

An American National Standard

IEEE Application Guide for Capacitance Current Switching for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis

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Foreword

(This Foreword is not a part of ANSI/IEEE C37.012-1979, American National Standard Application Guide for Capacitance Current Switching for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis.)

The development of standards for the rating, testing, and manufacture of high-voltage circuit breakers began almost simultaneously with the application of the first circuit breakers in early power supply systems.

A number of engineering and manufacturers trade organizations were interested in standards for high-voltage circuit breakers as well as other types of electrical equipment and worked to develop standard requirements for capabilities, sizes, and testing procedures. Among these groups were the AIEE¹, the National Electric Light Association (NELA), the Electric Power Club (a predecessor of NEMA — the National Electrical Manufacturers Association), the Association of Edison Illuminating Companies (AEIC), and the Edison Electric Institute (EEI).

During the years up to 1940, these organizations adopted and published a number of standardization proposals concerning rating, testing, and other requirements for high-voltage circuit breakers.

In 1941, a unified series of standards for circuit breakers, based on those of AIEE, AEIC, and NEMA, were published for trial use by the American Standards Association (ASA). This comprised the first American Standard for high-voltage circuit breakers. In 1945, this series was issued as an approved American Standard with the familiar C37 number identification. This series included sections on rating, preferred sizes, testing, and application of circuit breakers. In 1952 and 1953, this series of standards was revised and supplemented by additional sections, forming the complete, basic group of American Standards for high-voltage circuit breakers. At the time of publication this group of standards included:

ANSI C37.4-1953	AC Power Circuit Breakers (included definitions, rating basis, and some test requirements)
ANSI C37.5-1953	Methods for Determining the RMS Value of a Sinusoidal Current Wave and Normal-Frequency Recovery Voltage, and for Simplified Calculation of Fault Currents
ANSI C37.6-1953	Schedules of Preferred Ratings for Power Circuit Breakers
ANSI C37.7-1952	Interrupting Rating Factors for Reclosing Service
ANSI C37.8-1952	Rated Control Voltages and their Ranges
ANSI C37.9-1953	Test Code for Power Circuit Breakers
ANSI C37.12-1952	Guide Specifications for Alternating Current Power Circuit Breakers

Under these original standards, the basis of the interrupting rating was established by 6.11 of ANSI C37.4-1953 as the highest current to be interrupted at the specified operating voltage and was the "... rms value including the dc component at the instant of contact separation as determined from the envelope of the current wave." Since this standard based the interrupting rating on the total current including dc component at the instant of contact separation, it has become known as the "Total Current Basis of Rating."

For circuit breaker application, a simplified method was available in ANSI C37.5-1953 which listed multiplying factors for use with the system symmetrical fault current to derive a maximum possible total rms current which could be present at contact separation. This current was used to choose the required circuit breaker rating from those listed in ANSI C37.6-1953, or subsequent revisions. The factors recognized typical system characteristics and circuit breaker operating times.

¹AIEE (American Institute of Electrical Engineers) merged with IRE (Institute of Radio Engineers) January 1, 1963 to form the joint organization IEEE (Institute of Electrical and Electronics Engineers).

In 1951, the AIEE Switchgear Committee began to give consideration to the development of a circuit breaker rating method based on symmetrical interrupting currents. This work was initiated with the goal of:

- 1) Simplifying application where high-speed relaying and fast clearing circuit breakers are used
- 2) Bringing American standards into closer agreement with accepted international standards (IEC-International Electrotechnical Commission) to avoid confusion on rating differences
- 3) Requiring that circuit breakers are proven to demonstrate a definite relationship between asymmetrical interrupting capability and symmetrical ratings

During the course of this work, principally in a working group of the AIEE Power Circuit Breaker Subcommittee, numerous reports of the proposals on the new rating, testing, and application methods were made to the industry as a whole through committee sponsored papers at AIEE meetings in 1954, 1959, and 1960. Suggestions made in discussions were considered by the working group and incorporated where practicable. The principal change from the 1953 "Total Current" standard was in the basis of rating. 4.5.1 of ANSI C37.04 established the Rated Short Circuit Current as "the highest value of the symmetrical component of the ... short-circuit current in rms amperes, measured from the envelope of the current wave at contact separation, which the circuit breaker is required to interrupt at rated maximum voltage ...". Certain related capabilities were also required, including operation under specified conditions of asymmetry based on typical circuit characteristics and circuit breaker timing. This rating structure became known as the *Symmetrical Current Basis of Rating* as compared to the previous *Total Current Basis of Rating*. However, as the new ratings were developed, it became apparent that changes from the older to the newer standard could not occur overnight due to requirements for rerating and retesting of many PCBs. It was, therefore, decided to retain both rating structures, with the understanding that all new circuit breaker developments would be directed toward the *symmetrical* standards. The circuit breakers based on the total *current* standards would be transferred to the new standards as work progressed in rerating programs. This transfer is being carried out and ANSI C37.6 and ANSI C37.06 have been revised accordingly a number of times.

