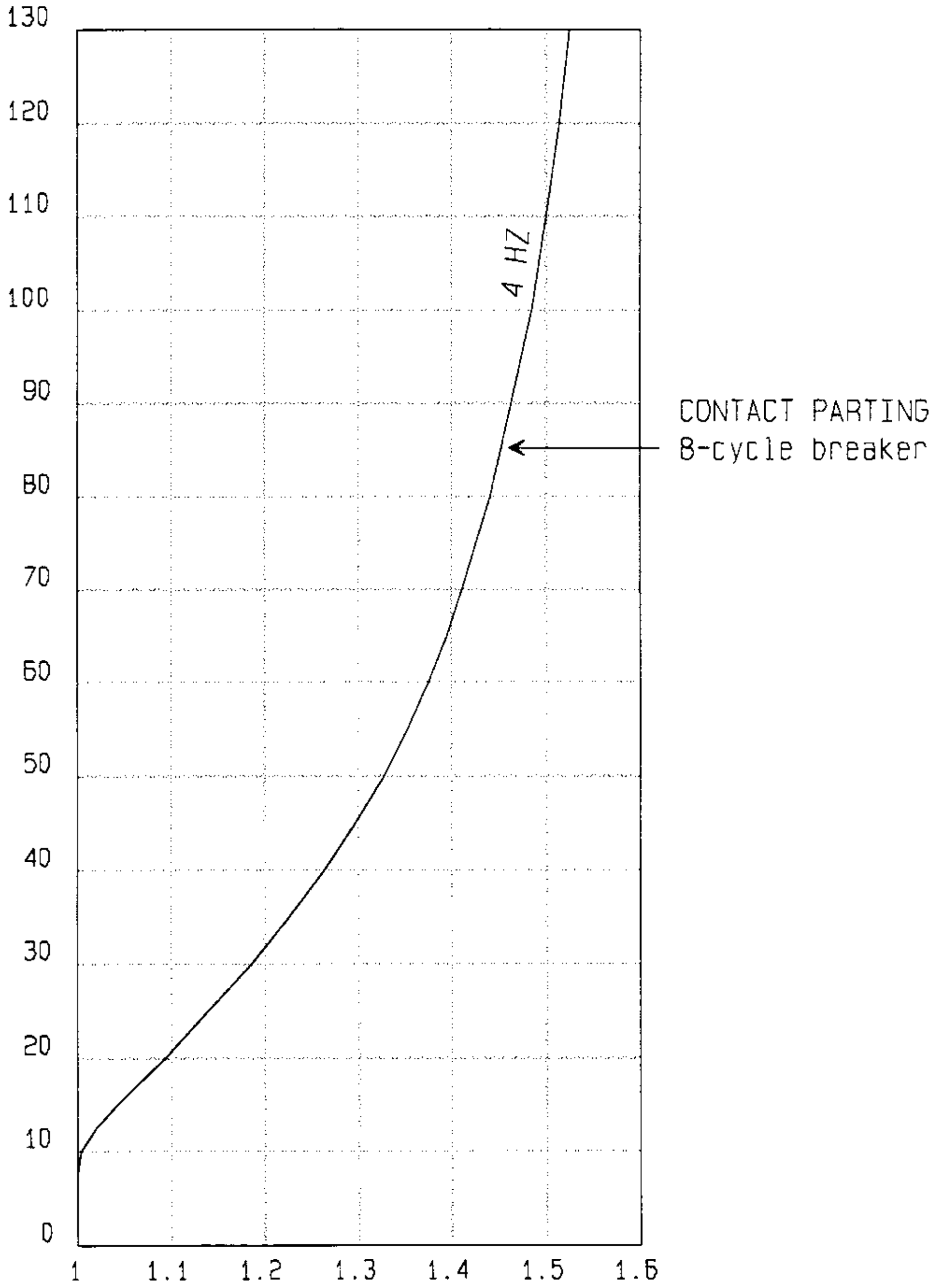

Figure A-12. C37.010 Three phase and single line to ground dc decrement curve for 8 cycle breakers.

