IEEE Guide for Synthetic Capacitive Current Switching Tests of AC High-Voltage Circuit Breakers

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Abstract: As an aid in testing circuit breakers under conditions of switching capacitive currents synthetic test circuits may be used. The design of the circuit should simulate the stress of actual service conditions as closely as possible. A number of circuits are given as examples. The limitation of the use of synthetic test methods is that the breaker under test must not display evidence of reignition or restriking. The known circuits do not properly represent the interaction between the source and the capacitive load under this condition. Such breakers must be tested using direct circuits.
Keywords: capacitive current switching, closing phenomena, opening phenomena, synthetic circuits, testing circuit breakers

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Introduction

(This introduction is not part of IEEE Std C37.083-1999, IEEE Guide for Synthetic Capacitive Current Switching Tests of AC High-Voltage Circuit Breakers.)

This is a new guide developed to provide a basis for synthetic capacitive-current switching tests of circuit breakers. It includes criteria for testing to demonstrate the capacitor switching current rating of circuit breakers on a single phase basis.

The guide contains typical circuits for use in demonstrating capacitive current switching capabilities, but these circuits are those in general use; they should not exclude the development or introduction of additional circuits.

There are major changes taking place in standards development in the area of capacitor switching. Within the various standards organizations the following changes are known:

— IEEE Std 37.09-1999, IEEE Standard Test Procedure for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis—Preferred Ratings and Related Capabilities is undergoing complete revision.

— A new IEEE standard, IEEE Std 1247-1998, IEEE Standard For Interrupter Switches for Alternating Current Rated Above 1000 Volts was approved.

— IEC 60056 (1987-03), High-Voltage Alternating Current Circuit Breakers, is also under complete revision. From what is known it is expected that the test requirements will be more statistical in nature with additional contact conditioning before the start of the test series.

The full impact of these revisions is not known at this time. The circuits and methods for testing shown in this guide are expected to remain valid. There may be a future need for modification in the voltage levels for some of the tests.

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IEEE Guide for Synthetic Capacitive Current Switching Tests of AC High-Voltage Circuit Breakers

1. Overview

This guide gives requirements for the synthetic testing of circuit breakers under conditions of switching capacitive currents. This is accomplished by simulating, as closely as possible, the stress conditions that may exist in actual service.

The phenomena of restriking and reignition causes interactions between the source and the capacitive load which, at present, cannot be simulated reliably by synthetic testing circuits described herein. Therefore, the synthetic method may only validate performance if there are no instances of restrikes. In the case of a circuit breaker that restrikes, direct tests would be required. See an alternative test method procedure in IEEE Std C37.09-1999.[1]

The phenomena of prestriking during making tests allows the possibility of interruption of high-frequency current during the closing operation. Such an interruption may cause reignition and would indicate that the circuit breaker may require direct testing.

Isolated bank and cable switching making duties are provided by direct short-circuit making tests. Therefore, no separate tests are required.

Due to cost considerations, synthetic circuits are not generally used to demonstrate making capabilities for back-to-back capacitive current switching and open wire line charging. Direct testing methods should be used to demonstrate these capabilities.

1.1 Scope

This guide provides a basis for synthetic capacitive current switching tests (see IEEE Std C37.04-1999) and to establish guidelines for testing to demonstrate the capacitive switching rating of circuit breakers on a single phase basis.

[1]Information on references can be found in Clause 2.

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The guide contains typical circuits for demonstrating capacitive current switching capability. These circuits are those in general use and their inclusion should not exclude the development of additional circuits to demonstrate specific capabilities.

1.2 Purpose

The purpose of this guide is to establish criteria for synthetic capacitive current switching tests and for the proper evaluation of results. Such criteria will establish validity of the test method without imposing restraints on innovation and improvement of test circuitry.

2. References

ANSI C37.06-1997, American National Standard for Switchgear—AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis—Preferred Ratings and Related Capabilities.[2]

IEEE Std C37.04-1999, IEEE Standard Rating Structure for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis.[3]

IEEE Std C37.09-1999, IEEE Standard Test Procedure for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis.

IEEE Std C37.012-1979 (Reaff 1988), IEEE Application Guide for Capacitance Current Switching for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis.

IEEE Std C37.081-1981 (Reaff 1988), IEEE Guide for Synthetic Fault Testing of AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis.

3. Definitions

3.1 auxiliary circuit breaker: The circuit breaker used to disconnect the current circuit from direct connection with the test circuit breaker.

3.2 current circuit: That part of the synthetic test circuit from which the major part of the power frequency current is obtained.

3.3 current injection method: A synthetic test method in which the voltage circuit is applied to the test circuit breaker before power frequency current zero.

3.4 direct test: A test in which the applied voltage, current, and recovery voltage are obtained from a single power source, which may be comprised of generators, transformers, networks, or combinations of these.

3.5 distorted current: The current through the test circuit breaker that is influenced by the arc voltage of both the test and auxiliary circuit breakers during the high-current interval.

3.6 injected current: The current that flows through the test circuit breaker from the voltage source of a current injection circuit when this circuit is applied to the test circuit breaker.

3.7 injected-current frequency: The frequency of the injected current.

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[2]ANSI publications are available from the Sales Department, American National Standards Institute, 11 West 42nd Street, 13th Floor, New York, NY 10036, USA (http://www.ansi.org/).

[3]IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA (http://www.standards.ieee.org/).

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3.8 injection time: The time with respect to the power frequency current zero when the voltage circuit is applied.

3.9 prestrike: The initiation of current between the contacts during a closing operation before the contacts have mechanically touched.

3.10 synthetic test: A test in which the major part of, or the total current, is obtained from a source or sources (current circuit), and the major part of, or all of the transient recovery voltage from a separate source or sources (voltage circuit).

3.11 test circuit breaker: The circuit breaker under test.

3.12 voltage circuit: That part of the synthetic test circuit from which the major part of the test voltage is obtained.

4. Capacitive current switching process

The switching of capacitive circuits is a usual requirement of power circuit breakers. These circuits may consist of unloaded open wire lines, unloaded cable circuits, or shunt capacitor banks (both single and back-to-back).

These switching operations include both energizing and de-energizing the capacitive circuit. Either operation can generate transient overvoltages on the system.

The transient overvoltage factor does not apply for synthetic tests because reignitions and restrikes invalidate the test results.

4.1 Closing phenomena

When switching open wire lines, the circuit breaker may be required to reclose on a line having a trapped charge. Reclosing operations can generate maximum switching surges, the amplitudes of which are dependent on the following factors:

a) The prestriking voltage
b) The source and line surge impedance
c) Closing sequence
d) Line length
e) Percent compensation
f) The value of pre-insertion resistor or reactor
g) The time the pre-insertion resistor or reactor is in the circuit

These transient voltages and related currents may have deteriorating effects on the circuit breaker and system (see IEEE Std C37.04-1999).

The energization of a shunt capacitor bank results in a transient inrush current, the magnitude and frequency of which are a function of the following:

a) The prestriking voltage
b) The capacitance of the circuit
c) The inductance and the location of the inductance in the circuit
d) Damping due to the circuit resistances or the pre-insertion closing resistors

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Cable current switching phenomena are similar to those of capacitor switching except that the inrush currents are further affected by the cable surge impedance and the length of cable.