The *symmetrical current* group of standard sections was published in 1964 and was given ANSI C37.04, C37.05, C37.06, etc, designations. These sections and the corresponding 1953 sections were:

Total Current Standard	Symmetrical Current Standard	Subject
ANSI C37.4	ANSI C37.03	Definitions
	ANSI C37.04 ANSI C37.04a	Rating Structure
ANSI C37.5	ANSI C37.05	Measurement of Voltage and Current Waves
ANSI C37.6	ANSI C37.06 ANSI C37.06a	Preferred Ratings
ANSI C37.7	ANSI C37.07	Reclosing Factors
ANSI C37.8	(included in ANSI C37.06)	Control Voltages
ANSI C37.9	ANSI C37.09 ANSI C37.09a	Test Code
ANSI C37.5 (Section 3.)	ANSI C37.010	Application Guide (expansion of material previously in C37.5)

Sections .04a, .06a, and .09a, also issued in 1964, were addenda concerned with supplemental dielectric capability requirements.

In ANSI C37.06-1964 and subsequent revisions prior to 1971, circuit breaker symmetrical current interrupting ratings were derived from ratings in ANSI C37.6-1961 by a relationship following a middle ground position between the total (asymmetrical) current of the former rating method and the full range of related requirements of the new rating method. For a given breaker this derivation was expressed by the formula:

$$\text{rated short circuit current} = I_{1961} \left(\frac{\text{nominal voltage}}{\text{rated maximum voltage}} \right) F$$

where

I_{1961} = interrupting rating in amperes appearing in ANSI C37.6-1961
 F = 0.915 for 3 cycle breakers
 0.955 for 5 cycle breakers
 1.0 for 8 cycle breakers

Rated short circuit current was tabulated for rated maximum voltage rather than for nominal voltage as had been the case under the total current basis of rating.

It was stressed that this derivation was for the numerical conversion only and that a given circuit breaker, designed and tested under the total current basis of rating, could not be assumed to have these capabilities under the symmetrical current basis of rating without approval of the manufacturer.

In the revision of ANSI C37.06 published in 1971, several simplifications were introduced, including the use of a new method for selection of interrupting current ratings for outdoor circuit breakers 121 kV and above. Values for rated short circuit current were chosen from the R-10 preferred number series, and the use of a reference nominal 3-phase MVA identification was discontinued. Also the rated voltage range factor K was changed to unity, 1.0, to simplify rating and testing procedures.

In the intervening years since the official publication of the primary sections of the symmetrical basis of rating standard for high-voltage circuit breakers, a number of revisions, additions, and improvements have been developed and published. Many of these additions were in subject areas of major importance in the rating, testing, and application of circuit breakers and were published as complete standards containing appropriate definitions, rating performance criteria, rating numbers, test procedures, and application considerations. This was done to avoid delay in publication and the necessity of reprinting other existing standards as each of these was completed. The result has been the publication of a substantial number of individual supplementary standards. The basic subject areas considered in these supplementary standards, and their initial publication dates, are shown below:

ANSI C37.071-1969	Requirements for Line Closing Switching Surge Control
ANSI C37.072-1971	Requirements for Transient Recovery Voltage
ANSI C37.0721-1971	Application Guide for Transient Recovery Voltage
ANSI C37.0722-1971	Transient Recovery Voltage Ratings
ANSI C37.073-1972	Requirements for Capacitance Current Switching
ANSI C37.0731-1973	Application Guide for Capacitance Current Switching
ANSI C37.0732-1972	Preferred Ratings for Capacitance Current Switching
ANSI C37.074-1972	Requirements for Switching Impulse Voltage Insulation Strength
ANSI C37.076-1972	Requirements for Pressurized Components
ANSI C37.078-1972	Requirements for External Insulating