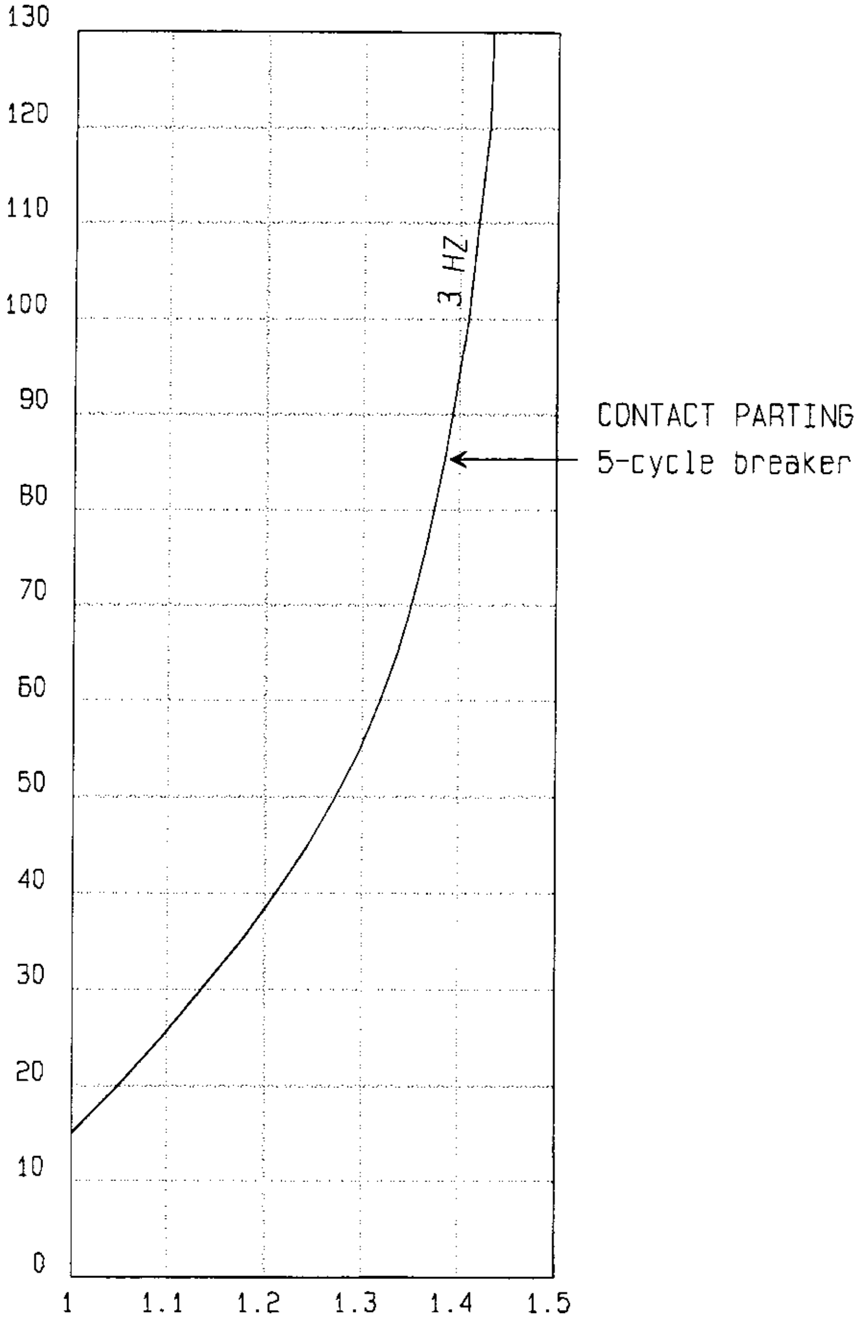

Figure A-13. Three phase and single line to ground dc decrement curve for 5 cycle breakers.

