IEEE Std C37.013-1997

(Revision of IEEE Std C37.013-1993)

IEEE Standard for AC High-Voltage Generator Circuit Breakers Rated on a Symmetrical Current Basis

Sponsor

Switchgear Committee
of the
IEEE Power Engineering Society

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IEEE Standards Board

Abstract: Ratings, performance requirements, and compliance test methods are provided for ac high-voltage generator circuit breakers rated on a symmetrical current basis that are installed between the generator and the transformer terminals. Guidance for applying generator circuit breakers is given. Pumped storage installations are considered a special application, and their requirements are not completely covered by this standard.

Keywords: ac high-voltage generator, application guidance, generator circuit breakers, symmetrical current-rating structure, terminals of large generators, testing procedures

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Introduction

(This introduction is not a part of IEEE Std C37.013-1997, IEEE Standard for AC High-Voltage Generator Circuit Breakers Rated on a Symmetrical Current Basis.)

This standard has been revised to clarify the meaning of rated maximum voltage as used in this standard and covers the requirements for ac high-voltage generator circuit breakers as applied directly to the outgoing terminals of generators. The rating, testing, and application requirements of these specialized circuit breakers are not adequately covered by the existing standards IEEE Std C37.04-1979, ANSI C37.06-1987, IEEE Std C37.09-1979, and IEEE Std C37.010-1979 series for ac high-voltage circuit breakers rated on a symmetrical current basis. In order to avoid the detailed integration and possible confusion by introducing the specialized requirements into the existing standards, it was determined that a separate standard was the most effective method for covering these devices.

A working group of the High-Voltage Circuit Breaker Subcommittee of the IEEE Switchgear Committee has revised this standard with input from various sources on all requirements for these specialized devices. The Working Group has developed an Application Guide, which is contained in Clause 6. of this standard. The guide is intended to assist the engineer applying a generator circuit breaker on an electric power system.

These efforts have contributed valuable standards to the industry. Further suggestions for improvement gained from the use of this standard will be welcomed.

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Y. I. Musa
C. L. Wagner

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D. R. Crawford
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CLAUSE PAGE

IEEE Standard for AC High-Voltage Generator Circuit Breakers Rated on a Symmetrical Current Basis

1. Scope

This standard applies to all ac high-voltage generator circuit breakers rated on a symmetrical current basis that are installed between the generator and the transformer terminals. Pumped storage installations are considered a special application, and their requirements are not completely covered by this standard.

NOTE — Since no other national or international standard on generator circuit breakers exists, this standard is used worldwide. The revision of IEEE Std C37.013-1993 takes care of this fact by adapting its content in some places to international practice.

2. References

The standard shall be used in conjunction with the following publications. When the following publications are superseded by an approved revision, the revision shall apply.

ANSI C37.06-1987 (R1994), Switchgear: AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis—Preferred Ratings and Related Required Capabilities.[1]

ASME Boiler and Pressure Vessel Code, 1995 Edition.[2]

IEC 60694: 1996, Common specifications for high voltage switchgear and controlgear standards.

IEEE Std 1-1986 (Reaff 1992), IEEE Standard General Principles for Temperature Limits in the Rating of Electrical Equipment and for the Evaluation of Electrical Insulation (ANSI).[3]

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[1] ANSI publications are available from the Sales Department, American National Standards Institute, 11 West 42nd Street, 13th Floor, New York, NY 10036-8002, USA.

[2] ASME publications are available from the American Society of Mechanical Engineers, 22 Law Drive, Fairfield, NJ 07007, USA.

[3] IEEE publications are available from the Institute of Electrical and Electronics Engineers, Service Center, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA.

IEEE Std 4-1995, IEEE Standard Techniques for High Voltage Testing (ANSI).

IEEE Std 100-1996, IEEE Standard Dictionary of Electrical and Electronics Terms.

IEEE Std 119-1974, IEEE Recommended Practice for General Principles of Temperature Measurement as Applied to Electrical Apparatus (ANSI/DoD).[4]

IEEE Std C37.04-1994, IEEE Standard Rating Structure for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis (ANSI).

IEEE Std C37.09-1979 (Reaff 1988), IEEE Standard Test Procedure for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis (ANSI/DoD).

IEEE Std C37.011-1994, IEEE Application Guide for Transient Recovery Voltage for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis (ANSI).

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 (ANSI).

IEEE Std C37.082-1982 (Reaff 1988), IEEE Standard Methods for the Measurement of Sound Pressure Levels of AC Power Circuit Breakers (ANSI).

IEEE C37.11-1997, IEEE Standard Requirements for Electrical Control for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis or a Total Current Basis.

IEEE Std C37.23-1987 (Reaff 1991), IEEE Standard for Metal-Enclosed Bus and Calculating Losses in Isolated-Phase Bus (ANSI).

IEEE Std C37.100-1992, IEEE Standard Definitions for Power Switchgear (ANSI).

IEEE Std C57.13-1993, IEEE Standard Requirements for Instrument Transformers (ANSI).

NEMA MG 1-1993, Motors and Generators.[5]

NEMA SG 4-1990, Alternating Current High-Voltage Circuit Breaker.

3. Definitions

The definitions of terms contained in this standard, or in other documents referred to in this standard, are not intended to embrace all legitimate meanings of the terms. They are applicable only to the subject treated in this standard. For additional definitions, see IEEE Std C37.100-1992.

A letter symbol (^{a}) indicates that at the time this standard was approved, there was no corresponding definition in IEEE Std C37.100-1992. A letter symbol (^{b}) following the definition indicates that the definition in this standard differs from that appearing in IEEE Std C37.100-1992.

3.1 design tests: Those tests made to determine the adequacy of the design of a particular type, style, or model generator circuit breaker to meet its assigned ratings and to operate satisfactorily under usual service conditions or

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[4] IEEE Std 119-1974 has been withdrawn; however, copies can be obtained from Global Engineering, 15 Inverness Way East, Englewood, CO 80112-5704, USA, tel. (303) 792-2181.

[5] NEMA publications are available from the National Electrical Manufacturers Association, 1300 N. 17th St., Ste. 1847, Rosslyn, VA 22209, USA.

under unusual conditions, if specified. Design tests are made only on representative circuit breakers of basically the same design, i.e., the same interrupters operating at the same contact speeds, and having at least the same dielectric strength. These tests are not intended to be used as a part of normal production. The applicable portions of these design tests may also be used to evaluate modifications of a previous design and to assure that performance has not been adversely affected. Test data from previous similar designs may be used for current designs, where appropriate.[b]

3.2 excitation current switching capability (of a generator circuit breaker): The highest magnetizing current that a generator circuit breaker shall be required to switch at any voltage up to rated maximum voltage at power frequency without causing an overvoltage exceeding the levels agreed upon between the user and the manufacturer.[a]

3.3 generator-source short-circuit current: The short-circuit current when the source is entirely from a generator through no transformation.[a]

3.4 production tests: Those tests made to check the quality and uniformity of workmanship and materials used in the manufacturing of generator circuit breakers.[b]

3.5 rated closing time (of a generator circuit breaker): The interval between energizing of the close circuit at rated control voltage and rated fluid pressure of the operating mechanism and the closing of the main circuit.[a]

3.6 rated continuous current (of a generator circuit breaker): The designated limit of current in rms amperes at power frequency that a generator circuit breaker shall be required to carry continuously without exceeding any of its designated limitations.[a]

3.7 rated interrupting time (of a generator circuit breaker): The maximum permissible interval between the energizing of the trip circuit at rated control voltage and rated fluid pressure of the operating mechanism and the interruption of the main circuit in all poles on an opening operation.[a]

3.8 rated maximum voltage (of a generator circuit breaker): The highest rms voltage for which the circuit breaker is designed, and the upper limit for operation. The rated maximum voltage is equal to the maximum operating voltage of the generator to which the circuit breaker is applied.[b]

3.9 rated mechanism fluid operating pressure (of a generator circuit breaker): The pressure at which a gas- or liquid-operated mechanism is designed to operate.[a]

3.10 system-source short-circuit current: The short-circuit current when the source of the short-circuit current is from the power system through at least one transformation.[a]

3.11 tests after delivery: Those tests made by the purchaser after delivery of the circuit breaker, which supplement inspection, to determine whether the circuit breaker has arrived in good condition. These tests may consist of timing tests on closing, opening, close-open no-load operations, and power frequency voltage withstand tests at 75% of the rated power frequency withstand voltage.[a]

4. Service conditions

4.1 Usual service conditions

Generator circuit breakers conforming to this standard shall be suitable for operating at their standard ratings under the following usual service conditions:

a) Ambient temperature for outdoor generator circuit breakers is not above 40 °C or below –30 °C; ambient temperature for indoor generator circuit breakers is not above 40 °C or below +5 °C.
b) Altitude is not above 1000 m (3300 ft).
c) For installations at nuclear power stations, static forces applied to the generator circuit breaker do not exceed the equivalent force of a 0.5 g acceleration applied horizontally at the center of gravity of the circuit breaker.

4.2 Unusual service conditions

4.2.1 Abnormal temperatures

The use of apparatus in ambient temperatures outside the limits of those specified in a) of 4.1 shall be considered as special.

4.2.2 Altitudes above 1000 m

For applications at altitudes higher than 1000 m, the basic impulse insulation level and rated continuous current shall be multiplied individually by correction factors in Table 1 to obtain appropriate values.

The rated short-circuit current, related required capabilities, and the rated interrupting time are not affected by altitude.

Table 1— Altitude correction factors

Altitude (m)	Insulation level	Rated continuous current
1000	1.00	1.00
1500	0.95	Refer to manufacturer
3000	0.80	Refer to manufacturer

NOTES:
1 — Intermediate values can be obtained by interpolation. See example in 7.2.2.2.
2 — A revision of the altitude correction factors is under consideration.

4.2.3 Conditions affecting construction or protecting features

There are application conditions that should receive special consideration. Such conditions should be brought to the attention of those responsible for the application, manufacture, and operation of the equipment.

Apparatus for use in such cases may require special construction or protection. Among such conditions are the following:

a) Exposure to damaging fumes or vapors, excessive or abrasive dust, explosive mixtures of dust or gases, steam, salt spray, oil spray, excessive moisture, dripping water, and other similar conditions;
b) Exposure to abnormal vibration, shock, tilting, or seismic forces;
c) Exposure during transportation or storage to conditions beyond temperatures listed in a) of 4.1;
d) Unusual space limitations;
e) Unusual operating duty, frequency of operation, and difficulty of maintenance;
f) Condensation on dielectric surfaces, produced by the generator circuit breaker cooling medium.

4.3 Impact on environment

Generator circuit breakers conforming to this standard shall have limited impact on the environment, as follows:

a) When operated under standard conditions, with all three poles operating simultaneously, the peak instantaneous sound pressure level of the generator circuit breaker shall be less than 140 dB (unweighted; see IEEE Std C37.082-1982)[6];
b) The effects of circulating currents induced by magnetic fields produced by continuous currents in the generator circuit breaker are addressed in Clause 7.

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

5. Ratings and required capabilities

The ratings and required capabilities of a generator circuit breaker are the designated limits of operating characteristics based on definite conditions and shall include the following items, where applicable:

a) Rated maximum voltage (see 5.1);
b) Power frequency (see 5.2);
c) Rated continuous current (see 5.3);
d) Rated dielectric strength (see 5.4);
e) Rated short-circuit duty cycle (see 5.5);
f) Rated interrupting time (see 5.6);
g) Rated closing time (see 5.7);
h) Rated short-circuit current (see 5.8);
i) Transient recovery voltage (TRV) rating (see 5.9);
j) Rated load current switching capability (see 5.10);
k) Capacitance current switching capability (see 5.11);
l) Out-of-phase current switching capability (see 5.12);
m) Excitation current switching capability (see 5.13);
n) Rated control voltage (see 5.14);
o) Rated mechanism fluid operating pressure (see 5.15);
p) Nameplate markings (see 5.16).

The establishment of the ratings and required capabilities and the assignment of them to a generator circuit breaker in accordance with these standards implies performance characteristics at least equal to those set forth in 5.1– 5.15. The ratings and required capabilities assigned to a generator circuit breaker are based on test data in accordance with Clause 6., but other equivalent or more effective methods of testing are not precluded.

Alternatively, for designs existing prior to the adoption of this standard, the ratings and required capabilities can be based on other tests that are judged to be equally effective on the basis of the experience gained from previous design or development tests or by service performance experience.

5.1 Rated maximum voltage

The rated maximum voltage of a generator circuit breaker is the highest rms voltage for which the circuit breaker is designed and is the upper limit for operation. The rated maximum voltage is equal to the maximum operating voltage of the generator (usually equal to 1.05 times the rated voltage of the generator) to which the circuit breaker is applied.

5.2 Power frequency

The power frequency of a generator circuit breaker is the frequency at which it is designed to operate, with the frequency being 50 Hz or 60 Hz. Applications at other frequencies should receive special consideration.

5.3 Rated continuous current

The rated continuous current of a generator circuit breaker is the designated limit of current in rms amperes at power frequency, which it shall be required to carry continuously without exceeding any of the limitations designated in 5.3.1 and 5.3.2. Typical values are 6.3 kA, 8 kA, 10 kA, 12 kA, 16 kA, 20 kA, etc.

5.3.1 Conditions of continuous current rating

The conditions on which continuous current ratings are based are as follows:

a) Circuit breakers are used under usual service conditions defined in 4.1.
b) Current ratings shall be based on the total temperature limits of the materials used for circuit breaker parts. A temperature rise reference is given to permit testing at reduced ambient temperature.
c) Circuit breakers designed for installation in enclosures shall have their ratings based on the ventilation of such enclosures and on a 40 °C ambient temperature outside the enclosure [see b) in 6.2.1.1].
d) Circuit breakers designed for operation with forced air cooling assistance shall have the ratings based on a 40 °C ambient temperature with the forced air cooling system operating.

5.3.2 Temperature limitations for continuous current ratings

5.3.2.1 Limitations on insulating materials

The temperatures of materials used to insulate main power circuit-conducting parts from phase-to-ground or from terminal-to-terminal of an open circuit breaker shall be limited to the values listed in Table 2. It is recognized that these limits are generally less than those associated with the insulating class in IEEE Std 1-1986, since such insulation may be subject to severe mechanical stress when used in a generator circuit breaker.

5.3.2.2 Limitations of main contacts

The temperatures of main contacts used in generator circuit breakers shall not exceed the values listed in Table 3. Contacts may be operated at other temperatures provided it can be shown by experience or tests acceptable to the user, that accelerated deterioration will not occur.

5.3.2.3 Limitations on conducting joints

The temperature of conducting joints in the main power circuit of a generator circuit breaker shall not exceed the values listed in Table 3. Conducting joints may be operated at other temperatures provided that experience or tests show that accelerated deterioration will not occur.

Table 2— Temperature limitations on insulating materials for continuous current ratings

Insulating class of material	Main power circuit limits, hottest spot total temperature (°C)
O	90
A	105
B	130
F	155
H	180
C	220

NOTES:
1 — See IEEE Std 1-1986 for explanation of insulating classes.
2 — If gaseous insulating material is used as conforming to one of the above classes, the manufacturer shall establish that it will not cause accelerated deterioration of other parts.

Table 3— Temperature limitations on main contacts and conducting joints for continuous current ratings

Conducting surface Conducting joint surface	Limit of hottest spot temperature rise (°C) at ambient temperature of 40 °C	Limit of hottest spot total temperature (°C)
Copper	30	70
Silver, silver alloy, or equivalent	65	105
NOTE — If an ambient temperature lower than 40 °C is specified, then the temperature rise can be higher, but the limit of the hottest spot total temperature shall not be exceeded.		

5.3.2.4 Limitations for parts subject to contact by personnel

Generator circuit breaker parts handled by the operator in the normal course of work duties shall have no greater a total temperature than 50 °C.

Generator circuit breakers having external surfaces accessible to an operator in the normal course of work duties shall have a total temperature on the surfaces no greater than 70 °C. If the bus duct connected to the generator circuit breaker is designed for a total temperature of 80 °C on the surfaces, then the circuit breaker surface temperature can be 80 °C.

Generator circuit breakers having external surfaces not accessible to an operator in the normal course of work duties shall have a total temperature on the surfaces no greater than 110 °C.

5.3.2.5 Limitations on other materials

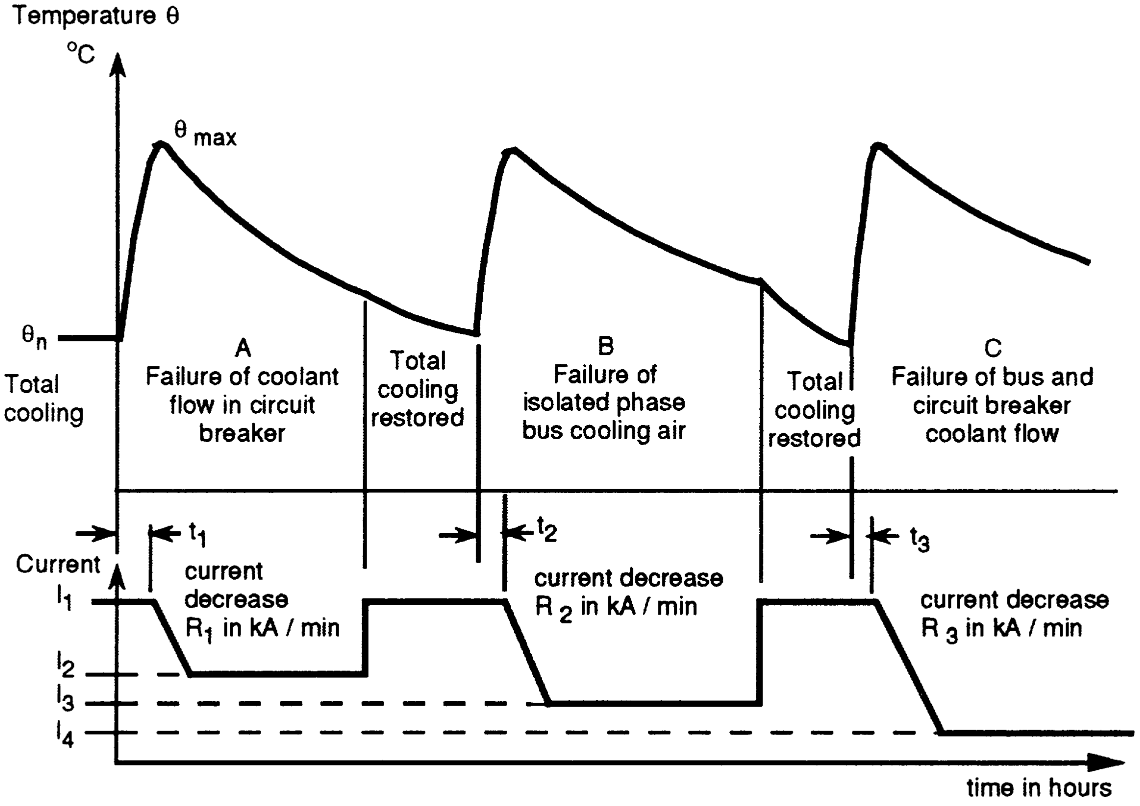
Other materials shall be chosen so that the maximum temperature to which they may be subjected shall not cause accelerated deterioration.

5.3.3 Emergency current ratings during loss of cooling

The operating considerations for generator circuit breakers require that emergency ratings are established to enable the circuit breaker to remain in service following loss of normally required auxiliary forced cooling systems. The following provisions shall be observed:

a) It is possible to operate the generator circuit breaker for limited time periods with circuit breaker parts at a higher total temperature than the limits specified for the continuous current rating.
b) The difference between the emergency temperature limits and the normal operating temperatures provide a definite allowable time period during which full load may be carried before the reduction in load current must be accomplished.
c) The generator circuit breaker may remain in service at a reduced load current, the value of which will depend on the type of emergency condition prevailing.
d) Where the circuit breaker continuous current rating is affected by several independent systems (e.g., interrupting medium, cooling medium, forced air cooling of isolated phase bus, etc.), the effect of losing each system individually and in combination should be established.
e) In addition to a) through d), certain generating station designs (e.g., single generator output connected by two generator circuit breakers to two unit step-up transformers) may also require special emergency operating conditions and ratings.

Factors are illustrated in Figure 1.



I_1 is rated current with all cooling systems in operation
I_2 is allowable load current if failure (A) of coolant in circuit breaker occurs
I_3 is allowable load current if failure (B) of isolated phase bus cooling air occurs
I_4 is allowable load current if failure (C) of bus and circuit breaker coolant flow occurs
θ_{max} is allowable hottest spot total temperature in °C
θ_n is hottest spot total temperature at rated continuous current in °C
t_1, t_2, t_3 are allowable times without a reduction in rated continuous current and without exceeding θ_{max}

Figure 1— Effect of various cooling failures and subsequent load reductions on generator circuit breaker temperature

Figure 1 illustrates typical emergency conditions in which the loss of two cooling systems, that of the generator circuit breaker and that of the bus duct, have been studied separately and simultaneously.

The following are the parameters that are required for correct operation under each type of emergency condition and for which values must be determined by the manufacturer:

t_1, t_2, t_3 The time available at rated current before the load must be reduced.
R_1, R_2, R_3 The rate at which the load current must be reduced in kA/min.
I_2, I_3, I_4 The emergency current assigned to circuit breaker for operating under each emergency condition for a specified maximum period of time.

5.4 Rated dielectric strength

The rated dielectric strength of a generator circuit breaker is its voltage withstand capability with specified magnitudes and waveshapes. In the event of loss of insulating medium pressure, the generator circuit breaker shall be able to withstand 1.5 times the following voltages:

a) In the open position, the phase opposition voltage across the contacts, the phase-to-ground, and the line-to-line voltage between phases.
b) In the closed position, phase-to-ground and line-to-line voltage between phases. (For applications requiring full dielectric withstand upon loss of insulating medium, agreement should be reached between the user and the manufacturer.)

5.4.1 Dielectric strength of external insulation

External insulation shall conform to the performance requirements of this standard. Requirements for the rated dielectric strength of the external insulation of generator circuit breakers are given in Table 4.

Table 4— Schedule of dielectric strength for ac generator circuit breakers and external insulation

Line	**Circuit breaker rated maximum voltage kV, rms**	**Insulation withstand voltages**	
		Power frequency 50 or 60 Hz ± 20%	**Impulse 1.2 × 50 µs wave**
		1 min dry kV, rms	**Full wave withstand kV, crest**
	Column 1	**Column 2**	**Column 3**
1	15.8 and below	50	110
2	15.9– 27.5	60	125
3	27.6–38.0	80	150

5.4.2 Rated power frequency withstand voltage (dry)

The rated power frequency withstand voltage (dry) is the voltage that a new generator circuit breaker must be capable of withstanding for 1 min (see Column 2 of Table 4 and 6.2.2).

5.4.3 Rated full wave impulse withstand voltage

The rated full wave impulse withstand voltage is the crest value of a standard 1.2 × 50 µs impulse voltage wave that a new generator circuit breaker must be capable of withstanding (see Column 3 of Table 4 and 6.2.2).

5.4.4 Rated switching impulse withstand voltage

For generator circuit breakers, the requirements for switching impulse withstand voltage are satisfied by the power frequency withstand voltage.

5.5 Rated short-circuit duty cycle

The rated short-circuit duty cycle of a generator circuit breaker shall be two unit operations with a 30 min interval between operations (CO–30 min–CO).

5.6 Rated interrupting time

The rated interrupting time of the generator circuit breaker is the maximum permissible interval between the energizing of the trip circuit at rated control voltage and rated fluid pressure of the operating mechanism and the interruption of the main circuit in all poles on an opening operation. Typical values are approximately 60–90 ms with the actual time being dependent on the rated short-circuit current. For generator circuit breakers equipped with resistors, the interrupting time for the resistor current may be longer.

5.7 Rated closing time

The rated closing time of a generator circuit breaker is the interval between energizing of the close circuit at rated control voltage and rated fluid pressure of the operating mechanism, and the closing of the main circuit.

5.8 Short-circuit current rating

The short-circuit current rating of a generator circuit breaker is the rms symmetrical component of short-circuit current to which all required short-circuit capabilities are related. Procedures for determining the symmetrical short-circuit current duties that compare with ratings and related required capabilities are found in Clause 7.

5.8.1 Rated short-circuit current

The rated short-circuit current of a generator circuit breaker is the highest rms value of the symmetrical component of the three-phase short-circuit current. It is measured from the envelope of the current wave at the instant of primary arcing contact separation, and is the current that the generator circuit breaker shall be required to interrupt at the rated maximum voltage and rated duty cycle when the source of the short-circuit current is from the power system through at least one transformation. It establishes also, by ratios defined in 5.8.2.6, the highest current that the generator circuit breaker shall be required to close and latch against and to carry. Typical values are 63 kA, 80 kA, 100 kA, 120 kA, 160 kA, etc.

NOTE — The rare cases when the generator-source short-circuit current is higher than the system source short circuit current need special consideration.

5.8.2 Related required capabilities

The generator circuit breaker shall have the following related required capabilities, which are based on the minimum time to primary arcing contact separation including a relay time of 1/2 cycle, but may be used with any relay time.

5.8.2.1 Required symmetrical interrupting capability for three-phase faults

For three-phase faults, the required symmetrical interrupting capability of a generator circuit breaker at the instant of primary arcing contact separation for operating voltages equal to rated maximum voltage shall not exceed the rated short-circuit current for the rated duty cycle irrespective of the direct current component of the total short-circuit current.

5.8.2.2 Required asymmetrical interrupting capability for three-phase faults

The required asymmetrical system-source interrupting capability of a generator circuit breaker at rated maximum voltage and for the rated duty cycle is composed of the rms symmetrical current and the percentage dc component. The values of the dc component in percent of the peak value of the symmetrical short-circuit current are given in Figure 2 for primary arcing contact parting times in milliseconds. This figure is based on a time constant of the decay of the dc component of 133 ms, which is considered to be conservative. For time constants different than 133 ms, use the formula for calculating the dc component given in 7.3.5.3.2.

