ANSI/IEEE C37.012-1979

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 AIEE[1], 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.

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[1] AIEE (American Institute of Electrical Engineers) merged with IRE (Institute of Radio Engineers) January 1, 1963 to form the joint organization IEEE (Institue 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:

C. L. Wagner, *Chair*
J. P. Lucas, *Secretary*
J. E. Beehler *(Executive Vice-Chairman of High-Voltage Switchgear Standards)*
W. E. Laubach *(Executive Vice-Chairman of Low-Voltage Switchgear Standards)*
W. R. Wilson *(Executive Vice-Chairman of IEC Activities)*

Organization Represented	**Name of Representative**
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U.S. Department of the Interior, Bureau of Reclamation	E. M. Tomsic
U.S. Department of the Navy, Naval Facilities Engineering Command	D. M. Hannemann

The personnel of the C37 Subcommittee on High Voltage Circuit Breakers which reviewed and approved this document were as follows:

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The basic Application Guide was prepared by a Working Group on Standards for Capacitance Current Switching of the IEEE High-Voltage Power Circuit Breaker Subcommittee of the IEEE Switchgear Committee. The personnel of the Working Group were as follows:

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When the IEEE Standards Board approved this standard on June 2, 1977, it had the following membership:

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CLAUSE PAGE

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/IEEEC37.04-1979.)

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.

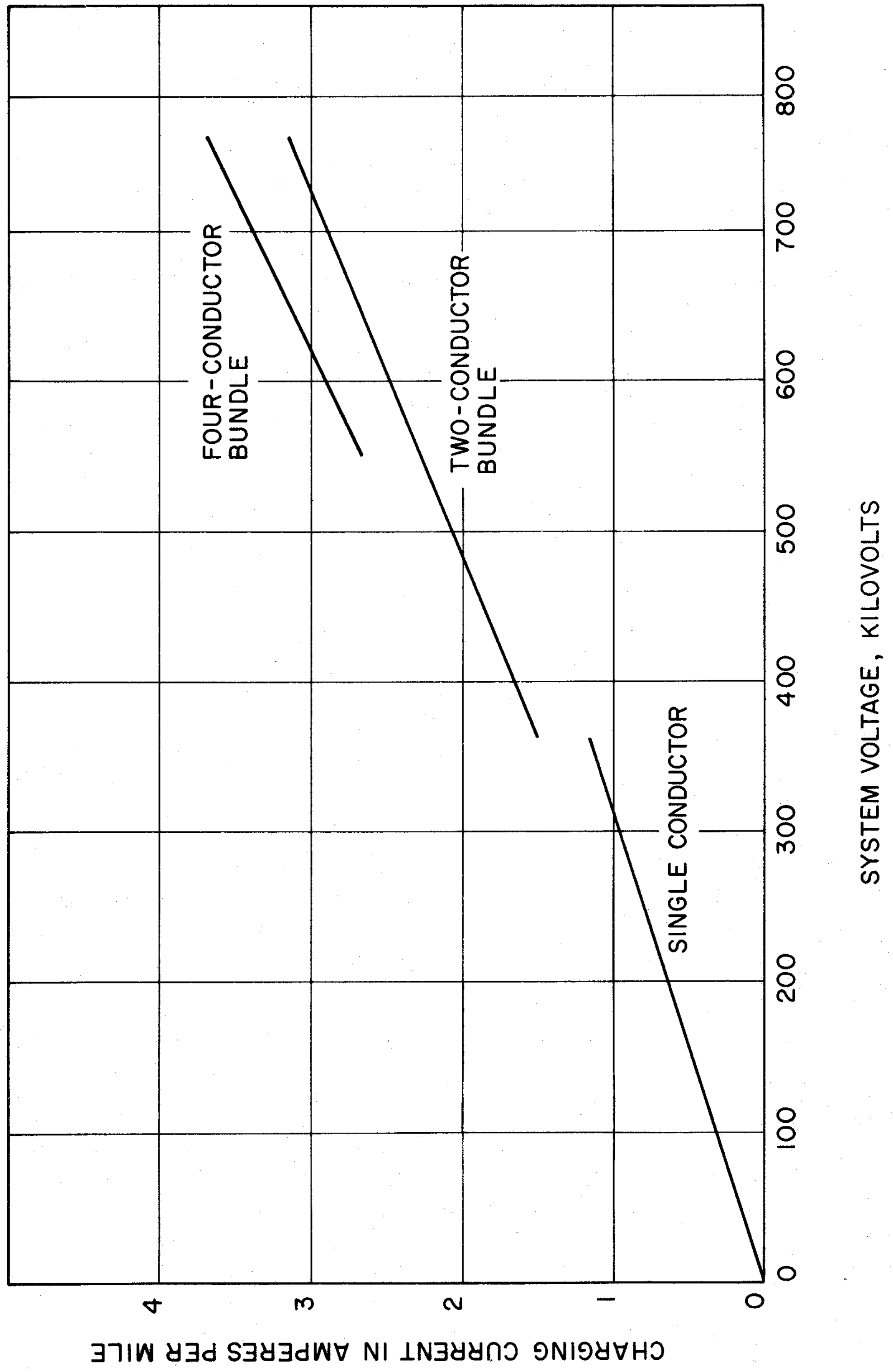

Figure 1— RMS Charging Current Versus System Voltage for Single-Conductor and Two-Conductor Bundle Lines

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 mile[1] 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

$$|I_{\mathrm{c}}| = \frac{|V_{\mathrm{s}}| \tanh \sqrt{-X_{\mathrm{L}}/X_{\mathrm{C}}}}{\sqrt{X_{\mathrm{L}}\ X_{\mathrm{C}}}} \approx \frac{|V_{\mathrm{s}}|}{X_{\mathrm{C}}}\left[1 + \frac{1}{3}\frac{X_{\mathrm{L}}}{X_{\mathrm{C}}}\right]$$

where

$|V_{\mathrm{s}}|$ = 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

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[1] 1 mile = 1.61 km.

[2] When 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.

[3] An 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

$|I_c'|$ = uncorrected current
S = line length, in hundreds of miles

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

$$F_c = \frac{X_C}{X_R} \tag{1}$$

where

X_R = 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

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

where

I_{1c} = compensated line charging current
I_c' = uncompensated line current (see Section 4.6.1)
F_c = compensation factor (Eq 1)

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

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

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

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

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

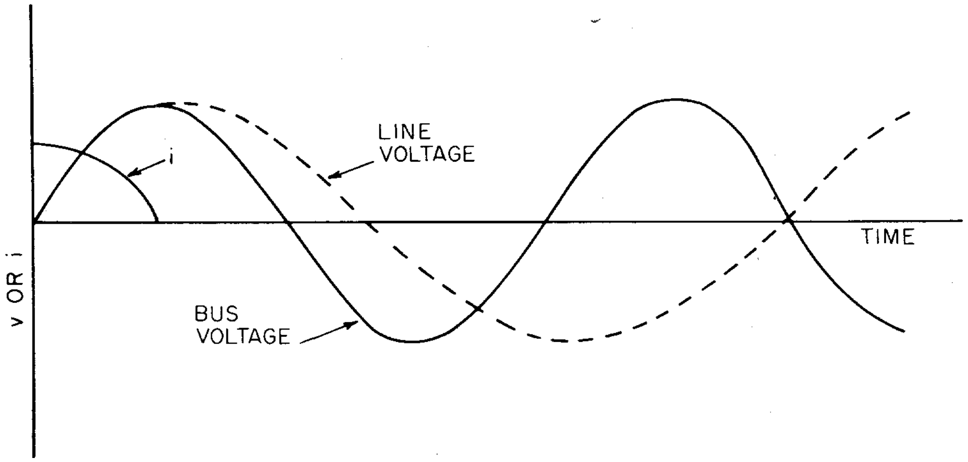

Figure 2— Typical Current and Voltage Relations for a Compensated Line

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.

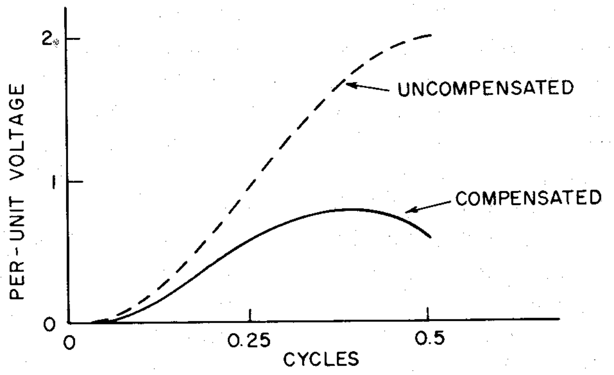

Figure 3— First Half-Cycle of Recovery Voltage

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

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

where

I = rated rms short-circuit current, in amperes
$\omega = 2\pi f = 377$ 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	$i_{\text{max pk}}$ (amperes)	$1.41\sqrt{I_{\text{sc}} \times I_1}$
	f (hertz)	$f_{\text{s}}\sqrt{\frac{I_{\text{sc}}}{I_1}}$
Energizing a bank with another on the same bus	$i_{\text{max pk}}$ (amperes)	$1747\sqrt{\frac{(V_{\text{LL}})(I_1 \times I_2)}{(L_{\text{eq}})\ \ (I_1 + I_2)}}$
	f (kilohertz)	$9.5\sqrt{\frac{(f_{\text{s}})V_{\text{LL}}(I_1 + I_2)}{(L_{\text{eq}})(I_1 \times I_2)}}$
Energizing a bank with an equal bank energized on the same bus	$i_{\text{max pk}}$ (amperes)	$1235\sqrt{\frac{(V_{\text{LL}})(I_1)}{L_{\text{eq}}}}$
	f (kilohertz)	$13.5\sqrt{\frac{(f_{\text{s}})(V_{\text{LL}})}{(L_{\text{eq}})(I_1)}}$

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
$i_{\text{max pk}}$ =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 relationships[4]:

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

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

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

where

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

---

[4] See Appendix B.

A typical circuit for back-to-back switching is shown in Fig 4. The inductance in the circuit that limits the transient oscillatory current is composed of the inductance of the bus between switching devices, L_{bus}, the inductance between the switching device and the capacitor banks, L_1 and L_2, and the inductance of the capacitor banks, L_{C1} and L_{C2}. The total inductance between capacitor banks, $L_{C1} + L_1 + L_{bus} + L_2 + L_{C2}$, is very small with respect to the inductance of the source L_s. In most cases, the total inductance between capacitor banks will be less than one percent of the inductance of the source, and the contribution of transient current from the source can be neglected.

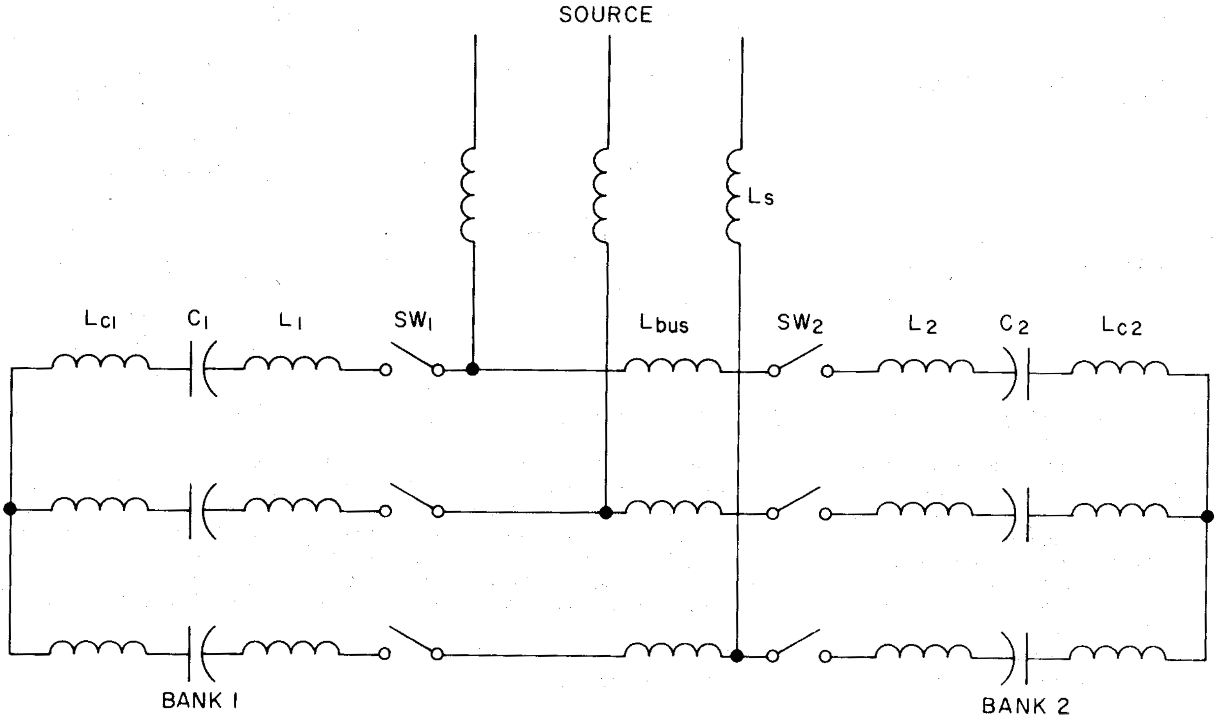

Figure 4— Typical Circuit for Back-to-Back Switching

SW_1	Circuit Breaker Energizing Capacitor Bank 1
SW_2	Circuit Breaker(s) Connecting Another Bank(s) to Bus
L_S	Source Inductance
L_{C1}, L_{C2}	Capacitor Bank Inductance
L_1, L_2	Bus Inductance Between Switching Device and Capacitor Bank
L_{bus}	Inductance of Bus Between Switching Devices

The inductance of the bus can be calculated similar to a transmission line using values of X_a (for one-foot spacing) and X_d (spacing factor) from tables available from suppliers of bus conductors for different bus configurations. (See 4.7.4.2.)

The inductance within the capacitor bank itself is not easy to obtain, but in general it is of the order of 10 µH for banks above 46 kV, and 5 µH for banks below 46 kV. Typical values of inductance per phase between back-to-back capacitor banks and bank inductance for various voltage levels are given in Table 2.

Inherent resistance of the circuit causes rapid decay of the transient current so that the first peak actually may only reach 90 to 95 percent of the maximum value calculated. These values are applicable to both grounded or ungrounded banks and with wye or delta connections. With an ungrounded neutral, the current in the first two phases to close will be 87 percent of calculated, but the current in the last phase will equal the value calculated. However, inherent resistance of the circuit will affect these currents by the factors indicated above.

The formula in Table 1 for back-to-back switching will give correct results when switching a bank against another bank. However, when switching against several other banks connected to the bus, the correct value of equivalent inductance to be used for the combination of banks connected to the bus is not easily obtained. For example, when switching a bank against three other banks energized on the bus, the calculated current will be too high if an inductance of $L/3$ is used. On the other hand, using a value of $3L$ will result in a current which is too low. If exact solutions cannot be made, conservative results should be used in calculating inrush currents by using the inductance divided by the number of capacitor banks, recognizing that the results will be from 20 to 30 percent too high.

4.7.4.2 *Considerations for Transient Inrush Currents.*

The inrush currents of different types of compact multisection banks with minimum spacing between the individual sections may differ by as much as 20 percent. Consequently, these inrush currents can be reduced significantly by increasing the lengths (inductance) of the circuits between the sections.