A special requirement is back-to-back switching of shunt capacitor banks or back-to-back cable charging.

Two cable circuits of any length or two capacitor banks of any size operating from the same bus without a large reactance between them require circuit breakers with back-to-back switching capability (see IEEE Std C37.04-1999). These are called “definite purpose circuit breakers” for which the schedule of preferred ratings (see ANSI C37.06-1997) show high-frequency peak inrush current that can be as high as 100 times the normal rated capacitance switching current (rms). To meet the standard, a definite purpose breaker must be able to close against rated peak inrush current and also withstand this current in case of a restrike on an opening operation. The inrush current during a maximum restrike would be two times the normal closing transient (considering no trapped charges in a normal case for capacitor banks).

General purpose circuit breakers have no back-to-back switching ratings and should not be applied for back-to-back switching.

The phenomenon of prestriking may result in the interruption of high-frequency current during the closing operation. This interruption may cause reignitions or restrikes. This phenomenon is addressed in 4.2.

4.2 Opening phenomena

An important consideration in the application of circuit breakers for capacitance current switching is the transient overvoltage which may be generated by a restrike during the opening operation.

At capacitance current zero, the capacitor is charged to nearly peak line to neutral (ground) voltage. Since the recovery voltage appearing across the circuit breaker contacts at that instant is small, the capacitance current may be interrupted at the first current zero occurring near contact parting. After interruption, the power frequency alternation of the source side voltage results in a characteristic (1-cos) type recovery voltage across the circuit breaker’s opening contacts, and one half cycle later approaches a value twice peak line to neutral voltage. If a restrike occurs at that time, the capacitor voltage immediately oscillates about the source voltage to an overvoltage factor approaching three times its initial value but of opposite polarity. If the transient current is interrupted at its first high-frequency current zero, a transient voltage peak is trapped on the capacitor, and one half cycle later, the recovery voltage approaches a value of nearly twice that of the first interruption or four times normal line to neutral voltage. These are theoretical values that in actual systems seldom exceed an overvoltage factor of 2.5. However, in the event of additional restrikes, the overvoltages generated can escalate to values producing flashover and damage to connected equipment.

Therefore, it is desirable to prevent restrikes or limit the overvoltage phenomenon resulting from high-voltage reignition to protect the power system. (Refer to IEEE Std C37.012-1979.)

5. Basic principles of synthetic capacitive current switching testing

Tests to determine the short-circuit interrupting capability or the capacitive-switching capability of a circuit breaker do not necessarily involve full real or reactive power in the usual sense. In any current interruption, the interrupted current and the recovery voltage occur in two successive intervals of time. This fortunate circumstance gives rise to a “synthetic” method for testing circuit breakers for ratings beyond the power rating of the testing station.

The basis for all synthetic testing circuits is an arrangement to provide the major current and voltage requirements from two different circuits, one a current circuit and the other a high-voltage circuit. Figure 1 shows the basic components of a synthetic testing circuit. Oscillatory circuits may also be used, see Figure 7, part (a).

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The current circuit, as might be expected, provides the major portion of the switching current, although it might also provide the initial portion of the recovery voltage. Similarly, the high-voltage circuit supplies the required high recovery voltage following current interruption, and it might also supply some of the current before interruption.

The current circuit requires only a relatively low-impedance, low-voltage source, while the high-voltage circuit is necessarily a high-impedance, low-current circuit. Both circuits, when closed, are effectively in parallel with the test breaker. For capacitor switching tests the high-voltage circuit may be connected for the entire current interval. For this case, the high-voltage closing switch may remain closed. This differs from fault interruption tests where the high-voltage source is switched in only shortly before or after current interruption. For fault interruption tests, the high-voltage closing switch must be a fast acting triggered gap, while for capacitor switching tests, it may be a circuit breaker.

It is noted that for capacitor switching tests, the capacitor bank to be switched is a part of the high-voltage circuit.

During the interval of transition from high current to high voltage, the high-current circuit must be isolated from the rapidly increasing voltage across the test breaker. This isolation occurs at a prearranged normal current zero, which determines the timing of the isolation switch or auxiliary circuit breaker.

The actual components required for each circuit may vary depending upon the method used for supplying currents and recovery voltage. Two separate generating stations can be used if available. Precharged capacitor banks and tuned circuits can be used for one or both sources. Current sources may be inductive or capacitive for capacitor switching tests. Resistance may be added for damping and control.

With these variations, synthetic capacitor switching circuits can appear to be quite different while still satisfying the basic requirements of the two circuit arrangement as shown in Figure 1.

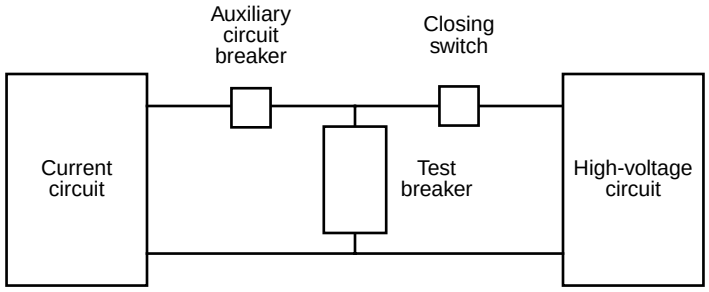


Figure 1—General synthetic test circuit

6. Requirements for synthetic capacitive current switching

The interrupting process that is characteristic of a circuit breaker requires the following:

a) Current to flow through closed contacts; and
b) Voltage to appear across open contacts.

These two conditions do not occur at the same time, thus permitting synthetic testing methods to be used to perform the tests. This clause sets forth the requirements to be met by a test circuit used to test the capacitive current switching ability of a circuit breaker.

In addition, other recommendations are detailed and must be carried out in accordance with the pertinent sections of IEEE Std C37.09-1999.

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6.1 General conditions

The use of synthetic testing methods to test the ability of a circuit breaker to interrupt capacitive currents must be done on one pole of a three pole device as a single phase test. This is acceptable since the currents are relatively low and adjacent phase electromagnetic interactions are considered minimal. Considerations must be given to testing a circuit breaker with three phases in one enclosure to assure that voltage stresses between phases are adequately simulated.

The synthetic testing method will permit evaluation only of circuit breakers that perform without restrikes during the demonstration tests.

The tested circuit breaker shall have the frame, enclosures, etc., grounded, as these parts would normally be grounded in service.

For synthetic testing of circuit breakers with shunt resistors, special circuits are required. Circuits and procedures are described in Clause 11.

6.2 Test circuit requirements

The waveforms of the voltage and currents that are normally supplied by an alternating source will be predominately sinusoidal. Oscillations due to closing of the test circuit, etc., will be dissipated before interruptions are attempted.

The voltage that is trapped on the capacitive load will be represented by a dc voltage of the appropriate magnitude (without decay).

The amplitude and waveform of the last loop of current before interruption must be at least equal to the required test value for a direct test.