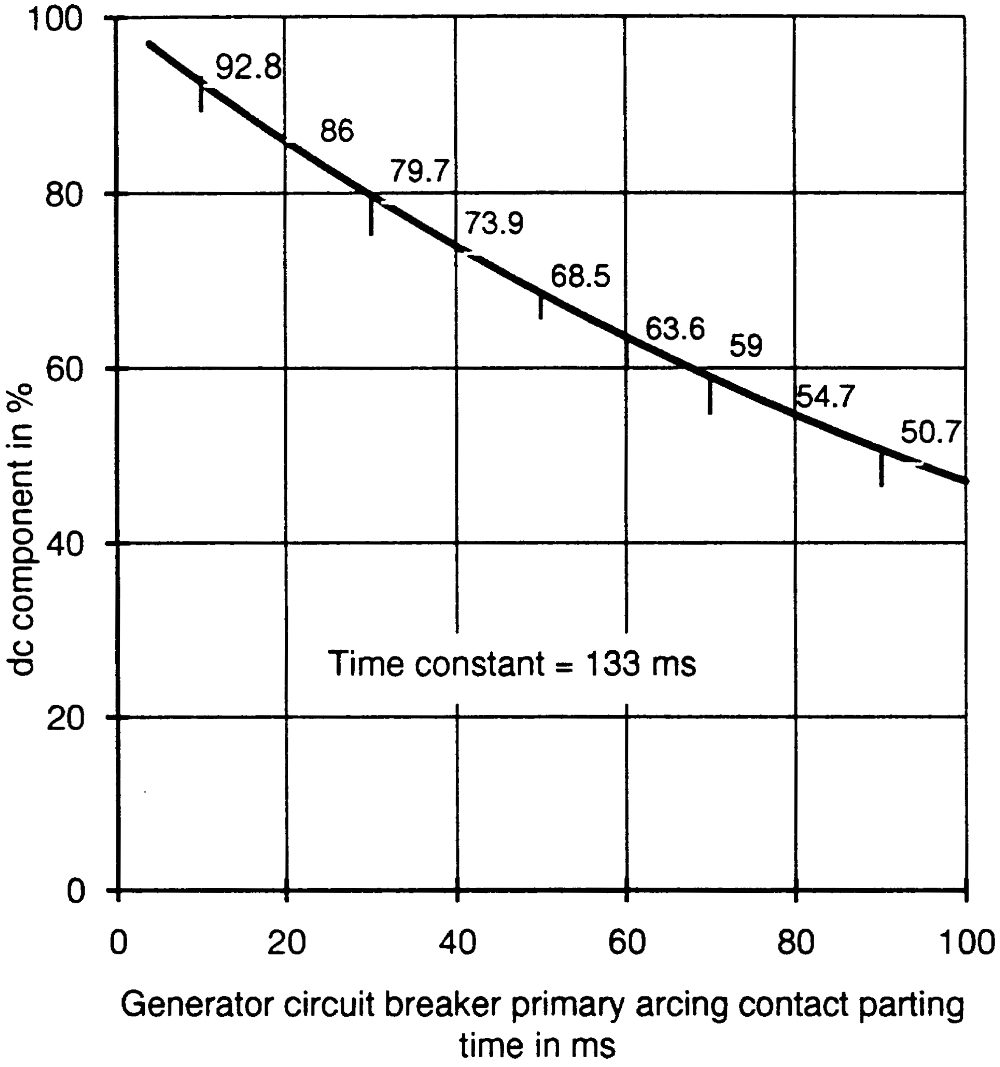


Figure 2— Asymmetrical interrupting capability: DC component in percentage of the peak value of the symmetrical three-phase system-source short-circuit current

The primary arcing contact parting time shall be considered equal to the sum of 1/2 cycle (present practical minimum tripping delay) plus the minimum opening time of the particular generator circuit breaker.

5.8.2.3 Required generator-source symmetrical interrupting capability for three-phase faults

No specific rating is assigned to cover the generator-source short-circuit current because its maximum value is usually less than the short-circuit current from the power system. If a rating is assigned, then the generator circuit breaker shall be tested for the following related capabilities. For three-phase faults, the required generator-source symmetrical interrupting capability of a generator circuit breaker is the highest value of the symmetrical component of the short-circuit current, measured from the envelope of the current wave at the instant of primary arcing contact separation that the generator circuit breaker shall be required to interrupt, at rated maximum voltage and rated duty cycle when the source of the short-circuit current is entirely from a generator through no transformations.

5.8.2.4 Required generator-source asymmetrical interrupting capability for three-phase faults

For three-phase faults, the required asymmetrical generator-source interrupting capability of a generator circuit breaker at rated maximum voltage and for the rated duty cycle is composed of the rms generator-source symmetrical current and a dc component. The value of the dc component is 110% of the peak value of the symmetrical generator-source short-circuit current for all generator circuit breaker primary arcing contact parting times. The primary arcing contact parting time shall be considered equal to the sum of 1/2 cycle plus the minimum opening time of the particular generator circuit breaker.

5.8.2.4.1 Required generator-source asymmetrical interrupting capability for maximum required degree of asymmetry

The maximum required degree of asymmetry of the current for the condition of maximum required degree for asymmetry is 130% of the peak value of symmetrical current for this condition. The symmetrical component of the short-circuit current under the condition of maximum degree of asymmetry is only 74% of the value of the required generator-source symmetrical interrupting capability.

5.8.2.5 Required interrupting capability for single-phase-to-ground faults

Generator circuit breakers are designed for use on high-impedance grounded systems where the single phase-to-ground short-circuit current will not exceed 50 A. In no case are the capabilities for single phase-to-ground faults required to exceed this value.

5.8.2.6 Required closing, latching, and carrying capabilities

The generator circuit breaker shall be capable of the following:

a) Closing and latching any power frequency-making current (50 Hz or 60 Hz) whose maximum crest (peak making current) does not exceed 2.74 times the rated symmetrical short-circuit current or the maximum crest (peak making current) of the generator-source short-circuit current, whichever is higher. No numerical value can be given for the peak value of the generator-source peak current since it depends on the generator characteristic data (see 5.8.2.3 and A.3.2).
b) Carrying the short-circuit current for a time of 0.25 s.

5.8.2.7 Required short-time current-carrying capability

The generator circuit breaker shall be capable of carrying for T*s* equals 1 s, any short-circuit current determined from the envelope of the current wave at the time of the maximum crest, whose value does not exceed 2.74 times the rated short-circuit current, and whose rms value *I* determined over the complete 1 s period does not exceed the rated short-circuit current considered above.

The mathematical expression for the rms value *I* of a short-circuit current over the period *Ts* is as follows:

$$I = \sqrt{\frac{1}{T_S}\left(\int_0^{T_S} i^2 dt\right)} = \sqrt{\int_0^1 i^2 dt}$$

where

i	is the instantaneous current in amperes (see Clause 7. of IEEE Std C37.09-1979)
t	is the time in seconds

It is not to be inferred that the generator circuit breaker is to be capable of interrupting after the required short-time current-carrying capability duty until it has cooled down to normal heat run temperature.

5.8.3 Interrupting performance

5.8.3.1 Rated performance

A generator circuit breaker shall perform at or within its rating without producing any injurious emissions.

5.8.3.2 Service capability duty requirements

Generator circuit breakers shall be capable of the following performances under short-circuit and load current interruption conditions:

a) One short-circuit duty cycle (CO–30 min–CO).
b) A number of load current interruptions in which the sum of the currents interrupted does not exceed 5000% of rated continuous current of the generator circuit breaker. The number of operations used to make up the 5000% is cumulative over a period of time and is a measure of the generator circuit breaker's reliability and a guide to maintenance. Thermal limitations of parts, such as opening resistors, require that the number of opening operations comprising the 5000% shall not exceed two in 30 min or four in 4 h.

5.9 Transient recovery voltage (TRV) rating

At its rated maximum voltage, each generator circuit breaker must be capable of interrupting three-phase grounded faults at rated short-circuit current in any circuit in which the three-phase grounded circuit TRV does not exceed the rated TRV envelope.

Each TRV rating is for a three-phase generator circuit breaker. It is not required that a single phase of a generator circuit breaker interrupt a single-phase circuit that produces a circuit TRV equal to the rated TRV envelope.

However, as discussed in 6.2.3.8, the single-phase test at 1.5 times phase-to-ground voltage is given as one of the basic approaches to demonstrating the rating in a design test. It is an optional design test, not a rating requirement.

5.9.1 Rated inherent TRV

The rated inherent TRV shall be defined by an oscillatory waveshape having a TRV rate, time delay, and crest voltage (E_2) as listed in Tables 5–6. The formula and method for determining the time-to-crest (T_2) are given in 7.3.6.3 and Figure 15.

Table 5— TRV parameters for system-source faults

Transformer rating MVA	T_2 in µs	Inherent TRV	
		E_2-crest voltage	TRV rate kV/µs
100 or less	0.62 V	1.84 V	3.5
101–200	0.54 V	1.84 V	4.0
201–400	0.48 V	1.84 V	4.5
401–600	0.43 V	1.84 V	5.0
601–1000	0.39 V	1.84 V	5.5
1001 or more	0.36 V	1.84 V	6.0

NOTES:
1 — Time delay shall be equal to or less than 1 µs.
2 — V is the rated maximum voltage in kV.

Table 6— TRV parameters for generator-source faults

Generator rating MVA	T_2 in µs	Inherent TRV	
		E_2-crest voltage	TRV rate kV/µs
100 or less	1.35 V	1.84 V	1.6
101–400	1.20 V	1.84 V	1.8
401–800	1.08 V	1.84 V	2.0
801 or more	0.98 V	1.84 V	2.2

NOTES:
1 — Time delay shall be equal to or less than 0.5 µs.
2 — V is the rated maximum voltage in kV.

5.9.2 First-pole-to-clear factor

The first-pole-to-clear factor shall be 1.5.

5.9.3 Amplitude factor

The amplitude factor shall be 1.5.

5.10 Rated load current switching capability

The operation endurance capabilities specified in Table 7 are the type and number of complete closing-opening operations that the generator circuit breaker shall be capable of performing at any voltage up to the rated maximum voltage under the following conditions:

a) The generator circuit breaker shall operate with rated control voltage and rated fluid (gas or liquid) pressure in the operating mechanism.
b) The frequency of operations is not to exceed two in 30 min and four in 4 h because the generator circuit breaker may be equipped with auxiliary devices, such as resistors, that have thermal limitations. When auxiliary devices such as resistors are not used, the manufacturer may provide alternate frequency of operation values.

c) The values listed in the rating tables have been established by experience and engineering judgment. Those involving currents are derived from service capability and circuit breaker condition (see 5.8.3.2) and are not separate ratings (see 6.2.8.2.)

5.10.1 Inherent TRV

The inherent TRV for a load switching operation shall be defined by an oscillatory waveshape having a TRV rate and time delay as listed in Table 8. The formula and method for determining the time-to-crest (T_2) are given in 7.3.6.3 and Figure 15.

5.10.2 Amplitude factor

The amplitude factor shall be 1.5.

Table 7— Operation endurance capabilities for generator circuit breakers

Circuit breaker ratings	**Number of operations (operation = 1 closing + opening)**		
	Between servicing (see NOTE 2)	**No-load mechanical (see NOTES 2–8)**	**Continuous current switching (see NOTES 2, 4, 5, 7, 8, and 9)**
Column 1	**Column 2**	**Column 3**	**Column 4**
Up to 38 kV	500	1000	50

NOTES:

1 — The integrated duty on the generator circuit breaker must be within the service capability as defined in 5.8.3. See Clause 6..

2 — Maintenance consists of cleaning, tightening, adjusting, lubricating, and dressing of contacts, etc., as recommended by the manufacturer under usual service conditions. Maintenance intervals are usually based on both an elapsed time and a number of operations, whichever occurs sooner. In determining maintenance intervals for particular applications, consideration must be given to actual conditions prevailing at the installation site. Refer to Clause 4. for service conditions and to Clause 7. for general application conditions. The number of operations specified in Column 2 are based on usual service conditions. When used as a guide for field application, they define maximum maintenance intervals.

3 — When closing and opening no-load.

4 — With rated control voltage applied (see Table 10).

5 — Frequency of operation (see 5.10).

6 — Requirements are based on specified maintenance intervals in accordance with Column 2.

7 — No functional part shall have been replaced prior to completion of the specified number of operations.

8 — After completion of the specified number of operations, the circuit breaker shall withstand 75% of its rated power frequency withstand voltage, and the resistance of the current carrying circuit from terminal to terminal measured with a current of at least 100 A flowing shall not be increase by more then the amount specified by the manufacturer compared to the value for the circuit breaker when new. Under these conditions, the circuit breaker is considered capable of carrying the rated continuous current, at power frequency, without injurious heating until maintained and of performing one interruption at rated short-circuit current or a related capability. After completion of this series of operations, functional part replacement and general maintenance may be necessary (see 6.2.8.3).

9 — If a short-circuit operation occurs before the completion of the listed operations, maintenance is recommended and possible functional part replacement may be necessary depending on previous duty, fault magnitude, and expected future operations.

Table 8— TRV parameters for load current switching

Generator rating MVA	T_2 in µs	Inherent TRV	
		E_2-crest voltage	TRV rate kV/µs
100 or less	1.08 V	0.92 V	1.0
101– 400	0.91 V	0.92 V	1.2
401– 800	0.77 V	0.92 V	1.4
801 or more	0.62 V	0.92 V	1.6

NOTES:
1 — Time delay shall be equal to or less than 1 µs.

2 — See 6.2.8.2 for test voltage values.

3 — V is the rated maximum voltage in kV.

5.11 Capacitance current switching capability

This is a special case where the line or bus capacitance is separated from the generator circuit breaker through transformation. If this capability is required, the user should consult the manufacturer.

5.12 Out-of-phase current switching capability

This capability applies to a generator circuit breaker used for switching the connection between two parts of a three-phase system during out-of-phase conditions. The generator circuit breaker may be assigned an out-of-phase current switching rating when its out-of-phase current switching capability has been demonstrated by the tests specified in Clause 6. Other equivalent or more effective methods of test are not precluded.

5.12.1 Assigned out-of-phase current switching rating

The assigned out-of-phase current switching rating is the maximum out-of-phase current that the generator circuit breaker shall be capable of switching at an out-of-phase recovery voltage equal to that specified in 6.2.9.2 and under prescribed conditions.

5.12.2 Interrupting time for out-of-phase current switching

The interrupting time for out-of-phase current switching is equal to the rated interrupting time.

5.12.3 Inherent TRV for out-of-phase current switching

The inherent TRV for out-of-phase current switching shall be defined by an oscillatory waveshape having the TRV rate, time delay, and crest voltage (E_2) as listed in Table 9 (see also 7.3.9.2). The formula and method for determining the time-to-crest (T_2) are given in 7.3.6.3 and Figure 15.

Table 9— TRV parameters for out-of-phase current switching

Generator rating MVA	T_2 in µs	Inherent TRV	
		E_2-crest voltage	TRV rate kV/µs
100 or less	0.89 V	2.6 V	3.3
101– 400	0.72 V	2.6 V	4.1
401– 800	0.63 V	2.6 V	4.7
801 or more	0.57 V	2.6 V	5.2

NOTES:
1 — Time delay shall be equal to or less than 1 µs.
2 — V is the rated maximum voltage in kV.

5.13 Excitation current switching capability

The excitation current switching capability is the highest magnetizing current that a generator circuit breaker shall be required to switch at any voltage up to rated maximum voltage at power frequency without causing an overvoltage exceeding the levels agreed upon between the user and the manufacturer. This capability may be determined by tests in accordance with 6.2.11.

5.14 Rated control voltage

The rated control voltage of a generator circuit breaker is the designated voltage that is to be applied to the closing or tripping devices to close or open the generator circuit breaker (see Table 10). Other control voltages may be specified according to other national or international standards depending on the point of original installation.

The transient voltage in the entire control circuit, due to interruption of control circuit current, shall be limited to 1500 V crest.

NOTE — The control voltage is allowed to vary above and below its rated value within a specified range (see Table 10). The control voltage is measured at the terminals of the operating coils with the operating current flowing. The maximum voltage is measured at the control power terminals of the operating mechanism at no-load and the minimum voltage is measured with the maximum operating current flowing. Rated voltages and their permissible ranges for the control power supply of generator circuit breakers shall be as shown in Table 10.

Table 10— Rated control voltages and their ranges for generator circuit breakers

Direct current voltage ranges (see NOTES 1, 2, 3, 4, 7, 8) closing and auxiliary functions				Alternating current voltage ranges (see NOTES 1, 2, 3, 4, 7, 8)	
Rated voltage	**Indoor circuit breakers**	**Outdoor circuit breakers**	**Tripping functions (all types)**	**Rated voltage (60 Hz)**	**Closing, tripping, and auxiliary functions**
24 (see NOTE 5)	—	—	14–28	Single phase	
48 (see NOTE 5)	38–56	36–56	28–56	120	104–127 (see NOTE 6)
125	100–140	90–140	70–140	240	208–254 (see NOTE 6)
250	200–280	180–280	140–280	Three-phase	
				208 Y/120	180 Y/104–220 Y/127
				240	208–254

NOTES:

1 — Relays, motors, or other auxiliary equipment that function as part of the control for a device shall be subject to the voltage limits imposed by this standard, whether mounted at the device or at a remote location.

2 — Mechanism devices in some applications may be exposed to control voltages exceeding those specified here due to abnormal conditions, such as abrupt changes in line loading. Such applications require study, and the manufacturer should be consulted. Also, application of switchgear devices containing solid-state control exposed continuously to control voltages approaching the upper limits of ranges specified herein require specific attention, and the manufacturer should be consulted before application is made.

3 — Includes supply for pump or compressor motors. Note that rated voltages for motors and their operating ranges are covered in NEMA MG 1-1993.

4 — It is recommended that the coils of closing, auxiliary, and tripping devices that are connected continually to one dc potential should be connected to the negative control bus so as to minimize electrolytic deterioration.

5 — 24 V and 48 V tripping, closing, and auxiliary functions are recommended only when the device is located near the battery or where special effort is made to ensure the adequacy of conductors between battery and control terminals. 24 V closing is not recommended.

6 — Includes heater circuits.

7 — Extended voltage ranges apply to all closing and auxiliary devices when cold. Mechanisms utilizing standard auxiliary relays for control functions may not comply at lower extremes of voltage ranges when relay coils are hot, as after repeated or continuous operation.

8 — DC control voltage sources, such as those derived from rectified alternating current, may contain sufficient inherent ripple to modify the operation of control devices to the extent that they may not function over the entire specified voltage ranges.

5.15 Rated mechanism fluid operating pressure

The rated mechanism fluid operating pressure of a generator circuit breaker is the pressure at which a gas- or liquid-operated mechanism is designed to operate. The pressure is allowed to vary above and below its rated value within a specified range.

5.16 Nameplate markings

The following minimum data, when applicable, shall appear on the nameplates of each generator circuit breaker and associated device.

5.16.1 Circuit breaker

The following circuit breaker and operating mechanism nameplates may be combined:

a) Manufacturer’s name;
b) Manufacturer’s type designation;
c) Manufacturer’s serial number (limited to 15 letters or numbers);
d) Year of manufacture;
e) Power frequency (Hz);
f) Rated continuous current (kA);
g) Rated maximum voltage (kV);
h) Rated full-wave impulse withstand voltage (kV peak);
i) Rated short-circuit duty cycle;
j) Rated short-circuit current (symmetrical, kA);
k) DC component in percentage of the peak value of the rated short-circuit current;
l) Close, latch and carry current (kA peak);
m) Short-time current (kA for 1 s);
n) Assigned out-of-phase switching current (kA);
o) Rated interrupting time (ms);
p) Rated insulating medium pressure or density at 20 °C;
q) Forced cooling: kind, pressure, temperature, quantity (if applicable);
r) Instruction book number;
s) Renewal parts catalog;
t) Weight of circuit breaker.

5.16.2 Operating mechanism

The following operating mechanism and circuit breaker nameplates may be combined:

a) Manufacturer’s name;
b) Manufacturer’s type designation;
c) Manufacturer’s serial number;
d) Year of manufacture;
e) Rated control voltage for closing coil;
f) Rated control voltage for tripping coil;
g) Rated control voltage for motors and pumps;
h) Closing current;
i) Tripping current;
j) Current for motors and pumps;
k) Rated fluid pressure or density at 20 °C;
l) Instruction book number.

5.16.3 Accessories

Nameplates of all accessories shall include the following:

a) Identification;
b) Pertinent operating characteristics.

5.16.4 Modernization of circuit breakers

Revised nameplates shall be furnished when modernization is involved. IEEE Std C37.59-1996 [B5] may be consulted if desired.

5.16.5 Instruction and warning signs

Essential markings shall be provided for instruction and warning signs as follows:

a) Identify operating devices and positions;
b) Give pertinent instructions for operation;
c) Call attention to special precautions.

6. Tests

6.1 General

The test procedure summarizes the various tests that are made on ac high-voltage generator circuit breakers, describes accepted methods used in making the tests, and specifies the tests that will demonstrate ratings under IEEE/ANSI standards. It does not preclude the use of other equivalent or more effective methods of demonstrating ratings. The tests are divided into the following classifications:

a) Design tests;
b) Production tests;
c) Tests after delivery.

6.2 Design tests

The design tests described in this test procedure provide methods of demonstrating the ability of a generator circuit breaker to meet the assigned ratings when operating at rated maximum voltage and power frequency. The electrical and mechanical endurance tests shall be made with generator circuit breakers of the same type.

6.2.1 Rated continuous current-carrying tests

Rated continuous current-carrying tests demonstrate that the generator circuit breaker can carry its rated continuous current at its power frequency without exceeding any of the temperature limitations in 5.3.2.

6.2.1.1 Conditions of test

a) The ambient temperature shall be between 10 °C and 40 °C inclusive, so that no correction factors need be applied.
b) The circuit breaker shall be tested indoors under usual service conditions. Enclosed generator circuit breakers shall be tested in their enclosures.
   If an isolated phase bus is used and is forced air-cooled, tests shall be conducted with the air quantity (m^3/sec) and air entrance temperature of the most unfavorable phase.
   If there is no forced air-cooling of the isolated phase bus, the connections of the generator circuit breaker to the isolated phase bus shall be such that no significant amount of heat is conducted away from or conveyed to the generator circuit breaker during the tests. The temperature rise at the terminals of the generator circuit breaker live parts and at the encapsulation at a distance of 1 m from the generator circuit breaker terminals shall be measured. The difference in the two temperature rises shall not exceed 5 °C. The type and size of the connection between the generator circuit breaker and the isolated phase bus shall be recorded in the test report.
   If other coolants are used (water, etc.), the coolant quantity and entrance temperature shall be adjusted to the prevailing rated service conditions.

Other apparatus incorporated in series and closely associated with the generator circuit breaker, such as current transformers, primary disconnecting contacts, buses, and the connections shall be mounted in their regular positions.

c) Indoor or outdoor generator circuit breakers, which are normally installed in such a manner that other connected apparatus has no appreciable effect on the generator circuit breaker temperature, shall be tested with parts of the isolated phase bus of a size corresponding to the current rating of the generator circuit breaker, connected to the circuit breaker terminals by means of typical terminal connectors of corresponding current rating or by other means that shall be evaluated as equivalent for the specific application.
d) In cases where the enclosure carries a current approximately equal to the rated continuous current, the return path during the test shall be the enclosure. The generator circuit breaker enclosure shall be made airtight when a bus duct forced air cooling system is part of the design.

6.2.1.2 Test procedure

Testing of generator circuit breakers often places special demands on the testing laboratories not only because of the high continuous current and short-circuit current ratings of the circuit breakers, but also because of their metal-enclosed design that allows them to be connected directly to metal-enclosed bus duct. In cases where the prescribed testing procedures will be difficult to meet, the test circuits and the test conditions shall take into account the practical application of the circuit breaker in the power system and also the conditions at the test laboratory. Three-phase generator circuit breakers shall be tested three-phase except in the following cases:

a) Where there is no possibility of magnetic or thermal influence between poles or modular units, single-phase tests may be made on a single-pole or modular unit;
b) Where there is no possibility of magnetic influence, but there may be thermal influence from other phases of the circuit breaker, tests may be made with single-phase current passed through the three poles in series;
c) Where test stations have inadequate energy levels, single-phase tests may be made.

The continuous current-carrying capability of the generator circuit breaker is influenced by the temperature of the connected isolated phase bus. This situation must be taken into account when performing heat run tests. The temperatures of the isolated phase buses measured at a distance of 1 m from the generator circuit breaker shall be agreed upon by the user and the manufacturer, and shall be specified in the type test report.

When testing a generator circuit breaker with a forced-cooled rating, the continuous current-carrying capability shall be determined with and without the forced cooling. The temperatures in the current-carrying path shall be measured during these tests. If the forced-cooling systems of the bus duct and the generator circuit breaker use the same air, the phenomenon becomes complicated when the cooling air is lost. The temperature of the bus duct does not remain constant but will also rise, and this rise must be taken into account during testing. The limit of total temperature of the bus duct has to be agreed upon by the user and the manufacturer, and the practical application in the power system has to be taken into account as well in order to carry out realistic tests.

6.2.1.3 Duration of rated continuous current test

The test shall be made over a period of time sufficient for the temperature rise to stabilize. This condition is usually reached when the increase in temperature rise of that generator circuit breaker live part with the highest temperature limit does not exceed 1 °C in 1 h. The time for the entire test may be shortened by preheating the generator circuit breaker with a higher value of current, unless a measurement of thermal time constant is required.