Table 2— Typical Values of Inductance Between Capacitor Banks

Rated Maximum Voltage (kV)	Inductance per Phase of Bus (μH/ft)	Typical Inductance Between Bank* (μ/H)
15.5 and below	0.214	10–20
38	0.238	15–30
48.3	0.256	20–40
72.5	0.256	25–50
121	0.261	35–70
145	0.261	40–80
169	0.268	60–120
242	0.285	85–170

*Typical values of inductance per phase between capacitor banks. This does not include inductance of the capacitor bank itself. Values of 5 μH for banks below 46 kV and 10 μH for banks above 46 kV are typical for the inductance of the capacitor banks.

Another effective measure to reduce transient inrush currents is to add inductance in the circuit between the capacitor banks.

The magnetic fields associated with high inrush currents during back-to-back switching in either the open wire transmission line conductors or the grounding grid during back-to-back switching can induce voltages in control cables by both capacitive and electromagnetic coupling. These induced voltages can be minimized by shielding the cables and using a radial configuration for circuits (circuits completely contained within one cable so that inductive loops are not formed).

The high-frequency transient inrush current associated with back-to-back switching can stress other equipment in the circuit as well as the circuit breaker. Wound-type current transformers will have turn-to-turn insulation stressed because of the high rates of rise of current and the resulting voltage that is developed across inductance in the circuit.

The following example will illustrate the use of the formulas in Table 1.

A 115 kV system is assumed as shown in Fig 5.

Capacitor banks shown have a nominal rating of 12 Mvar (capacitors rated 100 kvar, 13,280 V, five series sections with eight capacitors in parallel). Nominal current per bank is 60 A. In determining the rating of the circuit breaker required, the increase in current due to applied voltage, capacitance tolerance, and harmonics should be considered. The increase in current at maximum rated voltage is: maximum voltage to capacitor rated voltage = 121/115 = 1.05. Assume a positive tolerance of capacitors of +10 percent, multiplier of 1.1, and assume a multiplier for harmonic content for a grounded neutral bank of 1.1.

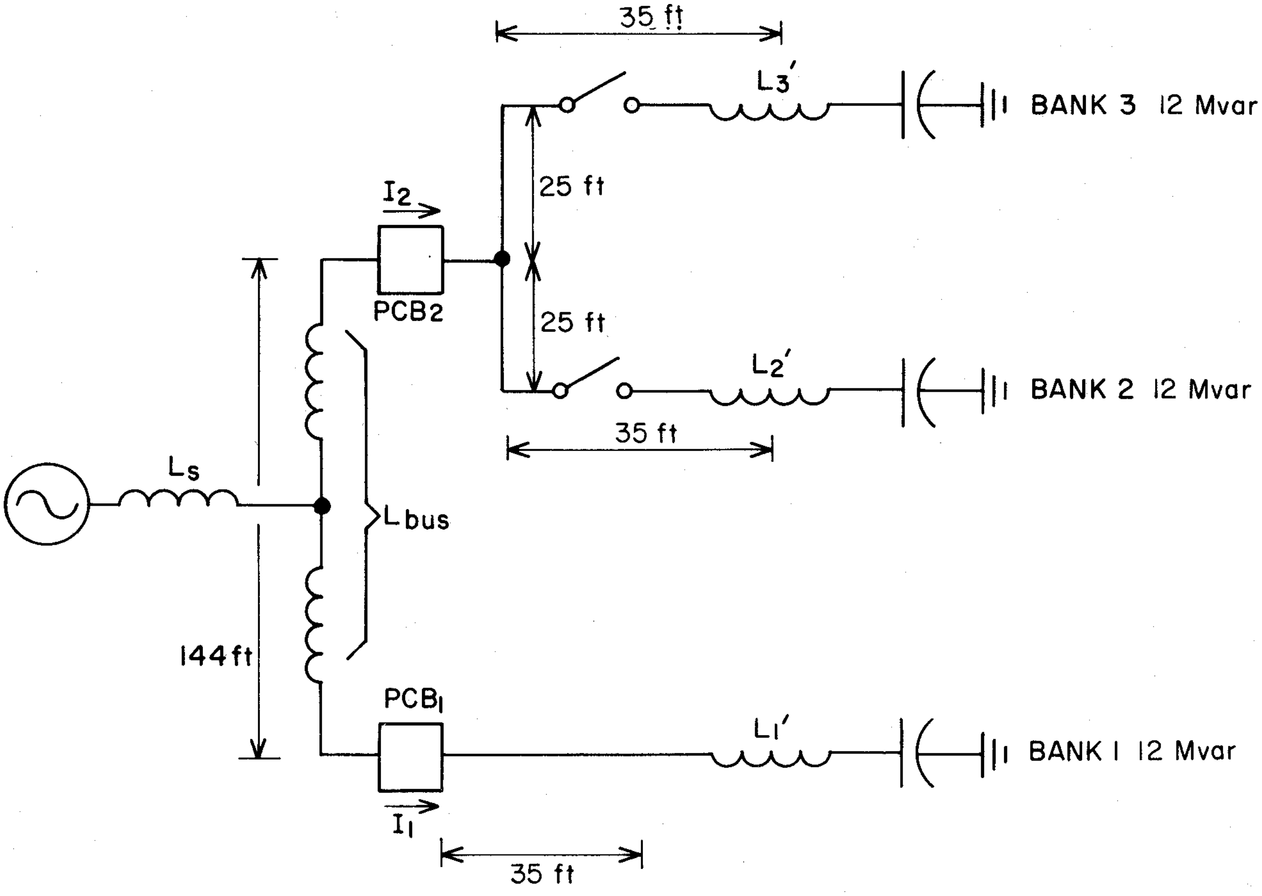

Figure 5— Example of 115 kV System

$V_{LL\ max}$	121 kV (115 kV nominal voltage)
L_S	Source Inductance, = 3.77Ω, 10 mH
L'_1, L'_2, L'_3	Inductance Between Circuit Breaker and Capacitor Bank, Including Inductance of Capacitor Bank
L_{bus}	Inductance of Bus Between Switching Devices Short Circuit of Source 18,600 A at 121 kV

The total multiplier used to determine the isolated and back-to-back current rating is 1.05 × 1.1 × 1.1 = 1.27, giving a current of 1.27 × 60 = 76 A. With capacitor banks 2 and 3 energized, the current through PCB_2 is 152 A.

Definite-purpose circuit breakers meeting the above requirements should be selected from the appropriate table in ANSI C37.06-1979. For illustration, the following ratings are assumed: rated maximum voltage 121 kV, rated continuous current 1600 A, rated short-circuit current 40 kA, rated isolated and back-to-back capacitance switching current 160 A.

The transient inrush current and frequency are calculated using the formulas in Table 1. In the example, L_1', L_2', and L_3' are the inductances between the respective capacitor banks and the circuit breakers, including the inductance of the capacitor bank. L_{bus} is the inductance of the bus between the circuit breakers.

The inductance values in Table 2 can be used or values can be calculated for the actual bus configuration used. In the example, the bus is an extruded aluminum tube with an 8 ft (2.4 m) phase spacing. The section between breakers is 3 in (76 mm) iron pipe size (IPS) and between breaker and capacitor it is 2 in (51 mm) IPS.

For 3 in (76 mm) IPS, X_a = 45.2 µΩ/ft [at 1 ft (304.8 mm) spacing] and for 2 in (51 mm) IPS, X_a = 54.2 µΩ/ft [at 1 ft (304.8 mm) spacing].

X_d for 8 ft (2.4m) phase spacing = 53 µΩ/ft

X_L (3 in) = $X_a + X_d$ 45.2 + 53.0 = 98.2 µΩ/ft

X_L (2 in) = $X_a + X_d$ 54.2 + 53.0 = 107.2 µΩ/ft

L (3 in) = 0.261 µH/ft

L (2 in) = 0.285 µH/ft

The distance between circuit breakers is 144 ft (43.9 m) of 3 in bus. The distance between bank 1 and PCB_1 is 35 ft (10.6 m). The distance between bank 2 and PCB_2 and bank 3 and PCB_2 is 60 ft (35 + 25) (18.3 m) of 2 in bus. Assume inductance of capacitor banks of 10 µH. The following inductance values are used in the example:

L_{bus} = (144) (0.261) = 37.6µH

L_1' = (35) (0.285) + 10 µH = 20.0 µH

$L_2' = L_3'$ = (60) (0.285) + 10 µH = 27.1 µH

In determining inrush current and frequency, the currents I_1 and I_2 as used in Table 1 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 example, the multiplier to be used is [(1.05) (1.1)] = 1.15. The currents are I_1 = (60) (1.15) = 69 A and I_2 = 69 A or 138 A, depending on whether bank 2 or 3 or both banks are energized.

Case I. Energization of capacitor bank 1 with banks 2 and 3 not energized (isolated switching),

$$\begin{aligned} i_{\text{max pk}} &= 1.4\sqrt{I_{\text{sc}} \times I_1} \\ &= (1.4)\sqrt{18\,600 \times 69} = (1.4)\sqrt{128 \times 10^4} \\ &= (140)(11.3) = 1582 \text{ A peak} \end{aligned}$$

$$\begin{aligned} f &= f_s\sqrt{\frac{I_{\text{sc}}}{I_1}} = 60\sqrt{\frac{18\,600}{69}} \\ &= 60\sqrt{269} = 985 \text{ Hz} \end{aligned}$$

The calculated rate of change of current for the single-bank switching is

$$\frac{(1582)(985)(2\pi)}{10^6} = 9.8 \text{ A}/\mu\text{s}$$

This is less than the maximum rate of change for a rated short-circuit current of 40 kA which is equal to $2\pi f I$ = (377) (1.4) (40) = 21.3 A/µs and therefore meets the requirements of isolated capacitor bank switching.

Case II. Energization of bank 1 with bank 2 energized on the bus (back-to-back switching against an equal-size bank),

$$i_{\text{max pk}} = 1235\sqrt{\frac{(V_{\text{LL}})(I_1)}{L_{\text{eq}}}}$$

The equivalent inductance L_{eq} is the sum of

$$L_1 + L_{\text{bus}} + L_2' = 20.0 + 37.6 + 27.1 = 84.7\mu\text{H}.$$

$$I_{\text{max pk}} = 1235\sqrt{\frac{(121)(69)}{84.7}} = 1235\sqrt{98.5}$$

$$= 12\ 250\ \text{A peak}$$

$$f = 13.5\sqrt{\frac{(f_{\text{s}})(V_{\text{LL}})}{(L_{\text{eq}})(I_1)}} = 13.5\sqrt{\frac{(60)(121)}{(84.7)(69)}}$$

$$= (13.5)(1.11) = 15.0\ \text{kHz}$$

The calculated back-to-back inrush current and frequency must be compared with the back-to-back switching capability listed in the appropriate tables of ANSI C37.06-1979. For a maximum voltage of 121 kV, the assumed rated values are 10 kA and 5.3 kHz. The calculated values of inrush current and frequency of 12.25 kA and 15.0 kHz exceed those assumed and inductance must be added between the capacitor banks to reduce the inrush current and frequency. Adding an inductance of 0.6 mH will limit the inrush current to approximately 5 kA and the frequency to approximately 5.0 kHz, both of which are below the assumed capability.

Case III. Energization of bank 1 with banks 2 and 3 energized on the bus. For this case, assume the equivalent inductance of banks 2 and 3 equal to one half of $L'2$ or (27.1)/2 = 13.6 µH. The total current of banks 2 and 3 is 138 A, which is under the assumed isolated bank switching capability of 160 A as listed in ANSIC37.06-1979 . For this case, I_1 69 A, I_2 = 138 A, and the equivalent inductance between the capacitor bank being energized and the banks already energized is the sum of $L'2/2 + L_{\text{bus}} + L'_1 = 13.6 + 37.6 + 20 = 71.2$ µH.

$$i_{\text{max pk}} = 1747\sqrt{\frac{(V_{\text{LL}})(I_1 \times I_2)}{L_{\text{eq}}(I_1 + I_2)}}$$

$$= 1747\sqrt{\frac{(121)(69)(138)}{(71.2)(207)}}$$

$$= 1747\sqrt{78.2} = 15\ 500\ \text{A peak}$$

$$f = 9.5\sqrt{\frac{(f_{\text{s}})(V_{\text{LL}})(I_1 + I_2)}{(L_{\text{eq}})(I_1 \times I_2)}}$$

$$= 9.5\sqrt{\frac{(60)(121)(207)}{(71.2)(69)(138)}} = 9.5\sqrt{2.22}$$

$$= (9.5)(1.49) = 14.1\ \text{kHz}$$

The calculated values of inrush current and frequency of 15.5 kA and 14.1 kHz exceed the assumed back-to-back switching capability of 10 kA and 5.3 kHz listed in ANSI C37.06-1979. As in the previous case of switching identical banks, adding an inductance of 0.6 mH will limit the inrush current and frequency to within the assumed back-to-back switching capability of 121 kV circuit breaker.

Based on the system and conditions studied, a circuit breaker having the following ratings would be applied: rated short-circuit current of 40 kA and rated isolated capacitor bank switching current of 160 A. The assumed back-to-back rating of 10 kA and 5300 Hz that goes with this rating will be exceeded unless additional inductance is added between the capacitor banks. A value of 0.6 mH is sufficient to keep within the assumed ratings available.

4.8 Cables

A circuit breaker may be required to energize or deenergize an unloaded cable during its normal operating duties. Prior to energization the cable is usually at ground potential. A cable may be switched from a bus that does not have other cables energized (isolated) or against a bus that has one or more cables energized (back to back). In the application of circuit breakers for cable switching duty, consideration must be given to the rated isolated cable switching current, the rated back-to-back cable switching current, and the rated transient inrush current, both amplitude and frequency.

4.8.1 *Isolated Cable.*

A cable is defined as isolated if the maximum rate of change, with respect to time, of transient inrush current on energizing an uncharged cable does not exceed the rate of change of current associated with the maximum symmetrical interrupting current (see 4.4). This limiting value is numerically equal to

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

where

I = rated rms short-circuit current, in amperes
ω = $2\pi f = 377$ for 60 Hz system

The ratio [(rated maximum voltage)/(operating voltage)] shall not exceed the voltage range factor *K*.

By this definition it is possible to have cable circuits which are physically back to back, but are considered isolated for application purposes provided a large inductance is located between the two cable circuits. The inductance must be large enough so that by itself it would limit fault current to a value less than or equal to the circuit breaker rating.

4.8.2 *Back-to-Bach Cables.*

Cables are considered switched back to back if the maximum rate of change of transient inrush current on energizing an uncharged cable exceeds that specified for an isolated cable (see 4.5).

4.8.3 *Cable Charging Current.*

The cable charging current is a function of system voltage, cable geometry, insulation dielectric constant, and cable length. The shunt capacitive reactance can be obtained from the manufacturer, or if the physical constants of the cable are known, the shunt capacitive reactance can be calculated [3]. For single-conductor and three-conductor shielded cables the shunt capacitive reactance can be written

$$X_c' = \frac{4.12}{f_s \mathrm{k}} \log_{10}\frac{2r_i}{d}\ (\mathrm{M}\Omega \text{ per phase per mile})\ ^{5}$$

where

f_s = system frequency, in hertz
k = dielectric constant of cable dielectric material
r_i = inside radius of sheath, in feet
d = outside diameter of conductor, in feet

Using the capacitive reactance, the cable charging current can be calculated and compared with the rated cable charging current of the circuit breaker. Before an application can be made, the inrush current rating should also be checked.