The voltage of the circuit supplying the principal test current through an auxiliary circuit breaker must be high enough to minimize the current distortion during arcing by the arc voltage of both the test and auxiliary current breakers. Current distortion is further addressed in 8.1.

Tests demonstrating capacitance current switching capabilities of circuit breakers are to be made at the rated frequency of 60 Hz. If tests are made outside this frequency range (e.g., 50 Hz) the instantaneous recovery voltage across the current interrupting contacts of the circuit breaker, during the first 8.33 ms, shall not be less than that which would occur for a 60 Hz test.

The power requirement for the current source must be large enough to limit the change of voltage with or without the capacitive load to 10% (see Clause 9). This is to restrain reignitions in a circuit breaker at contact part angles close to current zero, forcing the current to flow again until a larger gap is attained.

The test circuit breaker shall have one side of the tested pole connected to ground in several of the synthetic test circuits (see Clause 7). The other side of this tested pole will have the full recovery voltage (dc trapped charge and superimposed ac voltages) impressed upon it. The test circuit breaker must be able to withstand the higher voltage application without harm from one bushing to ground (tank for a dead tank design). It must be recognized that this may be more severe than a direct test the degree of severity being dependent on the voltage distribution. The direct test would apply the dc trapped voltage to one side of the tested pole while the ac voltage would be applied to the other side of the tested pole to obtain the combined voltage stress across the open contacts. Because most modern circuit breakers will not be symmetrical the tests should be split such that both bushings are alternately grounded during the testing. Since the recovery voltage may be higher than that of a direct test circuit the recovery voltage may be reduced to the rated voltage.

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6.3 Test voltage

By proper choice of test voltage to produce recovery voltages equivalent to those occurring in three-phase tests, synthetic single-phase tests may be made to demonstrate the capacitance current switching ratings of circuit breakers. Because of the phenomena occurring in three-phase capacitance current switching operations described in IEEE Std C37.09-1999, a factor B must be considered in choosing open circuit test voltage E_{01} for single-phase tests, in addition to the factor A, which is also described in IEEE Std C37.09-1999.

For grounded shunt capacitor bank or cable charging current switching tests on a three-phase basis, B = 1.

For ungrounded shunt capacitor bank current switching tests on a three-phase basis, B = 1.5.

Therefore, the open circuit phase-to-ground test voltage for single-phase tests is

$$E_{01} = 0.58\,V\frac{2}{(1+A)}B$$

where

V is the rated maximum voltage

A is $\frac{I_{sc}}{I_{sc} - I_c}$

I_{sc} and I_c are single-phase values of available short-circuit current and capacitance current

NOTE—The methods described in IEEE Std C37.09-1999 for determining laboratory test voltage are approximate because of the dependence of the prospective short-circuit current and, therefore A, on the open circuit voltage. These methods, however, can be used to define conditions for reasonable test recovery voltages, particularly where laboratory short-circuit current is not large.

7. Examples of synthetic capacitance current switching test circuits

Usually synthetic testing requires a two circuit arrangement, two sources of power at the power frequency must be supplied. One or both of these power sources may be an ac generating station or a precharged capacitor bank in a tuned circuit. For the purposes of this guide, these power sources will be referred to simply as ac sources or tuned circuits. Examples of some of the possible combinations are given in 7.1 through 7.5.

7.1 Test circuit with ac sources and capacitive branches

Since both branches of the synthetic circuit are capacitive, the two ac sources must be in phase, supplying current through the test breaker as shown in Figure 2. The total current in the test breaker is the sum of the two currents, the ratio of which depends on the available capacitor banks and source voltages. Typically, the major portion of the required test current is supplied from a relatively low-voltage, low-impedance, high-current source, called the current circuit, through an auxiliary breaker to the test breaker. The test sequence begins with the energization of both capacitive branches through the closed test breaker. The auxiliary circuit breaker is timed to interrupt at the same current zero as the test circuit breaker. The interruption of the current traps a voltage on the series capacitors. The trapped voltage on C_2 added to the time varying source, E_2, provides the required (1-cos) dynamic recovery voltage, V_B, across the test circuit breaker.

This is a relatively straightforward method requiring only one high-voltage source and operating with the two voltage sources in phase. However, the source supplying the high current at low voltage may be limited

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in current due to the available size of the capacitor bank. This limitation can be avoided in most testing laboratories by making the current circuit inductive rather than capacitive, as described in 7.2.

On the other hand, provided sufficient capacitance is available, the capacitive circuit offers an advantage over the inductive circuit in testing the resistor interrupter which introduces a large degree of phase shift between the two circuit currents. This is discussed in Clause 11.

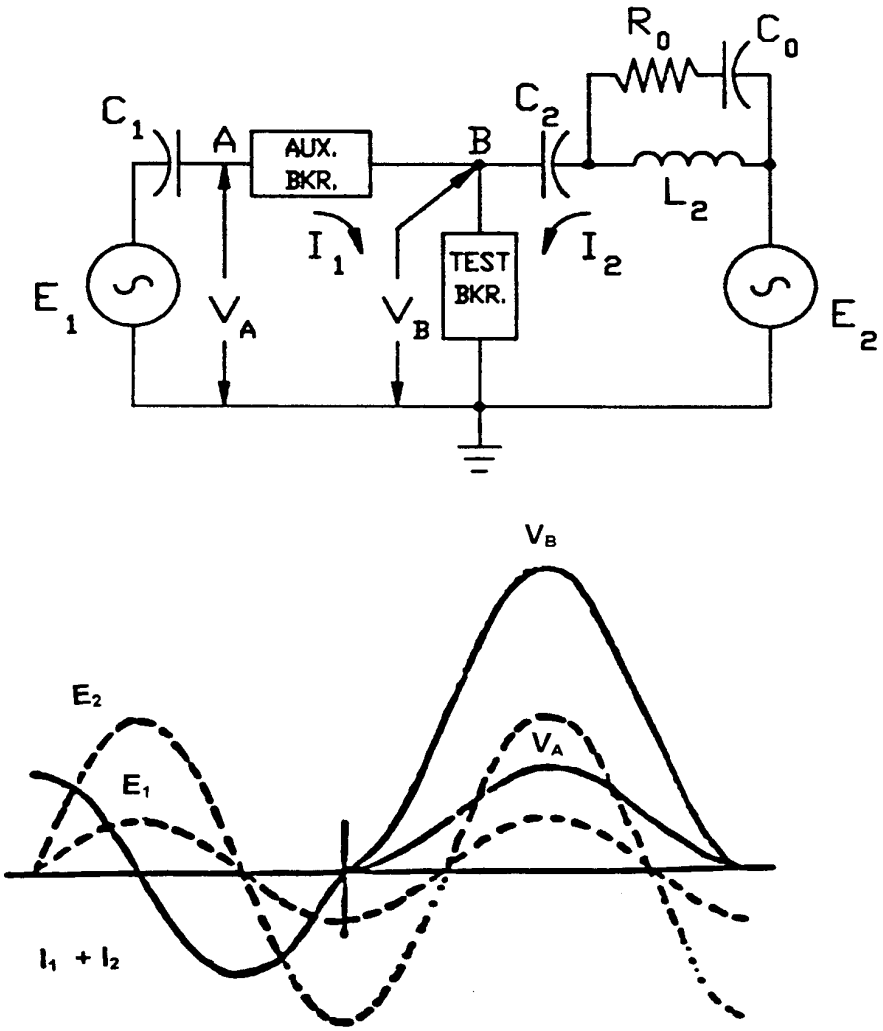


Figure 2—Test circuit with two capacitive branches

7.2 Test circuit with ac sources and an inductive branch

The current circuit branch, which supplies the major portion of the test current, is the one that is made inductive. The voltage circuit is always capacitive to take advantage of the trapped charge on the capacitor. When one branch is inductive and the other capacitive, the two power frequency sources must be in phase opposition for the branch currents to add in the test breaker (see Figure 3).