6.2.1.4 Temperature measurement

Temperatures shall be measured by the following methods (see IEEE Std 119-1974):

a) *Thermocouple*.
b) *Thermometer*. This is the preferred method for ambient temperatures.

c) *Infrared cameras or heat-sensitive devices.* Use of bolometers, infrared devices, or other temperature-measuring systems able to measure the temperature inner or outer parts of the generator circuit breaker by means of a viewport are acceptable provided that the tolerance of the measurement is within the accepted general limits (less than 0.5 °C).

d) *Location of measuring devices.* The measuring device shall be located where measurement of the hottest spot can be made even though it may involve drilling holes that destroy some parts on a design test. This will require the use of thermocouples in locations inaccessible to thermometers in order to obtain the hottest spot measurement. It is recognized that thermocouples cannot be located in the actual contact point of line or point contacts without destroying the effectiveness of such line or point contacts.

Measurements shall be made at junction points of insulation and conducting parts to prevent exceeding temperature limits of the insulation. Thermocouples shall be located so as to obtain the hottest spot measurement. For site tests, if required, it is sufficient to measure accessible parts and compare the measurements with like points on the design tests. Holes that destroy the effectiveness of the test (such as in multiturn coils) shall not be drilled.

6.2.1.5 Determination of ambient temperature

The ambient temperature shall be taken as that of the air surrounding the test circuit breaker. The ambient temperature shall be 10– 40 °C inclusive, so that no correction factors need be applied.

The ambient temperature shall be determined by taking the average of the readings of three thermometers placed in locations unaffected by drafts, horizontally 1000 mm from the projected periphery of the circuit breaker or enclosure, and approximately on a vertical line according to the following:

a) One approximately 1000 mm above the circuit breaker or enclosure (including bushings).
b) One approximately 1000 mm below the circuit breaker or enclosure. (In the case of floor-mounted circuit breakers or enclosures, it shall be 1000 mm above the floor or mounting base.)
c) One approximately midway between the above two positions.

In order to avoid errors due to the time lag between the temperature of large apparatus and the variations in the ambient temperature, all reasonable precautions must be taken to reduce these variations and the errors arising from them. Thus, the thermometer for determining the ambient temperature shall be immersed in a suitable heavy metal oil cup when the ambient temperature is subject to such variations.

A convenient form for such an oil cup consists of a metal cylinder with a hole drilled partly through it. This hole is filled with oil, and the thermometer is placed in it with its bulb well immersed. The response of the thermometer to various rates of temperature change will depend largely on the size, kind of material, and mass of the containing cup, and may be further regulated by adjusting the amount of oil in the cup. The larger the apparatus under test, the larger the metal cylinder that shall be used as an oil cup in determining the cooling air temperature. The smallest size oil cup used in any case shall be a metal cylinder 25 mm in diameter and 50 mm high.

6.2.1.6 Demonstrations of emergency conditions

Emergency conditions can be demonstrated by tests. These tests shall include, if applicable, but are not limited to, the following simulations:

a) Loss of cooling fluid.
b) Loss of insulating medium.
c) Failure of the cooling system, subdivided partially, if applicable, into fans, pumps, air circulators, or any other means of cooling applicable to the specific apparatus being tested. Failure of each cooling subsystem shall be simulated individually and simultaneously.
d) Failure of air cooling in the isolated phase bus.

All the above losses and failures shall be simulated individually and simultaneously.

For each type of failure, the following data shall be noted:

1) Maximum tolerable temperature limit to be determined by the manufacturer;
2) Maximum time the emergency condition can persist in order not to exceed the maximum tolerable temperature limit (t_1, t_2, etc.);
3) A rate of decrease of the continuous current (R_1, R_2, etc.);
4) A stabilization of the continuous current at a lower value such that the maximum temperature rise in the circuit breaker will be in accordance with 5.3.3 (I_1, I_2, etc.).

It is suggested that data for the rate of decrease of the current, the emergency condition, and its duration, etc., be presented graphically by the manufacturer as illustrated in Figure 1.

6.2.2 Rated dielectric strength

The dielectric strength of a generator circuit breaker is demonstrated by subjecting it to high voltages, both power frequency and impulse based on its rated maximum voltage.

Metal enclosed generator circuit breakers shall be tested in their enclosures. If current transformers, grounding switches, or other equipment is integrated in the design of the generator circuit breaker, the dielectric tests shall be made with this equipment included. Dielectric tests shall be made at minimum insulating fluid pressure.

It may be difficult to carry out the dielectric tests on generator circuit breakers equipped with resistors or capacitors that influence the inherent TRV. In such cases, they can be removed if they consume too much of the energy of the test circuit (e.g., due to capacitors when impulse testing or due to resistors during power frequency tests).

Withstand tests on generator circuit breakers shall be made at the factory under temperature and humidity conditions normally occurring during commercial testing. The generator circuit breaker shall be clean and in good condition and shall not have been put into commercial operation. Values for correction factors for atmospheric pressure and atmospheric humidity for impulse and power frequency tests are to be from IEEE Std 4-1995.

When refinements in correction factors in IEEE Std 4-1995 are made, it shall not be necessary to repeat design tests on designs for which such tests have been completed. Correction factors shall not be used on power frequency dry tests.

Generator circuit breakers with integrated series isolators may have a movable insulating barrier that can be closed if required in the isolator-open position as an additional protective measure to separate the generator circuit breaker’s energized and de-energized parts. Tests on such generator circuit breakers shall be made with the barrier in both the open and closed position.

If liquid coolants circulate under normal service conditions between the generator circuit breaker’s energized and grounded parts, the tests shall be made with the coolant circulating and with maximum coolant conductivity permitted by the manufacturer.

6.2.2.1 Rated power frequency withstand voltage (dry)

Tests are made to determine the ability of the generator circuit breaker to withstand the rated power frequency withstand voltage (see 5.4). The frequency of the power frequency test voltage shall be within ± 20% of the power frequency of the apparatus tested. The waveshape should be as close to a sine wave as practicable. The test shall be made with alternating voltage having a crest value equal to $\sqrt{2}$ times the rated power frequency withstand voltage. In these tests, an alternating voltage shall be applied to the terminals of the generator circuit breaker for 1 min, without damage or flashover, in each of the following methods:

a) With the generator circuit breaker in the open position, apply power frequency voltage to each terminal of the generator circuit breaker individually, with all other terminals and enclosures of the generator circuit breaker grounded;

b) With the generator circuit breaker contacts closed, apply power frequency voltage to each phase of the generator circuit breaker individually, with the enclosure of the generator circuit breaker grounded;
c) Tests shall be performed with the insulating medium at atmospheric pressure to simulate the loss of this medium and with a voltage corresponding to 1.5 times the phase opposition voltage (see 5.4).

6.2.2.2 Rated full wave impulse withstand voltage

Tests under dry conditions are made on generator circuit breakers to determine their ability to withstand their rated full wave impulse withstand voltages.

In these tests, both positive and negative impulse voltages, having a crest value equal to the rated full wave impulse withstand voltage of the generator circuit breaker and a waveshape of 1.2 × 50 µs, shall be applied to the terminals of the generator circuit breaker without damage or flashover in each of the following methods:

a) With the generator circuit breaker in open position:
    1) Apply positive impulse voltage three consecutive times without flashover to each terminal of the circuit breaker individually, with all other terminals and enclosures grounded;
    2) Apply negative impulse voltage three consecutive times without flashover to each terminal of the circuit breaker individually, with all other terminals and enclosures grounded.
b) With generator circuit breaker contacts closed:
    1) Apply positive impulse voltage three consecutive times without flashover to each phase of the generator circuit breaker individually, with the other phases and enclosures grounded;
    2) Apply negative impulse voltage three consecutive times without flashover to each phase of the generator circuit breaker individually, with the other phases and enclosures grounded.

If during the first group of three consecutive tests as applied to items a) and b) in 6.2.2.2, a flashover occurs on one test of a group, a second group of nine tests shall be made. If the circuit breaker successfully withstands all nine of the second group of tests, the flashover in the first group shall be considered a random flashover and the generator circuit breaker shall be considered as having successfully passed the test.

The wave form and application of the 1.2 50 µs full wave test voltage shall be as in IEEE Std 4-1995 and shall have the following limits:

a) A full wave test voltage with a virtual front time, based on the rated full wave impulse test voltage, that is equal to or less than 1.2 µs.
b) A crest voltage equal to or exceeding the rated full wave impulse voltage.
c) A time to the 50% value of the crest voltage that is equal to or greater than 50 µs.

If the capacitance of a test sample is too high for the test equipment to be able to produce a virtual front time as short as 1.2 µs while maintaining the crest value, the most rapid rise possible shall be used.

An alternative test procedure—depending on the point of installation—may be allowed as described in IEC Publication 60060-1 (1989) [B3] [7] and IEC Publication 60060-2 (1994) [B4] . This procedure uses 15 consecutive lightning impulses at rated withstand voltage. The generator circuit breaker shall be considered to have passed the test if the number of disruptive discharges on self-restoring insulation does not exceed two for each series of 15 impulses, and if no disruptive discharges on non-self restoring insulation occurs.

6.2.3 Short-circuit current rating

The short-circuit current rating of a generator circuit breaker is demonstrated by the series of tests in Table 11.

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[7] The numbers in brackets preceded by the letter B correspond to those of the bibliography in Clause 8.

If capacitors are installed between the step-up transformer and the generator circuit breaker, or if capacitors are part of the circuit breaker assembly, tests shall be carried out with the capacitor connected, or the influence of these capacitors on the TRV taken into account if they are not installed during the tests.

6.2.3.1 Rated short-circuit currents

The rated short-circuit current is demonstrated by a series of symmetrical and asymmetrical tests, and close-open tests as listed in Table 11.

The rated symmetrical current shall be the rated current value with the power frequency voltage associated with the rated maximum voltage and with a rated inherent transient recovery voltage in accordance with 5.9.1.

The rated asymmetrical current-interrupting capability is demonstrated within the same conditions as the symmetrical current.

Table 11— Test duties to demonstrate the short-circuit current rating first-pole-to-clear values for three-pole tests or conditions for single-pole tests

Test duty[2, 7, 8]	**Operating duty**	**Voltages (initial and recovery)**	**Current interrupted**		**Making current at first major peak**[1,11]	**Inherent transient recovery voltage** [1, 4]		**Control voltage and mechanism operating pressure before first operation**	**Remarks**
		First-pole-to-clear *V*, rms	**Magnitude A, rms symmetry** [1]	**Asymmetry**		**Crest voltage E_2**	**TRV rate kV/µs**		
110,14	C+ 0.25 s	0.58 V10	I	--	2.74 *I*			Min.	Closing, latching, and carrying
2	In closed position [13]	—	—	—	—	—	—	—	Short-time current-carrying
3[5, 6]	CO + 30 min + CO	0.87 V [9]	I	20% max.	1.40 *I*	1.84 *V*	(12)	Min.	Close-open test symmetrical
4 [3, 5, 6]	CO + 30 min + CO	0.87 V	I	% dc	2.74 *I*	1.84 *V*	(12)	Min.	Close-open test asymmetrical
4-A [3, 5,14]	C+ 30 min + C	0.58 V [10]	I	—	2.74 *I*	—	—	Min.	Close-open test asymmetrical equivalency, part 1.
4-B[3, 5]	0 + 30 min + 0	0.87 V [9]	I	% dc	—	1.84 *V*	(12)	Min.	Close-open test asymmetrical equivalency, Part 2.

Test duty[2, 7, 8]	**Operating duty**	**Voltages (initial and recovery)**	**Current interrupted**		**Making current at first major peak[1,11]**	**Inherent transient recovery voltage [1, 4]**		**Control voltage and mechanism operating pressure before first operation**	**Remarks**
		First-pole-to-clear *V*, rms	**Magnitude A, rms symmetry [1]**	**Asymmetry**		**Crest voltage E_2**	**TRV rate kV/µs**		

V is the rated maximum voltage of the generator circuit breaker in kV.
I is the rated short-circuit current of the circuit breaker.
% dc is the dc component of the short-circuit current assigned to the required performance of the generator circuit breaker (see 5.8.2.2).
NOTES:
1 — The voltage and current in a test must be equal to, or greater than, the specified values.

2 — No refitting or replacement of parts to the generator circuit breaker are permitted during each test duty 1, 2, 3, 4, or 4-A and 4-B.

3 — Alternate means of testing can be proposed if there are testing station limitations. Test duties 4-A and 4-B are equivalent to test duty 4.

4 — If imposed by testing station limitations, a tolerance of –5% in the TRV rate is permissible.

5 — If test duties 3 and 4 cannot be made at full recovery voltages, a two-part test combining test duties 3 and 4 and an out-of-phase switching test duty is acceptable provided that the thermal interrupting capabilities are demonstrated for at least the first 100 µs of the interruption (thermal zone) and the dielectric withstand for 2 or 3 cycles at full voltage after arc interruption (dielectric zone).

6 — Obtain the most severe switching condition in regard to the arcing time at least on one interruption.

7 — The test duty sequence is only a suggested sequence. The test duties can be performed in any sequence desired.

8 — If circuit breaker has auxiliary resistor chamber and auxiliary switch, tests should be performed with auxiliary resistor and switch in circuit.

9 — The first-pole-to-clear value of 0.87 V is calculated as follows $1.5\,V/\sqrt{3} = 0.87\,V$.

10 — The voltage before closing the circuit breaker is the phase voltage calculated as follows: $V/\sqrt{3} = 0.58\,V$.

11 — The making current at the first peak is calculated as follows: $(1 + e^{-t/\tau})\ \sqrt{2}\,I = 2.74\,I$ (with $\tau = X/R\omega = 133$ ms).

12 — Inherent transient recovery voltage values are defined in 5.9.1.

13 — In closed position, generator circuit breaker shall carry a current having an rms value, over one second, equal to rated short-circuit current.

14 — The duration of the current flow shall be 5 cycles. Test duty 1 can be replaced test duty 4-A if test duty 4-A and 4-B are carried out instead of test duty 4, due to test station limitation; then the time specified in test duty 1 has to be met in test duty 4-A.

6.2.3.2 Interrupting capability for single-phase-to-ground faults

As all known applications of generator circuit breakers are for high-impedance grounded systems, the single-phase-to-ground short-circuit current is always significantly lower than the three-phase short-circuit current and its demonstration is included with the three-phase short-circuit current test defined in 6.2.3.1.

6.2.3.3 Closing, latching and carrying capability

The generator circuit breaker shall have the required capability to close against a short-circuit current, to latch or the equivalent, and to carry the current as long as 0.25 s. This capability is specified in 5.8.2.6 and demonstrated by Test duty 1 (see Table 11).

6.2.3.4 Short-time current-carrying capability

The required short-time current-carrying capability of 1 s is demonstrated by Test duty 2.

6.2.3.5 Duty cycle

The duty cycle capability of the generator circuit breaker is demonstrated by Test duties 3 and 4 (or 4-A and 4-B). The time between two operations to interrupt short-circuit current shall be the rated value of 30 min, as specified in 5.5.

6.2.3.6 Condition of circuit breaker tested

The generator circuit breaker shall be new and in good condition. It may be reconditioned during the testing as permitted in accordance with 6.2.3.6.2

6.2.3.6.1 Generator circuit breaker used for test

The generator circuit breaker shall be representative of the type, style, or model as required for all design tests (see 3.1 for the definition of design tests).

6.2.3.6.2 Reconditioning of the generator circuit breaker during testing

The expendable parts or parts subject to wear may be replaced or refitted between each Test duty 1–4; but no parts can be replaced or refitted within each test duty, such as in Test duty 4 between the two opening operations within the 30 min interval.

6.2.3.6.3 Condition of the generator circuit breaker after tests

After the series of test duties, the generator circuit breaker shall be able to open and close freely and withstand 75% of its power frequency withstand voltage. A terminal-to-terminal resistance test shall be performed to ascertain that the current path resistance has not increased by more than the amount specified by the manufacturer and that the generator circuit breaker is capable of reliably carrying the rated continuous current.

6.2.3.7 Testing conditions

6.2.3.7.1 Power factor

For short-circuit switching tests, the power factor of the testing circuits shall not exceed 0.15 lagging.

6.2.3.7.2 Frequency of test circuit

Tests demonstrating short-circuit current capabilities shall be made, preferably at rated frequency.

6.2.3.7.3 Recovery voltage

Both inherent circuit transient recovery voltage and power frequency recovery voltage must be considered when demonstrating the rating of a generator circuit breaker.

a) *Power frequency recovery voltage.* Over the testing range at which it can be obtained, the power frequency recovery voltage shall preferably be equal to the specified recovery voltage subject to a tolerance of –5%. Higher voltages may be used at the manufacturer’s discretion. Indirect tests may be used to establish the interrupting capabilities of the circuit breaker (see the descriptions of the various acceptable testing methods in 6.2.3.8).
During the single-phase tests, the specified values shall be maintained for 1 cycle of the power frequency and thereafter may be reduced to the equivalent single-phase-to-ground voltage.

b) *Transient recovery voltage.* The inherent circuit TRV (unmodified by the generator circuit breaker) shall be such as to give the applicable oscillatory waveshape with values as listed in Table 5 for the rated short-circuit currents. Table 6 is included for information on TRV values for generator-source short-circuit currents.

> Asymmetrical current-interrupting capabilities shall be demonstrated using test circuits capable of producing the rated TRV envelopes unmodified by the generator circuit breaker when a symmetrical current is interrupted. The parameters of the test circuit shall be adjusted so as to produce the specified rated inherent circuit TRV.
> The actual TRV measured during test may differ from the inherent circuit TRV due to the influence of the generator circuit breaker (its resistors and/or capacitors).

6.2.3.7.4 Control voltage

The control voltage to be maintained in the closing and tripping circuits at the generator circuit breaker operating mechanism shall be as specified in Table 11.

6.2.3.7.5 Mechanism-fluid operating pressure

The operating pressure of the generator circuit breaker’s hydraulic or pneumatic mechanism shall be as specified in Table 11.

6.2.3.7.6 Contact speeds during single-pole tests and unit tests

During single-pole tests and unit tests, the closing speed and the opening speed of the contacts in the region of arcing shall be approximately the same as during a corresponding test on the complete generator circuit breaker. If the tests are being made on a single pole or part of a single pole, or if the three-phase short-circuit currents exert a significant influence on the opening and closing speeds of the circuit breaker, the opening and closing forces shall be adjusted so that the closing and opening speeds obtained on the tests shall be approximately those (± 5%) obtained with the corresponding short-circuit current on a three-pole generator circuit breaker.

6.2.3.7.7 Grounding of the generator circuit breaker and test circuit

The normally grounded parts of the generator circuit breaker shall be grounded. If three-phase tests are made, either the neutral of the supply or the shorting connection shall be grounded, but not both. If single-phase tests are made, the test circuit should have one side grounded.

6.2.3.7.8 Current asymmetry

Interrupting tests are required with both symmetrical and asymmetrical currents. Any interrupting test in which the asymmetry of the current in all phases at contact parting is less than 20% is considered a symmetrical test.

The asymmetry of the short-circuit current usually decreases with time, and will be different for system-source currents and generator-source currents. An asymmetry at contact parting time of at least 50% is specified to give typical asymmetrical currents. It is recognized that at contact parting, higher asymmetries may occur in some instances. However, very high asymmetries, in general the generator-source currents, may have a lower rate of change of current immediately before current zero, a lower instantaneous value of the power frequency recovery voltage at the time of interruption, and arcing at the short-circuit location.

Because of the difficulty of controlling high asymmetry on close-open operations, the asymmetry specified can be demonstrated by Test duty 4 in Table 11. This capability can be satisfied also by performing Test duties 4A and 4B.

6.2.3.7.9 Obtaining the most severe switching conditions

To demonstrate the required interrupting capabilities, it is important that the generator circuit breaker performs under the most severe switching conditions. A single test demonstrating required capability may not impose these conditions. Because the arc is extinguished at a current zero, the arcing time may vary over a relatively wide range for a given value of current interrupted. A current with a zero occurring at a favorable time with respect to contact parting versus one with a zero a few degrees earlier, may subject the circuit breaker to much lower stresses.

Single-phase tests have only two zeros per cycle. Therefore, symmetrical currents require exploring 180 ° of possible contact parting time, and asymmetrical currents require exploring 360 ° of contact parting time. Usually, the most severe switching condition has the longest arcing time but it shall not be longer than in a three-phase test because single-line-to-ground short-circuits cannot occur.

The most severe short-circuit interrupting rating may be demonstrated by two tests both for symmetrical and asymmetrical current (Test duties 3 and 4 of Table 11). In one test, the contact parting occurs at a time that causes the short arcing time, and in a second test, the contact parting occurs about 30 ° later and results in prolonged arcing in the pole for another 1/2 cycle, which is the long arcing time.

Both for symmetrical and asymmetrical current, the interrupting tests shall cover a test with the longest occurring arcing time, applied to a first-pole-to-clear condition, within a three-phase circuit. The contact parting times producing the long and short arcing times may be known from previous testing or they may be found as part of the test, probably by a greater number of tests. In some cases, the contact part time cannot be controlled with sufficient accuracy with respect to the current wave. In any case, the tests shall be repeated until the oscillographic records show that the long and short arcing times have been demonstrated.

6.2.3.8 Methods of demonstrating the short-circuit current rating of a generator circuit breaker

The three-phase short-circuit current is usually the most severe duty on a generator circuit breaker and tests to demonstrate the rating are based primarily on the three-phase conditions. The test duties that completely demonstrate the performance of a circuit breaker under short-circuit conditions are listed in Table 11.

Because of limitations of test facilities, both in the laboratory and in the field, there are ratings of generator circuit breakers for which interrupting tests cannot be conducted up to full rating, including TRV requirements. When generator circuit breakers are not tested to rating, indirect tests such as described in IEEE Std C37.081-1981, or other methods may be used by the manufacturer for assigning a rating to a particular generator circuit breaker.

These are only guides and require exercise of judgment as to which tests to apply and as to the interpretation of the results. These tests cannot be accurately defined at this time; consequently, the sequence of indirect tests to be conducted in any particular case is not specified. In cases where indirect test methods have been used in design tests, and the generator circuit breaker is also tested by the direct method 1 (three-pole test), the generator circuit breaker must be capable of performing all of the operations listed in Table 11.

Design tests may be conducted at stresses in excess of rating. In conformance tests, field tests, or in-service tests, the circuit breaker is not required to have the capability of passing tests or performing under stresses that exceed the applicable ratings or related required capabilities.

The method or methods of testing used with a particular generator circuit breaker depend on circumstances, such as the rating to be demonstrated, the reactive power available for testing, the generator circuit breaker construction, and the arcing time. The methods may be used separately or may be combined. Frequently, one method is used to supplement, enhance, or verify the results obtained by another method.

6.2.3.8.1 Three-pole tests (Method 1)

Three-pole tests consist of switching, by means of a three-pole circuit breaker, a three-phase source of reactive power having a recovery voltage substantially equal to the rated maximum voltage. The current interrupted shall be increased up to the required capabilities of the circuit breaker. Testing a three-pole generator circuit breaker to rating in accordance with all the requirements listed in Table 11 gives a complete demonstration of these ratings. In many cases, the energy levels and performance capabilities of existing test stations do not allow three-pole tests. Consequently, the emphasis is on single-pole tests, unit tests, two-part tests, and synthetic tests.

6.2.3.8.2 Single-pole tests (Method 2)

This method tests a single pole of a three-pole generator circuit breaker with single-phase power, applying to the pole the same currents and substantially the same pole-unit recovery voltages that would be impressed upon the most highly stressed pole during interruption of three-phase power by a complete three-pole generator circuit breaker under the corresponding conditions.

The pole tested may be a part of a three-pole or single-pole generator circuit breaker.

To simulate three-phase short-circuits in an ungrounded system, the power frequency pole-unit recovery voltage shall be 87% of the corresponding three-phase voltage, usually with one terminal of the pole grounded. As explained in 6.2.6, the maximum arcing time on single-pole tests may be about 0.1 cycle longer than on the corresponding three-phase test with symmetrical currents, and about 0.2 cycle longer with asymmetrical currents.

To simulate reduction in recovery voltage on the first-pole-to-interrupt after the other poles have interrupted, the power frequency pole-unit recovery voltage on a single-pole test may be reduced to 58% of the simulated phase-to-phase voltage one cycle or more after interruption of the current. This permits application of the recovery voltage during the first cycle and reduces the voltage stress on resistors that may still be in the power circuit. Closing tests may be made at 58% of the simulated three-phase voltage because this is the voltage to which the first pole to make contact is subjected.

To verify the rated short-circuit current of the generator circuit breaker, Table 11 shall be used, as applicable. It contains operating duties demonstrating all the required capabilities associated with the assigned rated short-circuit current. If there is a possibility that hot gases produced by switching may cause a flashover between poles of a completely assembled generator circuit breaker by mingling of the exhaust gases, adequate provisions shall be included in the single-pole tests to demonstrate that phase-to-phase flashover will not occur in service.

6.2.3.8.3 Unit tests (Method 3)

See IEEE Std C37.09-1979 , 4.6.6.3.

6.2.3.8.4 Two-part tests (Method 4)

See IEEE Std C37.09-1979 , 4.6.6.4.

6.2.3.8.5 Pre-tripped tests (Method 5)

See IEEE Std C37.09-1979 , 4.6.6.5.

6.2.3.8.6 Synthetic tests

The synthetic test method to be used for testing a generator circuit breaker shall be agreed upon by the user and manufacturer.

6.2.3.9 Suggested short-circuit performance data form

Test data is preferably presented in a form with an accompanying tabulation of pertinent data similar to that shown in IEEE Std C37.09-1979 , Table 3, where applicable.

6.2.4 Rated transient recovery voltage (TRV)

The ability to withstand rated TRVs, as specified in Table 11 for rated symmetrical and asymmetrical currents, is demonstrated during short-circuit tests.

6.2.5 Rated standard operating duty (standard duty cycle)

The standard duty cycle is demonstrated by Test duties 3 and 4 in Table 11. Because it may be difficult to obtain specified values of making current, asymmetry, and interrupting current in the same operation, and because it is desirable to demonstrate open operations as well as close-open operations, it is suggested that the listed alternate operating duties be used in some test duties (see Table 11).