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[5] See Footnote 2

4.8.4 *Cable Inrush Current.*

The energization of a cable by the closing of a circuit breaker will result in a transient inrush current. The magnitude and rate of change of this inrush current is a function of the following: applied voltage (including the point on the voltage wave at closing), cable surge impedance, cable capacitive reactance, inductance in the circuit (amount and location), any charges on the cable at the instant of closing, and any damping of the circuit because of closing resistors or other resistance in the circuit.

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

When cables are switched back to back (that is, when one cable is switched while other cables are connected to the same bus), transient currents of high magnitude and initial high rate of change may flow between cables when the switching circuit breaker is closed or restrikes on opening. This surge current is limited by the cable surge impedances and any inductance connected between the energized cable(s) and the switched cable. This transient current usually decays to zero in a fraction of a cycle of the system frequency. During back-to-back cable switching, the component of current supplied by the source is at a lower rate of change and so small that it may be neglected.

4.8.4.1 *Method for Calculating Transient Inrush Currents.*

A typical circuit for back-to-back cable switching is shown in Fig 6. The inductances L_1, L_2, and L_{bus} between the cables are often very small with respect to the inductance L_s of the source. In many cases they will be less than 1 percent of the source inductance. They consist of the inductances from the cables to the circuit breakers, the circuit breaker inductances, and the bus inductance of the current path. Values of inductance depend upon the physical configuration. A representative range is 0.2 to 0.3 μH per phase per foot.

In switching an isolated cable, if the source inductance is greater than 10 times the cable inductance, the cable can be represented as a capacitor (see 4.7). Otherwise, under transient conditions the cable can be represented by its surge impedance. An expression for surge impedance [3] is given for single-conductor and three-conductor shielded cables by

$$Z = \sqrt{\frac{L}{C}} = \frac{138}{\sqrt{k}} \log_{10}\left(\frac{r_2}{r_1}\right)(\Omega)$$

where

L = distributed inductance of cable, in henrys
C = distributed capacitance of cable, in farads
k = dielectric constant of cable dielectric material
r_2 = inside radius of sheath, in feet
r_1 = outside radius of conductor, in feet

Average values for k are between 2.5 and 4; an average value for Z is 50 Ω.

4.8.4.1.1 *Back-to-Back Cable Inrush Current.*

Neglecting the source contribution, back-to-back cables can be represented as shown in Fig 7. The initial pulse of current has a front expressed as

$$i(t) = \frac{E_m - E_t}{Z_1 + Z_2}\left[1 - \exp\left(-\frac{Z_1 + Z_2}{L}t\right)\right] \tag{A}$$

Assuming that the $L/(Z_1 + Z_2)$ time constant is less than $^1/_5$ of the travel time of the cable out and back, the initial crest of the inrush current is then $(E_m - E_t)/(Z_1 + Z_2)$, which for application should be less than the rated peak inrush current.

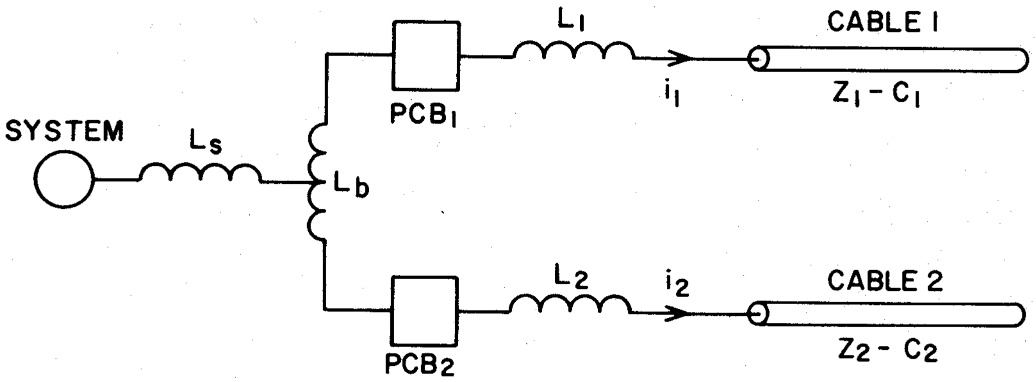

Figure 6— Typical Circuit for Back-to-Back Switching

PCB_1	Open for Isolated Cable Switching, Closed for Back-to-Back Switching
PCB_2	Switching Device
L_S	Source Inductance
L_1, L_2	Inductance Between Cables 1 and 2 and Bus
Z_1, Z_2	Surge Impedance of Cables 1 and 2
C_1, C_2	Capacitance of Cables 1 and 2
L_{bus}	Inductance of Bus Connecting the Cables

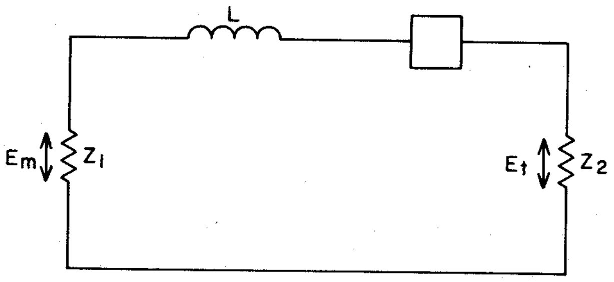

Figure 7— Equivalent Circuit for Back-to-Back Cable Switching

E_m	Crest of Applied Voltage
E_t	Trapped Voltage on Cable Being Switched
Z_1, Z_2	Cable Surge Impedance
L	Total Circuit Inductance Between Cable Terminals

Table 3— Frequency and Current Amplitude Relations

Condition	Quantity	When Using Surge Impedance
Energizing an isolated cable	$i_{\max\ pk}$	$\frac{E_m - E_t}{Z}$
	f_{eq}	$f_s\left[\frac{\sqrt{2}I_{sc}}{I_{MR}}\right]$
Energizing a cable with another on the same bus	$i_{\max\ pk}$	$\frac{E_m - E_t}{Z_1 + Z_2}$
	f_{eq}	$f_s\left[\frac{E_m - E_t}{\omega(L_1 + L_2)I_{MR}}\right]$
Energizing a cable with an equal cable energized on the same bus	$i_{\max\ pk}$	$\frac{E_m - E_t}{2Z}$
	f_{eq}	$f_s\left[\frac{E_m - E_t}{\omega(L_1 + L_2)I_{MR}}\right]$

Differentiating the expression for current at $t = 0$, the maximum initial rate of change of the inrush current is

$$\left(\frac{di}{dt}\right)_0 = \frac{E_m - E_t}{L} \text{ (A/s)}$$

This can reach extreme values since the magnitude of L can be arbitrarily small.

The cable inrush current is not oscillatory in the usual frequency-related sense, but the initial slope can be used to determine an equivalent frequency which can be compared with the rated inrush frequency. In general,

$$\left(\frac{di}{dt}\right)_R = 2\pi f_R I_{MR} \text{ (A/s)}$$

where

$(di/dt)_R$ = rate of change of rated inrush current
f_R = rated inrush current frequency
I_{MR} = rated peak inrush current (see ANSI C37.06-1979)

The equivalent frequency for a cable inrush current is then

$$f_{eq} = \frac{E_m - E_t}{2\pi L I_{MR}} \text{(Hz)}$$

and for proper breaker application, f_{eq} should be less than the rated inrush current frequency. Additional inductance may be added in series with the inductances making up L to meet the rated inrush frequency requirement. Frequency and current amplitude relations are summarized in Table 3.

4.8.4.1.2 *Alternate Configurations.*

Other combinations of circuit elements can produce inrush currents associated with cable switching. For example, a cable can be switched from a bus which has a capacitor bank connected as shown in Fig 8. The inrush current can be calculated using the equivalent circuit of Fig 9.

The maximum initial rate of change of current is given by the expression

$$\left(\frac{\mathrm{d}i}{\mathrm{d}t}\right)_0 = \frac{E_\mathrm{m} - E_\mathrm{t}}{L} \ (\mathrm{A/s})$$

and, as before, is limited by the loop inductance L. The equivalent frequency is determined as in 4.7.4.1, and required adjustments can be made by increasing the value of L (reactor, iron pipe, etc).

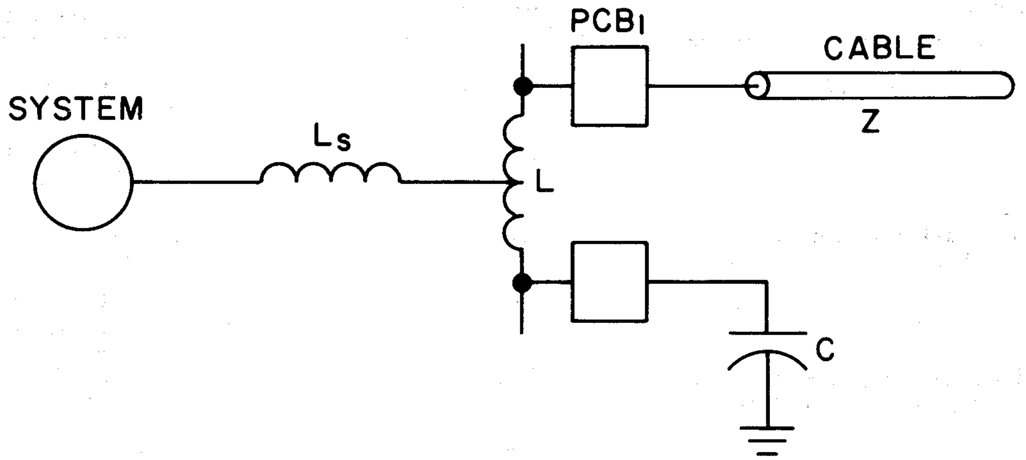

Figure 8— Bank-to-Cable Switching Circuit

PCB_1	Switching Device
L_S	Source Inductance
L	Total Inductance Between Bank and Cable
Z	Cable Surge Impedance
C	Capacitance of Bank

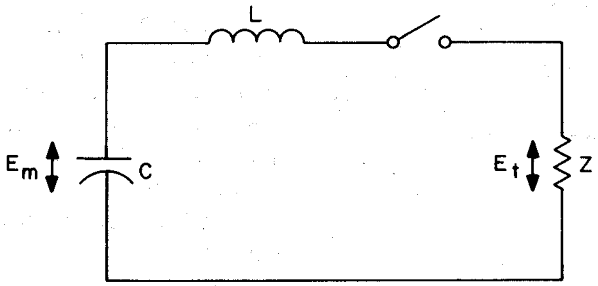

Figure 9— Equivalent Bank-to-Cable Switching Circuit

E_m	Crest of Applied Voltage
E_t	Trapped Voltage on Cable Being Switched
Z	Cable Surge Impedance
L	Circuit Inductance Between Bank and Cable
C	Capacitance of Bank

The form of the inrush current is a function of the circuit parameters which, in the equivalent circuit, form a series RLC circuit. Using standard methods of analysis, the maximum peak inrush currents are

$$\frac{Z^2}{4} = \frac{L}{C} \quad i_{\text{max pk}} = 0.368\frac{E_\text{m} - E_\text{t}}{Z}$$

$$\frac{Z^2}{4} < \frac{L}{C} \quad i_{\text{max pk}} \approx \frac{E_\text{m} - E_\text{t}}{\sqrt{L/C - Z^2/4}}\left[\exp\left(-\frac{Z\pi}{4L}\frac{1}{\sqrt{L/C - Z^2/4}}\right)\right]$$

$$\frac{Z^2}{4} > \frac{L}{C} \quad i_{\text{max pk}} = \frac{E_\text{m} - E_\text{t}}{\sqrt{Z^2 - 4L/C}}[\exp(-\alpha t_\text{m}) - \exp(-\beta t_\text{m})]$$

where

$t_\text{m} =$ $$t_\text{m} = \frac{\ln \alpha/\beta}{\alpha - \beta}$$

$\alpha =$ $$\alpha = \frac{Z}{L} - \sqrt{\frac{Z^2}{L^2} - \frac{4}{LC}}$$

$\beta =$ $$\beta = \frac{Z}{L} + \sqrt{\frac{Z^2}{L^2} - \frac{4}{LC}}$$

For application, the peak inrush current should be checked against the rated value for the circuit breaker in question.

Many other combinations of banks, cables, and lines will occur in practice. For example, a cable may be used to exit from a substation and then connect to an open wire transmission line after a short distance. One possible approach when considering circuits of this type is to compare the relative contributions of the cable and the line. For short cable runs this circuit could be considered the equivalent of a line with a capacitor to ground replacing the cable. Similar simplifications can be used for other configurations.

4.9 Switching Through Transformers

Circuit breakers may be required in some applications to switch capacitors, lines, or cables through an interposed transformer. The current switched by the circuit breaker will be N times the capacitor, line, or cable current on the other side of the transformer, where N is the transformer turns ratio.

Switching charging current through a transformer may be less difficult than switching the same number of amperes directly. The capacitive elements of the circuit will oscillate with the transformer inductance, which may also saturate, producing a less severe transient recovery voltage and a lower probability of restriking. If a restrike should occur, the additional inductance will help to limit the inrush current.

If the value of N is greater than 1, switching through a transformer will have the effect of increasing the current being switched. Dropping EHV and UHV lines with lower voltage circuit breakers can result in effective line charging currents in the 750–1000 A range. The capacitance switching rating of circuit breakers which may be exposed to this type of duty must be carefully checked before application is made.

Voltage and current relations are shown in Fig 10 as an example of capacitor switching through an interposed transformer.

4.10 Unusual Circuits

In the application of circuit breakers in stations having banks of capacitors it may be necessary to investigate the effects of transient currents and other special situations upon circuit breakers other than those specially equipped for and assigned to the routine capacitor switching.

The transient currents of capacitor banks may be considered in two aspects: the inrush currents upon energizing of the banks and the discharge currents into faults. Where the quantity of parallel capacitor banks installed in a station is large, the transient currents may have significant effects upon the breaker.

The transient currents may have large peaks and high frequency which may affect circuit breakers in the following ways.

1) A circuit breaker may be subjected to a transient inrush current which exceeds its rating. This may occur with the circuit breaker in the closed position or when closing into bolted-type faults.
2) The transient inrush current may have sufficient magnitude and rate of change to flash over the secondaries of linear couplers or bushing current transformers, or the associated control wiring.

There are also special situations that may arise in fault switching sequences where circuit breakers in a station may get involved in unplanned clearing of energized parallel banks. This section is intended to guide the engineer to take either the required corrective measures or to avoid the problems.