As in the previous case, the test begins with the circuits energized through the closed breakers. The auxiliary circuit breaker interrupts at the same current zero as the test circuit breaker. The interrupted capacitive current traps a voltage on the series capacitance, C_1, thereby providing, with the ac source, the required (1-cos) dynamic recovery voltage, V_B, across the test circuit breaker.

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The advantage of this method is that adequate test currents can be provided and controlled by changing station reactance rather than by the more difficult change of a capacitor bank. In addition, the current from the inductive source can be slightly asymmetrical and controlled within limits to adjust the current zero crossings between the two circuits to insure that both currents are extinguished simultaneously.

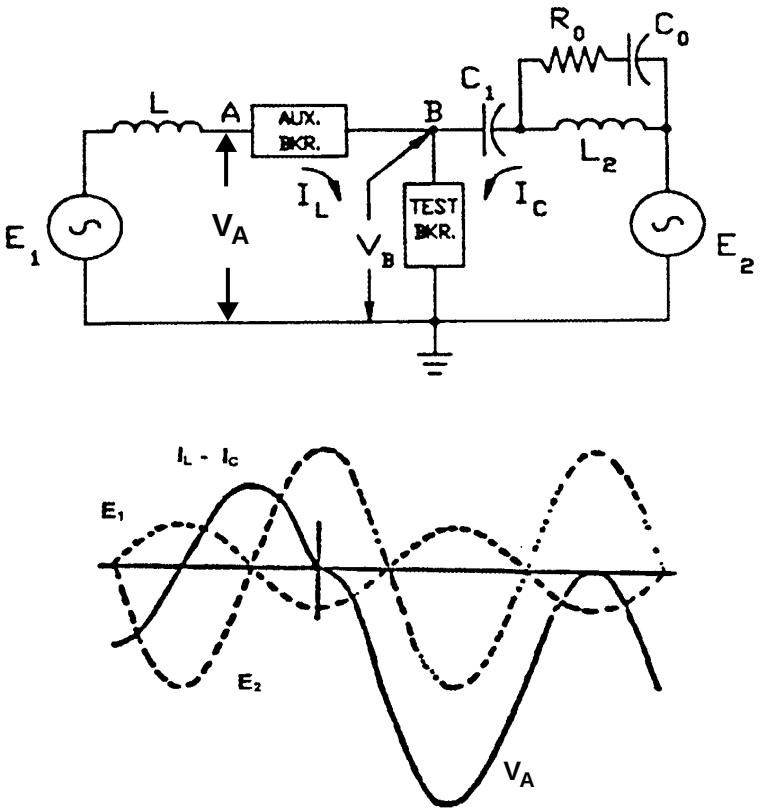


Figure 3—Test circuit with inductive current branch

7.3 Test circuit with one ac source and a tuned circuit current branch

In the circuit shown in Figure 4, the voltage branch with the ac source is energized through the test circuit breaker. The precharged capacitor, C_1, is discharged through the inductance, L_1, by firing the triggered gap through the auxiliary breaker. C_1 and L_1 are tuned to produce a high current at the lower frequency, and the firing is timed at a current zero to ensure that the two circuit currents are in phase through the test breaker. The auxiliary and test circuit breakers interrupt at the same current zero and a voltage is trapped on C_2. Again, the (1-cos) recovery voltage is obtained by the summation of the trapped charge on C_2 and the ac source voltage.

In Figure 4, the tuned circuit provides the major portion of the test current and is closed by a triggered gap. The recovery voltage is supplied by an ac source and a series capacitance as in the previously described circuits. However, the roles may be reversed with the current being supplied by the ac source and the high voltage by a tuned circuit, more nearly approximating the basic current injection test circuit for fault interruption testing.

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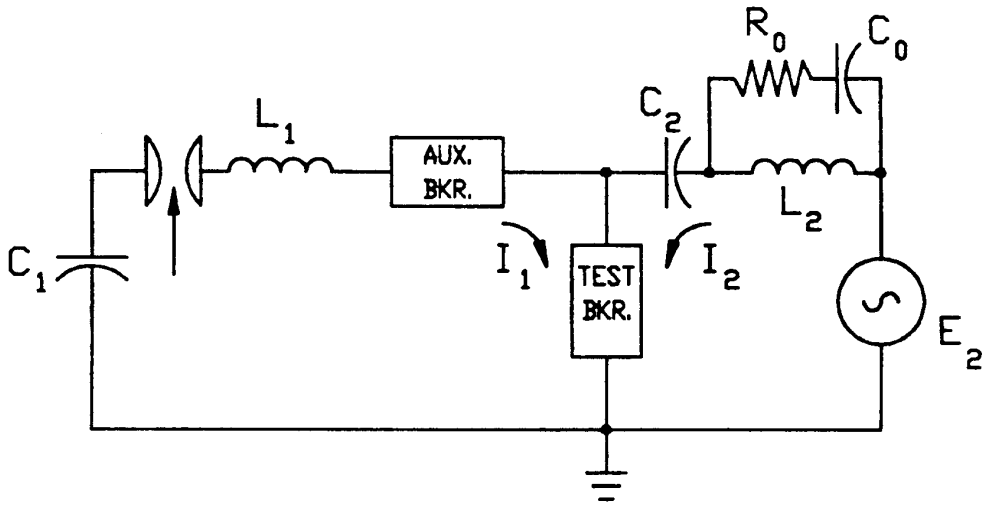


Figure 4—Test circuit with tuned circuit current branch

7.4 Test circuit with tuned circuit voltage branch

In the circuit shown in Figure 5 and the simplified circuit shown in Figure 6, the main current is supplied by the current circuit and the high voltage by a tuned circuit, which more nearly approximates the basic current injection test circuit for fault interruption testing. The impedance of the current circuit may be either inductive or capacitive. In this case, an inductive circuit has been used, giving the advantage of a less distorted current.

The current circuit supplies a high current at the power frequency while the recovery voltage is supplied by the voltage circuit by firing the triggered gap. When triggering the spark gap G, a high-frequency current I_v is injected due to the charging of capacitor C_v via inductance L_v. C_v represents the line capacitance and L_v the supply side inductance.

The mean current slope of the injected current is determined by L_v, R_v, C_v, and E_v and is chosen equal to the slope of the required test current. After current zero the capacitor C_v, charged up to $E \leq E_v$ gives the dc component of the voltage on the test breaker. The ac component is delivered by the oscillating circuit, C and L_{pf}, tuned to power frequency giving a damped oscillation.