6.2.6 Rated interrupting time

The interrupting time of a circuit breaker is demonstrated for different currents by the test duties in Table 11. Interrupting times of tests, when expressed in cycles, shall be in cycles of the power frequency.

The interrupting times shall meet the requirements of 5.6. On single-phase tests, a small plus tolerance is permitted because single-phase testing at 87% of the three-phase phase-to-phase voltage is not exactly the equivalent of a three-phase test. Because the current zeros occur less frequently than in a three-phase test and the 87% of voltage is impressed only on the first pole to interrupt, and only until the other two poles interrupt, the arcing time obtained on single-pole tests may exceed the arcing time obtained on the three-phase test. During a three-phase test with symmetrical currents, after the contact gap or time has been reached at which the arc will be extinguished, a current zero will occur in one of the phases within 60 °. The arc in this phase will be extinguished and the arcs in the other two phases will be extinguished 90 ° later, a total of not over 150 ° after the time at which arc extinction is certain to occur. During a single-phase test made in accordance with 6.2.3.7.9, the next current zero may occur 180 ° later. Consequently, on a single-phase test with symmetrical currents, the maximum arcing time may be about 0.1 cycle longer than can be obtained on the three-phase test being simulated.

On three-phase asymmetrical tests, the current zeros do not occur at 60 ° intervals; on single-phase tests, the current zeros may be nearly one cycle apart. In demonstrating the most severe conditions by an asymmetrical single-phase test, the arcing time may be about 0.2 cycle longer than can be obtained on a three-phase test being simulated by a single-phase test.

6.2.7 Short-circuit current with delayed current zero

It is generally accepted that the generator circuit breaker will be required, during its life, to interrupt short-circuit currents from the generator-source with delayed current zeros. It is also recognized that the magnitudes of these short-circuit currents are considerably lower than the magnitudes of the rated short-circuit currents. The capability of the generator circuit breaker to interrupt the delayed current zeros can be ascertained by computations that consider the effect of the arc voltage on the prospective short-circuit current. The determining arc voltage model is derived from tests with comparable magnitudes of current.

If this computation entails too many assumptions on the behavior of the generator circuit breaker during interruption under the most severe conditions, short-circuit tests shall be required. If tests are carried out, it must be recognized that, normally, the required current waveshape cannot be simulated accurately in test stations.

6.2.7.1 Testing conditions

Tests shall include a predetermined nonzero current waveform associated with the rated maximum voltage and an inherent circuit transient recovery voltage, and an approximate waveform obtained either by calculation or by measurement at the generator circuit breaker’s particular application.

6.2.7.2 Interrupting circumstances

The assumption of the behavior of the generator circuit breaker is dependent on the instant of contact parting and the portion of asymmetry shared by each of the three-phases.

The following two typical situations can be considered for a particular generator-source short-circuit current for a three-phase fault:

a) One phase carries 100% offset current with no current zero, which implies that in the other two phases the offset of current is shared equally. The maximum arc duration occurs with a reduced dc offset and a reduced ac current, and the first phase to clear is not the one with the 100% offset.
b) One phase is symmetrical, and the other two phases carry a reduced dc offset current, compared to the situation in a). The maximum arc duration occurs on the phase that has an unchanged dc offset and a reduced ac current after the occurrence of the first phase to clear, i.e., the symmetrical phase.

6.2.8 Load current switching tests

6.2.8.1 General

Tests are made to determine the ability of the generator circuit breaker to switch load current up to the rated continuous current of the generator, such as load currents that may be encountered in normal service.

When switching the generator from the system, both generator circuit breaker terminals remain energized. The power frequency recovery voltage appearing across the generator circuit breaker is equal to the sum of voltage drops on the reactances of the generator and transformer and the corresponding short-circuit reactance of the high-voltage system. Since the voltage drops are caused by the load current, the recovery voltage will always have a phase displacement of 90 ° to the load current and will be independent of the load phase angle of the generator. When switching the rated load current, the voltage drops of a generator-transformer bank generally do not reach 50% of rated maximum voltage. Therefore, the load switching capability of a generator circuit breaker could be tested using an inductive short-circuit test circuit as recommended. The test results are valid for any lagging or leading power factors.

6.2.8.2 Conditions of test severity

Load current switching tests shall be made under the following conditions:

a) The test circuit shall be similar to the usual short-circuit test arrangement. Power frequency and transient recovery test voltages shall be based on the rated maximum voltage, *V*. If three-phase tests are made, they shall be made with phase-to-phase voltage equal to 0.5 *V*. If single-phase tests are made, the test voltage shall be equal to 0.87 0.5 *V* = 0.44 *V*. The TRV rate of the first-pole-to-clear in three-phase tests and for the case of single-phase test circuits shall be as specified in Table 8.
   These recommendations are based on the generator step-up transformer and the generator having the same MVA rating. It is recommended that the recovery voltage and the TRV rate required for testing be computed for each generator circuit breaker application, taking into account capacitors installed at the transformer terminals.
b) The power factor of the testing circuit shall not exceed 0.15 lagging.
c) The normally grounded parts of the generator circuit breaker shall be grounded.
d) If three-phase tests are made, either the neutral of the supply or the shorting connection shall be grounded, but not both. If single-phase tests are made, the test circuit shall be grounded.
e) To assure satisfactory operation under all switching conditions, the tests shall be made with the circuit breaker contacts parting at various positions on the current wave. To meet this requirement, either three-phase or single-phase tests can be made.
   If three-phase tests are made, the test duty shall comprise 12 tests with random uncontrolled times. For single-phase tests, the test duty shall comprise either of the following:
   1) Twelve tests where the tripping times are controlled and distributed in steps of approximately 30 ° with respect to the current wave.
   2) Forty tests with random uncontrolled times.

   Each test shall consist of a make-break or a make-15 s-break operation. The time interval between two tests of a duty cycle shall be at least 3 min, taking into account thermal limitations of parts such as resistors.
f) The tests shall be made at power frequency with a tolerance of ± 10%.

g) Tests shall be made at the minimum interrupting and operating medium pressure and minimum control voltage specified by the manufacturer.

h) To satisfy the operation endurance capabilities described in Table 8, the generator circuit breaker shall be capable of 50 interruptions of the rated continuous current without refitting or replacement of parts. In order to achieve the demonstration of this performance, the set of 12 tests required in e) 1) can be performed more than four times, or the series of 40 tests with random uncontrolled times in e) 2) can be extended up to 50 tests.

6.2.8.3 Condition of generator circuit breaker after tests

After its performance in accordance with either of the duty requirements in 6.2.8.2, the circuit breaker shall be in the following condition:

a) The generator circuit breaker shall be in substantially the same mechanical condition as before the performance of the required duty cycle.

b) The generator circuit breaker shall be capable of withstanding 75% of rated power frequency withstand voltage.

c) The generator circuit breaker shall be capable of carrying its rated continuous current without damaging heating.

It is recognized that after completion of either of these duty requirements, the generator circuit breaker should be inspected and maintained as necessary. A terminal-to-terminal resistance test shall be performed to ascertain that the resistance of the current path has not increased by more than the amount specified by the manufacturer and that the generator circuit breaker is capable of reliably carrying the rated continuous current.

6.2.9 Out-of-phase current switching tests

The tests specified in this subclause are made only if an out-of-phase current switching rating has been assigned to the generator circuit breaker by the manufacturer.

6.2.9.1 General

The out-of-phase conditions are abnormal circuit conditions due to loss or lack of synchronism between generator and power system at the instant of operation of the generator circuit breaker. The phase angle difference between rotating phasors representing the generated voltages on each side of the generator circuit breaker may exceed the normal value and may be as much as 180 °. The out-of-phase current resulting from this condition is dependent on this phase angle and attains its maximum value at 180 ° (phase opposition). If the sum of the short-circuit reactances of transformer and network on the transformer side of the circuit breaker is less than the generator short-circuit reactance, the out-of-phase current at full phase opposition would exceed the generator substransient short-circuit current I''_d resulting from a terminal short-circuit. The resulting electrodynamic overstress for the generator windings must be prevented from occurring by adequate measures such as preventing incorrect synchronization and fast fault clearing on the high-voltage side of the transformer.

The majority of generator circuit breakers are expected to close but not to interrupt under full phase opposition conditions because the latter task could be solved more conveniently by the circuit breaker on the high-voltage side of the transformer. Only generator circuit breakers having full interrupting capability (to clear short-circuit currents on either side of the circuit breaker) could have an assigned out-of-phase current switching rating. The rating is limited as outlined in Table 12 and as described in subclauses 6.2.9.2– 6.2.9.3.

NOTE — When out-of-phase current switching is a matter of special importance and the user specifies the generator circuit breaker for full-phase opposition capability, a special generator circuit breaker may be required with an interrupting rating often exceeding rated short-circuit current interrupting capability, especially with the following:

a) Power frequency recovery voltage of $\sqrt{3}\,V$ and with transient recovery voltage to be computed for the first-pole-to-clear.
b) Phase opposition current having a magnitude between the system-source short-circuit current and generator-source short-circuit current. The value shall be computed for each individual installation.

6.2.9.2 Assigned out-of-phase current switching capability

Assigned out-of-phase current switching capability is specified in terms of the following:

a) *The maximum value of the out-of-phase recovery voltage for the first-pole-to-clear.* This value implicitly defines the maximum out-of-phase angle at which the generator circuit breaker shall be capable of switching under certain prescribed conditions.
   If a generator circuit breaker has an assigned out-of-phase current switching rating, it is based on an out-of-phase angle of 90 ° at rated maximum voltage.
b) *The maximum out-of-phase current that the generator circuit breaker shall be capable of switching at the maximum out-of-phase recovery voltage specified.* The value of the assigned out-of-phase current switching rating shall be 50% of the symmetrical system-source short-circuit current.
   For generator circuit breakers having an out-of-phase current switching rating, the rating shall be indicated on the nameplate.

Table 12— Test duties to demonstrate assigned out-of-phase current switching rating First-pole-to-clear values for three-pole tests or conditions for single-pole tests

Test duty (see NOTES 4, 5)	**Operating duty** (See NOTE 3)	**Power frequency recovery voltage** (see NOTE 1)	**Inherent transient recovery voltage**		**Current interrupted at contact separation**	
			E_2 Crest voltage	**TRV rate kV/µs**	**Magnitude (A, rms)** (see NOTE 1)	**% Asym.** (see NOTE 2)
1	CO symmetrical	1.22 V	2.6 V	(6)	50% I	Below 20%
2	CO asymmetrical	1.22 V	2.6 V	(6)	50% *I*	75%

V is the rated maximum voltage of the circuit breaker in kV.
I is the rated short-circuit current of the circuit breaker.
NOTES:
1 — The recovery voltage and current to be interrupted are based on 90 ° out-of-phase angle.

2 — The percent asymmetry expressed as percent of crest value of ac component.

3 — The instant of contact separation shall be chosen to produce the most severe switching conditions as determined by design tests.

4 — Reconditioning of the generator circuit breaker is permissible after Test duty 1. If additional tests become necessary, reconditioning of circuit breaker in accordance with 6.2.9.6 is permitted and only a repeat of the particular test duty is then required.

5 — Circuit breakers equipped with opening resistors should be allowed a sufficient time interval between opening operations for cooling down. In order to reduce the cooling time the resistors may be exchanged after each opening operation.

6 — Inherent transient recovery voltage is defined by an oscillatory waveshape. The TRV values for 90 ° out-of-phase switching conditions are listed in Table 9.

6.2.9.3 Conditions of test severity for use with respect to the assigned out-of-phase current switching capability

The out-of-phase current switching tests shall be carried out under the following conditions of severity:

a) Opening and closing operations carried out in conformity with the instructions given by the manufacturer for the operation and proper use of the generator circuit breaker and its auxiliary equipment;
b) Grounding condition of generator neutral: not effectively grounded, thus, the recovery voltage for the first-pole-to-clear will be $\sqrt{2} \times 0.87 V = 1.22 V$ corresponding to an out-of-phase angle of 90 °;
c) Absence of a fault on either side of the generator circuit breaker;
d) Frequency within ± 10% of power frequency of the generator circuit breaker;
e) Tests and further conditions of severity are outlined in Table 12 and described in 6.2.9.4 –6.2.9.8.

6.2.9.4 Arrangement of the generator circuit breaker for tests

The generator circuit breaker subjected to out-of-phase current switching tests shall be a complete assembly with its own operating mechanism and shall represent its type in all details of construction and operation as recorded in certified drawings and/or specifications. The generator circuit breaker operating mechanism shall be operated at the specified minimum control voltage and the specified minimum fluid operating pressure.

6.2.9.5 Behavior of the generator circuit breaker during tests

When performing any test duty up to its assigned out-of-phase current switching rating, the generator circuit breaker shall show no signs of undue stress during operation.

6.2.9.6 Condition of the generator circuit breaker after tests

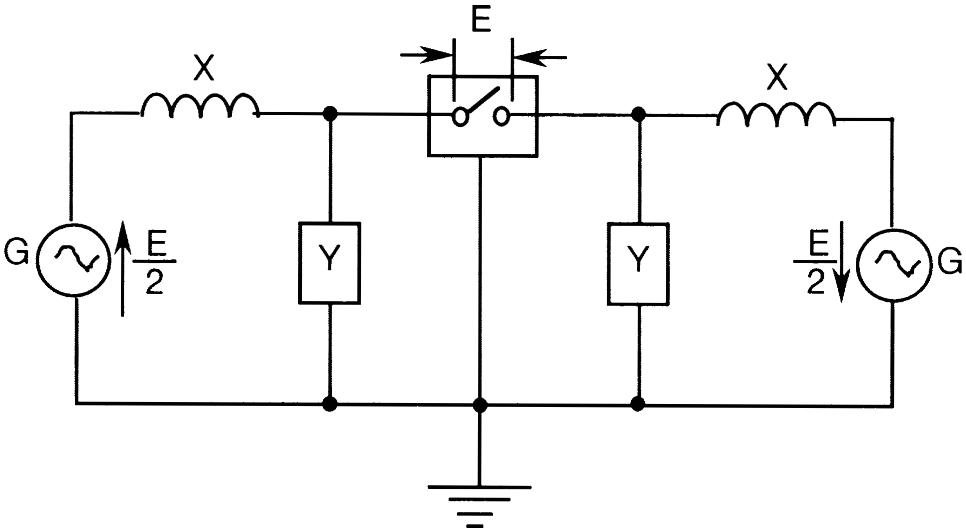
After performing the tests specified in Table 12, mechanical parts and insulators of the generator circuit breaker shall be substantially in the same condition as before the performance of the tests. The generator circuit breaker shall be capable of making, carrying, and breaking its rated continuous current at its rated maximum voltage, although the making and breaking capability of the generator circuit breaker may be materially reduced. Between test duties, the generator circuit breaker may be inspected and restored to its initial condition by maintenance work such as the following:

a) Repair or replacement of the arcing contacts and any specified renewable parts;
b) Renewal or filtration of the interrupting medium, and addition of any quantity of the medium necessary to restore its normal level;
c) Removal from the insulators of deposits caused by the decomposition of the interrupting medium.

6.2.9.7 Test circuit

The following conditions shall be satisfied:

a) The power factor of the test circuit shall not exceed 0.15 lagging;
b) For single-phase tests, the test circuit shall be arranged so that approximately one-half of the applied voltage and the recovery voltage is on each side of the generator circuit breaker (see Figure 3).

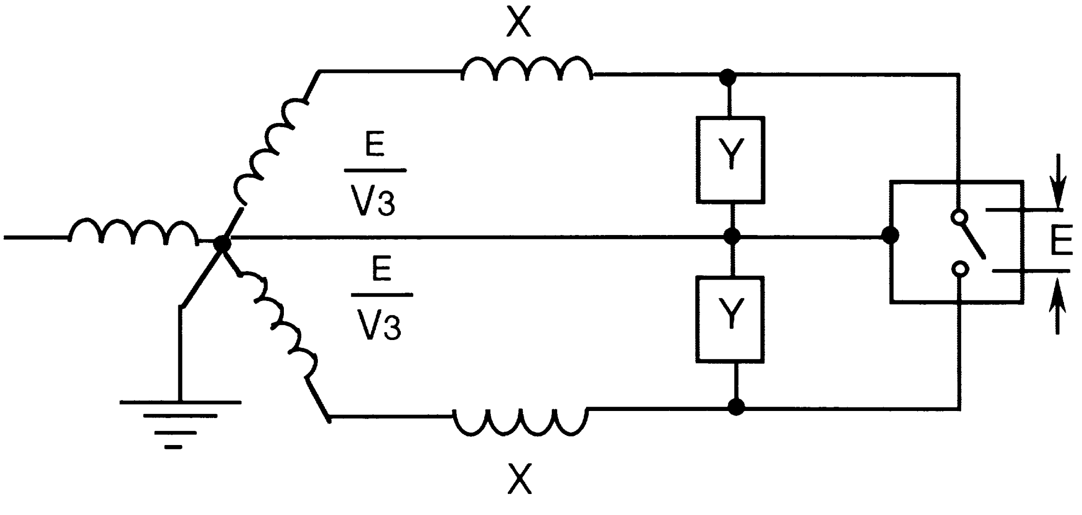


NOTE — The Y in the square represents combinations of capacitances and resistances.

Figure 3— Dual-voltage testing, 180 °

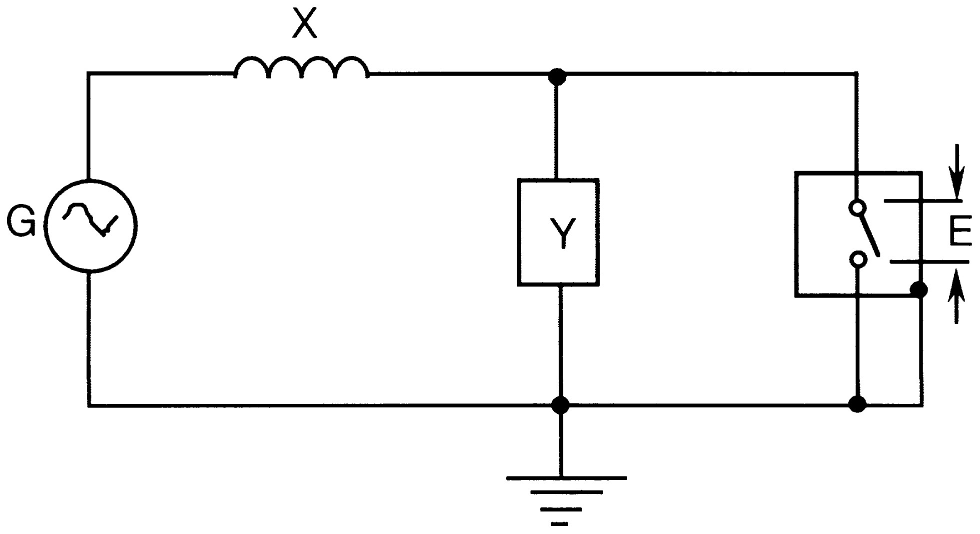
If it is not feasible to use this circuit in the testing station, it is permissible to use either of the following circuits shown in Figures 4 and 5 at the option of the manufacturer:

1) Two identical voltages separated in phase by 120 ° instead of 180 ° may be used provided that the total voltage across the generator circuit breaker is as stated in Table 12 (see Figure 4).
2) Tests with one terminal of the generator circuit breaker grounded may be used (see Figure 5).



NOTE — The Y in the square represents combinations of capacitances and resistances.

Figure 4— Dual voltage testing, 120 °



NOTE — The Y in the square represents combinations of capacitances and resistances.

Figure 5— Single-voltage testing with one side grounded

6.2.9.8 Test duties

The test duties to be performed are shown in Table 12 under 6.2.9.1.

6.2.10 Mechanical endurance life

No-load mechanical operation tests are made on a complete generator circuit breaker or on a single pole of the generator circuit breaker if all three poles are identical to ensure its satisfactory operation in normal service without excessive maintenance. In practical applications, the generator circuit breaker is connected to the bus duct by means of flexible copper or aluminum connections. The enclosure of the generator circuit breaker may be welded to the enclosure of the bus duct. These conditions should be taken into account during the tests. The test arrangement should be described in the test report and supported with photographs, if necessary.

All mechanical operation tests shall be made at rated control voltage and rated fluid (gas or liquid) pressure in the operating mechanism.

Tests involving 1000 no-load mechanical operations shall be conducted according to the following:

a) Eight hundred operations shall be performed at the ambient temperature of the test station at the rate of one CO operation every 3 min during a certain time determined by the limit of the test station, the manufacturer, and/or the user. To perform these 800 operations, several days will be needed, and these operations can be performed in several periods.
b) One hundred operations shall be performed at the minimum ambient temperature specified in item a of 4.1. For example, for outdoor generatorcircuit breakers where the temperature can reach –30 °C, these 100 operations shall be performed at this minimum temperature; for indoor circuit breakers where the temperature can reach 5 °C, these 100 operations shall be performed at this minimum temperature.
c) One hundred operations shall be performed at the maximum ambient temperature.

These 1000 no-load operations shall be performed without repair or replacement of any major parts and with the number of operations between servicing the unit (i.e., adjustments of recommended parts) at an interval of not less than 500 operations.

These mechanical operation tests may be made with any interval between operations that does not overheat bearings, momentary rated coils, valves, or other auxiliary devices.

To verify that the generator circuit breaker is in a condition that meets the requirements specified after completion of the no-load mechanical operation tests, the generator circuit breaker shall be inspected visually.

During the series of 1000 operations, the mechanical time of the main chamber contacts and any auxiliary chamber contacts shall be noted after every series of 250 operations. The average time on opening and on closing shall be within ± 10%.

6.2.11 Excitation current switching tests

Excitation current switching tests are not mandatory.

The generator circuit breaker may be called on to interrupt transformer excitation current. Because the current involved is small (i.e., a few amperes to a few tens of amperes) and the generator circuit breakers are designed to interrupt large short-circuit currents, current chopping may occur. Each generator circuit breaker design can respond differently. It is advised that overvoltages generated by the circuit breaker itself, over a range of excitation current representative of the system design, be investigated by the user.

It is recognized that no laboratory circuits represent the real network conditions exactly. Therefore, the test circuit has to be agreed upon by the manufacturer and the user so that, with such a test circuit, the necessary parameters can be determined that produce the probable overvoltages of the particular installation. To assure satisfactory research of the generated overvoltages, the tests shall be made with the generator circuit breaker contacts parting at various positions on the current wave and particularly before the zero current. To meet these requirements, either three-phase or single-phase tests can be made.

If three-phase tests are made, the test duty shall comprise two tests. For single-phase tests, the test duty shall comprise either of the following:

a) Ten tests with random uncontrolled times;
b) Three tests where the tripping times are controlled and interrupted in the minimum arcing time area of the generator circuit breaker considered.

Each test shall consist of an opening operation.

6.2.12 Sound level tests

Sound level tests shall be performed on a complete three-phase generator circuit breaker under no-load conditions. Test equipment shall be located in any accessible plane including above and below the generator circuit breaker. The peak instantaneous sound pressure level at any location 1.5 m from the envelope of the generator circuit breaker poles and equidistant between adjacent generator circuit breaker poles shall be less than 140 dB (unweighted) during circuit breaker open and close operations.

A sufficient number of measurement locations shall be chosen to identify and monitor the highest sound level locations. The test should be made at the site, if feasible, rather than in the laboratory. The tests shall be made taking into account IEEE Std C37.082-1982.

At the installation site, the sound level shall be determined for those locations accessible to personnel. Tests on site may lead to higher values than the allowed impulse sound pressure levels due to echoes. The maximum value of 140 dB (unweighted) refers to measurements in a room without echo.

6.2.13 EMC tests

EMC tests are under consideration. Refer to IEC 60694 : 1996.

6.3 Production tests

Production tests are normally made by the manufacturer at the factory as part of the process of producing the generator circuit breaker. If the generator circuit breaker is completely assembled prior to shipment, some of the production tests are made after final assembly; but other tests can often be made more effectively on components and subassemblies during or after manufacture.

If the generator circuit breaker is not completely assembled at the factory prior to shipment, appropriate tests on component parts shall be made to check the quality of workmanship and uniformity of material used and to assure satisfactory performance when properly assembled at its destination. This performance may be verified by making tests after delivery.

Production tests shall be made and shall include the following, as appropriate, for the type of generator circuit breaker specified:

a) Gas receiver tests;
b) Pressure tests;
c) Nameplate check;
d) Leakage tests;
e) Resistor, heater, and coil check tests;
f) Control and secondary wiring check tests;
g) Clearance and mechanical adjustment check tests;
h) Mechanical operation tests;
i) Timing tests;
j) Stored energy system tests;
k) Electrical resistance of current path tests;
l) Power frequency withstand voltage tests on major insulation components;
m) Power frequency withstand voltage tests on control and secondary wiring.

6.3.1 Gas receiver tests

6.3.1.1 Metal vessels

All metal vessels, except those having internal or external operating gas pressure not exceeding 101 kPa gauge (with no limitation on size), or those having an inside diameter not exceeding 15.2 cm (6 in) (with no limitation on pressure), shall be tested in accordance with Section VIII of the ASME Boiler and Pressure Vessel Code, 1995 edition, and/or any state and local codes or any appropriate international or national standards as applicable, at the point of original installation.

6.3.1.2 Porcelain components

If porcelain is used in the generator circuit breaker, the porcelain shall satisfy 5.4.2 in IEEE Std C37.09-1979, or any other international of national standard as appropriate.

6.3.1.3 Fiberglass-reinforced plastic pressurized vessels

When a fiberglass-reinforced vessel is used in the generator circuit breaker, the fiberglass-reinforced vessel shall satisfy Supplement 3.11 of NEMA SG 4-1990, or any other appropriate international or national standard as applicable at the point of original installation.

6.3.2 Pressurized systems

If safety valves or relief valves or rupture diaphragm on each pressurized gas system of a generator circuit breaker are specified they shall be in accordance either with Section VIII of the ASME Boiler and Pressure Vessel Code, 1995 edition, or any other international or national standard as applicable a the point of original installation.