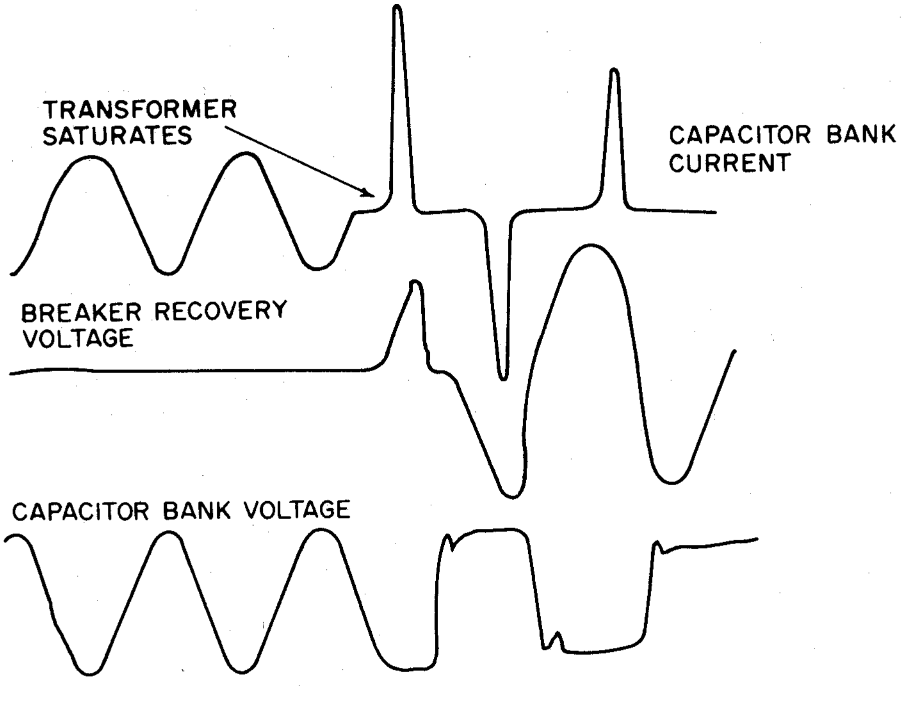

Figure 10— Voltage and Current Relations for Capacitor Switching Through Interposed Transformer

4.10.1 *Exposure to Transient Inrush Currents.*

Circuit breakers located in a position such as a tie circuit breaker between bus sections may be exposed to the transient inrush currents from energizing banks of capacitors when they are located on bus sections on both sides of the breaker (see Fig 11, PCB_1).

Seldom will the inrush current exceed the closing—latching capability of the breaker. However, a check may be required to determine that the rate of change of inrush current will not cause secondary flashover of linear couplers or of bushing current transformers located on the circuit breaker.

With linear couplers, the secondary voltage induced across the terminals from the transient capacitance current is proportional to the frequency and to the amplitude of this current as shown in the following formula:

$$\begin{matrix}\text{linear coupler}\\ \text{secondary volts}\\ (\text{crest})\end{matrix} = \begin{pmatrix}\text{linear}\\ \text{coupler ratio}\end{pmatrix} \times \frac{\begin{pmatrix}\text{transient}\\ \text{frequency}\end{pmatrix}}{\begin{pmatrix}\text{system}\\ \text{frequency}\end{pmatrix}} \times \begin{pmatrix}\text{crest}\\ \text{transient current}\end{pmatrix}$$

The following example will illustrate the use of the above formula.

Linear coupler ratio — 5 V per 1000

primary amperes

Frequency of transient

inrush current — 5400 Hz

Crest of transient

inrush current — 30,000 A

System frequency — 60 Hz

$$\begin{matrix}\text{linear coupler}\\ \text{secondary volts}\\ (\text{crest})\end{matrix} = \frac{5}{1000} \times \frac{5400}{60} \times 30\ 000 = 13\ 500\ \text{V}$$

Manufacturer’s voltage limits for linear couplers should not be exceeded.

With a bushing-type current transformer (BCT), the voltage developed in the secondary circuit is also proportional to the frequency and the amplitude of the transient inrush current, as shown in the following formula:

$$\begin{matrix}\text{voltage in}\\ \text{BCT secondary}\\ (\text{crest})\end{matrix} = \frac{1}{(\text{BCT ratio})} \times \begin{pmatrix}\text{crest}\\ \text{transient}\\ \text{current}\end{pmatrix} \times \begin{pmatrix}\text{relay}\\ \text{reactance}\end{pmatrix} \times \frac{\begin{pmatrix}\text{transient}\\ \text{frequency}\end{pmatrix}}{\begin{pmatrix}\text{system}\\ \text{frequency}\end{pmatrix}}$$

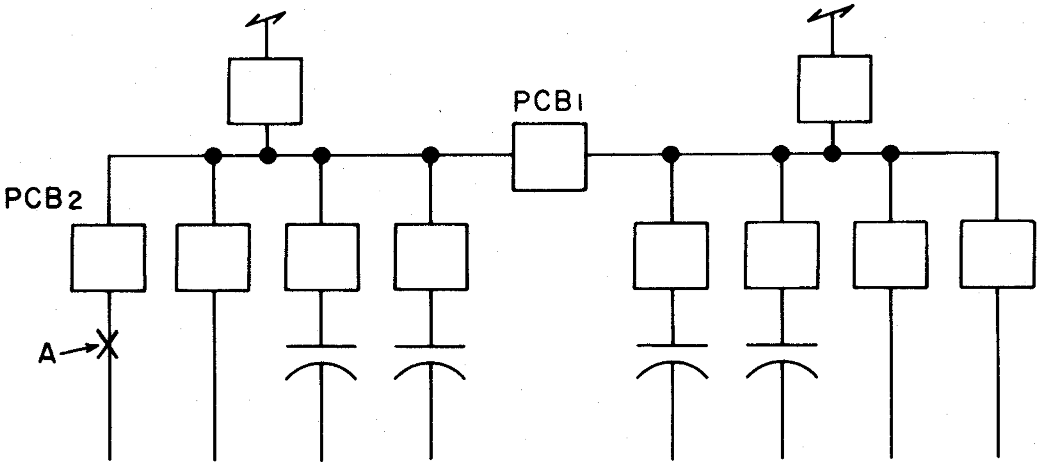

Figure 11— Station Illustrating Large Transient Inrush Currents Through Circuit Breakers from Parallel Capacitor Banks

The following example will illustrate the use of the above formula.

Bushing current transformer ratio = 1000/5

Frequency of transient inrush current = 5400 Hz

Crest of transient inrush current = 30,000 A

Relay reactance burden at 60 Hz = 0.32Ω

System frequency = 60 Hz

$$\begin{aligned}\begin{matrix}\text{voltage in BCT}\\ \text{secondary (crest)}\end{matrix} &= \frac{5}{1000} \times 30\ 000 \times 0.3 \times \frac{5400}{60}\\ &= 4050\ \text{V}\end{aligned}$$

The secondary voltage should not exceed those values specified in ANSI C57.13-1979, 4.7, Requirements, Terminology, and Test Code for Instrument Transformers.

4.10.2 *Exposure to Total Capacitor Bank Discharge Current.*

In a station where parallel capacitor banks are located on, or essentially on, a bus, any circuit breaker connected to the bus may be exposed during faults to the total discharge current of all the banks located behind the breaker. In Fig 11, PCB_2 will be subjected to this total discharge current with a fault occurring at location *A*. The worst case, or highest capacitor discharge current, occurs with a bolted three-phase fault where capacitor banks are ungrounded and for a case of a three-phase-to-ground or a line-to-ground fault where capacitor banks are grounded.

Applications which expose general-purpose circuit breakers to this capacitor bank discharge current should be checked to determine that the transient inrush current magnitude and frequency do not exceed the values established. Values are under consideration in the NEMA High-Voltage Power Circuit Breaker Technical Committee for eventual inclusion in the notes to Tables 1 through 4A of ANSI C37.06-1979.

The total discharge current (peak) of all banks behind the breaker is equal to the algebraic sum of the individual banks of capacitors. Neglecting resistance, the discharge current of an individual capacitor bank is equal to[6]:

$$I_{\mathrm{pk}} = \frac{\sqrt{2}}{\sqrt{3}} E_{\mathrm{LL}} \sqrt{\frac{C}{L}}$$

where

I_{pk} = crest value of discharge current
E_{LL} = rms phase-to-phase voltage
C = capacitance per phase of individual bank
L = inductance per phase between capacitor bank and fault location.

(This inductance is primarily made up of bus conductors and any additional inductance added to the bank for limiting the inrush currents.)

If there are *n* capacitor banks of approximately equal capacitance and separated by an approximately equal inductance to the fault, then the total discharge current is approximately equal to the sum of the crest current of each bank or *n* times that of one bank. This is demonstrated as follows:

$$I_{\mathrm{pk}} = \frac{\sqrt{2}}{\sqrt{3}} E_{\mathrm{LL}} \sqrt{\frac{Cn}{L/n}} = \frac{\sqrt{2}}{\sqrt{3}} E_{\mathrm{LL}}\, n\sqrt{C/L}$$

In addition to the checking of the crest current, it may be necessary also to check the rate of change of the discharge current with the manufacturer.

The transient discharge current passing through a circuit breaker must also be examined for its effects upon the linear couplers and bushing current transformers. The discharge currents may substantially exceed the magnitudes and the frequency of the inrush currents described in 4.10.1. This occurs because the contribution may come from a number of capacitor banks and is not limited by the inrush impedance seen when energizing a bank of capacitors. The formulas given in 4.10.1 for determining the induced voltages in the linear couplers or in bushing current transformers also may be used for determining the effects of the discharge currents.

4.10.3 *Exposure to Capacitive Switching Duties During Fault Switching.*

Where parallel banks of capacitors are located on bus sections in a station, caution must be exercised in the fault switching sequence so that the last circuit breaker to clear is not subjected to a Capacitive switching duty beyond its capability. This is especially a concern for a circuit breaker used as a bus section tie breaker with capacitors located on both sides of the circuit breaker as shown in Fig 11, PCB_1.

The worst case occurs in a station where the bus section tie circuit breaker is last to clear the bus for a fault that leaves one or more phases of the capacitor banks fully energized. In this situation, the bus tie circuit breaker must be properly equipped and rated for the parallel switching of the capacitor banks remaining on the bus section to be deenergized. In the example of Fig 11, this means that the tie circuit breaker must be capable of switching two banks of capacitors in parallel with two banks of capacitors on the source side. Another solution is to coordinate if possible the clearing times so that the tie circuit breaker is always first to clear to avoid the capacitor switching duty.

4.11 Effect of Load

The situation can occur where a circuit breaker is called upon to switch a combination of a capacitance current and a load current. The circuit breaker will have the required switching capability if the total current does not exceed the

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[6] See Appendix B.

rated continuous current of the circuit breaker and either (1) the power factor is at least 0.8 leading, or (2) the capacitance current does not exceed the rated capacitance switching current of the circuit breaker.

Where the above conditions are exceeded, the capability and performance of the circuit breaker is not defined by the standards and the manufacturer should be consulted. The test procedure in ANSI/IEEE C37.09-1979, does not require the test circuit to have a power factor below 0.8 lagging or leading to test the continuous current switching rating of the circuit breaker. When the power factor is below 0.8 leading, the voltage may be sufficiently out of phase with the current to cause unacceptable restriking. The situation will be more severe if there is also a bank of capacitors located on the source side of the circuit breaker.

4.12 Effect of Reclosing

Up to twice normal inrush currents are possible when reclosing is applied to a circuit breaker switching capacitance loads. When capacitor bank current is interrupted at or near a normal current zero, the voltage remaining on the bank may be near peak value. Reclosing a circuit breaker against such a charged capacitor bank may produce high inrush current.

When a capacitor bank is connected to the load side of a feeder breaker equipped with automatic reclosing, high inrush currents can be avoided by isolating the capacitor bank from other loads after the circuit breaker is tripped and before reclosing. The device used for regular capacitor bank switching can be employed for isolation. This technique is particularly recommended where other capacitor banks are connected to the same station bus.

A second technique to avoid high inrush currents during reclosing is to increase reclosing time delay. Normally, the discharge resistors inside each capacitor unit will reduce residual voltage as specified in ANSI/IEEE Std 18-1968, Shunt Power Capacitors.

Discharge curves are available from the capacitor supplier and should be consulted where reclosing time delay is applied.

4.13 Resistor Thermal Limitations

For circuit breakers equipped with arc shunting resistors the thermal capability of the resistors must be considered in determining the time interval between capacitance current switching operations.

1) For general-purpose circuit breakers the shunt resistors have the thermal capability specified in ANSI/IEEE C37.04-1979.
2) Definite-purpose circuit breakers designed for shunt capacitor bank or cable switching may not have arc shunting resistors rated for reclosing duty

If capacitance current switching field tests are planned which exceed the number of operations in (1), or which utilize a definite-purpose circuit breaker (2), the manufacturer should be consulted regarding the frequency of operations.

4.14 Current Pause Method

A current pause method of demonstrating capacitance current switching performance is described in ANSI/IEEE C37.09-1979. [7]

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[7] The background and mathematics involved in this method are given in Appendix B.

5. Considerations of Capacitance Currents and Recovery Voltages Under Fault Conditions

The requirements, preferred ratings and tests for capacitance switching are based on switching operations in the absence of faults. It is sometimes required, however, that a circuit breaker interrupt a capacitive circuit under faulted conditions. (An example is a transmission line circuit breaker which must interrupt fault current in one phase and capacitive current in the other two phases.) The presence of a fault can increase the value of both the capacitance switching current and recovery voltage above the values recognized in the standards for the unfaulted condition. [6]

5.1 Reasons for Successful Circuit Breaker Operation

Circuit breakers have been successful in interrupting capacitive circuits under faulted conditions. Reasons for successful operation include:

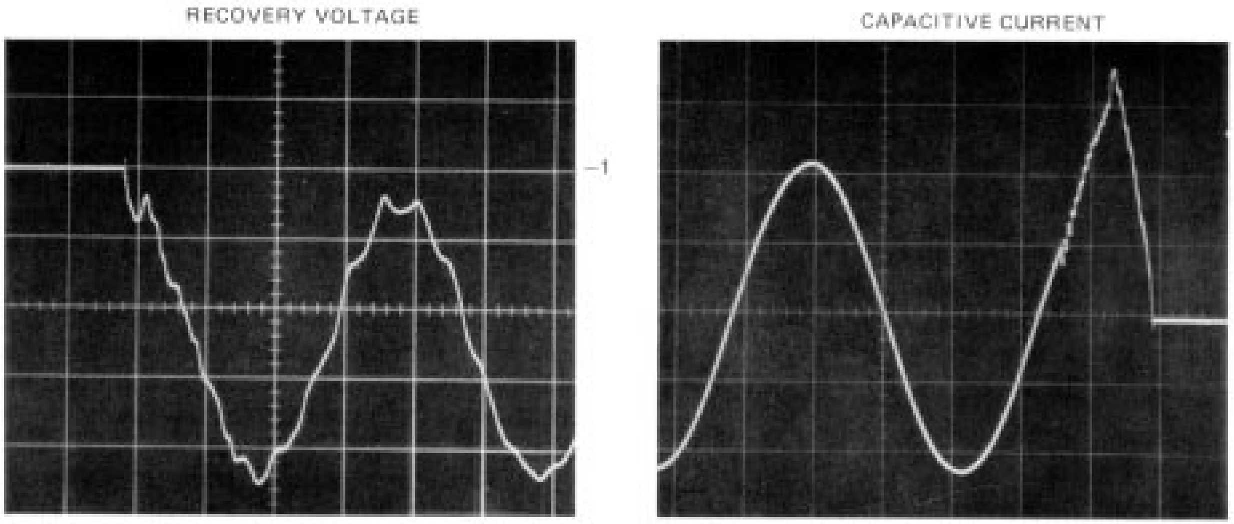
1) The highest values of recovery voltage and current usually do not occur simultaneously. A circuit condition which causes a high voltage may occur with a current value which is less than normal, and in like manner a high current may occur with a voltage less than rated.
2) When switching a capacitor bank, with its neutral, or the system neutral, or both, ungrounded, interruption of the first phase results in a single-phase circuit in the uninterrupted phases. Thus, since the two poles of the circuit breaker are in series at final interruption, the voltage across each pole is less than rated.