ANSI C37.0781-1972	Test Values for External Insulation
ANSI C37.079-1973	Method of Testing Circuit Breakers When Rated for Out-of-Phase Switching

A goal of work recently completed, and represented by the 1979 publication of these standards, has been the editorial incorporation of all the supplementary standards listed above into the proper primary standards documents. For circuit breakers rated on a symmetrical current basis, the consolidated standards sections are:

ANSI/IEEE C37.04-1979	Rating Structure
ANSI C37.06-1979	Preferred Ratings and Related Required Capabilities
ANSI/IEEE C37.09-1979	Test Procedure
ANSI/IEEE C37.010-1979	Application Guide — General
ANSI/IEEE C37.011-1979	Application Guide — Transient Recovery Voltage
ANSI/IEEE C37.012-1979	Application Guide — Capacitance Current Switching

The present ANSIC37.05, Measurement of Current and Voltage Waves, is incorporated into ANSI/IEEE C37.09; ANSI C37.07, Interrupting Capability Factors for Reclosing Service, is incorporated into ANSI/IEEE C37.04, ANSI C37.06, and ANSI/IEEE C37.09. Definitions which have been in C37.03-1964 are now in ANSI C37.100-1972.

Standards are presently being developed in a number of additional subject areas, which will be initially published as supplementary standards and incorporated into the primary subject document at some future date. Included among these subjects are requirements for current transformers, a guide for synthetic testing, sound level measurements, and seismic capability requirements.

For circuit breakers still rated on a total current basis, as listed in ANSI C37.6, the existing standards ANSI C37.4, ANSI C37.6, ANSI C37.7, and ANSI C37.9 will continue to be applicable.

Documents pertaining to guide specification and control schemes, which apply to both groups of ratings, are included in the ANSI C37 series as shown below:

ANSI C37.11-1972	Requirements for Electrical Control on AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis and a Total Current Basis
ANSI C37.12-1969	Guide Specifications for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis and a Total Current Basis

Periodic review of all these standards takes place through the normal ANSI procedure that standards are reaffirmed, revised, or withdrawn within no more than five year intervals from the original publication date.

Suggestions for improvement gained in the use of this standard will be welcome. They should be sent to the

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The basic data included in this consolidated document is the result of contributions made by many individuals over many years. At the time of approval, however, the American National Standards Committee on Power Switchgear, C37, which reviewed and approved this standard, had the following personnel:

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An American National Standard

IEEE Application Guide for Capacitance Current Switching for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis

1. Scope

This application guide for capacitance current switching applies to ac high-voltage circuit breakers rated in accordance with ANSI/IEEE C37.04-1979, Rating Structure for AC High-Voltage Circuit Breakers, and listed in ANSI C37.06-1979, Schedules of Preferred Ratings and Related Required Capabilities for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis. It is intended to supplement ANSI/IEEE C37.010-1979, Application Guide for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis. Circuit breakers rated and manufactured to meet other standards should be applied in accordance with application procedures adapted to their specific ratings.

2. Purpose

This guide is intended for general use in the application of circuit breakers for capacitance current switching. Familiarity with other American National Standards applying to circuit breakers is assumed, and provisions of those standards are indicated herein only when necessary for clarity in describing application requirements.

3. General Application Conditions

See Section 3. of ANSI/IEEE C37.010-1979.

4. Capacitance Current Switching Application Considerations

4.1 Maximum Voltage for Application

The operating voltage should not exceed the rated maximum voltage since this is the upper limit for operation.

4.2 Frequency

The rated frequency for circuit breakers is 60 Hz. Special consideration should be given to applications other than 60 Hz. At lower frequencies, the capacitance current switching ability will be adequate, but ac control devices may not be suitable for the application.

4.3 Capacitance Current

Circuit breakers are designed for application where the capacitance current, whether on an overhead line, cable, or capacitor bank, does not exceed the rated value, at any voltage, up to rated maximum voltage. For altitudes exceeding 3300 ft, (1000 m) the capacitance current does not have to be corrected, provided it does not exceed the corrected rated continuous current.

4.4 Interrupting Time

The interrupting time of a circuit breaker on capacitance current switching is the interval between the energizing of the trip circuit at rated control voltage and the interruption of the main circuit in all poles on an opening operation. Since capacitance currents are less than 25 percent of the required asymmetrical interrupting capability, the time required for interruption may be greater than the rated interrupting time. For circuit breakers equipped with resistors, the interrupting time of the resistor current may be longer. Note also that the interrupting time may be longer for close-open operations. (See 5.7 of ANSI/IEEE C37.04-1979.)