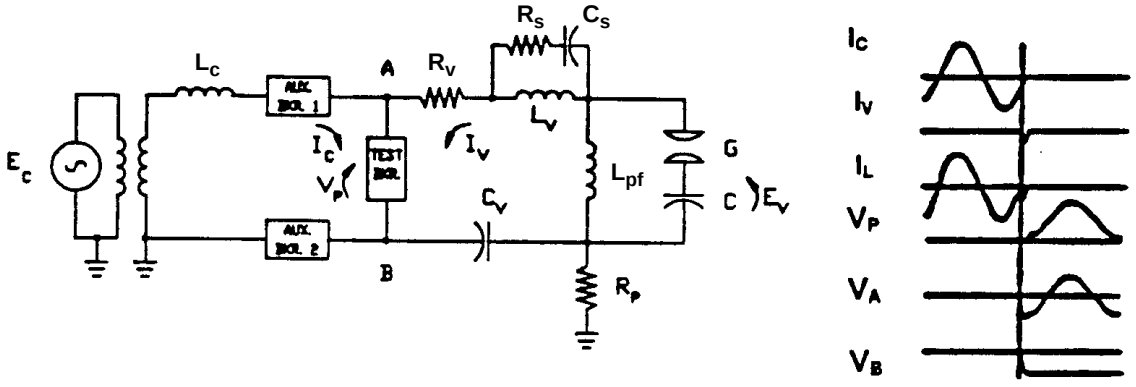


Figure 5—Test circuit with tuned circuit voltage branch (two auxiliary breakers)

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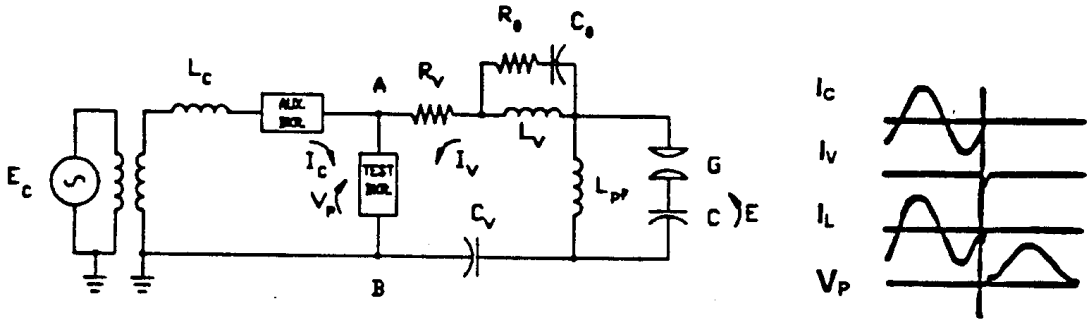


Figure 6—Test circuit with tuned circuit voltage branch

7.5 Test circuit not utilizing ac sources

This circuit, as shown in Figure 7, part (a), is designed so that the currents I_1 and I_2 are identical to the required test current. The two capacitors C_1 and C_2 are charged to opposite polarities. The test current I_2 is initiated by closing a switch (not shown) so that I_2 flows through the initially closed test circuit breaker. The test circuit breaker is then opened such that clearing will occur at current zero. Just prior to current zero, making switch MS is closed initiating current I_1.

Capacitor C_1 equals the direct test capacitance load. Also, use

$$\omega^2 L_m = \frac{1}{C_1}$$

or

$$\omega = \frac{1}{\sqrt{L_m C_1}}$$

to give I_1 a frequency of 60 Hz. The charging voltage V_{C1} equals the peak 60 Hz direct test source voltage in Figure 7, part (b).

Inductance L_s equals the direct test inductance while

$$C_2 = \frac{L_m}{L_s + L_m} C_1$$

and

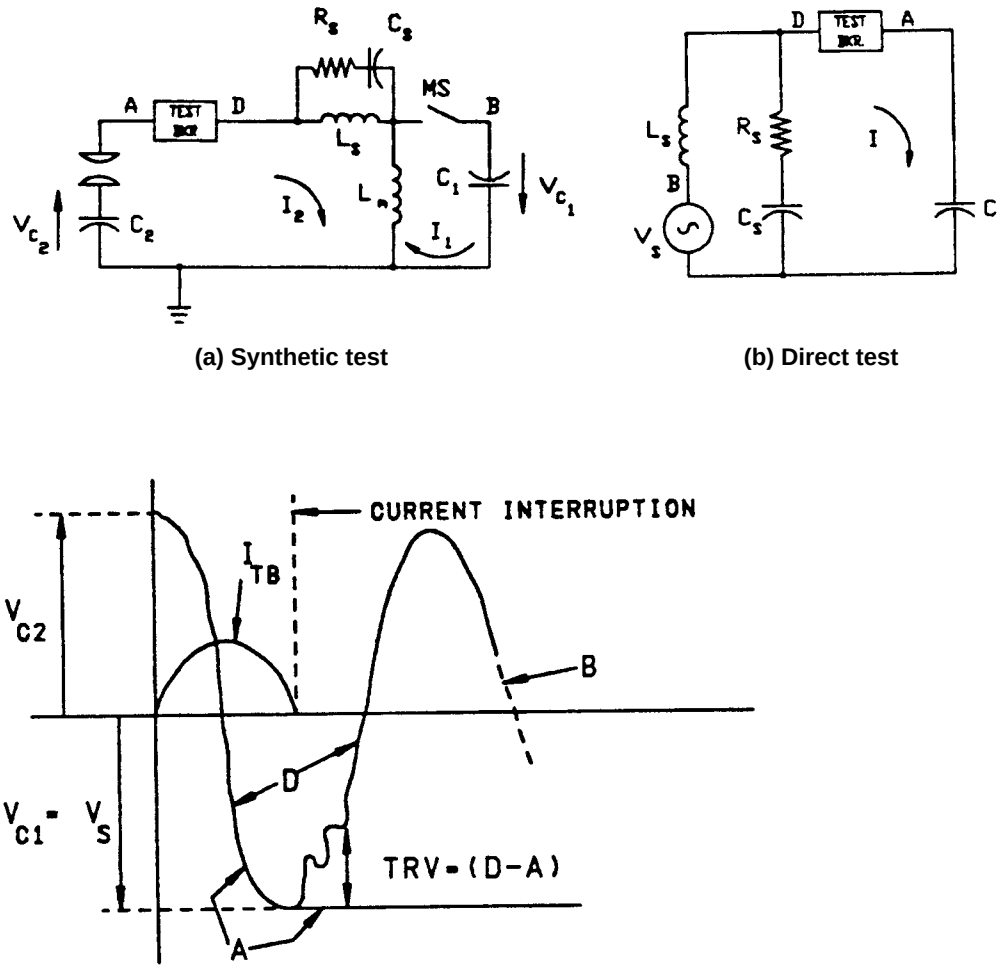
$$V_{c2} = \frac{L_s + L_m}{L_m} V_{C1}$$

thus assuring that $I_2 = I_1$.