5.2 Switching Open Wire Transmission Lines Under Faulted Conditions

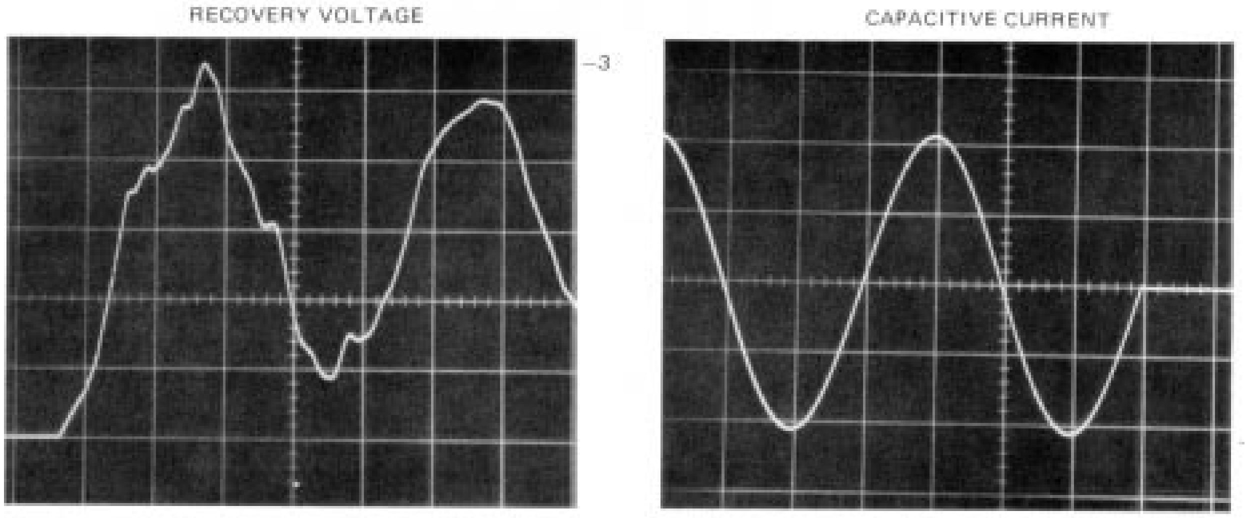
The voltages and currents which occur when switching a faulted transmission line are affected by the circuit parameters and the sequence in which the three phases interrupt. ANSI/IEEE C37.09-1979, 4.13.3.3 lists the maximum value of recovery voltage for switching an unfaulted transmission line as 2.4 E_{max} (phase-to-ground). When switching a faulted line this value may be exceeded, as may be the rated capacitance switching current value as listed in ANSI C37.06-1979.

The values listed in Tables 4 and 5 are typical of those which may occur on the unfaulted phases when switching a transmission line with a single phase-to-ground fault. Table 4 lists the voltages and currents for a 242 kV system, and Table 5 lists the values for a 550 kV system.

The highest voltage occurs on the unfaulted phase which interrupts prior to the faulted phase. The highest current occurs on the last phase to interrupt when the faulted phase is the first to interrupt. The current for this case is not a sine wave but is distorted, as shown in Fig 12. Under these conditions, the voltages and currents may exceed the 2.4 E_{max} phase-to-ground voltage and the rated current values on which the design tests are based.



[1]2.18 × E_{max} (phase-to-ground)
[2]1.77 × Rated Current
(A)



[3]2.74 × E_{max} (phase-to-ground)
[4]1.09 × Rated Current
(B)

Figure 12— (A) Recovery Voltage and Current for Last Phase to Clear When Faulted Phase is First in Sequence to Clear, (B) Recovery Voltage and Current for First Phase to Clear When Faulted Phase is Second in Sequence to Clear

In Tables 6 and 7, the values of recovery voltages (as a ratio to E_{max}, phase-to-ground) and currents (as a ratio to rated current) are listed for a phase-to-phase grounded fault.

For the phase-to-phase fault condition, the recovery voltage and capacitance current are less severe than for the phase-to-phase grounded fault condition.

5.3 Switching Capacitor Banks Under Faulted Conditions

The voltages and currents which can occur when switching a faulted capacitor bank depend upon the grounding conditions, whether the fault is to the bank neutral or to ground, and on the sequence in which the three phases interrupt. 4.13.3.3 of ANSI/IEEE C37.09-1979 lists the maximum value of recovery voltage in switching an unfaulted shunt capacitor bank as 3.0 E_{max} (phase-to-ground). When switching a faulted bank, this value may be exceeded, as may the rated capacitance switching current value.

Typical recovery voltages and currents for a three-phase capacitor bank are shown in Tables 8, 9 and 10. Table 8 lists reference condition values for an unfaulted balanced system. Table 9 lists values for a bank with one phase shorted to neutral and Table 10 lists values for a bank with one phase shorted to ground. It should be noted that all recovery voltages listed will be experienced one-half cycle after current interruption. It is unlikely that the first phase to interrupt will be stressed to the voltage values listed since the other two phases will normally interrupt before one-half cycle elapses.

The voltages and currents obtained with the reference condition shown in Table agree with the 3.0 E_{max} (phase-to-ground) voltage listed in 4.13.3.3 of ANSI/IEEE C37.09-197, and the current value (1.0) corresponds to rated capacitance switching current. Although the voltage across the last phases to interrupt when at least one of the neutrals (source or bank) is ungrounded can reach 3.46 E_{max} (phase-to-ground) the two phases are in series so that neither is stressed to 3.0 E_{max} (phase-to-ground) voltage.

A fault to neutral on one phase of a three-phase capacitor bank produces higher recovery voltages and currents when at least one neutral is ungrounded. Relative values are listed in Table 9. If an unfaulted phase is the first to interrupt, it is subjected to a 3.46 E_{max} (phase-to-ground) recovery voltage until the second and third phases interrupt. The highest capacitive current (3.06 times the rated value) is experienced in the faulted phase when it interrupts first.Following this interruption, the 3.46 E_{max} (phase-to-ground) recovery voltage is impressed across the interrupters in the two remaining phases.

A phase-to-ground fault produces the most severe conditions when the source is ungrounded and the bank neutral is grounded. Relative values are listed in Table 10. If an unfaulted phase is the first to interrupt, the current may reach 1.73 times the rated current value and the recovery voltage 3.46 E_{max} (phase-to-ground). The remaining phases are subjected to the same current, but upon interrupting, share the 3.46 E_{max} (phase-to-ground) recovery voltage. When the faulted phase is the first to interrupt, the current may be 3.06 times the rated current value and the recovery voltage 3.0 E_{max} (phase-to-ground). The second phase to interrupt will have a lower current but a higher recovery voltage of 3.46 E_{max} (phase-to-ground) which will be shared with the third phase. If the faulted phase reignites, one of the unfaulted phases will then interrupt and the conditions will be as previously described when an unfaulted phase was the first to interrupt.

For phase-to-phase ground faults, or phase-to-phase ungrounded faults, with the source grounded and the bank neutral ungrounded, recovery voltages and currents are no more severe than for the standard no-fault condition.

5.4 Switching Cables Under Faulted Conditions

The normal frequency capacitance currents and recovery voltages on a faulted cable circuit will be the same as for a grounded capacitor bank under faulted conditions.

5.5 Requirements

Specific tests for capacitance switching under fault conditions are not required. With no faults, the conditions of Section 4. apply. However, a related requirement of the circuit breaker, which accompanies the capacitance switching rating, is that the breaker must be capable of interrupting the capacitance current under faulted conditions within the following restrictions.

1) With faults, the interrupting time and the rated transient over-voltage factor of ANSI/IEEE C37.04-1979 may be exceeded.
2) The recovery voltages and capacitance currents on the unfaulted phases of overhead transmission lines must be within the limits specified in Tables 4, 5, 6 and 7 of this guide.
3) The recovery voltages and capacitance currents on the unfaulted phases of shunt capacitor banks or cables with single phase faults must be within the limits specified in Tables 9 and 10 of this guide.
4) The source must have a coefficient of grounding of 80 percent as defined in ANSI/IEEE Std 100-1977, IEEE Standard Dictionary of Electrical and Electronics Terms.
5) With ungrounded capacitor banks, the condition with one phase of the capacitor bank shorted is not covered in this application guide.

Applications outside the above limits should be referred to the manufacturer for consideration.

While the values of recovery voltage and current shown in Tables 4, 5, 6 and 7 are related to specific system voltages with specific system parameters as noted, the results are generally applicable to any rated voltage.

5.6 Examples of Application Alternatives

Other application options available are:

1) Use a circuit breaker of a higher rating in those cases of ground faults on ungrounded systems where the recovery voltage and current, or both, exceed the requirements of ANSI/IEEE C37.04-1979
2) Reduce the capacitor bank size so that the current under faulted conditions does not exceed the rated capacitance switching current of the circuit breaker.
3) Use a high speed switch to ground the source or capacitor bank neutral before switching the capacitor bank under faulted conditions.
4) Change the capacitor bank configuration from an undergrounded Y to a Δ on systems 15 kV and below. The capacitor fusing must be checked.

6. Revision of American National Standards Referred to in this Document

When the American National Standards referred to in this document are superseded by a revision approved by the American National Standards Institute, Inc, the revision shall apply.

ANSI/IEEE C37.010-1979, Application Guide for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis.

ANSI/IEEE C37.04-1979, Rated Structure for AC High-Voltage Circuit Breakers.

ANSI C37.06-1979, Schedules of Preferred Ratings and Related Required Capabilities for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis.

ANSI/IEEE C37.09-1979, Test Procedure for AC High-Voltage Circuit Breakers.

ANSI/IEEE C57.13-1979, Requirements, Terminology, and Test Code for Instrument Transformers.

7. References

[1] GABRIELLE, A. F., MARCHENKO, P. P., and VASSELL, G. S. Electrical Constants and Relative Capabilities of Bundled-Conductor Transmission Lines. *IEEE Transactions on Power Apparatus and Systems,* vol 83, Jan 1964, pp 78–92.

[2] STEVENSON, William, Jr. *Elements of Power System Analysis.* New York: McGraw-Hill, 1962, pp 114–133.

[3] *Electrical Transmission and Distribution Book.* East Pittsburgh, Pa.: Westinghouse Electric Corporation, 1950.

[4] IEEE Committee Report Bibliography on Switching of Capacitive Circuits Exclusive of Series Capacitors, *IEEE Transactions on Power Apparatus and Systems,* vol PAS 89, Jun/Jul 1970, pp 1203–1207.

[5] PFLANZ, H. M., and LESTER, G. N. Control of Overvoltages on Energizing Capacitor Banks, Paper T 72-541-1.

[6] JOHNSON, I.B.; SCHULTZ, A.J.; SCHULTZ, N.R.; and SHORES, R.B., *AIEE Transaction,* pt III, 1955 pp 727–736.

Table 4— Recovery Voltages and Currents on Unfaulted Phases of 242 kV Open Wire Transmission Line with a Phase-to-Ground Fault

First Phase to Interrupt				**Second Phase to Interrupt**				**Third Phase to Interrupt**				**Source Impedance equivalent (kA)**	$\frac{X_0}{X_1}$ **(5)**
Fault at Source End (8)		**Fault at Remote End (8)**		**Fault at Source End (8)**		**Fault at Remote End (8)**		**Fault at Source End (8)**		**Fault at Remote End (8)**			
E	***I***	***E***	***I***	***E***	***I***	***E***	***I***	***E***	***I***	***E***	***I***		
Faulted phase first				1.77	1.14	1.80	1.13	2.0	1.58	2.33	1.56	40	3.0
				1.77	1.18	1.85	1.13	2.0	1.72	2.37	1.56	30	3.0
2.55	1.17	2.48	1.13	Faulted phase second				1.88	1.44	1.92	1.13	40	3.0
2.74	1.22	2.45	1.13					2.04	1.18	1.88	1.13	30	3.0
2.13	1.14	2.06	1.13	2.44	1.17	2.27	1.13	Faulted phase third				40	3.0
2.17	1.19	2.07	1.13	2.54	1.22	2.28	1.13					30	3.0

NOTES:

1 — Current is interrupted in normal sequence, at succeeding current zeros.

2 — Tests made at a rated line charging current of 160A at 242 kV.

3 — Line length chosen to provide 160A line charging current for 242 kV; C_1/C_0 2.0; line represented by distributed parameters, completely transposed (equal coupling between phases).

4 — Source impedance chosen to give a three-phase ungrounded fault current at the circuit breaker terminals as shown.

5 — Source coefficient of grounding is 80% for $X_0/X_0 \leq 3.0$.

6 — For the fault at the remote end, it is assumed that the remote end circuit breaker interrupts first, and that the voltages and currents imposed on it are the same as for the fault at the source end. The reported values are the voltages and currents imposed on the source end circuit breaker with the remote end circuit breaker already cleared.

7 — These values were obtained by digital computer and transient network analyzer studies.

8 — The numerical values listed for E and I are ratios of the peak value of transient recovery voltage to ^{E}max (phase-to-ground), and the ratio of the peak value of switched capacitance current to the peak value of rated capacitance switching current.

Table 5— Recovery Voltages and Currents on Unfaulted Phases of 550 kV Open Wire Transmission Line with a Phase-to-Ground Fault

First Phase to Interrupt				Second Phase to Interrupt				Third Phase to Interrupt				Source Impedance equivalent (kA)	$\frac{X_0}{X_1}$
Fault at Source End (8)		Fault at Remote End (8)		Fault at Source End (8)		Fault at Remote End (8)		Fault at Source End (8)		Fault at Remote End (8)			(5)
E	***I***	***E***	***I***	***E***	***I***	***E***	***I***	***E***	***I***	***E***	***I***		
Faulted phase first				2.06	1.05	1.80	1.11	2.16	1.56	2.18	1.76	40	1.0
				1.65	1.09	1.82	1.11	2.66	1.66	2.18	1.17	40	3.0
				1.70	1.12	1.77	1.12	2.87	1.67	2.21	1.75	40	3.0
2.36	0.95	2.84	1.08	Faulted phase second				2.14	1.05	2.21	1.11	40	1.0
2.74	1.13	2.74	1.09					1.82	1.09	1.98	1.11	40	3.0
2.74	1.14	2.74	1.11					1.98	1.12	2.05	1.12	20	3.0
2.12	1.05	2.21	1.11	2.08	0.95	2.41	1.08	Faulted phase third				40	3.0
2.12	1.09	2.21	1.10	2.43	1.13	2.44	1.09					40	3.0
2.14	1.12	2.20	1.12	2.43	1.14	2.44	1.11					20	3.0

NOTES:

1 — Current is interrupted in normal sequence, that is at each succeeding current zero.

2 — Tests made at a rated line charging current of 400A at 550 kV

3 — Line length chosen to provide a rated line charging current of 400A at 550 kV; $C_1/C_0 = 2.0$; line represented distributed parameters, completely transposed (equal coupling between phases).

4 — Source impedance chosen to give a three-phase ungrounded fault current at breaker terminals as shown.

5 — Source coefficient of grounding is 80% for $X_0/X_1 \leq 3.0$.

6 — For the fault at the remote end, it is assumed that the remote end circuit breaker interrupts first, and that the voltages and currents imposed on it are the same as for the fault at the source end. The reported values are the voltages and currents imposed on the source end circuit breaker with the remote end circuit breaker already cleared.

7 — These values were obtained by digital computer and transient network analyzer studies.

8 — The numerical values listed for E and I are ratios of the peak value of transient recovery voltage to ^{E}max (phase-to-ground), and the ratio of the peak value of switched capacitance current to the peak value of rated capacitance switching current.