4.5 Transient Overvoltage

An important consideration for application of circuit breakers for capacitance current switching is the transient overvoltage which may be generated by restrikes during the opening operation. In ANSI C37.100-1972, a transient overvoltage

factor is defined as the ratio of the transient voltage appearing between a circuit breaker disconnected terminal and the neutral of the disconnected capacitance during opening to the operating line-to-neutral crest voltage prior to opening. The rated transient overvoltage factor is specified for two types of circuit breakers:

- 1) General-purpose circuit breakers. The transient overvoltage factor should not exceed 3.0.
- 2) Definite-purpose circuit breakers. The transient overvoltage factor shall not exceed the following more than once in 50 random three-phase operations:
 - a) 2.5 for circuit breakers rated 72.5 kV and below
 - b) 2.0 for circuit breakers rated 121 kV and above

The selection of the type of circuit breaker to be applied should be coordinated with the insulation capability of other components on the system.

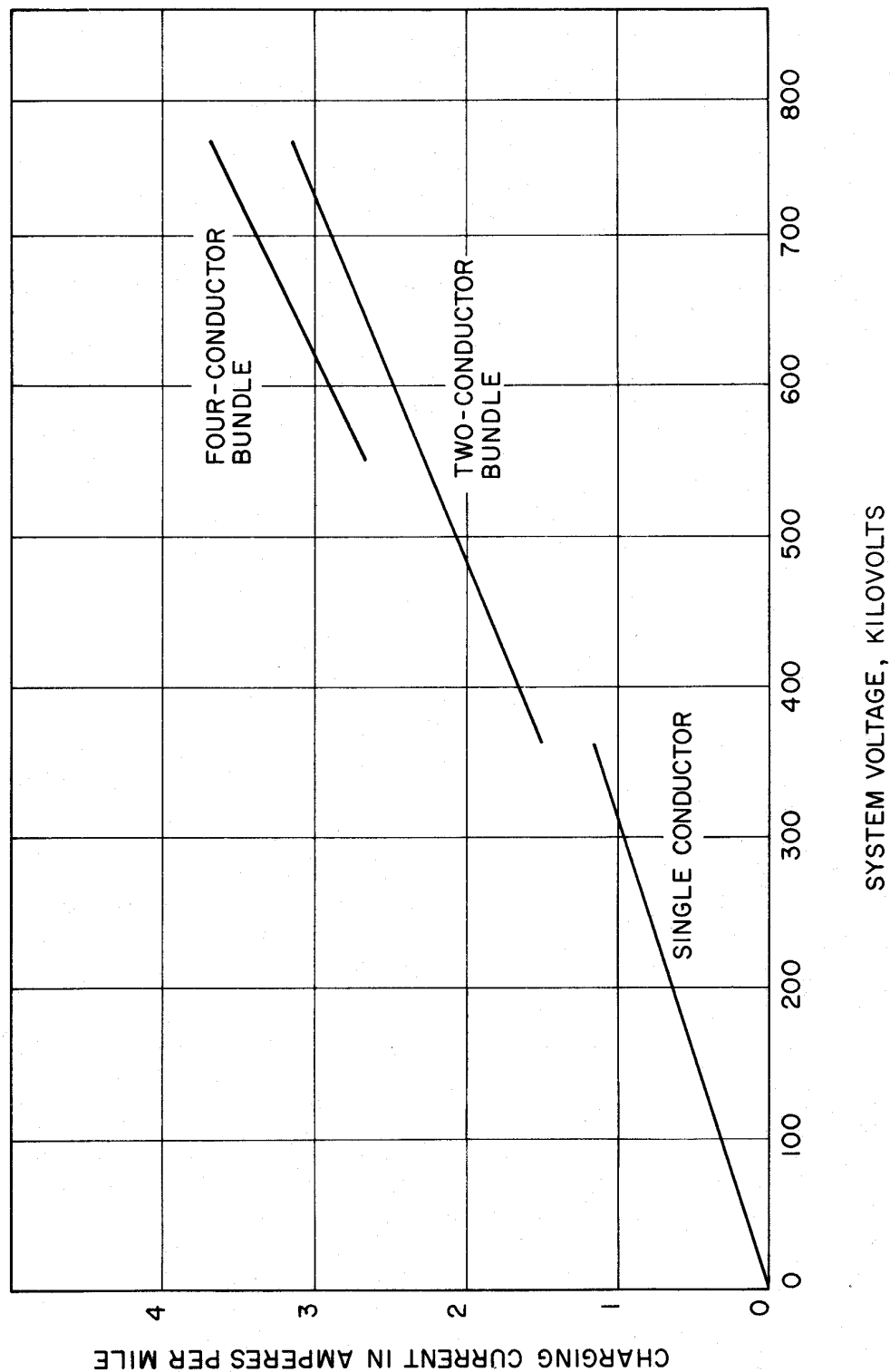


Figure 1— RMS Charging Current Versus System Voltage for Single-Conductor and Two-Conductor Bundle Lines

4.6 Open Wire Transmission Lines

A circuit breaker may be required to energize or deenergize an unloaded open wire transmission line during its normal operating duties. Prior to energization, the line may or may not contain a trapped charge. The test program of 4.13 of ANSI/IEEE C37.09-1979, Test Procedure for AC High-Voltage Circuit Breakers recognizes the possible conditions encountered during the switching of open wire lines. The application of either general or definite-purpose circuit breakers to open wire line switching is determined by the open wire line current switching rating assigned in ANSI C37.06-1979, Tables 1A, 2A, 3A, 4A and 5A.

4.6.1 Open Wire Line Charging Switching Current.

When considering the assigned open wire line charging switching current rating, application is determined by the value of the line charging current. This current is a function of system voltage, line length, and line configuration.

For a first approximation of single- and double-circuit overhead line charging currents, the capacitive reactance at 60 Hz can be estimated as follows:

Single conductor 0.18 MΩ per phase per mile (0.29 MΩ per phase per kilometer)

Two-conductor bundle — 0.14 MΩ per phase per mile (0.23 MΩ per phase per kilometer)

Three-conductor bundle — 0.13 MΩ per phase per mile (0.21 MΩ per phase per kilometer)