When a pressurized metal vessel containing an interconnected system of metal, fiberglass-reinforced plastic, and porcelain elements is provided with a device qualifying under Section VIII of the ASME Boiler and Pressure Vessel Code, 1995 edition, this device may be used to protect the interconnected system. Any porcelain that is pressurized shall be protected by the overpressure relief device.

6.3.2.1 Pressure tests

This test is made on assembled generator circuit breakers having gas receivers, associated valves, piping, and other auxiliary pressure devices.

With the apparatus completely assembled, the pressure shall be raised until the safety valve operates, and this pressure shall be applied to all parts of the system that can be subjected to this pressure in service.

6.3.3 Nameplate check

The nameplates shall be checked for accuracy and completeness of identification and rating.

6.3.4 Leakage tests

Systems containing gas under pressure shall be placed under normal operating pressure and the supply of additional gas cut off by removal of compressor power or by closing a valve to a common supply. The leakage must not cause a decrease in pressure with time that exceeds a rate specified by the manufacturer.

6.3.5 Resistor, heater, and coil check tests

All resistors and heaters shall be checked either by operation or resistance measurements. All closing, tripping, control valve, and relay coils shall be checked either by resistance measurement or turn counters and shall be within prescribed manufacturing limits.

6.3.6 Control and secondary wiring check tests

Secondary wiring shall be checked to ensure that all connections are made in accordance with the secondary wiring diagram. Relays and other devices should be checked by actual operation, if feasible. Those circuits for which operation is not feasible shall be checked for continuity. A check shall be made for the proper sequence of operation of mechanically-operated auxiliary switches and devices.

6.3.7 Clearance and mechanical adjustment check tests

The engagement of contacts, and the positions of critical members of operating linkage and important clearances, including positions of any latches, if any, shall be checked to assure that they are within prescribed manufacturing limits during open and close operations. A close and an open operation shall be performed and the checks repeated. The unit being tested shall be checked to assure that it has opened completely during the open test.

6.3.8 Mechanical operation tests

Mechanical operation tests are made to check the adjustments if the design of the generator circuit breaker makes provision for it. The tests determine the ability of the generator circuit breaker or its components to operate correctly over the entire range of control voltage specified for its rated control voltage in Table 10, and over its entire range of operating pressure without damage to parts or substantial change in adjustments.

Following these tests, components shall be inspected visually to determine that no critical parts have sustained damage and all are in first class operating condition. Normally, this is accomplished without disassembly.

All mechanical operation tests shall include the following:

a) At minimum control voltage and maximum fluid operating pressure:
    1) Five close operations;
    2) Five open operations.
b) At maximum control voltage and maximum fluid operating pressure:
    1) Five close operations;
    2) Five open operations.
c) At rated control voltage and rated fluid operating pressure, five close-open operations with the shunt trip coil energized simultaneously with the closing of the main circuit through the generator circuit breaker. During these tests, the control switch shall be held in the close position to demonstrate that the circuit breaker is electrically trip-free (see IEEE C37.11-1997 , 2.2).

All interlocks shall be checked to ascertain that they function as intended, and to make certain that the closing operation will be completed after momentary contact of the closing control switch (see IEEE C37.11-1997).

6.3.9 Timing tests

Timing tests are made to determine the time required for circuit breakers or components to operate during open, close, and close-open operations.

Timing tests may be made by any of the following methods:

a) An oscillograph with suitable travel indicators connected to an appropriate point or points of the generator circuit breaker linkage or contacts;
b) A cycle counter or interval timer to determine the time interval after the energizing of the closing or tripping circuit to the parting or closing of contacts;
c) A time travel recorder to record graphically, as a function of time, the position of the part to which it is mechanically attached.

Oscillographs with travel indicators and time travel recorders can produce records from which the speed of the part can be calculated.

These tests, when used as production tests, are a means of checking the operation of a new generator circuit breaker within the speed range selected during development of this type of circuit breaker. After a generator circuit breaker has been in service, these tests may be used to determine whether it is still operating correctly.

Opening and closing times shall be obtained for all generator circuit breakers.

6.3.10 Stored energy system tests

Power-operating mechanisms that store energy in compressed air or other gas shall be subjected to the following tests:

a) The pressure switches shall be set and tested for operation at the correct pressures;

b) The pressure relief valve shall open within its selected range of pressure above normal pressure and shall close before the low-pressure cutoff device operates;
c) Starting at normal pressure in the reservoir, a compressed gas generator circuit breaker shall make at least two close-open operations before a low-pressure cutoff device operates.

6.3.11 Electrical resistance of current path test

The dc resistance of the current-carrying circuit from terminal to terminal of each pole unit in the closed position shall be measured with at least 100 A flowing in the circuit and shall not exceed the limit set for the rating of the generator circuit breaker by the manufacturer.

6.3.12 Power frequency withstand voltage tests on major insulation components

Power frequency withstand voltage tests for 1 min shall be made either on completely assembled generator circuit breakers at the voltages and conditions specified in 6.2.2 or on major insulation components, such as bushings, insulation braces, and operating rods.

6.3.13 Power frequency withstand voltage tests on control and secondary wiring

All control wiring associated with current transformer secondaries and voltage device secondaries shall receive a power frequency withstand voltage test of 2500 V for 1 min. All other control wiring shall receive a power frequency withstand voltage test of 1500 V for 1 min.

If the generator circuit breaker control circuit includes a motor, the motor may be disconnected during dielectric tests on the control circuit and subsequently tested, in place, at its specified dielectric withstand voltage, but at not less than 900 V.

6.4 Tests after delivery

Production tests are normally made by the manufacturer at the factory as part of the process of producing the generator circuit breaker and are made on some components or subassemblies. Tests after delivery are performed on the generator circuit breaker totally assembled in its final location. Tests at the site shall be made and shall include the following, as appropriate, based on the type of the generator circuit breaker:

a) Leakage tests;
b) Gauge tests;
c) Stored energy system test;
d) Electrical resistance of current path tests;
e) Clearance and mechanical adjustment check tests;
f) Timing tests;
g) Power frequency withstand voltage tests.

6.4.1 Leakage tests

This test is made on the completely assembled generator circuit breaker with its pumps, compressor plant, associated valves, field piping, and any other devices required by the design of the particular system to operate satisfactorily. With the apparatus completely assembled, the pressure shall be raised to the normal operating pressure to all parts of the system that can be subjected to this service pressure. The supply of additional air or gas shall then be cut off by closing a valve to the common supply. The leakage must not cause a decrease in pressure with time, which exceeds a rate specified by the manufacturer.

6.4.2 Gauge tests

All gauges and safety valves used in the completely assembled generator circuit breaker should be recalibrated once they are installed in their final locations.

6.4.3 Stored energy system tests

With all field piping connected, and without the compressor(s) or pump(s) running or without replenishing the gas in the reservoir(s), the generator circuit breaker shall make the number of close-open operations assigned by the manufacturer before a low-pressure cutoff device operates.

6.4.4 Electrical resistance of current path tests

The test described in 6.3.11 as a production test shall be re-performed on site before final commissioning of the generator circuit breaker.

6.4.5 Clearance and mechanical adjustment check tests

If the generator circuit breaker is subject to clearance and mechanical adjustments, the above clearance and mechanical adjustments will be performed on the circuit breaker once it is installed. The tests will be a repeat of the tests performed during production of the unit as described in 6.3.7.

6.4.6 Timing tests

Once the generator circuit breaker is fully installed, it will be timed as specified in 6.3.9. This is a repeat of the tests performed during production of the unit. The field tests will be limited to timing tests, and the results shall be within the range of the production test results.

6.4.7 Power frequency withstand voltage tests

This power frequency test checks the power frequency withstand voltage capability of the generator circuit breaker once it is installed.

In these power frequency tests, an alternating voltage shall be applied to the terminals of the generator circuit breaker for 1 min without damage or flashover using the following method. With the generator circuit breaker contacts closed, apply a power frequency voltage of 75% of the design withstand value, as tested under 6.2.2.1, to each phase of the generator circuit breaker individually, with the enclosure of the generator circuit breaker grounded.

7. Application guide

7.1 General

This clause is intended for general use as a guide in the application of ac high-voltage generator circuit breakers. Familiarity with other standards applying to generator circuit breakers is assumed, and provisions of those standards are indicated herein only when necessary for clarity in describing application requirements. A typical application example is presented in Annex A.

7.2 General application conditions

7.2.1 Usual service conditions

Usual service conditions for generator circuit breakers are defined in 4.1. These conditions specify limits in altitude, ambient temperature, and seismic forces.

7.2.1.1 Provisions for system growth

Power system facilities must be increased from time to time to serve larger loads. Although the generator is unlikely to be replaced with a larger generator, system growth usually results in higher values of short-circuit current. Therefore, liberal allowance in the generator circuit breaker rating for an expected future increase in system-source short-circuit current is advisable.

7.2.1.2 System design

Methods for limiting the magnitude of short-circuit currents or reducing the probability of high-current short-circuits by system design are outside the scope of this standard. Such methods should be considered where short-circuit currents approach the maximum capability of the circuit breaker.

7.2.2 Unusual service conditions

Unusual service conditions are listed in 4.2. Special specification, installation, operation, and maintenance provisions should be considered where these conditions are encountered, and should be called to the attention of the manufacturer as necessary.

7.2.2.1 Application at abnormal temperatures

The use of apparatus in ambient temperatures outside the limits of those specified in a) of 4.1 are considered special. In most applications, the generator circuit breaker is installed as an integral part of the isolated phase bus. Under these conditions, the isolated phase bus cooling directly affects the temperature inside of the enclosed generator circuit breaker. The ambient temperature and circuit breaker thermal time-constant govern the continuous current application described in 5.3.

7.2.2.2 Application at altitudes above 1000 m

Rating corrections for altitudes above 1000 m are listed in Table 1.

Example. Consider an indoor generator circuit breaker having a rated maximum voltage of 21 kV, a continuous current rating of 18 kA, a rated short-circuit current of 120 kA at rated maximum voltage, and a rated interrupting time of five cycles. Assume that this generator circuit breaker is to be operated at an altitude of 1900 m. The insulation withstand test voltages from Table 4 have to be modified with the altitude correction factors (ACF) from Table 1 by interpolating between the values given in Table 1 as follows:

$$\text{ACF} = \left[0.95 - (0.95 - 0.80)\left(\frac{1900 - 1500}{3000 - 1500}\right)\right] = 0.91$$

The rated short-circuit current at rated maximum voltage, related required capabilities, and the rated interrupting time are not affected by altitude. The rated continuous current may have to be corrected (see Table 1).

7.2.2.3 Exposure to damaging fumes or vapors, steam, salt spray, oil spray, excessive moisture, dripping water, and other similar conditions

Equipment subject to such conditions may require the following special construction or protective features:

a) Provisions to avoid condensation on all electrical insulation and current-carrying parts;
b) Bushings with extra creepage distance;
c) Special maintenance, including insulator cleaning in cases where particulate exposure represents a hazard to insulation integrity;
d) The use of materials resistant to fungus growth.

7.2.2.4 Exposure to excessive or abrasive, magnetic, or metallic dust

Equipment subject to such conditions may require the following special construction or protective features:

a) Totally enclosed equipment or compartments and provision for conditioned ventilating air;
b) Derating where current-carrying equipment designed for ventilated operation is enclosed in a non-ventilated compartment.

7.2.2.5 Exposure to explosive mixtures of dust or gases

Generator circuit breakers are not designed for use in explosive atmospheres. For this type of service, special consideration should be given so that acceptable equipment is selected.

7.2.2.6 Exposure to abnormal vibration, shock, or tilting

Generator circuit breakers are designed for mounting on substantially level structures free from excessive vibration, shock or tilting. Where any of these abnormal conditions exist, recommendations for the particular application should be obtained from the manufacturer.

7.2.2.7 Seasonal or infrequent use

Equipment stored or de-energized for long periods, such as during generator maintenance, should be protected against accelerated deterioration. Before energizing for service, operating performance and insulation integrity should be checked.

7.2.2.8 Application of unusual forces

During normal operation, the generator circuit breaker may be subjected to abnormal thermal and seismic forces, in addition to normal short-circuit current and thermal forces.

Abnormal thermal forces are due to the thermal cycling of connections to the generator circuit breaker. The application of a generator circuit breaker, as part of a long rigid bus system, may produce severe compression and tensile forces on generator circuit breaker bushings. Consult the manufacturer for this application.

Applications at nuclear power stations, where seismic forces exceed 0.5 g should be checked with the manufacturer.

7.2.2.9 Application effects of magnetic fields

Occasionally, the busbars in power plants are not enclosed and in general, effects of magnetic fields for generator continuous current below 6300 A is usually of no concern. However, the magnetic field in the neighborhood of the bus between generator and transformer may have adverse effects on equipment and building steel if the bus current exceeds 6300 A. For such a case, the manufacturer should be consulted for values of magnetic fields outside of the generator circuit breaker housing because induced voltages and currents could produce undesired heating effects. For this reason, and to avoid electromagnetic forces between the current-carrying busbars, phase-segregated metal-enclosed bus duct is usually used.

Precautions need to be observed for the following conditions:

a) The difference in the return current through the generator circuit breaker enclosure and the current flow in the busbar is above 6300 A.
b) The generator circuit breaker enclosure external magnetic field plus the magnetic field caused by the difference in current flowing through the enclosure and active part of the circuit breaker is higher than the magnetic field of a 6300 A current.

These precautions include avoidance of metal connections and/or the placement of metal support structures adjacent to and between generator circuit breaker poles and bus phases.

7.3 Application considerations

In usual applications, the principal function of the generator circuit breaker is to carry generator rated load current and provide a means for interruption of short-circuit current from the generator as well as from the power system. However, the generator circuit breaker can be used for load, transformer excitation, or out-of-phase current switching. In some cases, these switching requirements may be the determining factor in the selection of a generator circuit breaker rather than short-circuit current interruption requirements.

7.3.1 Maximum voltage for application

The maximum operating voltage of the generator cannot exceed the rated maximum voltage of the generator circuit breaker since this is the generator circuit breaker’s upper limit for operation.

NOTE — The operating voltages of generators with ratings of 200 MVA to 1500 MVA vary widely, from approximately 10 kV to 27 kV. Consequently, when defining short-circuit duties, the rated maximum voltage is the maximum operating voltage of the generator to which the circuit breaker is connected.

7.3.2 Power frequency

The rated frequency for generator circuit breakers is 50 Hz or 60 Hz, depending on the system power frequency in which the generator circuit breaker is installed.

7.3.3 Continuous current

7.3.3.1 Application considerations for normal operation

Generator circuit breakers are usually designed as an integral part of the bus duct between the generator and transformer. The generator circuit breaker must be able to carry the rated continuous current of the generator. The metal enclosed bus duct is usually phase-segregated. In many cases, the generator circuit breaker is equipped with a cooling system using air or water.

Current-carrying capabilities of generator circuit breakers under various conditions of ambient temperature and load vary from other high-voltage circuit breakers. Generator circuit breakers have two current-carrying parts that have to be considered—the active part with the interrupting device, and the metal enclosure. Various parts of the generator circuit breaker and the connected bus duct have different temperature limits that are detailed in Table 13.

Table 13— Summary of temperature limits of metal-enclosed generator circuit breaker for rated continuous current

Item	Component description	Limit of total temperature (°C)
1	Circuit breaker parts handled by operator in normal course of duties	50
2	External surfaces not accessible to operator	110
3	Enclosure and support structures with easy access	80[a]
4	Contact surfaces—hottest spot: – copper – silver, silver alloy or equivalent	70 105
5	Breaker terminals to be connected to bus duct: – active part with conducting joints: • copper connection • silver surfaced, bolted – enclosure with conducting joints: • aluminum connection, bolted or welded	70 105 80*
6	Insulation as limited by material classification	See Table 2

*It is generally recommended that the temperature of the generator circuit breaker enclosure be kept below 70 °C. However, as part of the bus duct that has a temperature limit of 80 °C defined in IEEE Std C37.23-1987, the generator circuit breaker enclosure is also subjected to this temperature. The same recommendation is valid for the connection of the generator circuit breaker to the bus duct.

7.3.3.2 Continuous load current-carrying capability based on actual ambient and connected bus duct temperature

For determining the value of continuous current-carrying capability based on the actual ambient and the connected bus duct temperature, consult the manufacturer.

If the bus duct connected to the generator circuit breaker has a temperature limit at the connection equal to the maximum authorized by IEEE Std C37.23-1987, it will heat up the generator circuit breaker in the majority of cases. As a consequence, the generator circuit breaker continuous current-carrying capability would have to be reduced. An economical compromise must be found to adapt the current-carrying capability of the bus duct and the generator circuit breaker.

7.3.3.3 Emergency conditions

Following the loss of normally required auxiliary forced-cooling systems, the temperature of the circuit breaker parts will increase. For generator circuit breakers, 5.3.3 establishes the parameters involved. In 6.2.1.6, the tests for such emergency conditions are explained.

7.3.4 Rated dielectric strength

Three different withstand voltage levels are specified for generator circuit breakers in Table 4. The full dielectric withstand voltage-to-ground and across the open gap is only obtained with the insulating medium at rated pressure unless otherwise agreed to by the user and manufacturer.

In the event of pressure loss of the insulating medium, the loss of dielectric withstand is progressive. If the insulating medium is a gas other than compressed air, the inner parts of the generator circuit breaker may remain filled with the gas at atmospheric pressure that has higher dielectric properties than the ambient atmospheric air. For a certain time under this circumstance, the generator circuit breaker is able to withstand more than the operating voltage, even in phase opposition conditions. This time should be used to remove the generator circuit breaker from service by complete electrical isolation, preferably by automatic means, before any ingress of humidity, dust, or both, has taken place. This electrical isolation should be completed within 1 h of the loss of insulation medium pressure.

Unusual circumstances may exist where, due to operational conditions, a time longer than 1 h is desirable before the generator circuit breaker is isolated from the source. If such a situation exists, the generator circuit breaker should be prevented from operating. To provide for this unusual circumstance, the following data should be requested from the manufacturer:

a) Withstand voltage-to-ground and across contacts with the insulating medium at atmospheric pressure;
b) The current-carrying capability of the generator circuit breaker with the insulating medium at atmospheric pressure.

7.3.5 Short-circuit current ratings

7.3.5.1 Background of short-circuit current rating

The symmetrical short-circuit current, which a generator circuit breaker can experience, is explained by Figure 6, a general diagram of a power station, with a short-circuit shown in the following different locations:

a) The system-source short-circuit current (location a, Figure 6);
b) The generator-source short-circuit current (locations b & c, Figure 6);
(Location b has a higher short-circuit current than location c; therefore location c can be disregarded for the following considerations.)

In all practical applications, the system-source symmetrical short-circuit current is higher than that of the generator-source case because the sum of the short-circuit reactance of the transformer and the system is lower than the subtransient and transient reactances of the generator.

The generator-source short-circuit current has no direct relationship to the system-source short-circuit current. Because the system-source short-circuit current is higher than the generator-source short-circuit current, it has been specified as the rated short-circuit current of a generator circuit breaker.

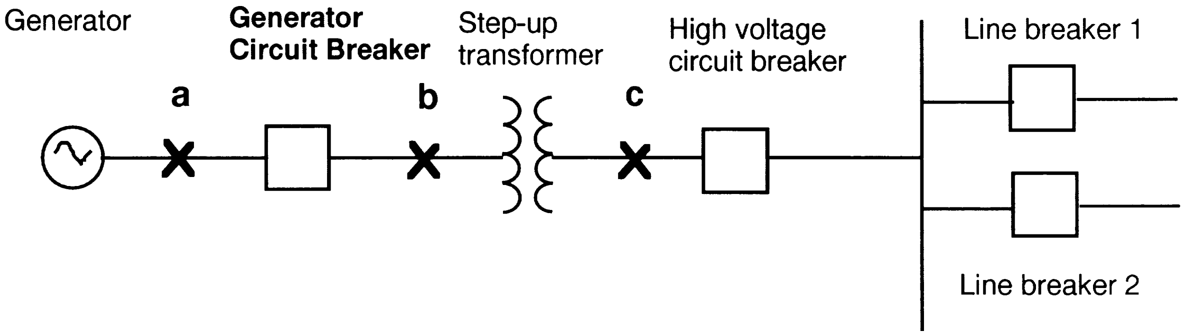


Figure 6— General circuit diagram of a power station

7.3.5.2 Rated short-circuit current

The definition for rated short-circuit current given in 5.8.1 states that it is the highest rms value of the symmetrical component of the three-phase short-circuit current that the generator circuit breaker is required to interrupt at rated maximum voltage and rated duty cycle.

7.3.5.3 Related required capabilities

The following are related required capabilities concerned with the short-circuit current:

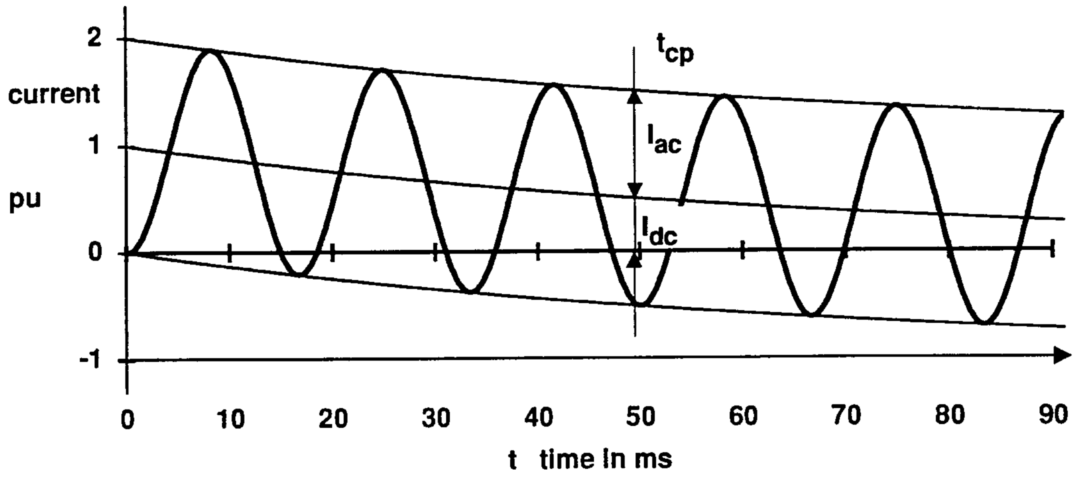
a) System-source short-circuit currents:
   1) Symmetrical interrupting capability;
   2) Asymmetrical interrupting capability;
   3) Short-time current-carrying capability.
b) Generator-source short-circuit currents:
   1) Symmetrical interrupting capability;
   2) Asymmetrical interrupting capability;
   3) Asymmetrical interrupting capability for maximum degree of asymmetry.
c) Generator-source or system-source: closing, latching, and carrying capability.

7.3.5.3.1 Required symmetrical interrupting capability for three-phase faults

This capability is based on the rated short-circuit current.

7.3.5.3.2 Required asymmetrical interrupting capability for three-phase faults

This capability is based on the rated short-circuit current. Its dc component decays with a time constant of 133 ms and depends on the primary contact parting time, which is the sum of 1/2 cycle tripping delay plus the minimum opening time of the generator circuit breaker. It is calculated with the formula below and illustrated by Figure 7. The numerical values are shown in Figure 2.



I_{ac} is $\sqrt{2}$ Isym= peak value of the symmetrical ac component of the short-circuit current
I_{dc} is the dc component of the asymmetrical short-circuit current
t_{cp} is the contact parting time

Figure 7— Asymmetrical system-source short-circuit current

The degree of asymmetry a at the time $t$cp is determined by the following equation:

$$a = \frac{I_{dc}}{I_{ac}} = \text{degree of asymmetry}$$

with the dc component

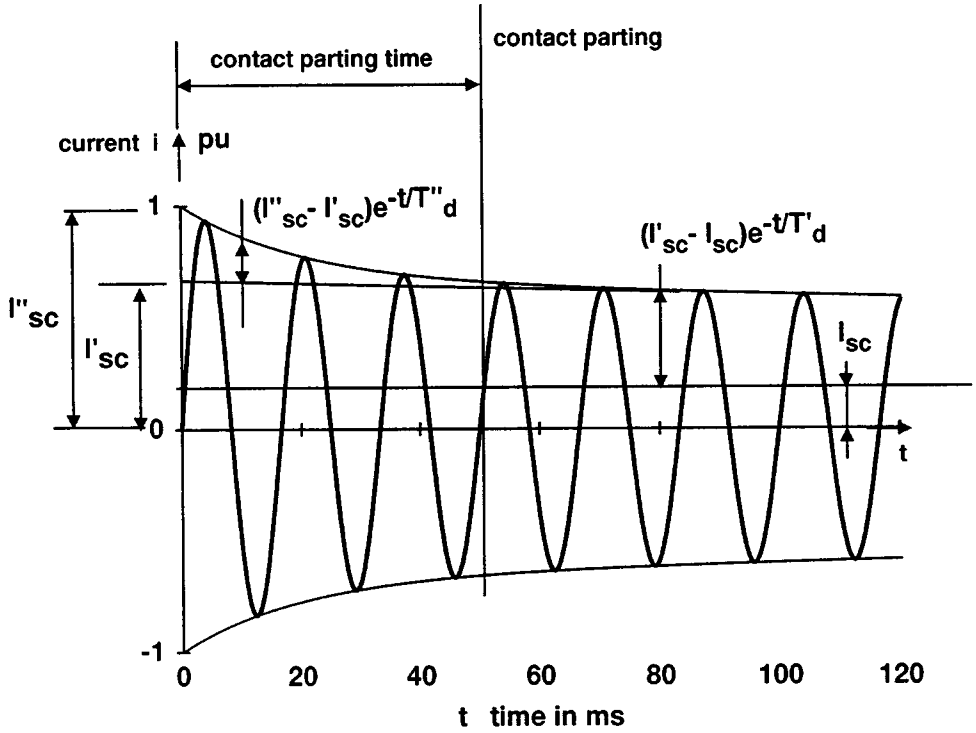
$$I_{\mathrm{dc}} = I_{\mathrm{ac}} e^{-t_{cp}/\tau}$$

where

τ	is 133 ms

7.3.5.3.3 Required generator-source symmetrical interrupting capability

The generator-source symmetrical short-circuit current is significantly lower than the system-source short-circuit current. Its value is measured from the envelope of the current excursion at the moment of primary contact separation when the source of the current is entirely from a generator without transformation. This envelope has to be calculated from a full-load rated power factor condition taking the generator constants into account. It must be recognized that the ac component of this short-circuit current decays with the subtransient and transient time constants of the generator and is illustrated by Figure 8.