When the test breaker interrupts current I_2, capacitor C_2 is at its maximum charge and $L_m C_1$ resonant circuit produces the (1-cos) voltage while the $L_s R_s C_s$ circuit produces the same TRV as a direct test source [see Figure 7, part (c)].

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(a) Synthetic test

(b) Direct test

(c) Currents and voltages for cases (a) and (b) above

Figure 7—Test circuit not utilizing ac sources

8. Parameters, test procedures, and tolerances

Test procedures must be applied in accordance with Clause 6. Of prime importance, the parameters of the synthetic test circuit shall be such that the switched current and the recovery voltage meet or exceed the rated requirements for the circuit breaker under test. Care should be taken so that the initial part of the recovery voltage is not too great. This could prompt early reignitions unrealistically reducing the probability that the device under test will restrike.

In addition, there are procedures that may be applied to limit current distortion, reduce oscillation, insure proper timing, and produce a practical and valid test. Tolerances on these items are generally not critical.

Parameters that are flexible to some degree are the percentages of total current supplied by the current and voltage sources, the size of the capacitor bank being switched, the type of reactance (capacitive or inductive) of the high-current circuit, the amount of damping added, and the impedance of the high-voltage circuit.

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8.1 High-current interval

In synthetic testing, the ratio of current circuit voltage to arc voltage is necessarily lower than in direct testing. However, it must be sufficiently high to insure that the arc voltage of both the auxiliary circuit breaker and test circuit breaker are maintained without producing undue distortion in the circuit.

The allowable current distortion on synthetic tests should not be more than the actual or calculated distortion effects encountered on direct tests. However, in the absence of equivalent direct test data, to assure full severity, a maximum permissible influence is stated in terms of tolerance of current amplitude and loop duration.

8.1.1 Current amplitude

The switched current shall be measured at the instant of contact separation, as measured in direct testing. The amplitude of the final current loop shall not be less than 95% of the ac component as measured at contact separation, taking into consideration the test duty and procedures given in 8.1.2 and 8.1.3.

8.1.2 Current loop duration

The duration of the final loop shall not depart in either direction by more than 10% of the prospective value of the test frequency loop duration. Current forcing effects are discussed in 9.2.

8.1.3 Procedures for adjusting the current circuit

In general, current waveshape distortion is minimized if the ratio of source voltage to auxiliary and test breaker arc voltages is sufficiently high.

If the circuit breaker arc voltage can be shown to modify the current more than the allowable percentage, compensation techniques can be used to satisfy the requirements. Current amplitude may be increased by reducing the inductance of the current circuit or increasing the current source voltage, or both. Reduction in loop duration may be offset by introducing a small degree of asymmetry. Care in adjusting the asymmetry must be exercised since asymmetry can also be used to compensate for small phase differences between the currents from the two sources.

8.2 Recovery voltage interval

The recovery voltage shall comply with the requirements of IEEE Std C37.04-1999 and IEEE Std C37.09-1999. The actual recovery voltage during the test may differ from this because of the effect of the circuit breaker. Note use of circuits such as given in Figure 7, part (a) only provide valid recovery voltage through the first interval.

The development of proper recovery voltage for tests on breakers equipped with low ohmic value opening resistors (typically less than 10 Ω) requires special consideration. The synthetic test circuits in general use are unsuitable for testing this type of breaker. Synthetic test circuits for this type of breaker are under study.

9. Voltage regulation and transients

9.1 High-impedance source

In most short-circuit test laboratories, when the capacitance load is switched off, there is a sudden voltage change to a lower level. This produces a transient effect that can jeopardize the test. It is present in synthetic as well as direct tests (Figure 8).

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Up to interruption, the current has a capacitance phase shift of nearly 90°. At interruption, the capacitor bank being switched is charged to the crest value of the voltage. It remains charged to this voltage, which is somewhat higher than the open circuit source voltage because of the resonance effect of the capacitance current flowing through the source inductance. Upon interruption, the slightly elevated voltage crest drops down to the source voltage crest exhibiting an oscillatory recovery voltage transient, similar to the recovery voltage on clearing a fault. This transient shows a steep rate of change which may cause reignition of the current thereby reestablishing the current for another half cycle. This additional half cycle allows a greater contact separation resulting in a less severe test.

If the breaker interrupts at the desired current zero, the source voltage continues for a half cycle to the next crest of opposite polarity. This puts twice crest voltage across the interrupter contacts at a time of minimum contact separation. This provides the most severe switching condition for the breaker. In this case, slightly more than twice the crest voltage has been applied by the added amount of a voltage step at interruption.

This sudden voltage change at interruption is referred to as “regulation of the circuit” or “system voltage regulation” and is a result of the limited kVA of the source. Because of this, the voltage change may be considerably larger in a laboratory test than on a power system.

The larger regulation effect in laboratory circuits is recognized by IEEE Std C37.09-1999 in testing duplicate system conditions as closely as possible. Also taken into account is the type of capacitive load and its connection with respect to ground. For synthetic testing, these factors are to be calculated to make a synthetic test equivalent to a test in a three-phase circuit.

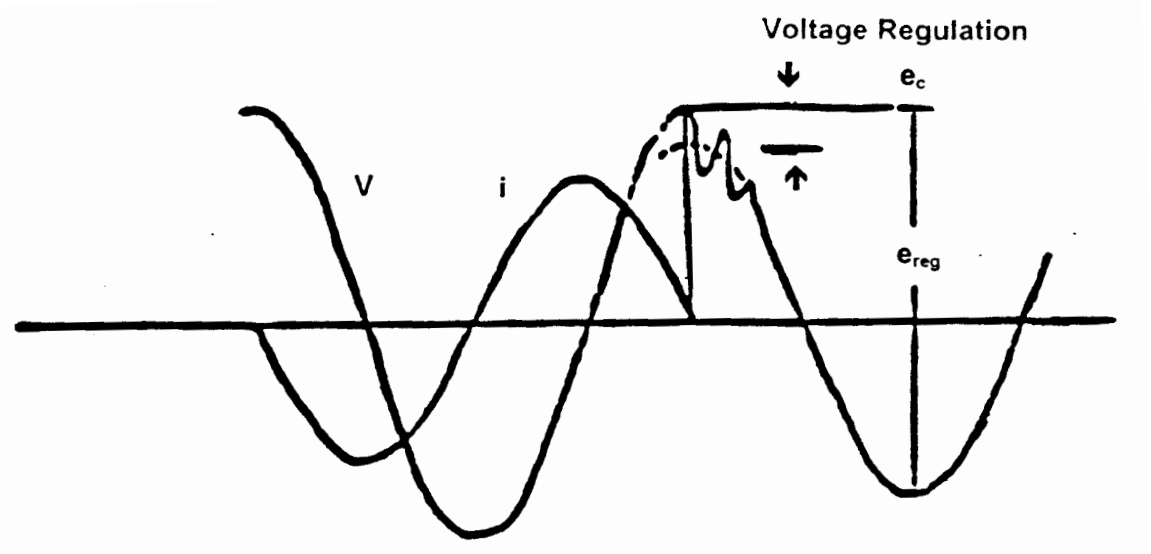


Figure 8—Voltage regulation at interruption

9.2 Forced current zero

Circuit breakers with current forcing characteristics must be tested by direct test methods. Even in the case of breakers that do not exhibit forcing characteristics, the interaction within the circuit may cause the current forcing and introduce harmonics or oscillatory transients that cause current zeros to occur at other than voltage crests. If this happens, the charge held on the capacitor bank being switched will not be at crest value. High transient voltages can occur and the conditions in the synthetic circuit no longer represent an acceptable test (see Figure 9).