Four-conductor bundle — 0.12 M— per phase per mile (0.19 MΩ per phase per kilometer)

The curve of Fig 1 shows rms charging current in amperes per mile¹ as a function of system voltage for single-conductor and two-conductor bundle lines.² If the estimated current is greater than 90 percent of the preferred line current rating, a more accurate calculation based on the actual line configuration and methods similar to that discussed in reference [1] should be used.³

These calculations assume a transposed line and neglect the rise in voltage at the open end (Ferranti effect). The voltage rise has the effect of increasing the line charging current and is a function of line length.

The additional current can be calculated using, for example, ABCD constants and considering the line open-circuited at the receiving end. The magnitude of the charging current is then

$$|I_c| = \frac{|V_s| \tanh \sqrt{-X_L/X_C}}{\sqrt{X_L X_C}} \approx \frac{|V_s|}{X_C} \left[1 + \frac{1}{3} \frac{X_L}{X_C} \right]$$

where

- $|V_s|$ = magnitude of sending end line-to-ground voltage
- X_C = line positive-sequence capacitive reactance per phase, in ohms
- X_L = line positive-sequence inductive reactance per phase, in ohms

The term in brackets is a modifying factor which is applied to the current determined previously (see Fig 1) and, for a single-conductor line with 0.8 Ω per phase per mile inductive reactance and 0.18 MΩ per phase per mile capacitive reactance, the current magnitude is approximately

¹1 mile = 1.61 km.

²When using the quantity MΩ per phase per mile, it should be remembered that the shunt capacitive reactance in megohms for more than one mile decreases because the capacitance increases. For more than one mile of line, therefore, the value of shunt-capacitive reactance as given above should be divided by the number of miles of line.

³An example of this calculation is given in Appendix A.

$$\begin{aligned}
 |I_c| &= |I_c'| \left[1 + \frac{1}{3} \frac{0.8(100S)}{0.18 \times 10^6 / (100S)} \right] \\
 &= |I_c'| [1 + 0.0148S^2]
 \end{aligned}$$

where

$$\begin{aligned}
 |I_c'| &= \text{uncorrected current} \\
 S &= \text{line length, in hundreds of miles}
 \end{aligned}$$

The corresponding equation for a two-conductor bundle with 0.6 Ω per phase per mile inductive reactance and 0.14 M Ω per phase per mile capacitive reactance is

$$|I_c| = |I_c'| [1 + 0.0143S^2]$$

Examination of these equations indicates an error of approximately 1.5 percent at 100 mi. The Ferranti effect can be neglected for lines less than this length.