I_{sc}''	is the subtransient component of the generator-source short-circuit current
I_{sc}'	is the transient component of the generator-source short-circuit current
I_{sc}	is the steady state component of the generator-source short-circuit current
T_{d}''	is the subtransient time constant of the generator
T_{d}'	is the transient time constant of the generator =

Figure 8— Generator-source short-circuit current

7.3.5.3.4 Required generator-source asymmetrical interrupting capability for three-phase faults

The ac component of the short-circuit current, when the source is from a generator without transformation, may decay faster than the dc component. The decay of the ac component is governed by the subtransient and transient time constants T_d'', T_d', T_q'', T_q' of the generator and the decay of the dc component by the short-circuit time constant, $T_a = X_d''/\omega R_a$, where X_d'' is the direct axis subtransient reactance and R_a represents the armature resistance. As a consequence, the dc component at contact parting can be higher than the peak value of the ac component. A survey of many generators with different ratings revealed that at full load and with maximum generator-source symmetrical interrupting short-circuit current, the degree of asymmetry could be 110% as a conservative value. This value varies very little within a practical range of contact parting times.

7.3.5.3.5 Required generator-source asymmetrical interrupting capability for maximum degree of asymmetry

The highest value of asymmetry occurs when, prior to the fault, the generator is operating in the underexcited mode with a leading power factor. Under this condition, the dc component may be higher than the symmetrical component of short-circuit current and may lead to delayed current zeros. This principle is illustrated in Figure 9 and explained in 7.3.5.3.5.1–7.3.5.3.5.3.

When a short-circuit occurs, but prior to the fault the generator is carrying load with lagging power factor, the asymmetrical short-circuit current excursion is similar to curve (a), whereas for a leading power factor its excursion follows the curve (b) in Figure 9.

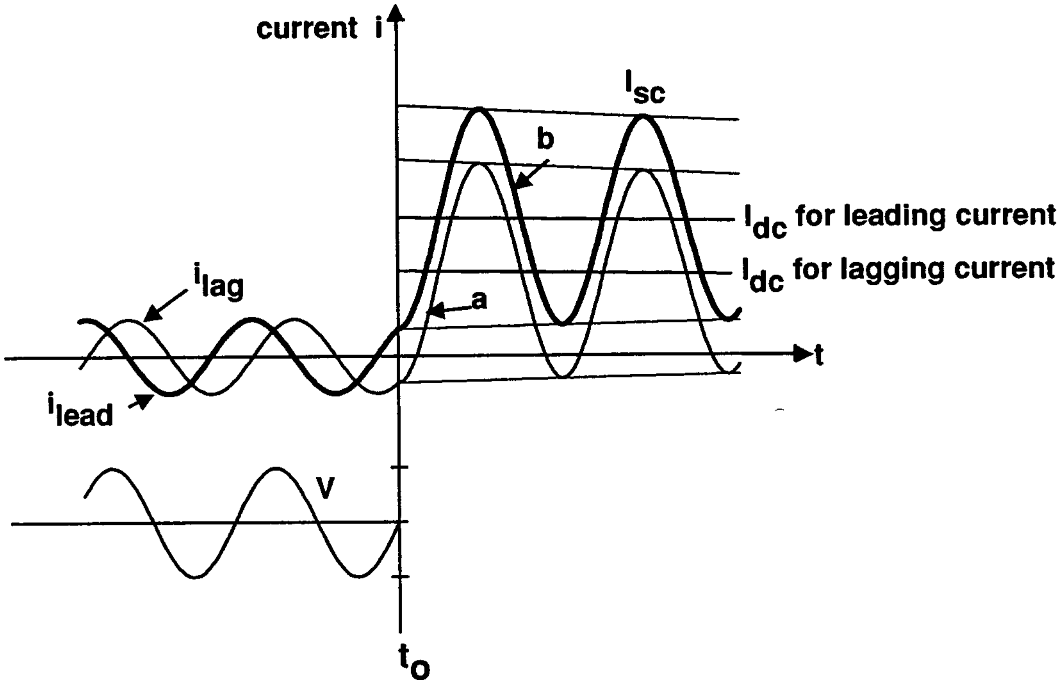


Figure 9— DC component of generator-source short-circuit current for leading or lagging load current prior to short-circuit

The analysis of a large number of generators resulted in a maximum degree of asymmetry of 130% of the actual short-circuit current. The symmetrical component of the short-circuit current for this case is only 74% of the value of the required generator-source symmetrical interrupting current.

7.3.5.3.5.1 Origin of high asymmetries with delayed current zeros

A short-circuit current will flow if the generator circuit breaker is closed into a short-circuit or as a consequence of a flashover in at least two phases to ground or between phases. Under a no-load condition of the generator, if a short-circuit is initiated at a voltage minimum, an asymmetrical short-circuit current with a dc component will occur.

The ac component of the short-circuit current will decrease exponentially in time with the short-circuit subtransient and transient time constants T_d'', T_d', T_q'', T_q' of the generator, depending on the specific case. (Often only the open circuit time constants T_{do}'', T_{do}', T_{qo}'', and T_{qo}' are known. For computation of the short-circuit currents, the short-circuit time constants T_d'', T_d', T_q'', and T_q' can be calculated using relatively simple formulas). The dc component of the short-circuit current decays exponentially in time, with the short-circuit time constant $T_a = X_d'' /(2\pi\ f\ R_a)$. Depending on the value of these time constants, which may vary in a relatively wide range for different sizes and designs of generators, the ac component of the short-circuit current may decrease faster than the dc component, leading to delayed current zeros for a certain period of time.

Typical values for time constants mentioned in the preceeding paragraph are T_d'' and T_q'' =25– 45 ms, T_d' = 0.8–1.5 s, T_q' = 250– 400 ms, T_a = 150– 400 ms.

Figure 10 shows an example of a calculation of short-circuit current for a generator-source fed fault.

As described in 7.3.5.3.5, the highest value of asymmetry occurs when, prior to the fault, the generator is operating in the underexcited mode with a leading power factor. Under such a condition, the symmetrical component of short-circuit current is lower than the required generator-source symmetrical short-circuit current. In the case where the generator is carrying load with a lagging power factor prior to the fault, the asymmetry will be lower, and delayed current zeros should not be expected.

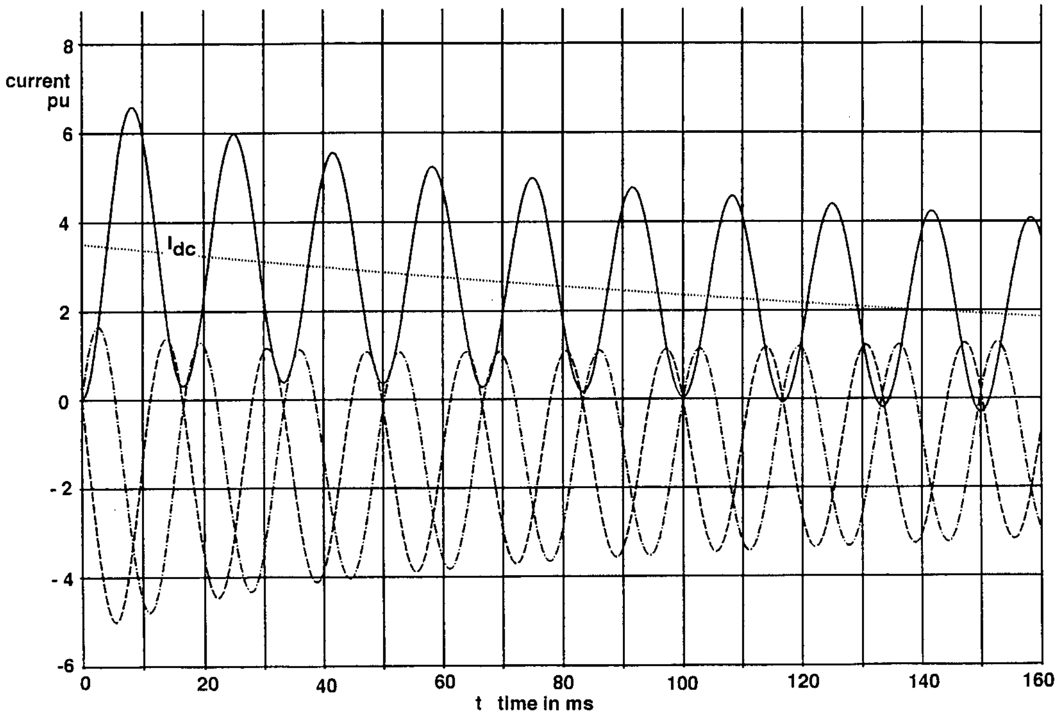


Figure 10— Short-circuit current for generator-source fed fault

7.3.5.3.5.2 Interruption of short-circuit currents with delayed current zeros

Additional resistance in series with the armature resistance, $R_a = X_d'' / (2\pi f T_a)$, forces the dc component of the short-circuit current to decay faster. If R_{add} is the additional resistance, the dc component decreases more quickly with the time constant $T_a = X_d'' / [2\pi f(R_a + R_{add})]$. Such additional resistance may be the connection from the generator to the fault location, but especially the arc resistance of the fault and the circuit breaker arc resistance after contact separation. If there is an arc at the fault location, this arc resistance further reduces the time constant of the dc component from the beginning of the fault and the circuit breaker arc resistance after contact separation. The values of these additional series resistances are normally high enough to force a fast decay of the dc component of the short-circuit current so that current zeros are produced.

Figure 11 shows the current from the example shown in Figure 10, in the phase with the highest asymmetry. At the moment of contact parting, the decay of the dc component changes suddenly due to the influence of the arc voltage of the generator circuit breaker. The dc component of the current does not decrease exponentially because arc resistance due to arc voltage is not constant. Arc resistance at the fault location was not taken into account in this example. However, within one cycle after contact separation, current zeros occur.

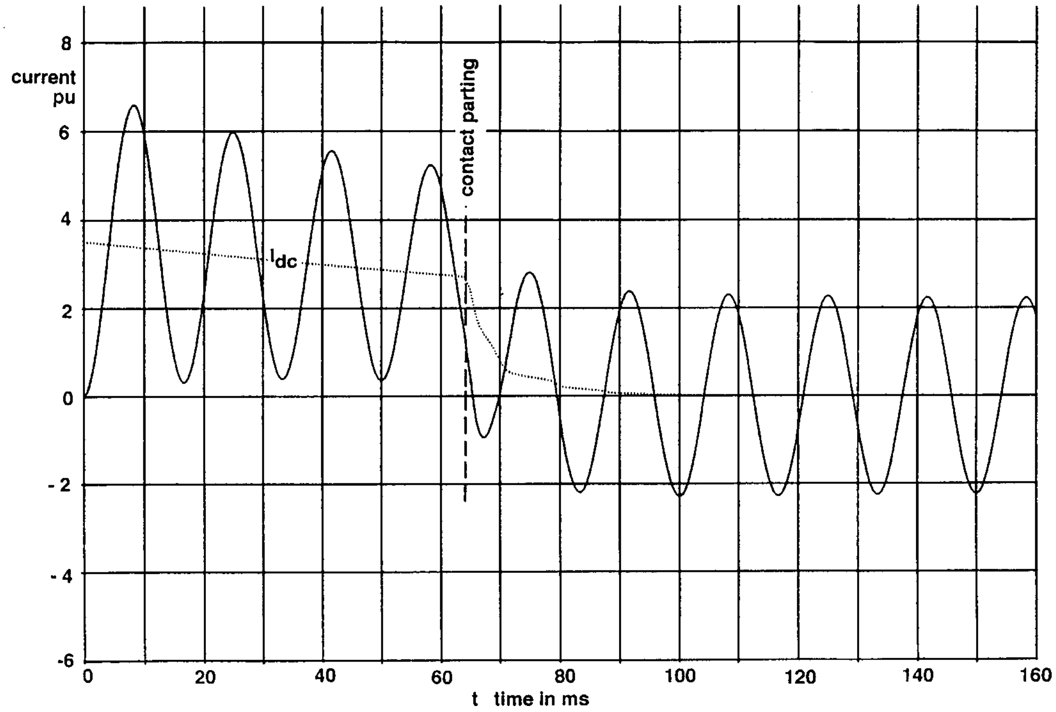


Figure 11— Short-circuit current with circuit breaker arc voltage after contact separation

7.3.5.3.5.3 Proof of the capability of the generator circuit breaker

Demonstrating the capability of a generator circuit breaker to interrupt short-circuit currents with delayed current zeros may be difficult and limited in high power testing stations. Since various designs of generators behave differently, it may not be possible to simulate the required current shape in the testing station.

If, in some cases, three-phase tests in power testing stations are possible, the conditions described in 6.2.7.2 shall be observed.

The capability of the generator circuit breaker to interrupt such currents can be ascertained by calculation considering the effect of arc voltage. The arc voltage versus current can be determined by other tests.

The following two cases are of interest:

a) *Generator at no-load with the generator circuit breaker closing into a three-phase fault.* The maximum asymmetry appears in one phase. In the computation, the arc voltage of the generator circuit breaker after contact separation must be taken into account.

b) *Generator in service with leading power factor.* An arcing fault is assumed in at least two phases. For the computation, arc voltage or arc resistance at the fault location starting at the initiation of the fault, and the arc voltage or arc resistance of the generator circuit breaker starting at contact separation have to be taken into account.

7.3.5.3.6 Required closing, latching, and carrying capability

The short-circuit current into which the generator circuit breaker must close is determined by the higher value of either the system-source short-circuit current or the generator-source short-circuit current. In the majority of applications the system-source short-circuit current (rated short-circuit current) is higher than the generator-source short-circuit current.

The ratio of the maximum asymmetrical short-circuit peak current at 1/2 cycle to the rated short-circuit current of the generator circuit breaker is determined by the following formula:

$$\frac{I_{\text{peak}}}{I_{\text{sym}}} = \sqrt{2} \times \left(e^{-\frac{t}{133}} + 1 \right) = 2.74$$

with t approximately 1/2 cycle in ms for 50 Hz or 60 Hz respectively.

In the rare cases where the generator-source short-circuit current might be higher than the system-source short-circuit current special considerations are necessary. The required generator-source symmetrical interrupting capability at contact parting time depends on the decay of the ac current with the generator time constants T_d'', T_d', T_q'' and T_q' and varies from one application to another. As stated in 5.8.2.6, no specific values are given for this case and the current has to be established by calculation. This calculation will then also establish the peak value of the generator-source short-circuit current. The equation in A.3.2 could be used for an estimation.

7.3.6 Inherent transient recovery voltage for system-source and generator-source short-circuits

7.3.6.1 Background

The principles in IEEE Std C37.011-1979 are applicable when TRV problems are considered during the interruption process of short-circuit currents by a generator circuit breaker. An exception is that the short-line fault rating does not apply.

The generator circuit breaker is a special application because it is installed between a generator and step-up transformer, the characteristics of which largely dictate the waveshape of the inherent TRV for various duties. Therefore, the TRV ratings are defined for the generator-source and the system-source fed fault, depending on the generator or transformer ratings (see Tables 5, 6, and 8). These ratings are determined for the first-pole-to-clear and for symmetrical current interruption. Rated TRVs are inherent values assuming an ideal generator circuit breaker. These values may be modified by the generator circuit breaker characteristics or by the asymmetry of the current.

A system with a TRV that exceeds the rated values must be modified in such a way as to lower the TRV. This is achieved by placing a low ohmic resistor in parallel with the main interrupting device of the generator circuit breaker or by connecting capacitors to its terminals, usually on the transformer side.

7.3.6.2 Basis of standardized TRV parameters for the interrupting of short-circuit currents

Several cases should be considered based on the following:

a) System-source fed faults where the short-circuit is located on the generator side of the generator circuit breaker;
b) Generator-source fed faults where the short-circuit is located on the transformer side of the generator circuit breaker.

The neutral of the generator is not solidly grounded, thus the phase-to-ground short-circuit current is not significant. A three-phase fault is the most severe case and gives the maximum short-circuit current and the maximum TRV rate.

7.3.6.2.1 Influence of the station configuration

The most commonly used station one-line configuration is shown in Figure 12, where the generator and the step-up transformer have essentially the same rating. Other arrangements having the same total rating as in Figure 12 are shown in Figures 13 and 14. In each case, the auxiliary transformer is a minor source of short-circuit current and can be neglected.

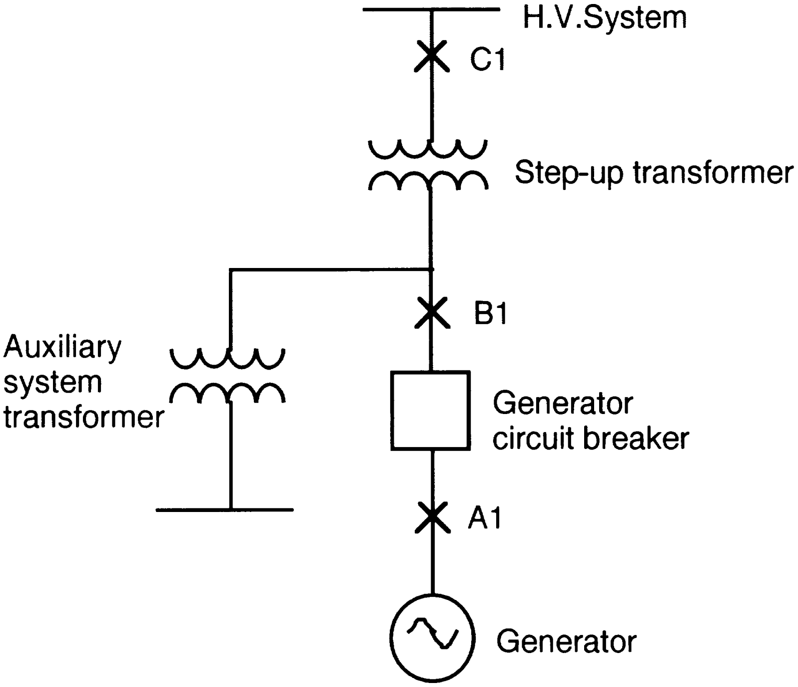


Figure 12— Single-line diagram of unit generator system

7.3.6.2.1.1 System-source fed faults

For a system-source fed fault at A1 in Figure 12, the short-circuit current is determined by the sum of the transformer reactance, X_t and the high voltage (HV) system reactance, X_s. The maximum value of short-circuit current is obtained for a given transformer when X_s is minimum or assumed to be zero.

The natural frequency of the transformer is much higher than the natural frequency of the HV system. Therefore, the TRV first oscillates at the value of voltage drop in the transformer, $X_t I \sqrt{2}$ to the prospective value of 1.5 $X_t I \sqrt{2}$, where I is the rms value of the available symmetrical short-circuit current.

The voltage drop in the transformer is equal to the total normal frequency recovery voltage for $X_s = 0$. Therefore, the TRV rate is maximum when the short-circuit current is maximum. This is contrary to what is observed in HV systems, where the TRV rate increases when the short-circuit current decreases.

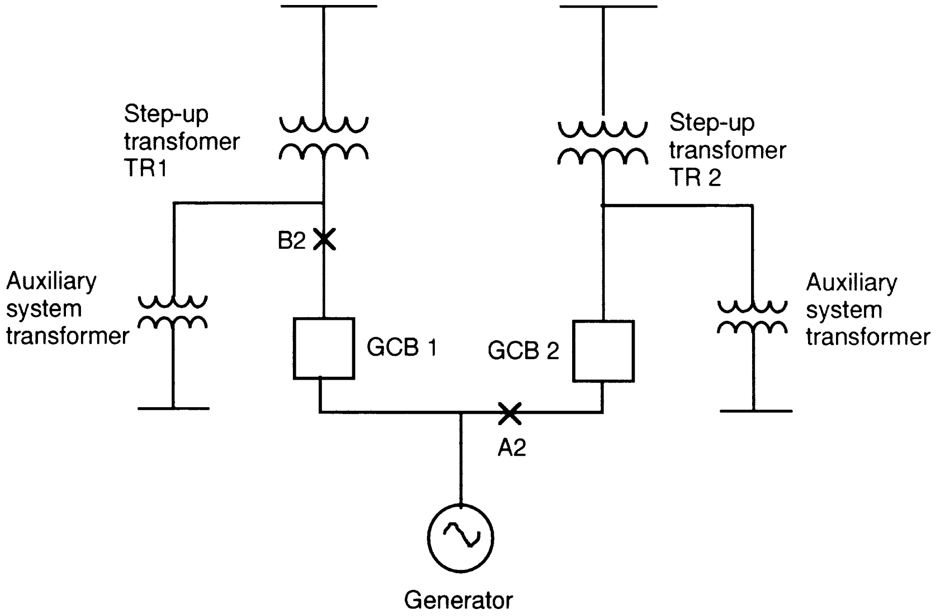


Figure 13— Single-line diagram of half-sized transformer unit system

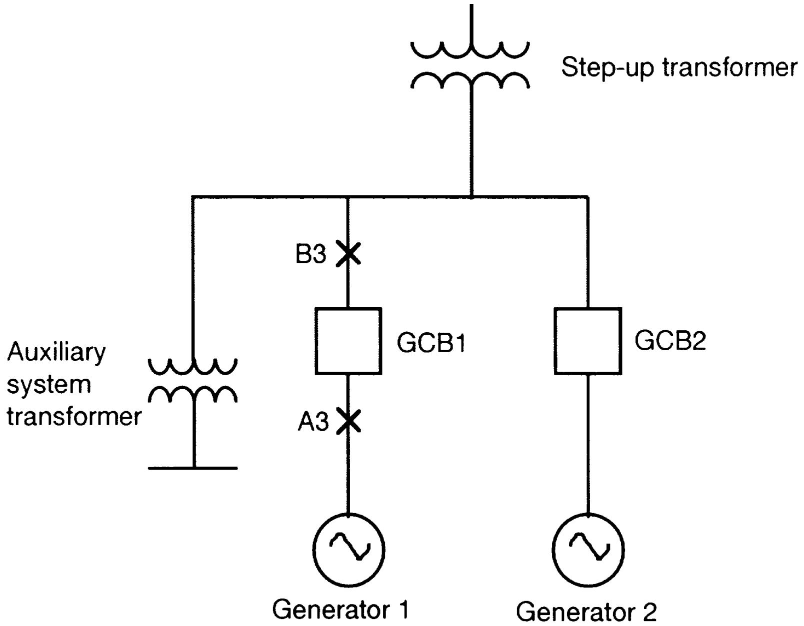


Figure 14— Single-line diagram of system with half-sized generators

Practically, the maximum observed TRV rate is 75–90% of the theoretical value determined from the natural frequency of the step-up transformer, taking into account the capacitance of the low-voltage side, including the auxiliary transformer.

A larger reduction in TRV rate is observed if capacitors are installed on the low voltage side of the step-up transformer. The TRV rate is reduced from 6 kV/μs to a value of 4 kV/μs with the addition of 0.1–0.2 μF of capacitance per phase. The standardized values of TRV rate do not take into account this capacitance.

For a system-source fed fault at A2 in Figure 13, the situation is the same as for a fault at A1 in Figure 12, except that the short-circuit current and the TRV parameters seen by the individual circuit breakers are related to a step-up transformer of lower rating.

For a system-source fed fault at A3 in Figure 14, the short-circuit current is higher because the fault is also fed by the generator, G2. However, the TRV rate is lower because of the capacitance of the G2 generator windings. If the generator G2 is out of service, the situation is the same as for a fault at A1 in Figure 12, except that the generator G1 is approximately half the rating.

7.3.6.2.1.2 Generator-source fed faults

For a generator-source fed fault at B1 in Figure 12, the short-circuit current is lower than for the system-source fed fault at A1 in Figure 12, because of the higher reactance of the generator windings.

Although the short-circuit current and TRV rate are lower for generator-source fed faults than for system-source fed faults, generator-source fed faults cannot be ignored because of the high degree of asymmetry of the short-circuit current (see 5.8.2.4), thus the corresponding TRV parameters must be specified.

For a generator-source fed fault at C1 in Figure 12, on the HV side of the transformer, the short-circuit current is lower when compared to a fault at B1 in Figure 12. This fault location can usually be ignored because the resulting stresses on the generator circuit breaker are much lower than for faults at A1 and B1 in Figure 12.

The TRV results from transformer and generator voltage oscillations. The magnitude of each oscillation is approximately proportional to the transformer and generator reactances, respectively.

For a generator-source fed fault at B2 in Figure 13, if the transformer TR2 is out of service, the oscillation is the same as for a fault at B1 in Figure 12 with the short-circuit current and TRV parameters determined by the rating of the generator. If the transformer TR2 is in service and the generator circuit breaker GCB1 is the first to open, the short-circuit current is higher than for a fault at B1 in Figure 12, and TRV parameters are intermediate in value, between TRV parameters for the full-sized generator and TRV parameters for the half-sized transformer. This case needs special consideration to determine the required TRV parameters.

7.3.6.3 Rated inherent transient recovery voltage

The rated voltages of generators and associated step-up transformers are not standardized. The short-circuit currents therefore will vary widely.

After reviewing available equipment data, TRV parameters were standardized based on the power rating of the step-up transformer and generator, respectively.