Table 6— Recovery Voltages and Currents on Unfaulted Phases of 242 kV Open Wire Transmission Line with a Phase-to-Phase Grounded Fault

First Phase to Clear				Second Phase to Clear				Third Phase to Clear				Source Impedance Equivalent (kV)	X_0
Fault at Source End (8)		Fault at Remote End (8)		Fault at Source End (8)		Fault at Remote End (8)		Fault at Source End (8)		Fault at Remote End (8)			(5)
E	*I*	*E*	*I*	*E*	*I*	*E*	*I*	*E*	*I*	*E*	*I*		
Faulted phase first				1.68	1.06	1.62	1.01	Faulted phase third				40	3
				1.63	1.08	1.6	1.03					20	3
Faulted phase first				Faulted phase second				2.28	1.55	2.37	1.33	40	3
								2.37	1.62	2.45	1.32	20	3
2.34	1.04	2.28	1.03	Faulted phase second				Faulted phase third				40	3
2.36	1.0	2.33	1.03									20	3

NOTES:

1 — Current is interrupted in normal sequence, at succeeding current zeros.

2 — Tests made at a rated line charging current of 160A at 242 kV.

3 — Line length chosen to provide 160A line charging current for 242 kV; C_1/C_0 2.0; line represented by distributed parameters, completely transposed (equal coupling between phases).

4 — Source impedance chosen to give a three-phase ungrounded fault current at circuit breaker terminals as shown.

5 — Source coefficient of grounding is 80% for $X_0/X_1 \leq 3.0$.

6 — For the fault at the remote end, it is assumed that the remote end circuit breaker interrupts first, and that the voltages and currents imposed on it are the same as for the fault at the source end. The reported values are the voltages and currents imposed on the source end circuit breaker with the remote end circuit breaker already cleared.

7 — These values were obtained by digital computer and transient network analyzer studies.

8 — The numerical values listed for E and I are ratios of the peak value of transient recovery voltage to Emax (phase-to-ground), and the ratio of the peak value of switched capacitance current to the peak value of rated capacitance switching current.

Table 7— Recovery Voltages and Currents on Unfaulted Phases of 550 kV Open Wire Transmission Line with a Phase-to-Phase Grounded Fault

First Phase to Clear				**Second Phase to Clear**				**Third Phase to Clear**				**Source Impedance Equivalent (kV)**	$\frac{X_0}{X_1}$
Fault at Source End (8)		**Fault at Remote End (8)**		**Fault at Source End (8)**		**Fault at Remote End (8)**		**Fault at Source End (8)**		**Fault at Remote End (8)**			**(5)**
E	***I***	***E***	***I***	***E***	***I***	***E***	***I***	***E***	***I***	***E***	***I***		
Faulted phase first				1.98	0.87	1.7	0.98	Faulted phase third				40	1
				1.65	1.06	1.6	1.04					40	3
				1.63	1.06	1.56	1.05					20	3
Faulted phase first				Faulted phase second				2.05	0.92	2.3	1.52	40	1
								2.3	1.75	2.3	1.52	40	3
								2.3	1.64	2.35	1.5	20	3
2.08	0.87	2.33	1.03	Faulted phase second				Faulted phase third				40	1
2.34	1.06	2.37	1.04									40	3
2.34	1.06	2.37	1.13									20	3

NOTES:

1 — Current is interrupted in normal sequence, that is at each succeeding current zero.

2 — Tests made at a rated line charging current of 400A at 550 kV.

3 — Line length chosen to provide a rated line charging current of 400A at 550 kV; $C_1/C_0 = 2.0$; line represented distributed parameters, completely transposed (equal coupling between phases).

4 — Source impedance chosen to give a three-phase ungrounded fault current at breaker terminals as shown.

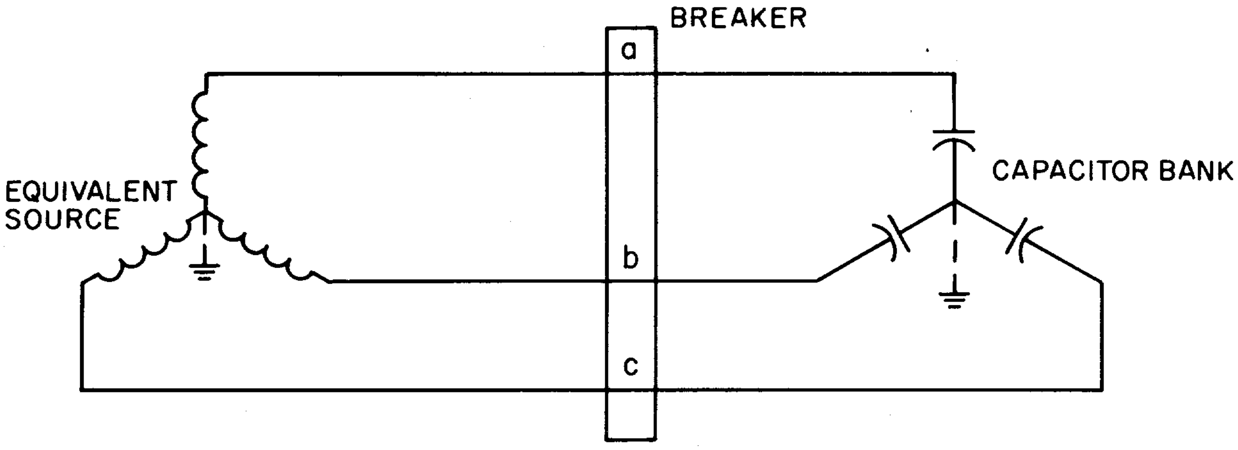
5 — Source coefficient of grounding is 80% for $X_0/X_1 \leq 3.0$.

6 — For the fault at the remote end, it is assumed that the remote end circuit breaker interrupts first, and that the voltages and currents imposed on it are the same as for the fault at the source end. The reported values are the voltages and currents imposed on the source end circuit breaker with the remote end circuit breaker already cleared.

7 — These values were obtained by digital computer and transient network analyzer studies.

8 — The numerical values listed for E and I are ratios of the peak value of transient recovery voltage to E_{max} (phase-to-ground), and the ratio of the peak value of switched capacitance current to the peak value of rated capacitance switching current.

Table 8— Recovery Voltage and Currents on Unfaulted Balanced Shunt Capacitor Bank (Reference Condition)

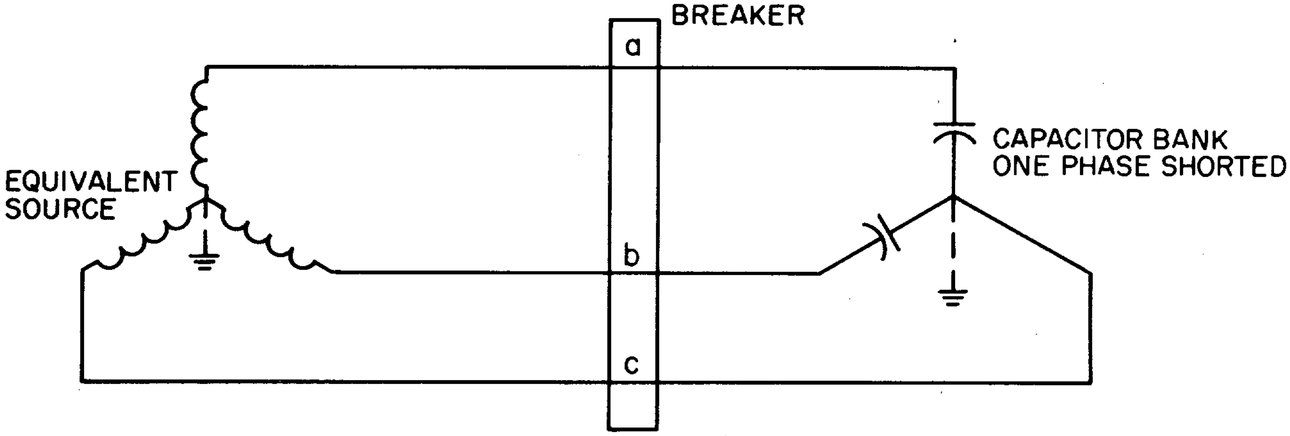


)

Grounding		First Phase to Interrupt			Remaining Phase or Phases to Interrupt			
Source	Bank	Phase	Voltage (V) (1)	Current (A) (2)		Voltage (V) (1)	Current (A) (2)	Two Interrupters in Series
grounded	grounded	a	2.0	1.0	b or c	2.0	1.0	no
grounded	ungrounded	a	3.0	1.0	b and c	3.46	0.86	yes
ungrounded	grounded	a	3.0	1.0	b and c	3.46	0.86	yes
ungrounded	ungrounded	a	3.0	1.0	b and c	3.46	0.86	yes

NOTE — The values were obtained by analysis and from studies on a miniature system.
1) Ratio peak recovery voltage to E_{max} (phase-to-ground).
2) Ratio of peak value of switched capacitance current to the peak value of rated capacitance switching current.

Table 9— Recovery Voltage and Currents on Unfaulted Phases of Shunt Capacitor Bank with Fault to Neutral on One Phase



Grounding		First Phase to Interrupt			Remaining Phase or Phases to Interrupt			
Source	Bank	Phase	Voltage (1)	Current (2)	Phase	Voltage (1)	Current (2)	Two Interrupters in Series
grounded	grounded	a	2.0	1.0	b	2.0	1.0	no
*grounded	ungrounded	a	3.46	1.73	b and c	3.46	1.73	yes
*ungrounded	grounded	a	3.46	1.73	b and c	3.46	1.73	yes
*ungrounded	ungrounded	a	3.46	1.73	b and c	3.46	1.73	yes
grounded	grounded	c	fault	fault	a or b	2.0	1.0	no
*grounded	ungrounded	c	3.0	3.06	a and b	3.46	0.86	yes
*ungrounded	grounded	c	3.0	3.06	a and b	3.46	0.86	yes
*ungrounded	ungrounded	c	3.0	3.06	a and b	3.46	0.86	yes

NOTE — These values were obtained by analysis and from studies on a miniature system.

1) Ratio of peak recovery voltage to E_{max} (phase-to-ground).
2) Ratio of peak value of switched capacitance current to the peak value of rated capacitance switching current.

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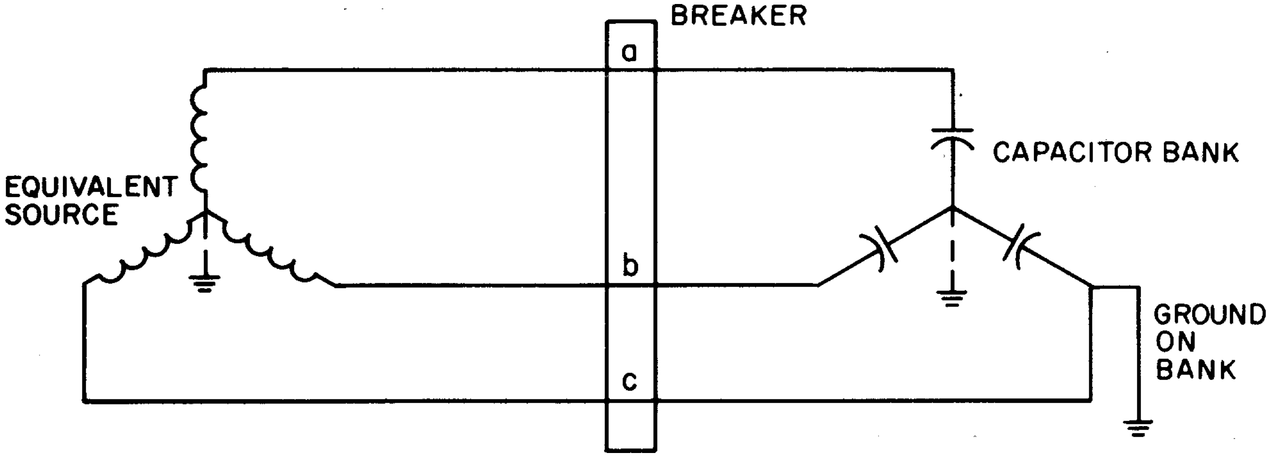
*Consult manufacturer for these applications.

Table 10— Recovery Voltages and Currents on Unfaulted Phases of Shunt Capacitor Bank with Fault to Ground on One Phase



Grounding		First Phase to Interrupt			Remaining Phase or Phase to Interrupt			
Source	Bank	Phase	Voltage (1)	Current (2)	Phase	Voltage (1)	Current (2)	Two Interrupters in Series
grounded	grounded	a	2.0	1.0	b	2.0	1.0	no
grounded	ungrounded	a	2.2	0.88	b	2.0	0.5	no
*ungrounded	grounded	a	3.46	1.73	b and c	3.46	1.73	yes
*ungrounded	ungrounded	a	3.0	1.0	b and c	3.46	0.86	yes
grounded	grounded	c	fault	fault	a or b	2.0	1.0	no
grounded	ungrounded	c	fault	fault	a and b	2.6	0.86	yes
*ungrounded	grounded	c	3.0	3.06	a and b	3.46	0.86	yes
*ungrounded	ungrounded	c	3.0	1.00	a and b	3.46	0.86	yes

NOTE — These values were obtained by analysis and from studies on a miniature system.
1)Ratio of peak recovery voltage to E_{max} (phase-to-ground).
2)Ratio of peak value of switched capacitance current to the peak value of rated capacitance switching current.

*Consult manufacturer for these applications.

Annex A Example of Open Wire Transmission Current Calculation

(Informative)

(These Appendixes are 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 method which follows is based essentially on the material contained in Reference [1]. The capacitive reactance can be calculated for single-circuit transmission lines using

$$X' = X_{a(eq)}' + X_d' \tag{A1}$$

where

X' = capacitive reactance per phase of an open wire transmission line, in meg-ohms per mile
$X_{a(eq)}'$ = equivalent conductor component of capacitive reactance per phase in a bundle for 1 ft spacing
X_d' = $X_d' = 0.06831 \dfrac{60}{f_s} \log_{10} D (\mathrm{M\Omega/mi})$

with

f_s = system frequency, in hertz
D = equivalent phase spacing, in feet

or for a single-circuit line,

$$D = \sqrt[3]{d_{ab}\, d_{bc}\, d_{ca}} \tag{A2}$$

where d_{ab}, d_{bc}, and d_{ca} are the distances in feet between conductors. Also,

$$X_{a(eq)}' = \frac{X_a' - X_{12}' - X_{13}' - \ldots - X_{1n}'}{n} \tag{A3}$$

for n conductors in a bundle configuration.

X_a' = $X_a' = 0.06831 \dfrac{60}{f_s} \log_{10} \dfrac{1}{r_1} (\mathrm{M\Omega/mi})$

X_{12}' = $X_{12}' = 0.06831 \dfrac{60}{f_s} \log_{10} d_{12} (\mathrm{M\Omega/mi})$

X_{13}' = $X_{13}' = 0.06831 \dfrac{60}{f_s} \log_{10} d_{13} (\mathrm{M\Omega/mi})$

X_{1n}' = $X_{1n}' = 0.06831 \dfrac{60}{f_s} \log_{10} d_{1n} (\mathrm{M\Omega/mi})$

where

r_1 = radius of one conductor in bundle, in feet
$d_{12}, d_{13}, \ldots, d_{1n}$ =distance between conductors in the bundle, in feet

For a single conductor,

$$X_{a(eq)} = X_a' \tag{A4}$$

for a two-conductor bundle,

$$X_{a(eq)}' = \frac{X_a' - X_{12}'}{2}$$

and for a three-conductor bundle,

$$X_{a(eq)}' = \frac{X_a' - X_{12}' - X_{13}'}{3}$$

Sample Calculation. Determine the line charging current that a circuit breaker must interrupt for application on a 550 kV system. The line parameters are

Voltage	550kV phase-to-phase rms
Length	150 mi (241.5 km)
Phase spacing	38 ft (horizontal) (11.6 m)
Subconductor	two 1780 kcmil ASCR per phase
Subconductor spacing	18 in (457 mm)

As a first approximation, Fig 1 is used by entering the curve at 550 kV and determining the current as 2.27A/mi. The charging current is thus

I_c = (2.27)(150) = 340 A

If a more accurate calculation is required, Eq 1 can be evaluated as follows.