4.6.2 Compensated Open Wire Transmission Line Current.

Extremely long lines are often compensated with shunt reactors to reduce the amount of charging current required of the system. The compensation factor F_c is defined as

$$F_c = \frac{X_C}{X_R} \quad (1)$$

where

$$X_R = \text{inductive reactance of compensating reactor}$$

The factor F_c times 100 is the “percent compensation.” If X_R is greater than X_C the line is undercompensated, if X_R is less than X_C the line is overcompensated. The compensated line charging current is then given by

$$I_{1c} = I_c' (1 - F_c) \quad (2)$$

where

$$\begin{aligned}
 I_{1c} &= \text{compensated line charging current} \\
 I_c' &= \text{uncompensated line current (see Section 4.6.1)} \\
 F_c &= \text{compensation factor (Eq 1)}
 \end{aligned}$$

Assuming a line compensated at 60 percent, the line charging current is

$$I_{1c} = I_c' (1 - 0.6) = 0.4 I_c'$$

or 40 percent of the uncompensated value. If the breaker rating is chosen based on I_{1c} , the line could not be switched without the compensating reactor(s) connected. The voltage rise caused by the Ferranti effect and also the location of the reactor(s) will change the line current slightly.

4.6.3 Line Charging Transient Recovery Voltage.

The open wire line charging switching current rating is assigned on the basis of a standard transient recovery voltage associated with this type of circuit. The tests discussed in 4.13 of ANSI/IEEE C37.09-1979, which demonstrate performance, are based on the test voltages of 4.13.4 of ANSI/IEEE C37.09-1979. The open wire line charging current switching tests require a maximum voltage of 2.4 times rated maximum phase-to-ground voltage across the circuit breaker one half-cycle after interruption (assumes $C_1 = 2 C_0$ where C_1 is the positive-sequence capacitance and C_0 is the zero-sequence capacitance). This is the difference voltage of the source and line sides, including the effects of coupled voltage on the first phase to clear. The test voltage requires a 1-cosine waveshape.

Deviations from the test voltage characteristics may increase or decrease the probability of the circuit breaker restriking. For example, if the line is compensated, the line side component is not a trapped voltage but is an oscillation with a frequency determined by the compensating reactors and the line capacitance. The resonant frequency of the compensated line is approximated by

$$f_L = \frac{1}{2\pi\sqrt{LC}} = f_s \sqrt{\frac{X_C}{X_R}} \text{ (Hz)} \quad (3)$$

where

- f_L = line resonant frequency, in hertz
- L = reactor inductance, in henrys
- C = total capacitance of line, in farads
- f_s = system frequency, in hertz

A simple substitution indicates

$$f_L = f_s \sqrt{F_c} \text{ (Hz)} \quad (4)$$

Since F_c , the compensation factor, is usually less than 1, the line resonant frequency is correspondingly less than the system frequency.

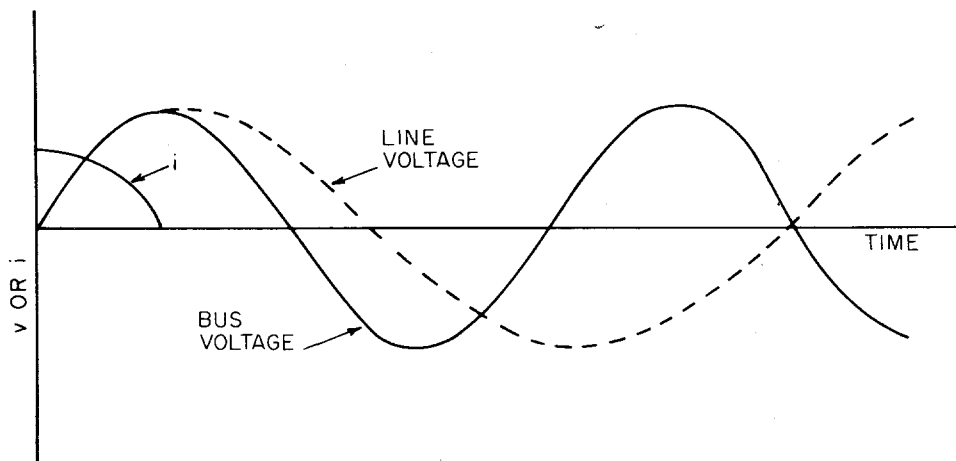


Figure 2— Typical Current and Voltage Relations for a Compensated Line

Typical current and voltage relations are given in Fig 2.