Table 5 gives the parameters of the rated TRV applicable when the fault is located on the generator side of the generator circuit breaker and the source of the short-circuit current is the power system through a step-up transformer. The values are applicable to the interrupting operation of rated short-circuit current according to 5.8.1 and required symmetrical interrupting capability for three-phase faults according to 5.8.2.1. For the required asymmetrical interrupting capability for three-phase faults according to 5.8.2.2, the same inherent TRV parameters are to be used but the actual TRV will be less severe due to the asymmetry. At the instant of current interruption at current zero, the normal frequency recovery voltage is shifted in phase due to the dc component of the asymmetrical current and the TRV oscillates around a lower instantaneous normal frequency recovery voltage value than for the symmetrical case.

Table 6 gives the parameters of the rated TRV applicable when the fault is located on the transformer side of the generator circuit breaker and the source of the short-circuit current is the generator. The values are applicable to the interrupting operation of the required generator-source symmetrical interrupting capability for three-phase faults according to 5.8.2.3. For the required generator-source asymmetrical interrupting capability for three-phase faults according to 5.8.2.4, and the required generator-source asymmetrical interrupting capability for maximum required degree of asymmetry according to 5.8.2.4.1, the same inherent TRV parameters are to be used but the actual TRV will be less severe due to the asymmetry for the same reason stated above. At the interruption of the short-circuit current with maximum asymmetry, the transient oscillation of the recovery voltage will be very small or even non-existent since at the moment of short-circuit current interruption, the normal frequency voltage value may be very small or zero.

TRV parameters listed in Tables 5 and 6 apply to the first-pole-to-clear for a three-phase fault, with a first-pole-to-clear factor equal to 1.5. The TRV oscillates as shown in Figure 15.

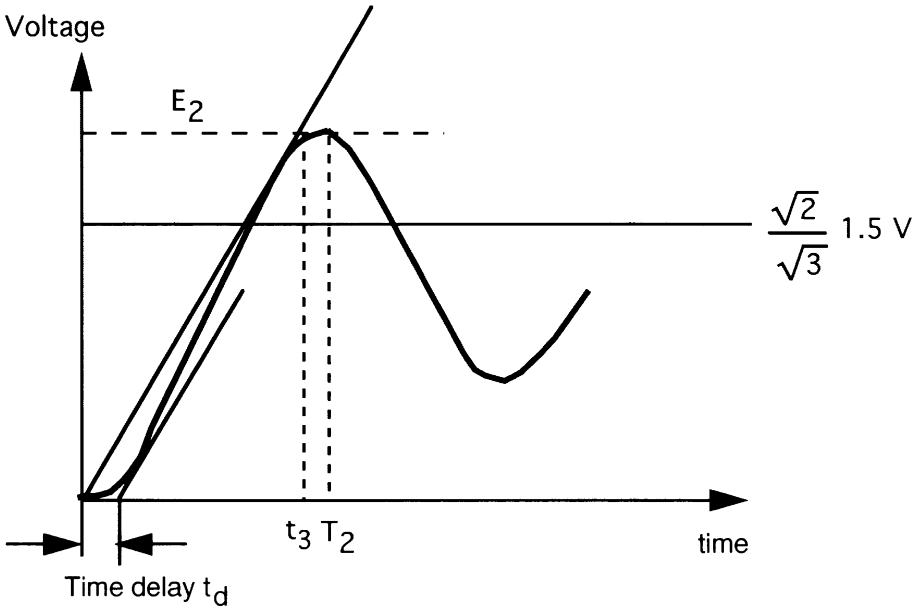


Figure 15— Inherent TRV curve for first-pole-to-clear for required symmetrical interrupting capability for three-phase faults

The curve rises to the crest value, E_2 equal to 1.84 V where V is the rms value of the rated maximum voltage in kV and the value 1.84 is equal to

$$\sqrt{\left(\frac{2}{3}\right)} \times 1.5 \text{ (= first-pole-to-clear factor)} \times 1.5 \text{ (= amplitude factor)}$$

The rising part of the TRV curve is bounded by two lines. One line goes through the origin and tangent to the TRV curve with a slope equal to the TRV rate. The other line has the same slope and goes through the point t_d, time delay.

Near the crest, the TRV curve has approximately a 1 – cosine wave-shape with a time-to-crest equal to

$$T_2 = \frac{t_3}{0.85} = \frac{E_2}{0.85 \times \mathrm{TRV\ rate}}$$

7.3.6.4 First-pole-to-clear factor

The first-pole-to-clear factor is 1.5 and corresponds to the worst condition of a three-phase grounded fault on a high impedance grounded system.

7.3.6.5 Amplitude factor

Analysis of the available data gives 1.5 as a realistic value, with no capacitance connected to the terminals of the generator circuit breaker.

7.3.7 Load current switching

During normal service of the generator, the load current is reduced to zero before an opening operation of the generator circuit breaker is initiated. However, the interruption of full load current may be required occasionally for emergency circumstances. Inherent transient recovery voltages are shown in Table 8 for this situation.

7.3.7.1 Power frequency recovery voltage

The single-line diagram, Figure Auto_L2_First, and the equivalent circuit, Figure Auto_L2, show a generator supplying a load having an impedance Z_L through a transformer T with a reactance, X_t and a transmission line with a reactance X_L. The generator is synchronized with the rest of the system symbolized by a single generator E''_{Gn}, a single transformer X_{tn}, and a single load, Z_n.

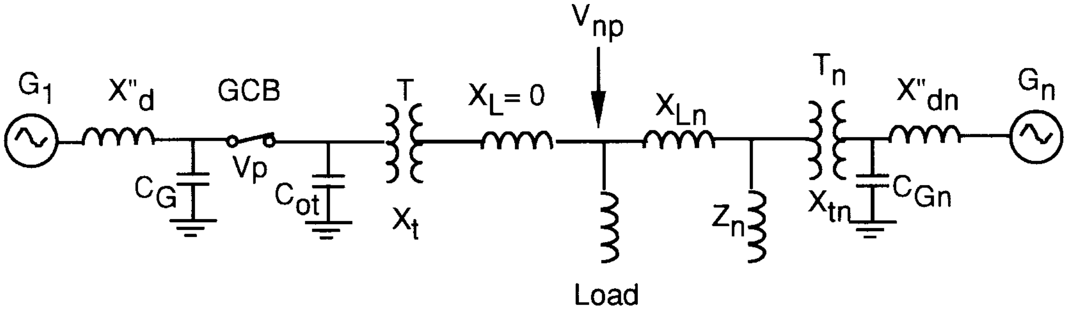


Figure 16.A— Single-line diagram of power system

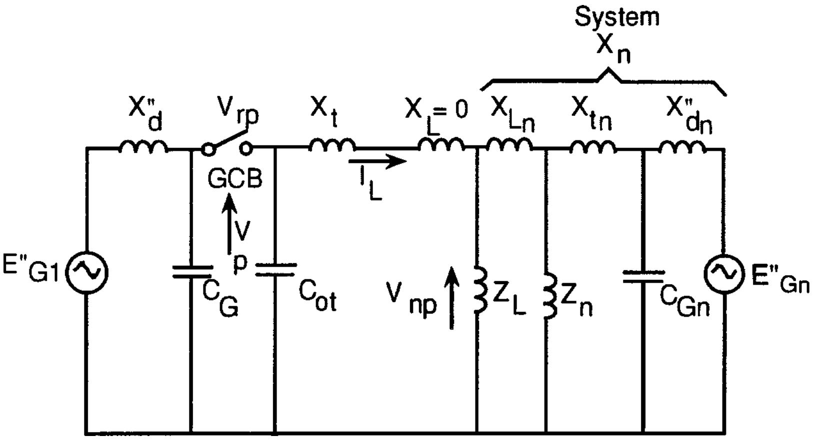


Figure 16.B— Equivalent circuit of power system

In comparison with the sum of reactances from the generator G_1 to the load $Z_{L,}$ the short-circuit reactance of the HV network is small and can be neglected. Thus, when I_L is interrupted and the network only serves the load $Z_{L,}$ there is no voltage drop in the HV network.

The magnitude of the load current I_L determines voltage drops through the reactances of generator G1 and transformer *T.*

These voltage drops have a phase shift of 90° leading, to the current $I_{L,}$ irrespective of the load phase angle ϕ, as shown on vectorial diagrams Figure 16C and Figure 16D, the latter corresponding to an almost pure resistive load.

Figure 16C—Voltage diagram for lagging power factor load

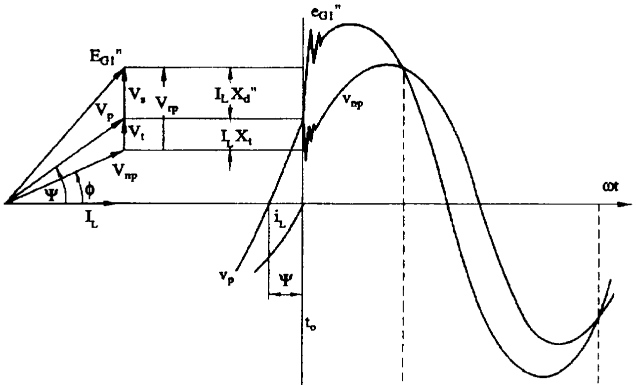


Figure 16D—Voltage diagram for a unity power factor load

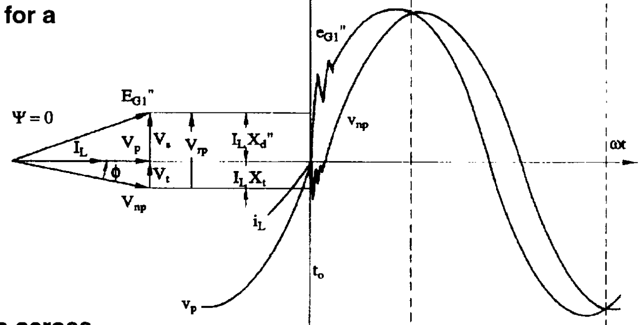
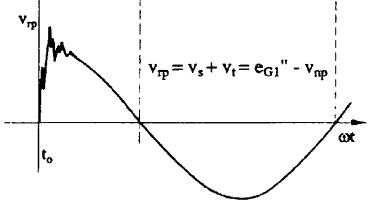


Figure 16E—Recovery voltage across the generator circuit breaker



C_G	is the capacitance, generator side
C_{ot}	is the capacitance, transformer side
$E_{G1}''(e_{G1}'')$	is the generator voltage at generator circuit breaker terminals after time t_o
I_L (i_L)	is the load current
V_{np}	is the system voltage (at the load terminals)
V_p (v_p)	is the operating voltage at the circuit breaker terminals before time t_o
V_{rp} (V_{rp})	is the recovery voltage across the switch
X_d''	is the subtransient generator reactance
X_L	is the line reactance (from transformer to load)
X_n	is the HV system short-circuit reactance = $X_{dn}'' + X_{tn} + X_{Ln}$
X_t	is the transformer reactance
Z_L	is the load impedance
G_1	is the generator (load current I_L)
GCB	is the generator circuit breaker
T	is the transformer
ψ	is the phase angle at generator circuit breaker location
ϕ	is the load phase angle
ω	is the angular frequency of the system

After the interruption of I_L, these voltage drops are zero. The voltage on the transformer side of the generator circuit breaker decreases from V_p to V_{np}, with the natural frequency of the transformer side circuit. The voltage on the generator side of the generator circuit breaker increases from V_p to E_{G1}'' with the natural frequency of the generator side circuit. The amplitude of the voltage across the transformer, which was $\sqrt{2}\ I_L\ Xt$ before interruption of I_L, drops to zero.

For rapid changes in load conditions of the generator, the subtransient reactance X_d'' has to be taken into account and the amplitude of the voltage drop Vs is equal to $\sqrt{2}\ I_L\ X_d''$.

The power frequency recovery voltage appearing across the generator circuit breaker terminals (see Figure 16E) consists of the sum of the voltage variations on each side of the generator circuit breaker, following load interruption, i.e., $IL\ (X_d'' + Xt)$, in kV rms, and for the first-pole-to-clear in a three-phase system the voltage is equal to 1.5 $I_L\ (X_d'' + Xt)$. The power frequency recovery voltage across the generator circuit breaker terminals expressed in pu (per unit) of the rated maximum voltage is equal to

$$1.5\frac{V}{\sqrt{3}} \times (X_d'' + X_t)$$

where

V is the rated maximum voltage in pu;
X_d'' is the per unit reactance value of the generator;
X_t is the per unit reactance value of the transformer.

In practice, even for the larger units, the sum of $X_d'' + X_t$ does not exceed 0.5 pu, therefore the recovery voltage across the generator circuit breaker during a full load interruption will not exceed 50% of the recovery voltage value which appears after a short-circuit interruption and consequently is standardized at

$$1.5\frac{V}{\sqrt{3}}0.5 = 0.43V$$

for interruption of the rated continuous current of the generator.

7.3.7.2 Inherent transient recovery voltage

The TRV across the first-pole-to-clear for load current switching is normally a dual frequency oscillatory curve, as shown in Figure 17; the natural frequency of the transformer being higher than the natural frequency of the generator. Also, the first peak of the transformer side voltage is smaller than the first peak of the generator side voltage because Xt is always smaller than X_d''.

Theoretical calculations prove to be difficult and yield pessimistic results. Measurements at the site by injecting current at low voltage with the high-voltage side of the transformer short-circuited (representing a fault on the high-voltage side by neglecting the HV system reactances) are preferable.

Standardized TRV rate values have been selected by reviewing available results of measurements. Standardized values do not consider the use of capacitors, which would reduce the TRV rate for system-source fed faults.

7.3.7.3 Endurance capability

The endurance capability gives the user some guidance for the servicing and maintenance of generator circuit breakers. Several subclauses in this standard deal with service and endurance capability (see 5.8.3.2, 5.10, 6.2.8, and 6.2.10). Also, if during servicing the user anticipates a need for more than the two CO operations specified in 6.3.10, the specification should reflect the need for added storage capacity.

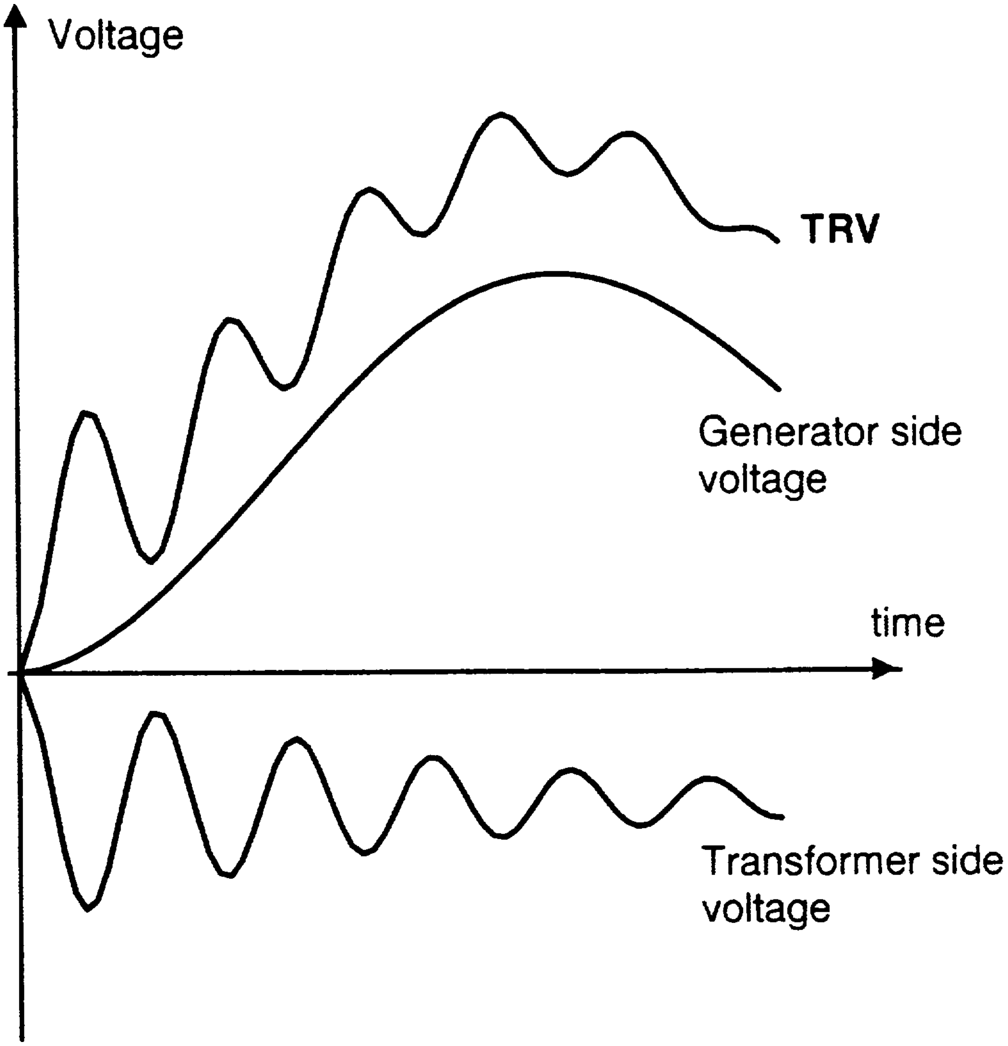


Figure 17— TRV curve for the first-pole-to-clear

The endurance capability consists of the following two types of requirements:

a) Electrical endurance that essentially is a measure of contact wear and gives guidance as to when to replace arcing contacts or other parts of the generator circuit breaker, which are exposed to the arc or stressed electrically during switching. A total of 50 load current interruptions [see item h) in 6.2.8.2] and one short-circuit duty cycle CO–30 min–CO (see Table 11) ensure that the circuit breaker meets the minimum requirements for electrical endurance.

b) Mechanical endurance, to ensure that the minimum number of operations can be performed without the need for servicing or overhaul. The number of operations is specified as 1000 (see 6.2.10). If a greater number is desired, it is subject to agreement between the user and the manufacturer.

7.3.8 Capacitive current switching

The generator circuit breaker normally is not called on to switch purely capacitive currents because in practical cases, the auxiliary transformer is connected to the bus duct between the generator circuit breaker and generator step-up transformer. Therefore, the cases described below are to be considered as special, and if the generator circuit breaker is required to have such a duty, the manufacturer should be consulted.

7.3.8.1 Switching of line charging current

It is improbable that a generator circuit breaker will have to interrupt the line charging current through a transformation, i.e., an unloaded line with the auxiliary transformer disconnected. This duty is performed by the line side HV circuit breaker; therefore, for practical applications of generator circuit breakers, this case can be disregarded.

7.3.8.2 Switching of a high-voltage side bus capacitance

It is assumed that the generator circuit breaker will have to switch the HV bus capacitance including the additional capacitance of connected HV apparatus through the main transformer, with the auxiliary transformer disconnected. This condition is essentially the same as switching the transformer magnetizing current because the magnetizing current is normally of the same order of magnitude or greater than the additional capacitive current.

7.3.8.3 Switching of HV bus capacitance plus capacitors on the LV side of the transformer

Additional capacitors on the LV side of the transformer essentially do not change the conditions stated in 7.3.8.2. Assuming a capacitance of 200 nF, the capacitive impedance parallel to the transformer would be 13.2 kΩ, and the current to be switched would be of the same order of magnitude as in the case defined in 7.3.8.2. This capacitance may increase slightly the chopped current, but this is compensated for by the reduction in the chopping overvoltage. The TRV is also reduced by this capacitance.

7.3.8.4 Switching of capacitance

The value of capacitance connected to the LV side of the transformer is in the order of 200 nF. This case can be regarded as real capacitance current switching if the plant operation is such that this capacitance alone can be switched. The capacitive current is in the order of 1 to 2 A. Generator circuit breakers are capable of switching such capacitive currents restrike-free.

7.3.9 Out-of-phase current switching

7.3.9.1 Out-of-phase current

During out-of-phase conditions, the current through the generator, the generator circuit breaker, the transformer, and the HV system at t = 0, i.e., at the moment of initiation of the out-of-phase condition, can be calculated using the following formula, provided that the generator, transformer, and system reactances are in per unit on the generator rated MVA basis and the single-line diagram of the station is as shown in Figures 12 and 13.

$$I_{oph} = \frac{\delta I_n}{X_d'' + X_t + X_s}$$

where

I_{oph} is the maximum out-of-phase current

δ is $\dfrac{\text{out-of-phase voltage}}{\text{rated maximum voltage}}$

δ is 1.4 for a 90 ° out-of-phase angle, and 2 for a 180 ° out-of-phase angle

I_{n} is the generator rated continuous current

X_{d}'' is the pu generator subtransient reactance

X_{t} is the pu transformer reactance based on generator rating

X_s is the pu system reactance $= \dfrac{\text{rated power of generator}}{\text{system short-circuit power}}$ (1)

If the generator is connected to the system in full phase opposition, $\delta = 2$, I_{oph} will in general exceed the generator terminal short-circuit current, which is not acceptable for the safety of the generator. Therefore, precautions should be taken to avoid this situation (automatic synchronization or fast-clearing of short-circuits on the HV system to avoid losing synchronization).

A generator circuit breaker is not required to interrupt the full phase opposition current with a recovery voltage twice the maximum operating voltage, thus the assigned out-of-phase current switching rating will not exceed 50% of the rated short-circuit current of the generator circuit breaker, which corresponds to a maximum out-of-phase angle of 90°.

7.3.9.2 TRV parameters

Circuits involved in out-of-phase current switching have the same configuration as for load current switching. Therefore, the TRV is standardized in the same manner according to 7.3.7.1 taking into account a normal frequency recovery voltage equal to $\sqrt{2}$ times the maximum operating voltage of the generator. The TRV parameters ar given in Table 9.

7.3.10 Excitation current switching

During routine operation, a generator step-up transformer is seldom switched in an unloaded condition. However, consideration should be given to switching of transformer excitation current. The excitation current is 10–50 A, depending on the rating and no-load characteristics of the transformer. Excitation current switching is not so much a matter of the generator circuit breaker capability, but a question of whether overvoltages are produced due to current chopping.

The value of chopped current, and consequently the overvoltages produced, are dependent on the generator circuit breaker, system configuration, and also the various system parameters. Modern transformers have a low no-load current value compared to older designs, and their magnetic characteristics are such that a relatively low amount of energy is released when current chopping occurs during switching, leading to moderate chopping overvoltages. Furthermore, the transformer LV side is usually protected by additional capacitance and by surge arresters.

Chopping overvoltages are produced only on the transformer side of the generator circuit breaker. No overvoltages occur on the generator side because the inductance of the generator is much lower than the magnetizing impedance of the transformer, and the energy content is low and not of sufficient magnitude to produce overvoltages.

Air-blast generator circuit breakers are usually shunted by low-ohmic damping resistors in series with an auxiliary interrupter. This low-breaking capacity switch interrupts these small inductive currents, thus, current chopping levels are in the order of those of air-blast distribution circuit breakers. Some air-blast generator circuit breakers may be equipped with voltage-dependent resistors connected across the magnetizing current interrupter.

Experience indicates that the current chopping level of SF_6 self-blast generator circuit breakers is low and should not produce overvoltages of concern.

In a test circuit it is difficult to simulate real conditions prevailing in the power system when installation of a generator circuit breaker is planned. Tests can only reveal the chopping behavior of the generator circuit breaker under the conditions of the test circuit. These results cannot be transferred directly to the power system conditions, but they are the basis for carrying out computations using real power system conditions and component parameters, such as transformer magnetizing characteristics, and capacitance values of transformers, buses, surge capacitors, etc.

In general, no difficulties should be expected due to switching of excitation currents. If tests and/or calculations are to be carried out for a specific application, they should be performed based on agreement between the user and the manufacturer.

7.4 Guide to specification

7.4.1 General

When requesting proposals for ac generator circuit breakers, the purchaser should furnish to the manufacturer a specification containing the information outlined in 7.4.2–7.4.6.

7.4.2 System characteristics

a) Single-line diagram of the power station;
b) Maximum generator line-to-line voltage;
c) Power frequency;
d) Generator data (rating, reactances, time constants, armature resistance, and overload rating);
e) Generator grounding;
f) Main transformer data (rating and reactances, resistances or time constant);
g) Main transformer tap changer steps, if any, and change of reactance with tap-changer operation;
h) Maximum system short-circuit current on high-voltage side of main transformer (including future requirements);
i) High-voltage system time constant;
j) Value of surge capacitors, if any.

7.4.3 Application

a) Type of power station (fossil, hydro, nuclear, continuous-load, or peak-load power station; synchronous condenser station);
b) Indoor or outdoor installation of the circuit breaker;
c) Minimum and maximum phase spacings;
d) Generator-connected bus temperature at circuit breaker terminals;
e) Cooling of bus duct (if forced air cooling, overpressure of air);
f) Number of operations per year.

7.4.4 Generator circuit breaker electrical characteristics

a) Rated maximum voltage;
b) Insulation withstand voltage level;
c) Rated continuous current;
d) Rated short-circuit current;
e) Rated interrupting time.

7.4.5 Operating mechanism and auxiliaries

a) Control voltage(s);
b) Maximum trip coil current.

7.4.6 Miscellaneous

a) Limiting dimensions at circuit breaker location;
b) Interlocks and key coordination system;
c) Abnormal conditions (environmental and others).

8. Bibliography

[B1] “Generator circuit breaker: Transient recovery voltages in most severe short-circuit conditions,” CIGRE *Electra*, No. 113, Jul. 1987, pp. 43–50.

[B2] “Generator circuit breaker: Transient recovery voltages under load current and out-of-phase conditions,” CIGRE *Electra*, No. 126, Oct. 1989, pp. 55–63.

[B3] IEC 60060-1 (1989) High-voltage test techniques—Part 1: General definitions and test requirements.

[B4] IEC 60060-2 (1994) High-voltage test techniques—Part 2: Measuring systems.

[B5] IEEE Std C37.59 IEEE Standard Requirements for Conversions of Power Switchgear Equipment.