The line is represented by Fig A1, and the equivalent phase spacing is

$$D = \sqrt[3]{(38)(38)(76)} = (38)\sqrt[3]{2}$$
$$= 47.9 \text{ ft}$$

Then

$$X_d' = \quad X_d' = 0.06831 \frac{60}{60} \log_{10} 47.9 = 0.115 \text{ M}\Omega/\text{mi}$$

The conductor radius is 0.0668 ft, making

$$X_a' = \quad X_a' = 0.06831 \frac{60}{60} \log_{10} \frac{1}{0.0668} = 0.0803 \text{ M}\Omega/\text{mi}$$

But for a two-conductor bundle,

$$X_{a(eq)}' = \frac{X_a' - X_{12}}{2}$$

Since d_{12} = 18/12 ft

$$X_{12}' = \quad X_{12}' = 0.06831 \frac{60}{60} \log_{10} \frac{18}{12} = 0.012 \ \text{M}\Omega/\text{mi}$$

Therefore,

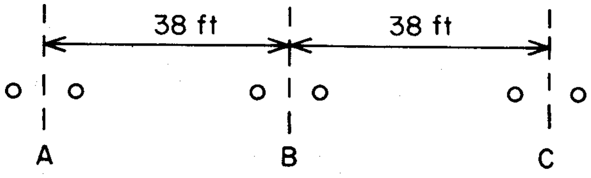


Figure A1 —

$$X_{a(eq)}' = \frac{0.0803 - 0.012}{2}$$
$$= 0.03415 \text{M}\Omega/\text{mi}$$

Then from Eq A1,

$$X' = 0.03415 + 0.115$$

$$= 0.1\ 492 \ \text{M}\Omega/\text{mi}$$

which corresponds to a current of 319 A. The estimated current of 340 A from the curve is slightly on the conservative side.

If the Ferranti effect is considered, the value of the inductive reactance per mile is required. Again from reference [1],

$X_L = X_{a(eq)} + X\text{d}$

where

$$X_{a(eq)} = \frac{0.2794}{2} \frac{f_s}{60} \left[\log_{10} \frac{1}{\text{GMR}} - \log_{10} d_{12} \right] (\Omega/\text{mi})$$

$$X_d = 0.2794 \frac{f_s}{60} \log_{10} D (\Omega/\text{mi})$$

and GMR is the geometrical mean radius in feet, the other symbols as before.

The GMR for a 1780 kcmil ACSR conductor is 0.0536 ft. Substituting,

$$X_{a(eq)} = \frac{0.2794}{2} \left(\frac{60}{60} \right) \left[\log_{10} \frac{1}{0.0536} - \log_{10} 1.5 \right]$$
$$= 0.1529 \ \Omega/\text{mi}$$

$$X_d = 0.2794 \left(\frac{60}{60} \right) \log_{10} (47.9)$$
$$= 0.469 \Omega/\text{mi}$$

Then

$X_L = 0.1529 + 0.469 = 0.622\ \Omega/\text{mi}$

Substituting in the Ferranti effect equations of Section 4.6.1, the current is

$$\begin{aligned}|I_c| &= \frac{|V_s|}{X_c}\left[1 + \frac{1}{3}\,\frac{(0.622)(150)^2}{(0.1492)} \times 10^{-6}\right]\\ &= |I_c'|\ [1.03]\end{aligned}$$

where $|I_c'| = 319$ A. The corrected current is 330 A.

The final step is to consult the table of ratings to verify the capability of the circuit breaker.

Annex B Basic Relations During Capacitance Current Switching

(Informative)

Foreword

The switching of capacitive currents can be a severe duty for the circuit breaker. Such currents, the charging current of an unloaded transmission line or cable, or the load current of a static capacitor bank are, in most cases, a maximum of a few hundred amperes. Since the capacitance can retain a voltage charge, the capacitance current arc is usually interrupted at a very early current zero after the circuit breaker contacts separate. After interruption, the normal frequency alternation of the voltage on the source side of the breaker results in a recovery voltage across the circuit breaker contacts which, one half-cycle after interruption, can approach two to three times crest line-to-neutral voltage. A breakdown across the contact gap during this interval will produce transient overvoltages. The maximum magnitude of such overvoltages may generally be related to the time interval between the interruption and the occurrence of the breakdown across the contacts by use of generalized circuit breaker operating characteristics.

This Appendix has been prepared in an attempt to provide the basis for an understanding of the Standard for Capacitance Current Switching, its requirements, and the methods suggested for demonstration of these requirements.

B1 Capacitance Current Switching Rating

The capacitance current switching ratings assigned to circuit breakers are related to a number of factors which include the following.

1) The circuit breaker design, whether general purpose or specifically designed or modified for capacitance current switching.
2) Voltage rating, 72.5 kV and below, and 121 kV and above
3) System and capacitance load grounding conditions
4) The presence of other shunt capacitor banks on the system, that is, back-to-back capacitor banks

The transient overvoltage limit during opening shall be as specified for the following categories of circuit breakers:

Design	Rated Voltage	Rated Transient Over-Voltage Factor
General purpose	All voltages	3.0
Definite purpose	72.5 kV and below	2.5
Definite purpose	121 kV and above	2.0

This performance is demonstrated by making the required series of capacitance current switching tests with measured transient over-voltages equal to or less than allowable limits.

At the option of the manufacturer, an alternative method of demonstrating performance for circuit breakers rated 121 kV and above is to make tests in which the prospective over-voltages, based on the time interval (current pause) before restrike, are less than the allowable limit.

For tests where the overvoltage is to be determined by this time interval relation, the allowable time before restrike is included as part of ANSI/IEEE C37.04-1979. The derivation of these relations, considering the switching of shunt capacitor bank current or line charging current and considering the use of arc shunting resistors, is presented in this Appendix.

B2 Investigation of Transient Currents When Energizing

B2.1 Energizing Capacitor Banks

The equivalent circuit for energizing capacitor banks, assuming that the time of closing the switch occurs when the power frequency voltage is a maximum and that the time duration of the transient is small when compared with the power frequency, is shown in Fig B1. If this is not the case, both the transient and power frequency currents must be added together to arrive at the actual current.

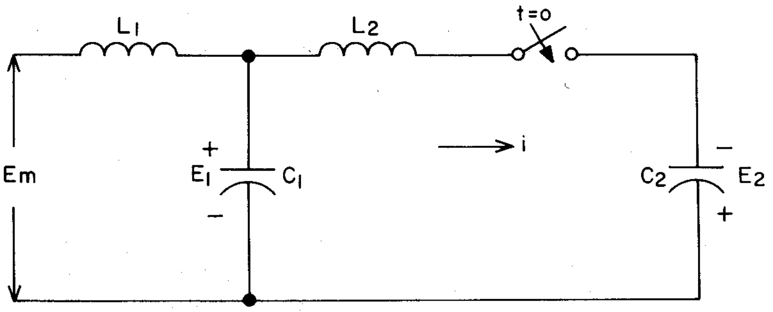


Figure B1 —

In the Laplace domain the general equation for the current is

$$i(s) = \frac{E_1 + E_2}{s\left(sL_2 + \frac{1}{sC_2} + \frac{1}{sC_1 + 1/L_1}\right)} \tag{B1}$$

The energization current of a single deenergized capacitor bank is represented mathematically by letting $C_1 = L_1 = E_2 = 0$ and $E_1 = E_m$. Thus

$$i(s) = \frac{E_m}{s(sL_2 + 1/sC_2)} = \frac{E_m\sqrt{1/L_2C_2}}{\sqrt{L_2/C_2}(s^2 + 1/L_2C_2)} \tag{B2}$$

$$\text{Since} L(\sin\omega t) = \frac{\omega}{s^2 + \omega^2} \tag{B3}$$

$$i = \frac{E_m}{\sqrt{\frac{L_2}{C_2}}} \sin\frac{t}{\sqrt{L_2C_2}} \tag{B4}$$

and

$$\frac{di}{dt} = \frac{E_m}{L_2} \cos\frac{t}{\sqrt{L_2C_2}} \tag{B5}$$

The energization current when energizing a back-to-back capacitor bank is represented mathematically by letting $L_1 = \infty$, $E_1 = E_m$, and $E_2 = 0$. Substituting these values in Eq B1,

$$i(s) = \frac{E_m}{s[sL_2 + (1/s)(1/C_1 + 1/C_2)]} \tag{B6}$$

if

$$\left(\frac{1}{C_1} + \frac{1}{C_2}\right) = \frac{1}{C_{eq}} \text{ or } C_{eq} = \frac{C_1 C_2}{(C_1 + C_2)} \tag{B7}$$

If C_2 is replaced by C_{eq}, the time domain solution for the current is the same as Eq B4.

It is noted that the above solutions are related to a single-phase condition. The solutions for the current for the last phase to close on a three-phase system are identical to those derived. Currents for the second phase to close in a three-phase system will be 0.866 of those derived.

If the voltage across the switch ($E_1 + E_2$) is zero, there will be no transient energization current, and if on closing there is a trapped charge on the capacitor bank such that $E_1 + E_2 = 2E_m$, the currents will be twice those derived in the equation.

To relate the transient current to steady-state quantities the following relations are used:

$$E_m = \frac{\sqrt{2}E_{LL}}{\sqrt{3}} \tag{B8}$$

where

E_{LL} = phase-to-phase voltage, in kilovolts

$$\frac{E_{LL}}{\sqrt{3}i} = X_C = \frac{1}{2\pi f C}$$

and

$$i = \frac{\omega C E_{LL}}{\sqrt{3}} \text{ or } C = \frac{i\sqrt{3}}{\omega E_{LL}} \tag{B9}$$

where

ω = $2\pi f = 377$ for a 60 Hz system
i = current in capacitor bank, in kiloamperes
C = capacitance of bank, in farads

$$L_{sc} = \frac{E_{LL}}{\sqrt{3}I_{sc}\omega} \tag{B10}$$

where

L_{sc} = inductance limiting the short-circuit current I_{sc}, in kiloamperes

The maximum crest transient closing current will occur where

$$t = \sqrt{LC}$$

when energizing a capacitor bank. From Eqs B4, B8, B9, and B10 this current is

$$I_{\max} = \frac{E_{\mathrm{m}}}{\sqrt{L/C}} = \frac{\sqrt{2}\ E_{\mathrm{LL}}}{\sqrt{3}\sqrt{L/C}} = \sqrt{2I_{\mathrm{sc}}i}\ (\mathrm{kA}) \tag{B11}$$

The maximum crest transient closing current when energizing a back-to-load capacitor bank is found by combining Eqs (B7) and (B9),

$$C_{\mathrm{eq}} = \frac{\sqrt{3}}{\omega E_{\mathrm{LL}}}\left(\frac{i_1\ i_2}{i_1 + i_2}\right)(\mathrm{F}) \tag{B12}$$

where

i_1 = current in C_1
i_2 = current in C_2

Combining Eq B12 and the maximum amplitude of Eq B4,

$$\begin{aligned} I_{\max} &= \frac{\sqrt{2}E_{\mathrm{LL}}}{\sqrt{3L_2}}\sqrt{\frac{\sqrt{3}}{\omega E_{\mathrm{LL}}}\left(\frac{i_1\ i_2}{i_1 + i_2}\right)} \\ &= 1.07\sqrt{\frac{E_{\mathrm{LL}}\ i_1\ i_2}{\omega L_2\ (i_1 + i_2)}} \end{aligned}$$

For ω = 377 Hz,

$$I_{\max} = 0.0553\sqrt{\frac{E_{\mathrm{LL}}\ i_1\ \ i_2}{L_2(i_1 + i_2)}}(\mathrm{kA})$$

The maximum rate of rise of current from Eqs (B5) and (B10) is

$$\frac{\mathrm{d}i}{\mathrm{d}t} = \frac{E_{\mathrm{m}}}{L_{\mathrm{sc}}} = \frac{\sqrt{2}\ E_{\mathrm{LL}}}{\sqrt{3}\ E_{\mathrm{LL}}}\sqrt{3}I_{\mathrm{sc}}\omega = \sqrt{2}\omega I_{\mathrm{sc}}\ (\mathrm{kA/s}) \tag{B13}$$

The frequency of the oscillatory transient when energizing a back-to-back capacitor bank is

$$f_0 = \frac{1}{2\pi\sqrt{LC}}\ (\mathrm{Hz}) \tag{B14}$$

and combining Eqs B14 and B12

$$\begin{aligned} f_0 &= \frac{\sqrt{\omega E_{\mathrm{LL}}(i_1 + i_2)}}{\sqrt{2\pi\, L_2\ \sqrt{3}\ \ i_1\, i_2}} \\ &= 0.122\sqrt{\omega}\sqrt{\frac{E_{\mathrm{LL}}(i_1 + i_2)}{L_2(i_1\ \ i_2)}}(\mathrm{Hz}) \end{aligned}$$

For ω = 377 Hz,

$$f_0 = 2.37\sqrt{\frac{E_{\mathrm{LL}}(i_1 + i_2)}{L_2(i_1\ \ i_2)}}(\mathrm{Hz}) \tag{B15}$$

B2.2 Energizing Lines or Cables

The equivalent circuit for energizing lines or cables until the first reflection returns from remote end is shown in Fig B2. In the Laplace domain with i = 0 and t = 0,

$$i(\mathrm{s}) = \frac{E_\mathrm{m} + E_\mathrm{t}}{\mathrm{s}(\mathrm{s}L + Z)} = \frac{E_\mathrm{m} + E_\mathrm{t}}{L\mathrm{s}(\mathrm{s} + Z/L)} \tag{B16}$$

or in the time domain,

$$i = \frac{E_\mathrm{m} + E_\mathrm{t}}{Z}\left[1 - \exp\left(-\frac{Zt}{L}\right)\right] \tag{B17}$$

$$\frac{\mathrm{d}i}{\mathrm{d}t} = \frac{E_\mathrm{m} + E_\mathrm{t}}{L}\exp\left(-\frac{Zt}{L}\right) \tag{B18}$$

where

Z = surge impedance of connected cable or line, in ohms
E_t = voltage due to charge trapped on line or cable at time of closing

The initial rate of rise of current is the same for capacitor banks or cables if the charges trapped on each have the same magnitude. This can be seen by comparing Eqs (B18) and (B5).