The first half-cycle of recovery voltage is, for this example, as shown in Fig 3. Compensation thus reduces the probability of restriking at a particular current. Under these conditions improved performance may result, the breaker

becoming restrike-free or possibly able to interrupt higher values of charging current. The manufacturer should be consulted on applications which markedly alter the transient recovery voltage.

If the C_1/C_0 ratio is greater than 2, higher voltages may be coupled to the first phase to clear, resulting in increased probability of restrikes. In this case the manufacturer should also be consulted since circuit breaker designs are sensitive to both current magnitude, and recovery voltage waveshapes.

4.7 Capacitor Banks

A circuit breaker may be required to switch a capacitor bank from a bus that does not have other capacitor banks energized (isolated) or against a bus that has other capacitor banks energized (back to back). In the application of circuit breakers for capacitor switching duty, consideration must be given to the rated isolated shunt capacitor bank switching current, rated back-to-back shunt capacitor bank switching current, rated transient inrush current, and rated transient inrush current frequency.

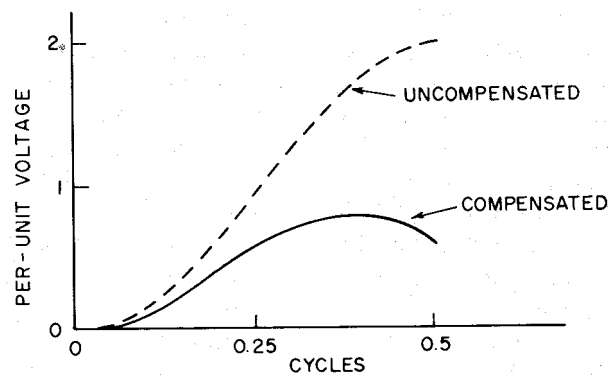


Figure 3— First Half-Cycle of Recovery Voltage

4.7.1 Capacitor Bank Current.

Circuit breakers are to be applied according to the actual capacitance current they are required to interrupt. The rating should be selected to include the following effects.

- 1) *Voltage Factor.* The nameplate reactive power rating of the capacitor bank, in kilovars, is to be multiplied by the ratio of the maximum service voltage to the capacitor bank nameplate voltage when calculating the capacitance current at the applied voltage. This factor can be as large as 1.1, since capacitors can be operated continuously up to 10 percent above the capacitor rated voltage.
- 2) *Capacitor Tolerance.* The manufacturing tolerance in capacitance is -0 to $+15$ percent with a more frequent average of -0 to $+5$ percent. A multiplier in the range of 1.05 to 1.15 should be used to adjust the nominal current to the value allowed by tolerance in capacitance.
- 3) *Harmonic Component.* Capacitor banks provide a low-impedance path for the flow of harmonic currents. When capacitor banks are ungrounded, no path is provided for zero-sequence harmonics (third, sixth, ninth, etc), and the multiplier for harmonic currents is less. A multiplier of 1.1 is generally used for a grounded neutral bank and 1.05 for an ungrounded neutral.

In the absence of specific information on multipliers for the above factors, it will usually be conservative to use a total multiplier of 1.25 times the nominal capacitor current at rated capacitor voltage for ungrounded neutral operation and 1.35 times the nominal current for grounded neutral operation.

4.7.2 Isolated Capacitor Bank.

A bank of shunt capacitors is considered isolated when the inrush current on energization is limited by the inductance of the source and the capacitance of the bank being energized. As defined in 5.13.2 of ANSI/IEEE C37.04-1979, a capacitor bank is also considered isolated if the maximum rate of change, with respect to time, of transient inrush current on energizing an uncharged capacitor bank does not exceed the maximum rate of change of the symmetrical interrupting current at the voltage at which the circuit breaker is applied. The limiting value is equal to

$$\left(\frac{di}{dt}\right)_{\max} = \omega\sqrt{2}\left[\frac{\text{rated maximum voltage}}{\text{operating voltage}}\right]I \text{ (A/s)}$$

where

$$I = \text{rated rms short-circuit current, in amperes}$$

$$\omega = 2\pi f = 377 \text{ for 60 Hz system}$$

The ratio [(rated maximum voltage)/(operating voltage)] shall not exceed the voltage range factor K as given in ANSI C37.06-1979, Tables 1 through 5.