Since synthetic test circuits have two branches with the possibility of a wide range of circuit components, unfavorable interactions may occur. Care must be taken to dampen transients and control resonance effects even at the expense of not fully meeting the power factor, symmetry, or other requirements.

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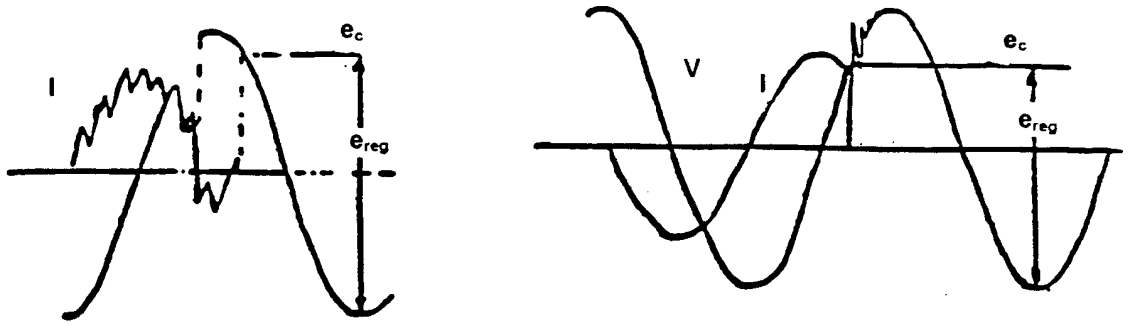


Figure 9—Forced current zero examples

10. Closing (making) tests

Due to the inherent limitations of synthetic testing, it is not feasible to make close-open demonstration tests. As an alternative, synthetic tests may be carried out as two-part tests. The following discussion relates to the making portion of a two-part test.

The making test for a circuit breaker on a capacitive circuit will initiate the discharge of an oscillatory current whose magnitude and frequency are dependent on the system parameters (see 4.1). In contrast to fault making tests, the energy associated with this high-frequency discharge and subsequent power frequency capacitive current does not produce significant electromagnetic forces opposing the closing contacts. Further, closing resistors may be used to reduce the magnitude and duration of the high-frequency prestrike current and related disturbance to the power system.

It should be noted that in closing capacitive circuits, the capacitor bank or circuit that is being connected may have a trapped charge. Thus, as the contacts close, the instantaneous voltage between contacts may be significantly higher than that of normal system voltages. The trapped charge may initiate an earlier prestrike and develop a somewhat longer pre-arcing interval. Even under this prolonged pre-arcing condition, the mechanical duty, contact erosion and arc products are not generally severe for an individual test. Experience has shown that there can be significant localized burning of the contacts the cumulative effects of which lead to diminished interrupting capability. It is recommended that capacitive inrush current testing be performed along with interrupting testing.

10.1 Making without current interruption

If the closing speed of a circuit breaker and the dielectric media between contacts are such that pre-arcing current is initiated and sustained until contacts make, the circuit connection will be made with a minimum disturbance to the system. Because of the low making energies available, the normal short circuit making duties are considered to have demonstrated the capacitive current making requirements for circuit breakers.

10.2 Making with current interruption

If the closing speed and dielectric media between circuit breaker contacts are such that a prestrike occurs with momentary interruption of the high-frequency inrush current and subsequent breakdown, overvoltages may be generated on the power system. This characteristic high-frequency current interruption may occur on circuit breakers with high di/dt interruption capability. To determine if a circuit breaker has this high-frequency inrush current interruption capability, it should be tested at full rated closing voltage with the capacitive current at rated value and 30% of rated value. As such, the synthetic test method shall not be used.

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11. Circuit breakers equipped with opening resistors

Circuit breakers equipped with opening resistors place added requirements on the test circuit and the capability of the laboratory. In discussing synthetic tests of such circuit breakers, direct tests are discussed first since the synthetic tests should be designed to produce the same stress as would result from the actual circuit.

11.1 Direct test circuit

A direct testing circuit for testing circuit breakers with opening resistors is shown in Figure 10. This type of circuit is applicable to circuit breakers with separate interrupters for the main contacts and resistor contacts, or for circuit breakers that use a single interrupter with resistance inserted in series with the main contacts. The voltage and current between breaker terminals following opening of the main contacts are shown in Figure 10.

Both the current amplitude and phase angle are reduced with insertion of the resistance into the current path. Both of these conditions make it easier to interrupt the current. Not only is the current reduced, but the current zero is shifted to a point in time with respect to the voltage wave resulting in a less severe recovery voltage.

Also, from Figure 10, it is apparent that the recovery voltage first appearing across the main contacts will be of the same form as the current through the opening resistor.

Direct testing of circuit breakers with opening resistors provides the proper stresses on each interrupter. However, for higher currents and voltages a two-part synthetic test can be made to test each interrupter separately with the stress each would see on a direct test.

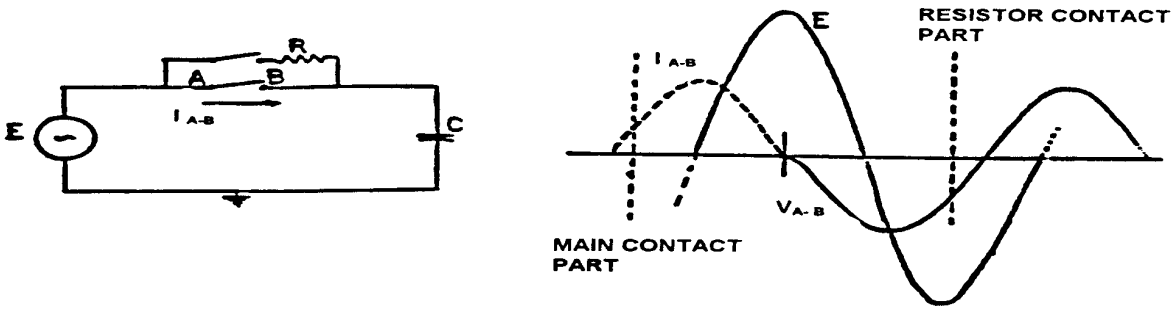


Figure 10—Direct test circuit for circuit breakers with opening resistors

11.2 Two-part synthetic test circuits

11.2.1 Tests on main interrupter

For circuit breakers with separate main contacts and resistor contacts, the main contacts may be tested by themselves on a synthetic circuit as shown in Figure 11. The voltage stress across the contacts is provided by the product of current and resistance of the resistive element across the contacts. In this way the recovery voltage can be modified to be equivalent to the stress of a direct test circuit.

As in capacitor switching synthetic circuits previously described, the auxiliary breaker is timed to interrupt with the main contacts.