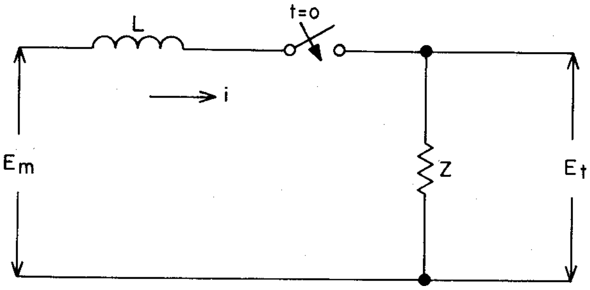


Figure B2 —

B3 Investigation of Overvoltages Occurring When Interrupting Capacitor Bank Current

B3.1 Capacitor Overvoltage from a Single Restrike Through the Primary Arcing Contacts—Circuit Breaker with Arc Shunting Resistor

In the equivalent circuit of switching a capacitor bank (Fig B3), the resistor is inserted (equivalent to interruption of the primary arc current) at a voltage peak (also a current zero). The basic equation of this circuit is

$$E_\mathrm{m}\cos\omega t = RI + \frac{1}{C}\int I\,\mathrm{d}t \tag{B19}$$

The capacitor voltage e_c may be found from Eq B19 as

$$e_c = \frac{E_m}{1 + (\mathrm{R}/X_c)^2} \left[\frac{E_{co} - E_m + (\mathrm{R}/X_c)^2 E_{co}}{E_m} \exp\left(-\frac{\omega \mathrm{t}}{\mathrm{R}/X_c}\right) + \cos \omega t + \frac{R}{X_c} \sin \omega t \right] \tag{B20}$$

where

E_{C0} = initial capacitor voltage (actually E_m)
R/X_c = ΩRC

For this case, $E_{C0} = E_m$, Eq B20 reduces to

$$e_c = \frac{E_m}{1 + (\mathrm{R}/X_c)^2} \left[\left(\frac{R}{X_c}\right)^2 \exp\left(-\frac{\omega t}{R/X_c}\right) + \cos \omega t + \frac{R}{X_c} \sin \omega t \right] \tag{B20a}$$

When a restrike occurs, the maximum voltage on the capacitor will be

$$E_c(\text{peak voltage transient}) = 2E_m \cos\theta - e_c \tag{B21}$$

where

θ = degrees preceding the restrike (current pause)

Combining this with Eq (B 20a) and solving for the ratio of peak transient to E_m

$$\frac{E_c(\text{peak transient})}{E_m} = 2\cos\theta - \frac{1}{1 + (R/X_c)^2} \left[\left(\frac{R}{X_c}\right)^2 \exp\left[-\frac{\theta}{57.2 R/X_c}\right] + \cos\theta + \frac{R}{X_c} \sin\theta \right] \tag{B22}$$

From Eq B22 the current pause may be determined for a maximum overvoltage ratio of 2 in terms of the relative value of R/X_C. This has been plotted in Fig 13 of ANSI/IEEE C37.09-1979 where for convenience it is shown as the allowable current pause in degrees as a function of

$$\frac{(\text{phase-to-phase operating volts})}{(\text{resistance per phase}) \times (\text{capacitance current})} = \frac{V_{LL}}{RI_e}$$

It should be noted that for the case of no resistor ($R = \infty$), that is, $V_{LL}/RI_c = 0$, the maximum current pause for an overvoltage of 2 or less is 120°.

B3.2 Voltage from Two Restrikes Through the Primary Arcing Contacts, Each After a Current Pause of 180°—Circuit Breaker with Arc Shunting Resistor

In this case it is desirable to find the limiting value of R/X_C for which there may be two restrikes through the primary arcing contacts, each after a current pause of 180° without exceeding the allowable over-voltage limit of either 2.0 or 3.0 times normal phase voltage crest.

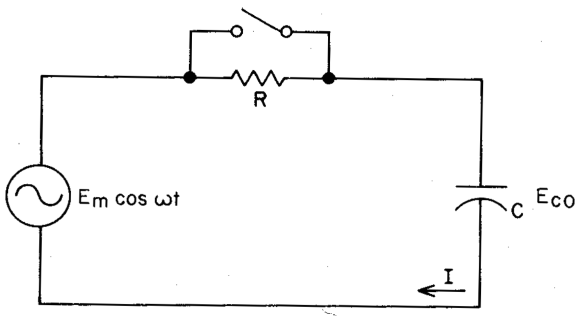


Figure B3 —

In Eq B21 the maximum transient voltage that could be left on the capacitor is given for a single restrike. In this equation if θ is 180°, it becomes

E_{c1} (peak voltage transient) = E_m

$$E_{C1}(\text{peak voltage transient}) = E_m \left[2 + \frac{1}{1+(R/X_C)^2}\left(\left(\frac{R}{X_C}\right)^2 \exp\left(-\frac{\pi}{R/X_C}\right) - 1\right)\right] \tag{B23}$$

This voltage discharges through the resistor, according to Eq B20. When E_{C1} (peak voltage transient of Eq B23 is substituted for E_{C0} in Eq B20 and the current pause ω*t* is 180° before the second restrike, the capacitor voltage at the instant of the second restrike will be

$$E_{C2} = \frac{E_m}{1+(R/X_2)^2} \left[\left(\frac{E_{C1} - E_m + (R/X_C)^2 E_{C1}}{E_m}\right)\exp\left(-\frac{\pi}{R/X_C}\right) - 1\right] \tag{B24}$$

After the second restrike, again assuming full transient reversal of the capacitor voltage, the peak voltage transient will be

$$E_{C2}(\text{peak voltage transient}) = 2\mathrm{E}_m + E_{C2} \tag{B25}$$

From Eqs B24 and B25, the limiting ratio of R/X_C maybe determined for which E_{C2} (peak voltage transient) will not exceed the allowable levels of 2.0 or 3.0 E_m.

Two restrikes each with one half-cycle current pause will result in maximum overvoltage ratio no higher than		**R/X_C is less than**		**V_{LL}/RI_c is more than**		**I_C is less than**
2.0	if	1.70	or	1.02	or	$0.98V_{LL}/R$
3.0	if	4.00	or	0.43	or	$2.31V_{LL}/R$

B3.3 Overvoltage from Restrikes Through the Secondary (Resistor) Arcing Contacts—Capacitor Banks

When the arc shunting resistor circuit is interrupted in a circuit breaker equipped with resistors, the equivalent circuit is as shown in Fig B4. In this equivalent circuit for restrikes through the resistor or secondary arcing contacts, the source inductance *L* is considered since this is a damped RLC oscillatory circuit. In the cases of restrikes through the primary arcing contacts, the same type circuit actually exists, but it is less damped and the maximum oscillation or “swing" of two times is considered for the capacitor voltage, Eq B21.

In the RLC circuit of Fig B3, the voltage relations are

$$E_{\mathrm{m}} \cos \omega t = L\frac{\mathrm{d}I}{\mathrm{d}t} + RI + \frac{1}{C}\int I\,\mathrm{d}t \qquad \text{(B26)}$$

Solving for E_C,

$$e_{\mathrm{c}} = E_{\mathrm{m}} + (E_{\mathrm{co}} - E_{\mathrm{m}}) \exp\left(-\frac{Rt}{2L}\right)\cos\beta t \qquad \text{(B27)}$$

where $\beta = 1/\sqrt{LC}$ for the case of relatively small damping, that is, a circuit where R^2 is less than $4L/C$. (This is not usually the case in practical arc shunting resistor applications. However this mathematical approach to the limiting resistance is simpler than the other possible approach.)

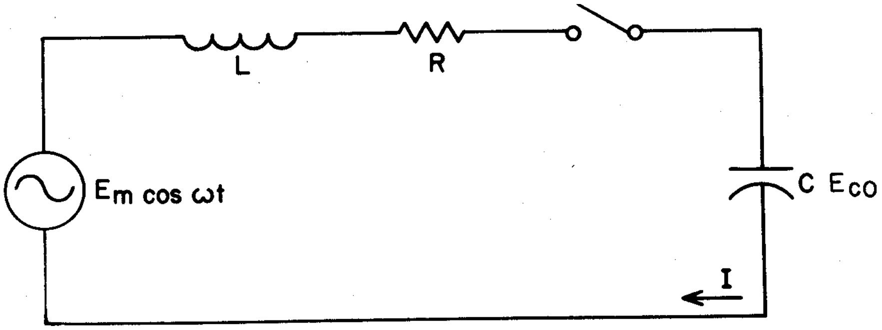


Figure B4 —

In this underdamped case it is further assumed that the value of E_{C0} at the time of a restrike through the secondary arcing contacts is E_m. (This assumes *R* to be small enough to cause no significant phase shift in the current after the resistor is inserted in the circuit.)

For a restrike through the secondary arcing contact after a current pause of 180° following interruption of the resistor current, the peak transient voltage on the capacitor will be

$$E_{\mathrm{c}}(\text{peak voltage transient}) = E_{\mathrm{m}}\left[1 + 2\exp\left(-\frac{R\pi}{2L\beta}\right)\right] \qquad \text{(B28)}$$

For an overvoltage no higher than $2E_m$, *R* must be

$$R \geq 0.441\sqrt{\frac{L}{C}} \qquad \text{(B29)}$$

Since L is related to the system short-circuit capacity at the circuit breaker, and C is related to the capacitive current, Eq B29 may be manipulated to show the following:

If the system short-circuit capacity is at least one third or more of the circuit breaker rating, then for a single restrike through the secondary contacts after a zero current pause of 180°, the overvoltage ratio will be less than 2.0 if R is greater than

$$\frac{(0.441)\text{operating phase-to-phase voltage})}{\sqrt{(\text{capacitive current})\times\begin{pmatrix}\text{circuit breaker rated}\\ \text{short-circuit current}\\ \text{at operating voltage}\end{pmatrix}}}$$

With a similar consideration for two restrikes through the secondary arcing contacts, each with 180° zero current pause, it may be found that the peak transient voltage on the capacitor will be

$$E_C(\text{peak voltage transient}) = E_m + 2E_m\left[1+\exp\left(-\frac{R\pi}{2L\beta}\right)\right]\exp\left(-\frac{R\pi}{2L\beta}\right) \tag{B30}$$

For an overvoltage no higher than $3E_m$ R must be

$$R \geq 0.309\sqrt{\frac{L}{C}} \tag{B31}$$

For an overvoltage no higher than $2E_m$, R must be

$$R \geq 0.665\sqrt{\frac{L}{C}} \tag{B32}$$

Or in terms of circuit constants and assuming the system short circuit capacity is at least one third or more of the circuit breaker rating, then for double restrikes, one finds overvoltages no greater than $2.OE_m$ if I_c is greater than

$$\frac{0.44\left(\frac{\text{operating voltage phase-to-phase}}{\text{pole unit arc shunting resistance}}\right)^2}{(\text{circuit breaker rated short-circuit current})} \tag{B33}$$

or one finds overvoltages no greater than $3.0E_m$ if I_c is greater than

$$\frac{0.10\left(\frac{\text{operating voltage phase-to-phase}}{\text{pole unit arc shunting resistance}}\right)^2}{(\text{circuit breaker rated short-circuit current})} \tag{B34}$$

B4 Transmission Line Switching — Double Restrike Through Resistor

It is desirable to establish the minimum values of R for transient voltages of two times and three times normal voltage for specified conditions of restriking. Consider the equivalent circuit shown in Fig B5.

Then at the first restrike,

$$i_f = \frac{E_m + e_0}{R + Z_0} \tag{B35}$$

$$e_f = Z_0\ i_f = (E_m + e_0)\frac{Z_0}{R + Z_0} \tag{B36}$$

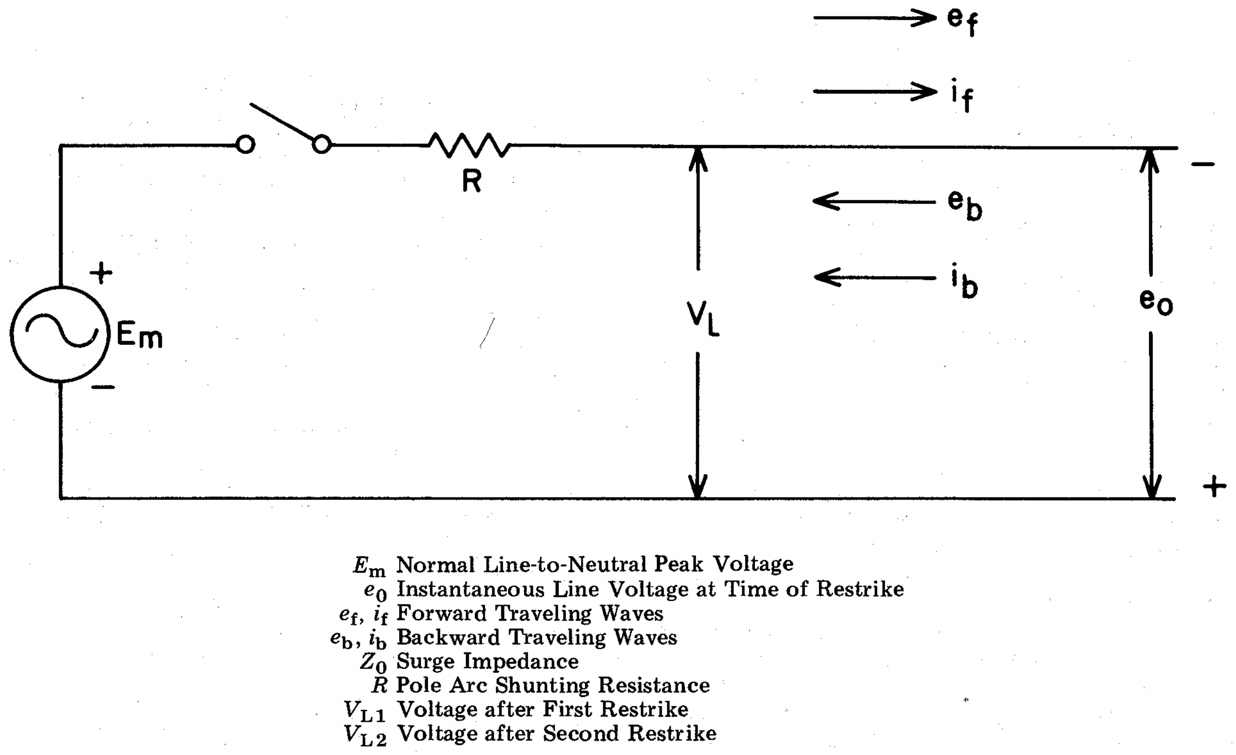
$$i_b = -i_f \qquad e_b = -Z_0 i_b \tag{B37}$$

$$V_L = -e_0 + e_b + e_f \tag{B38}$$

In the general case,

$$V_L = -e_0 + 2(E_m + e_0)\frac{Z_0}{R + Z_0} \tag{B39}$$

At the instant of restrike $e_o = E_m$ with opposite polarity. Thus



E_m	Normal Line-to-Neutral Peak Voltage
e_0	Instantaneous Line Voltage at Time of Restrike
e_f, i_f	Forward Traveling Waves
e_b, i_b	Backward Traveling Waves
Z_o	Surge Impedance
R	Pole Arc Shunting Resistance
V_{L1}	Voltage after First Restrike
V_{L2}	Voltage after Second Restrike

Fig B5

$$V_{L1} = -E_m + \frac{4Z_0E_m}{R + Z_0} \tag{B40}$$

It has been assumed that the circuit breaker cleared at the first natural frequency current zero. Then $e_o = V_{L1}$ just prior to the second restrike and

$$V_{L2} = -V_{L1} + 2(E_m + V_{L1})\frac{Z_0}{R + Z_0} \tag{B41}$$

Substituting and solving for the voltage ratio,

$$\frac{V_{\mathrm{L2}}}{E_{\mathrm{m}}} = 1 - \frac{4Z_0}{R + Z_0} + 8\left(\frac{Z_0}{R + Z_0}\right)^2 \tag{B42}$$

Solving for R, where Z_{o} = 450 Ω for the two voltage ratio cases of 3.0 and 2.0, respectively

(1) R 110 Ω for double restrikes and less than three times normal voltage

(2) R 210 Ω for double restrikes and less than two times normal voltage