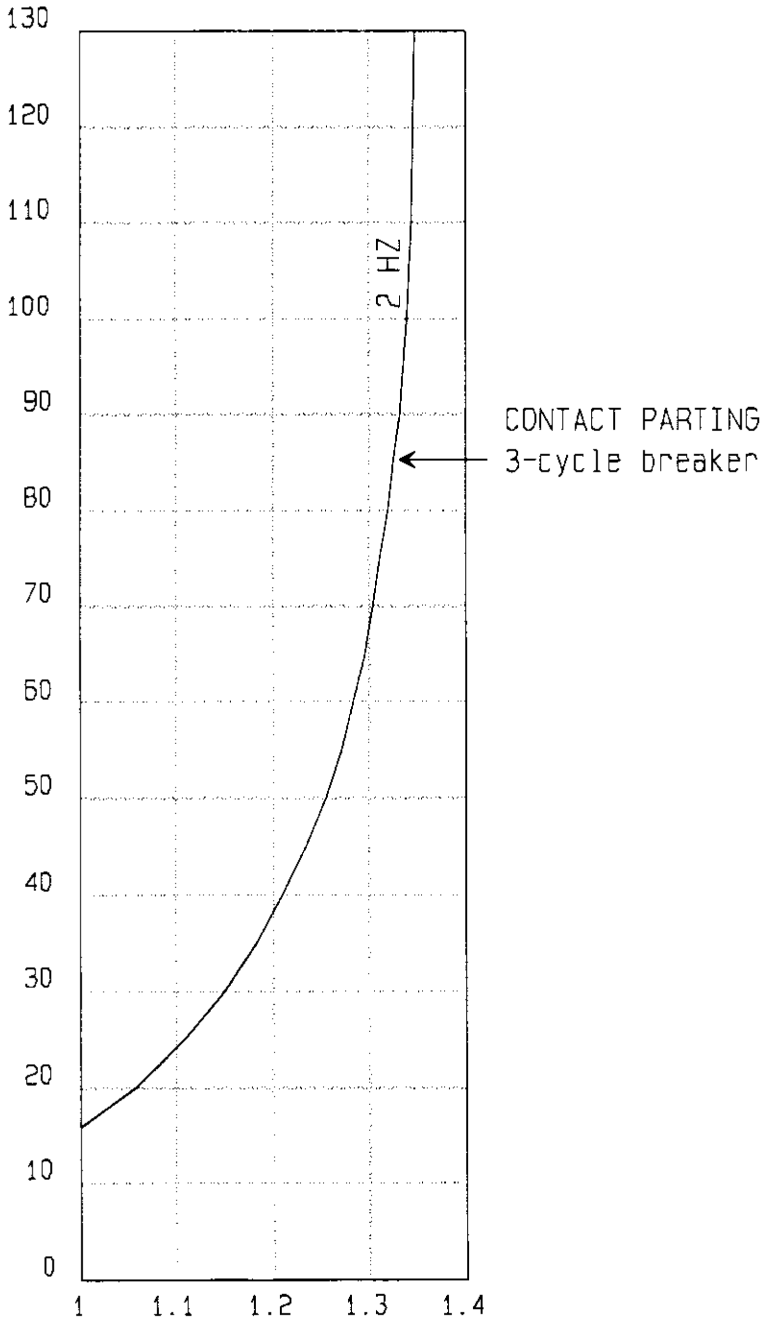

Figure A-14. Three phase and single line to ground dc decrement curve for 3 cycle breakers.