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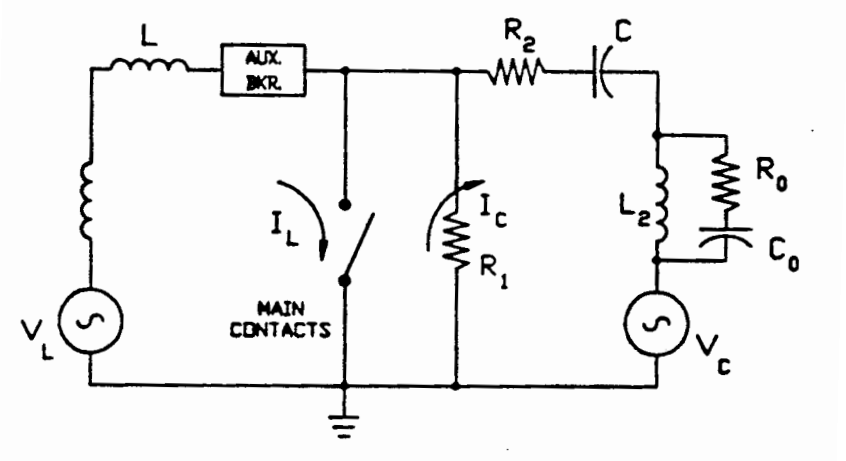
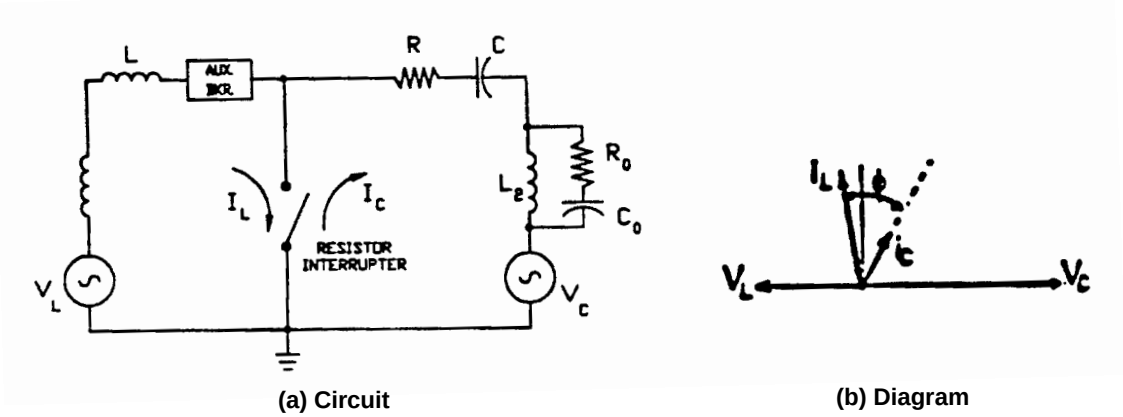


Figure 11—Circuit for testing main contacts of breaker with opening resistor

11.2.2 Tests on resistor interrupter

For circuit breakers with separate resistor contacts, the test on the resistor contacts may be made on a synthetic circuit as shown in Figure 12. In this case, the series resistance in the high-voltage circuit is selected to make the stress equivalent to a direct test. However, because of the series resistance and the inductive reactance of the circuit, the two currents may be out of phase, as indicated by the phase angle, in the vector diagram. This may require some degree of asymmetry from the current source to adjust the current zeros for interruption at the same time. If this is a problem, the circuit of Figure 13 may be used, provided that sufficient capacitance and resistance is available. In this case, both currents are capacitive and the currents add in phase through the interrupter as indicated in the vector diagram in Figure 12.



(a) Circuit **(b) Diagram**

Figure 12—Circuit for testing resistor interrupter

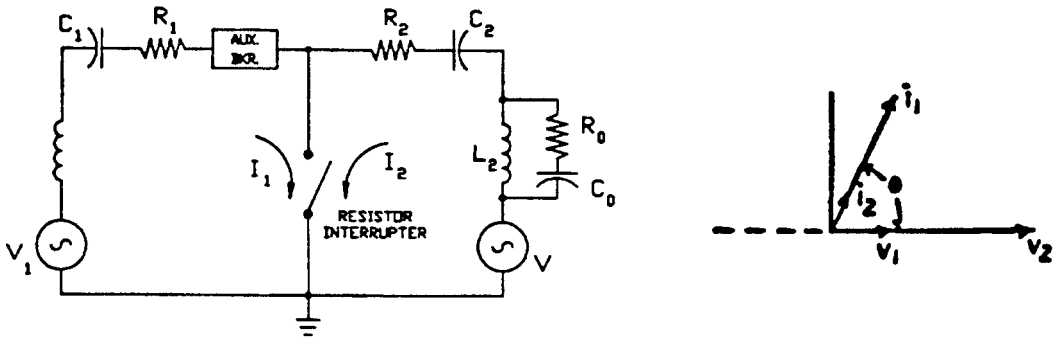
12. Test duties

12.1 Test duties 1A and 1B

The test duties required to demonstrate the capacitive current interrupting ability of a circuit breaker on a single phase basis are listed in Table 5 of IEEE Std C37.09-1999. Only the test duties 1A and opening duty of 1B need be demonstrated. Consequently, note 4 and note 11 of Table 5 do not apply. These requirements include the test voltage levels, current levels, number of operations, and other circuit breaker and test circuit conditions.

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(a) Circuit **(b) Diagram**

Figure 13—Circuit for testing resistor interrupter

12.2 Other test duties

As no synthetic circuits yet exist to demonstrate making capabilities for capacitor current switching, closing duties, back-to-back switching, or open wire line charging, these tests cannot be included in the test duties.

13. Test records

13.1 General

The test records for demonstrating the synthetic capacitive current interrupting capability of a circuit breaker should include the following:

a) Circuit breaker identification
   1) Include value of shunting resistance or capacitance
   2) State whether test performed on a complete single pole of the circuit breaker or a unit interrupter
b) Test duty
c) Isolated shunt capacitor bank or cable
d) Complete description of the test circuit used for the test program listing component values

13.2 Recording of test results

Test results should be recorded as follows:

a) Capacitive current switched
b) Test circuit voltage
   1) Open circuit voltage of current source
   2) Open circuit voltage of voltage source
   3) Open circuit voltage across test circuit breaker one-half cycle after current interruption
c) Interrupting time, through primary arcing contacts
d) Interrupting time, through secondary arcing contacts
e) Arcing time
f) Number of tests
g) Confirmation that no restrikes occurred
h) Time from power frequency current zero to restrike
i) Maintenance performed on test circuit breaker for each duty

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13.3 Data reporting modifications

The following modifications will be necessary to report the data listed above due to the character of the test:

a) The method of test will be single phase only, although it may involve a unit interrupter.

b) The synthetic test will be able to determine if restrikes occur (number) but not whether the circuit breaker will interrupt after a restrike. If restrikes occur, the synthetic circuit does not test whether or not the breaker will clear these restrikes nor does the synthetic circuit properly indicate the transient overvoltages due to a restrike. For these reasons if a restrike occurs the breaker must be tested with a direct circuit for proper evaluation of performance.

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