4.7.3 Back-to-Back Capacitor Bank.

The inrush current of a single bank will be increased when other capacitor banks are connected to the same bus. As defined in 13.3 of ANSI/IEEE C37.04-1979, a capacitor bank is considered switched back to back if the highest rate of change of inrush current on closing exceeds that specified for isolated capacitor banks of 5.13.2 of ANSI/IEEE C37.04-1979.

4.7.4 Inrush Current.

The energization of a capacitor bank by the closing of a circuit breaker will result in a transient inrush current. The magnitude and frequency of this inrush current is a function of the following: applied voltage (point on the voltage wave at closing), capacitance of the circuit, inductance in the circuit (amount and location), any charge on the capacitor bank at the instant of closing, and any damping of the circuit due to closing resistors or other resistance in the circuit.

The transient inrush current to a single (isolated) bank is less than the available short-circuit current at the capacitor bank terminals. Since a circuit breaker must meet the momentary current requirements of the system, transient inrush current is not a limiting factor in isolated capacitor bank applications.

When capacitor banks are switched back to back, that is, when one bank is switched while another bank is connected to the same bus, transient currents of prospective high magnitude and with a high natural frequency may flow between the banks on closing of the switching device or in the event of a restrike on opening. This oscillatory current is limited only by the impedance of the capacitor bank and the circuit between the energized bank or banks and the switched bank. This transient current usually decays to zero in a fraction of a cycle of the system frequency. In the case of back-to-back switching, the component supplied by the source is at a lower frequency and so small it may be neglected.

Table 1—Inrush Current and Frequency for Switching Capacitor Banks

Condition	Quantity	When Using Currents
Energizing an isolated bank	$i_{\max \text{ pk}}$ (amperes)	$1.41 \sqrt{I_{\text{sc}} \times I_1}$
	f (hertz)	$f_s \sqrt{\frac{I_{\text{sc}}}{I_1}}$
Energizing a bank with another on the same bus	$i_{\max \text{ pk}}$ (amperes)	$1747 \sqrt{\frac{(V_{\text{LL}})(I_1 \times I_2)}{(L_{\text{eq}})(I_1 + I_2)}}$
	f (kilohertz)	$9.5 \sqrt{\frac{(f_s)V_{\text{LL}}(I_1 + I_2)}{(L_{\text{eq}})(I_1 \times I_2)}}$
Energizing a bank with an equal bank energized on the same bus	$i_{\max \text{ pk}}$ (amperes)	$1235 \sqrt{\frac{(V_{\text{LL}})(I_1)}{L_{\text{eq}}}}$
	f (kilohertz)	$13.5 \sqrt{\frac{(f_s)(V_{\text{LL}})}{(L_{\text{eq}})(I_1)}}$

f_s = System frequency

L_{eq} = Total equivalent inductance per phase between capacitor banks, in microhenrys

I_1, I_2 = Currents of bank being switched and of bank already energized, respectively. Capacitor bank being switched is assumed uncharged, with closing at a voltage crest of the source voltage. The current used should include the effect of operating the capacitor bank at a voltage above nominal rating of the capacitors and the effect of a positive tolerance of capacitance. In the absence of specific information, a multiplier of 1.15 times nominal capacitor current would give conservative results

$i_{\max \text{ pk}}$ = A peak value calculated without damping. In practical circuits it will be about 90 percent of this value

V_{LL} = Rated maximum voltage in kilovolts

I_{sc} = Symmetrical rms short-circuit current, in amperes.

4.7.4.1 Method for Calculating Transient Inrush Currents.

Table 1 gives the formula for calculating inrush current and frequency for both isolated and back-to-back capacitor bank switching, neglecting resistance. These formulas are based on the following fundamental relationships⁴:

$$i = \frac{E}{\sqrt{L/C}} \sin(t/\sqrt{LC})$$

$$i_{\max \text{ pk}} = \frac{\sqrt{2}E_{\text{LL}}}{\sqrt{3}} \sqrt{\frac{C_{\text{eq}}}{L_{\text{eq}}}}$$

$$f = \frac{1}{2\pi\sqrt{L_{\text{eq}}C_{\text{eq}}}}$$

where

C = farads
 L = henrys
 I = amperes
 f = hertz

⁴See Appendix B.