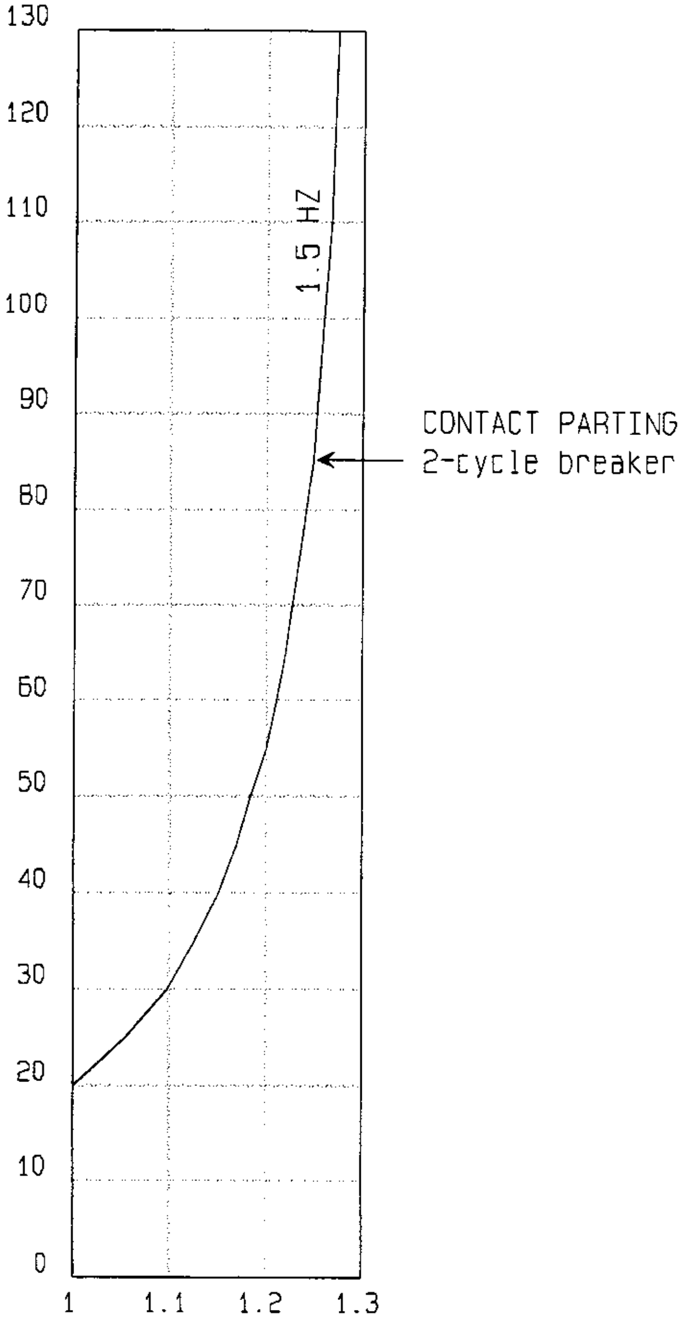

Figure A-15. Three phase and single line to ground dc decrement curve for 2 cycle breakers.

B.1 Comparison Between Ohms Law and ANSI Fault Current Calculation Methods

Complex Network Methods (Ohms Law)	ANSI
DAPPER calculates balanced and unbalanced fault currents for the power system based on "traditional" complex algebra.	A_FAULT calculates balanced and unbalanced fault duties for protective devices based on ANSI C37 standards.
All fault current calculations based on Complex Impedance.	Low Voltage model uses E/Z. High Voltage model uses either E/X or E/Z as defined by the user.
X/R Ratio formed from the complex impedance values.	X/R derived separately from a R and X network.
ac decrement for motors manually accomplished by user changing motor x_d'' values and re-running the DAPPER Fault Study. DAPPER V4.5 allows user to "toggle" off induction motors.	ac decrement for motors based on ANSI multiplying factors:
No separate low voltage report provided.	Reports low voltage fault duties based on the device test power factor and the low voltage factor from C37.13-1990.
Momentary asymmetrical (dc offset) fault currents reported in either peak or RMS values. The user may define phase or sequence fault values, and any user defined time greater than 1/2 cycle.	HV momentary asymmetrical offset RMS values reported based on separately derived X/R ratio (dc offset) and the 1/2 cycle ac multiplying factors for motors. Momentary fault duty value also reported as the symmetrical value times 1.6, as allowed by ANSI. User may model network as E/Z or E/X.
Interrupting RMS values as reported on the complex impedance's X/R ratio, at any user defined time (DAPPER V4.5). User may "toggle" off the offsets of induction motors.	HV interrupting (dc offset) RMS values reported on the separately derived X/R ratio, on either E/Z or E/X network configuration, the ac multiplying factors associated with motors, local/remote generation ratio, and for pre-1964 and post 1964 ANSI standard. Ac decrement based on the clearing times for breakers, not their total operating times. Local/remote ac decrement can be interrupted between remote, local, or predominately local generation.
Transformer taps and phase angles can be modeled or not - user preference.	Transformer taps can be modeled or not - user preference.
Full reporting of bus voltages and branch flows available anywhere in the network.	Branch flows available for branches directly connected to the fault location..

	utility	co-gen	sync	Induction Motors				
				< 50 hp any speed	50-1000 hp @ 1800 rpm	>1000 hp @ 1800 rpm	50-250 hp @ 3600 rpm	>250 hp @ 3600 rpm
low voltage duty	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
momentary duty	1.0	1.0	1.0	excluded	1.2	1.0	1.2	1.0
interrupting duty	1.0	1.0	1.5	excluded	3.0	1.5	3.0	1.5

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