[B6] Ruoss, E.M., and Kolarik, P. L., “A New IEEE/ANSI Standard for Generator Circuit Breakers,” *IEEE Transactions on Power Delivery*, vol. 10, no. 2, Apr. 1995, pp. 811-816.

Annex A Example of the application of a generator circuit breaker

(Informative)

The application guide appearing in Clause 7. was used in developing this example.

When requesting proposals for ac high-voltage generator circuit breakers, it is important that the purchaser provide the manufacturer with a specification containing the information outlined in 7.4. This information alerts the manufacturer to the application conditions in 7.2 and 7.3.

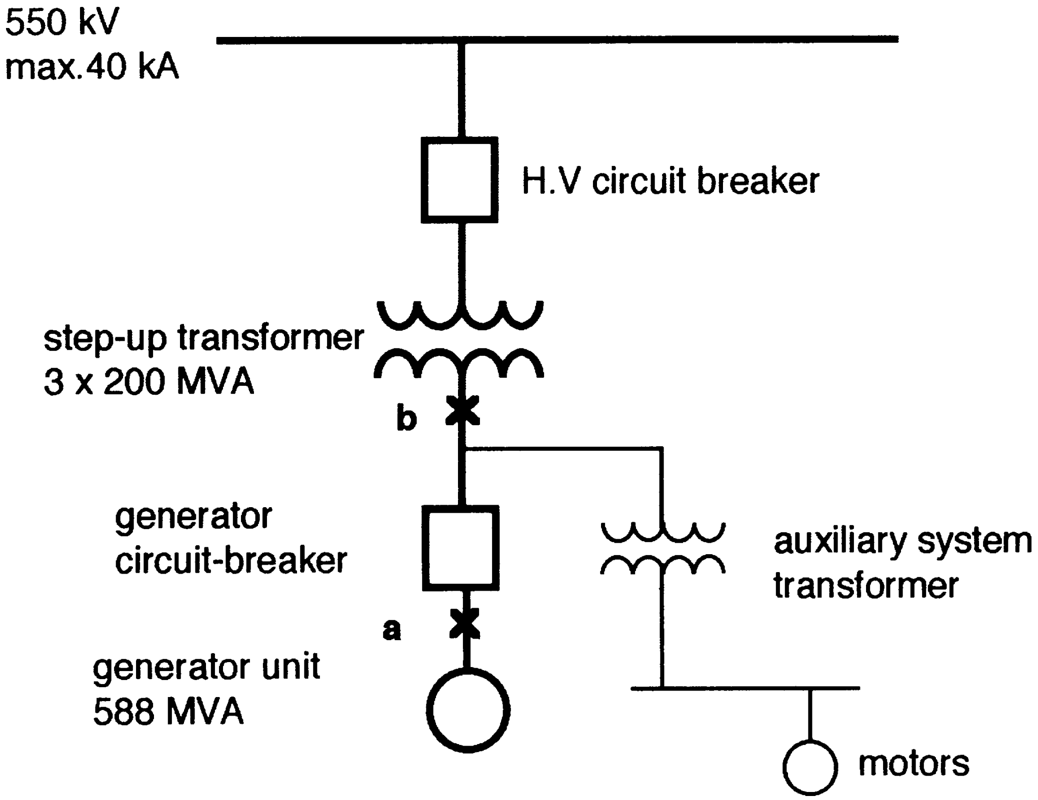


Figure A.1—Single-line station diagram

The example given in A.1 describes an actual indoor generator circuit breaker application for a 588 MVA, coal-fired, continuous-load power plant. The generator circuit breaker is forced-air cooled.

A.1 System characteristics

System characteristics are described as follows:

a) Single-line diagram	See Figure A1
b) Maximum generator line-to-line voltage (kV)	21
c) Power frequency (Hz)	60
d) Generator data (rated values):	
1) Rated power (MVA)	588
2) Rated voltage (kV)	21
3) Reactance values in pu:	At rated voltage (saturated)
i) Synchronous direct axis (X_d)	2.0
ii) Transient direct axis (X_d')	0.31
iii) Subtransient direct axis (X_d'')	0.24
iii) Synchronous quadrature axis (X_q)	2.04
iv) Transient quadrature axis (X_q')	0.5
v) Subtransient quadrature axis (X_q'')	0.25
vi) Negative sequence (X_2)	0.24
vii) Zero sequence (X_0)	0.1
4) Time constants in seconds:	
i) Transient open-circuit (T_{do}')	5.63
ii) Transient short-circuit (T_d')	0.84
iii) Subtransient open-circuit (T_{do}'')	0.034
iv) Subtransient short-circuit (T_d'')	0.025
v) Transient open-circuit quadrature (T_{qo}')	—
vi) Transient short-circuit quadrature (T_q')	0.255
vii) Subtransient open-circuit quadrature (T_{qo}'')	—
viii) Subtransient short-circuit quadrature (T_q'')	0.025
ix) Armature short-circuit (T_a)	0.31
5) Generator grounding	High resistance grounding through distribution transformer
6) Inertia constant (H) (kW s/kVA)	If available
7) Capacitance of armature winding-to-ground (all phases tied together) (μF)	0.9

e) Generator step-up transformer data (rated values):	
1) Rated voltage (kV)	550/21
2) Rated power (MVA)	3 × 200
3) Connection	Wye grounded/delta
4) Short-circuit reactance at rated voltage (pu)	0.14
5) Tap changer range on HV side (1.25% steps)	– 10% /+ 5%
i) Overall change in short-circuit reactance	– 5% /+ 2.5%
6) Time constant X/ωR (ms)	160
f) System source short-circuit current on high-voltage side of generator step-up transformer (future requirement) (kA)	40
g) Time constant X/ωR of the high-voltage system (ms)	45

A.2 System source short-circuit current

A.2.1 System source symmetrical short-circuit current

The following example is based on a fault at location “a” (see Figure A.1)

The system source symmetrical short-circuit current is the highest rms value of the symmetrical component of the polyphase short-circuit current that the generator circuit breaker has to interrupt at rated maximum voltage and rated duty cycle.

For a 40 kA system source short-circuit current contribution on the 550 kV side, the required system short-circuit reactance seen from the 21 kV low-voltage side is as follows:

$$X_{\mathrm{sys}} = \frac{550}{40\sqrt{3}}\left(\frac{21}{550}\right)^2 = 11.57 \times 10^{-3}\ \Omega$$

The short-circuit reactance of the main transformer with a rated power of 600 MVA and a short-circuit pu reactance of 14% yields a reactance of the following:

$$X_{\mathrm{t}} = 0.14 \times \frac{21^2}{600} = 102.9 \times 10^{-3}\ \Omega$$

Therefore, the short-circuit contribution from the system side is as follows:

$$I_{\mathrm{sc}} = \frac{V}{\sqrt{3} \times (X_{\mathrm{sys}} + X_{\mathrm{t}})} = \frac{21}{\sqrt{3}((11.57 + 102.9) \times 10^{-3})} = 105.9\ \mathrm{kA}$$

The contribution to the short-circuit current from the auxiliary system motors is a small fraction of the current from the high-voltage system. It can be determined as follows if the motors are connected through two auxiliary transformers each rated 35 MVA, 0.08 pu short-circuit reactance, and with a time constant of 106 ms (X/R ratio of 40). The maximum rating of all motors combined is 60 MVA with the conservative assumption that all are in service at the same time.

The motor short-circuit impedance is as follows:

$$Z_{\mathrm{M}} = \frac{I_{\mathrm{rM}}}{I_{\mathrm{lM}}} \times \frac{V^2}{P_{\mathrm{M}}} = 0.2 \times \frac{21^2}{60} \cong X_{\mathrm{M}} = 1.47\ \Omega$$

with $I_{\mathrm{rM}}/I_{\mathrm{lM}}$ being the ratio of rated motor current to the locked rotor motor current and equal to approximately 0.2.

$X_{\mathrm{aux\ transf}} = 0.08\ \ 21^2/\ 70 = 0.504\ \Omega$

The initial symmetrical rms short-circuit current contribution from the auxiliary system is as follows:

$$I''_{\mathrm{aux\ sys}} = \frac{V}{\sqrt{3}X_{\mathrm{aux\ tot}}} = \frac{21}{\sqrt{3}(1.47 + 0.504)} = 6.14\ \mathrm{kA}$$

This initial current decays and the current interrupted at a contact parting time of 40–80 ms can be estimated as being equal to 0.7–0.85 times the initial current $I''_{\mathrm{aux\ sys}}$. If the factor is 0.8, which is based on the selected generator circuit breaker having an 80 ms (5 cycle) contact parting time, the symmetrical rms short-circuit current contribution from the auxiliary system will be 4.9 kA.

The total system-source symmetrical short-circuit current seen by the generator circuit breaker is as follows:

$$I_{\mathrm{sc\ tot}} = 105.9 + 4.9 = 110.8\ \mathrm{kA}$$

Based on the above, a short-circuit current rating of 120 kA will be chosen for the generator circuit breaker.

A.2.2 System-source asymmetrical short-circuit current

The following example is based on a fault at location “a” (see Figure A.1), and on the calculations in A.2.1.

The dc component of the asymmetrical system-source short-circuit current is equal to the following:

$$I_{\mathrm{dc}} = (\sqrt{2}I_{\mathrm{sym}})e^{-t/\tau}$$

*I*symis the system-source symmetrical short-circuit current Isc that was determined to be 105.9 kA through the step-up transformer for a 40 kA system short-circuit current contribution on the high-voltage side of the step-up transformer

*I*dcis the dc component of the asymmetrical system-source short-circuit current

τ is $\left(\frac{1}{\omega} \times \frac{X}{R}\right)$
X is the short-circuit reactance of system elements
R is the resistance of system elements
ω is the angular power frequency

As for the system-source symmetrical short-circuit current the total dc component is composed of the contribution from the high-voltage system through the step-up transformer and the dc component of the auxiliary system. It has to be determined at primary arcing contact parting time.

The high-voltage system time constant is 45 ms, and its short-circuit reactance is determined as follows:

$X_{\mathrm{sys}} = 11.57\ 10^3\ \Omega$ (see A.1.1).

It follows that:

$$R_{sys} = \frac{11.57 \times 10^{-3}}{377 \times 45 \times 10^{-3}} = 0.681 \times 10^{-3} \Omega$$

The time constant of the generator step-up transformer is 160 ms and the transformer short-circuit reactance was calculated to be $X\mathrm{t} = 102.9 \times 10^{3}\ \Omega$.

This leads to the following step-up transformer resistance:

$$R_{t}= \frac{102.9 \times 10^{-3}}{377 \times 160 \times 10^{-3}} = 1.706 \times 10^{-3} \Omega$$

The total system-source reactance and resistance are

$$X\mathrm{sys{+}t} = X\mathrm{sys} + X\mathrm{t} = 11.57 \times 10^{-3} + 102.9 \times 10^{-3} = 114.47 \times 10^{-3} \Omega$$

$$R\mathrm{sys{+}t} = R\mathrm{sys} + R\mathrm{t} = 0.861 \times 10^{-3} + 1.706 \times 10^{-3} = 2.387 \times 10^{-3} \Omega$$

Therefore, the time constant $\tau_{sys,tot}$ of the decay of the dc component of the short-circuit current from the high-voltage system through the step-up transformer is as follows:

$$\tau_{sys,tot}= \frac{114.47 \times 10^{-3}}{377 \times 2.387 \times 10^{-3}} = 127.2 \text{ ms}$$

The auxiliary system transformer’s short-circuit reactance was evaluated to be 0.504 Ω and is assumed to have a time constant of 100 ms [(X/R)aux tr = 37.5]. Therefore, the resistance is as follows:

R_{aux} transf = 0.0133 Ω

For the motors a reactance of XM = 1.47 Ω was calculated. The resistance RM for motors greater than 1 MW rated power is approximately 0.1 times XM. Therefore,

RM = 0.147 Ω

The time constant of the decrement of the dc current component from the auxiliary system is as follows:

$$t_{aux\ sys}= \frac{X_{aux\ tr} + X_{M}}{\omega(R_{aux\ tr} + R_{M})} = \frac{0.504 + 1.47}{377(0.0133 + 0.147)} = 32.7 \text{ ms}$$

The total dc component of the total system-source short-circuit current (including the dc component of the auxiliary system contribution), at a primary arcing contact parting time of the generator circuit breaker of 58.3 ms (opening time 50 ms plus a tripping delay of 0.5 cycles), is the sum of the contribution from the high-voltage system through the step-up transformer and the auxiliary system contribution.

$$I_{dc\ sys\ tot} = 105.9\sqrt{2}e^{-58.3/127.2} = 94.5 \text{ kA}$$

$$I_{dc\ aux} = 6.14\sqrt{2}e^{-58.3/32.7} = 1.46 \text{ A}$$

$$I_{dc\ tot} = 94.5 + 1.46 = 96.16 \text{ kA}$$

The dc component at primary arcing contact parting time is therefore 61.6% of the peak value of the total symmetrical system-source short-circuit current.

A.3 Generator source short-circuit current

A.3.1 Generator source symmetrical short-circuit current

This current is measured from the envelope of the current excursion at the moment of primary arcing contact separation when the source of the short-circuit current is entirely from a generator without transformation.

The generator-source symmetrical short-circuit current can be calculated using the following formula for no-load conditions:

$$I_{\text{gen source sym rms}} = \frac{P}{\sqrt{3}V}\Bigl[\Bigl(\frac{1}{X_d''}-\frac{1}{X_d'}\Bigr)e^{-t/T_d''}+\Bigl(\frac{1}{X_d'}-\frac{1}{X_d}\Bigr)e^{-t/T_d'}+\frac{1}{X_d}\Bigr]$$

where V is the rated maximum voltage, P is the rated power of the generator, and the reactances are in pu.

Using the data given for the generator in this example, the generator-source symmetrical short-circuit current at a primary arcing contact parting time equal to 58.3 ms results in the following:

$$I_{\text{gen source sym rms}} = 50.6\ \text{kA}$$

A.3.2 Generator-source asymmetrical short-circuit current

The generator-source asymmetrical short-circuit current for the phase with the highest asymmetry, the generator being in the no-load mode, can be calculated by the following equation:

$$I_{\text{gen source asym}} = \frac{P\sqrt{2}}{V\sqrt{3}}\Bigl\{\Bigl[\Bigl(\frac{1}{X_d''}-\frac{1}{X_d'}\Bigr)e^{-t/T_d''}+\Bigl(\frac{1}{X'_d}-\frac{1}{X_d}\Bigr)e^{-t/T_d'}+\frac{1}{X_d}\Bigr]\cos\omega\mathrm{t}$$

$$-\frac{1}{2}\Bigl(\frac{1}{X_d''}+\frac{1}{X_q''}\Bigr)e^{-t/T_a}-\frac{1}{2}\Bigl(\frac{1}{X_d''}-\frac{1}{X_q''}\Bigr)e^{-t/T_a}\cos2\omega\mathrm{t}\Bigr\}$$

with P = rated power, V = rated maximum voltage, the reactance values of the generator in pu.

Since X_d'' is approximately equal to X_q'' for most generators, the equation can be written as follows:

$$I_{\text{gen source asym}} = \frac{P\sqrt{2}}{V\sqrt{3}}\Bigl\{\Bigl[\Bigl(\frac{1}{X_d''}-\frac{1}{X_d'}\Bigr)e^{-t/T_d''}+\Bigl(\frac{1}{X_d'}-\frac{1}{X_d}\Bigr)e^{-t/T_d'}+\frac{1}{X_d}\Bigr]\cos\omega\mathrm{t}-\frac{1}{X_d''}e^{-t/T_a}\Bigr\}$$

Figure A.2 shows a computer calculation of the three-phase asymmetrical short-circuit current for the example in this annex, assuming that the fault occurs with the generator in the no-load mode. This improbable case may occur when the generator circuit breaker is closed into a bolted fault such as a closed grounding switch. At the location of the fault therefore, no arcing is taken into account. The asymmetry at the primary arcing contact parting time of the generator circuit breaker is 109.5%.

Figure A.3 exhibits for comparison the calculated asymmetrical three-phase short-circuit current but with the assumption of an arc at the fault location influencing the asymmetry of the short-circuit current. Due to the arc voltage, the asymmetry is reduced to 68% in comparison to Figure A.2 with an asymmetry of 109.5%.

A free-burning arc in air has an arc voltage of 10 V/cm, which means that the arc voltage of a fault in the bus duct is at least 300 V. In the case of a failure occurring in a transformer, an arc would burn in oil with a considerably higher arc voltage.

The influence of the generator circuit breaker arc on the phase with the maximum asymmetry is illustrated in the computer calculation in Figure 11.

The generator-source asymmetrical short-circuit current is normally calculated by using appropriate computer programs. For the generator-source asymmetrical short-circuit current with maximum degree of asymmetry and with the generator in an under-excited mode, no approximate formula can be given so the short-circuit current is calculated using appropriate computer programs.

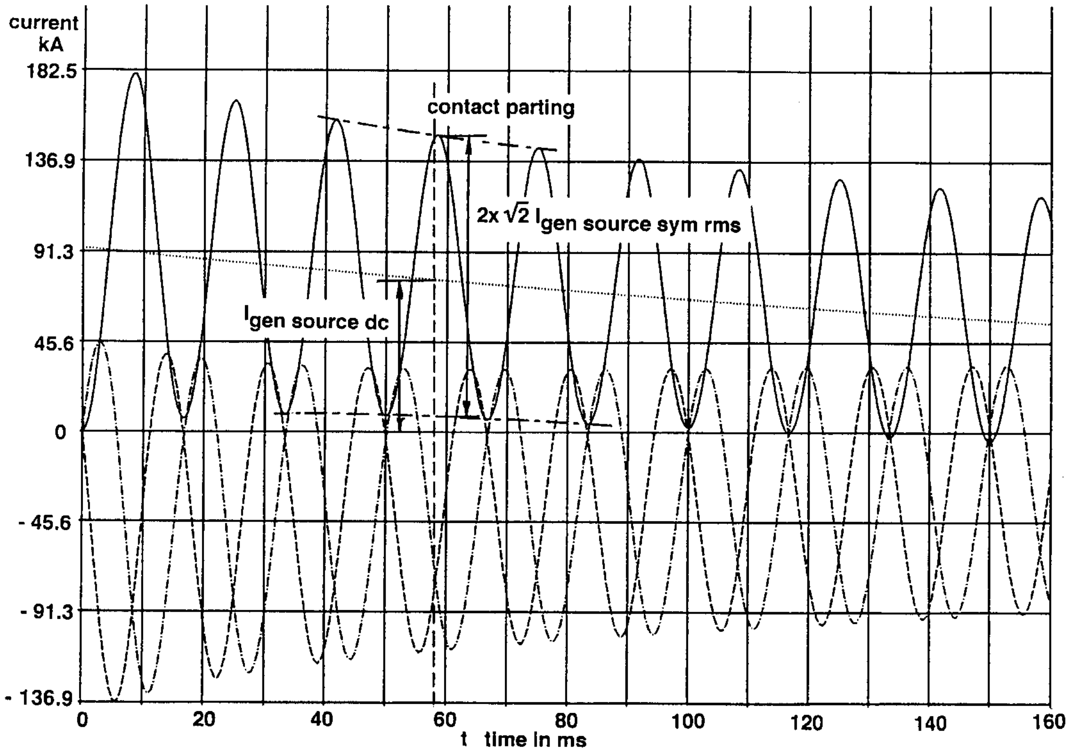


Figure A.2—Asymmetrical generator source short-circuit current with no arc at the fault location

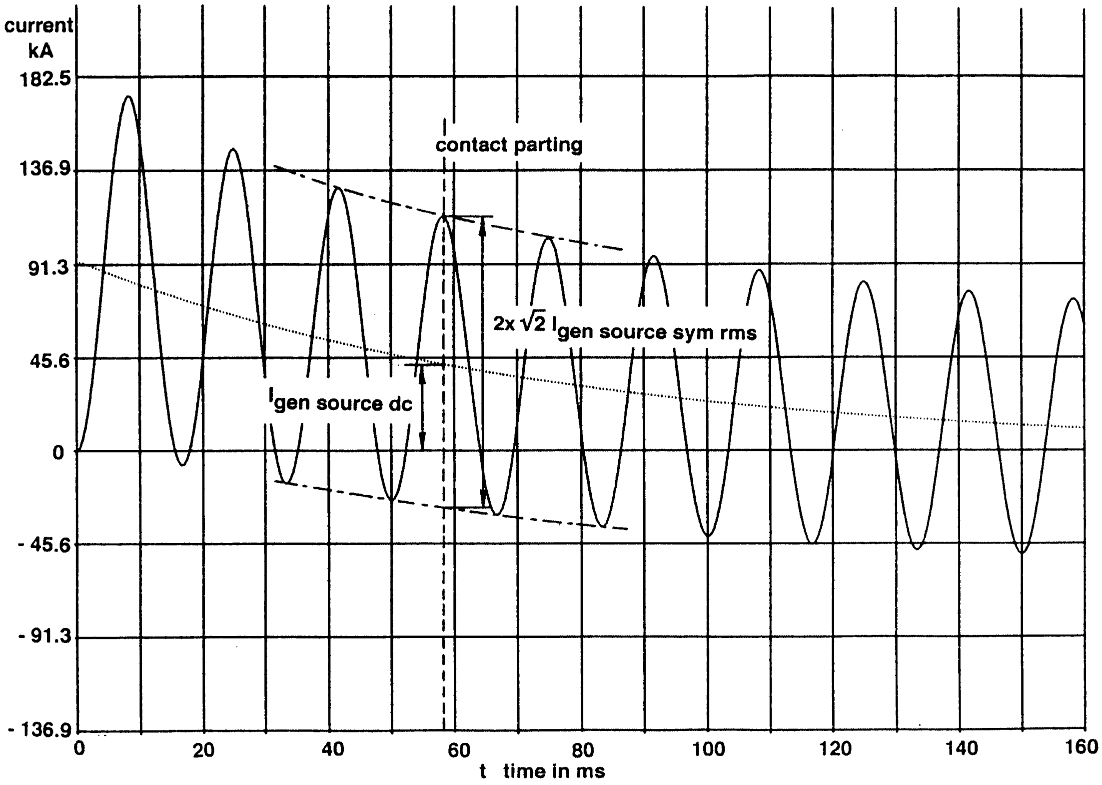


Figure A.3—Asymmetrical generator source short-circuit current with arc at the fault location

A.4 Transient recovery voltage

The inherent TRV for the system fed fault can be determined in the same manner as a transformer fed fault. The natural frequency of the transformer in the short-circuit mode has to be known. This frequency can be measured by means of a low-voltage injection method. When capacitors are used, they have to be accounted for in the actual TRV.

The TRV parameters given in this standard are the result of data from a large number of transformers and generators, normally from measurements, and they cover the most severe cases. See [B1] and [B2] .

A calculation of the TRV for the system fed fault, as well as for the generator fed fault, may be inaccurate because the appropriate modeling is complicated, and the necessary accurate data, which are partially frequency dependent, may not be available.

A.5 Out-of-phase conditions

An out-of-phase condition can occur under the following two conditions:

a) Instability in a high-voltage transmission system where the high-voltage circuit breakers are tripped by the relevant protective scheme before a maximum 180° phase opposition is reached. This case can be disregarded for generator circuit breakers
b) Synchronizing with the generator circuit breaker, if performed incorrectly, can result in an out-of-phase condition if the generator circuit breaker has to be tripped

The symmetrical out-of-phase current (I_{oph}) for the latter case at the moment of current initiation (t = 0), can be calculated using the following expressions:

$$I_{\mathrm{oph}} = \frac{V_{\mathrm{oph}}}{X_{\mathrm{d}}'' + X_{\mathrm{t}} + X_{\mathrm{s}}}$$

V_{oph}	is the out-of-phase voltage
X_{d}''	is the subtransient reactance of the generator in ohms
X_{t}	is the transformer short-circuit reactance in ohms
X_{s}	is the short-circuit system reactance in ohms

or

$$I_{\mathrm{oph}} = \delta\left(\frac{I_{\mathrm{n}}}{X_{\mathrm{d}}'' + X_{\mathrm{t}} + X_{\mathrm{s}}}\right)$$

where the reactances are in pu.

δ	is the out-of-phase factor
X_{s}	is the rated power of the generator divided by the system short-circuit power in pu
I_{n}	is the generator rated continuous current

This equation is valid for system diagrams such as Figure 12 or schematic diagram, Figure A.4, with generator and generator step-up transformer on same base rating, in series.

The ultimate out-of-phase current is lower than the initial out-of-phase current at t = 0 because it decreases based on the time constants of the generator, the transformer, and the system. The accurate calculation of the current excursion has to be performed by computer programs that simulate the generator behavior correctly.

However, for power station single-line diagrams such as Figure 12, the out-of-phase current can be approximately calculated using the following formula when the generator is in a no-load situation prior to the out-of-phase condition (see Figure A.4).

$$\begin{aligned} I_{\mathrm{oph}} = \frac{\delta P\sqrt{2}}{V\sqrt{3}}\Bigg\{\Bigg[&\left(\frac{1}{X_d'' + X_s + X_t} - \frac{1}{X_d' + X_s + X_t}\right)e^{-t/T''} + \left(\frac{1}{X_d' + X_s + X_t} - \frac{1}{X_d + X_s + X_t}\right)e^{-t/T'} + \\ &\frac{1}{X_d + X_s + X_t}\Bigg]\cos\omega\mathrm{t} - \frac{1}{X_d'' + X_s + X_t}e^{-t/T}\Bigg\} \end{aligned}$$

$$T'' = T_{do}''\left(\frac{X_d'' + X_s + X_t}{X_d' + X_s + X_t}\right) = T_d''\left(\frac{X_d'}{X_d''} \times \frac{X_d'' + X_s + X_t}{X_d' + X_s + X_t}\right) \text{ because } T_{do}'' \cong T_d''\left(\frac{X_d'}{X_d''}\right)$$

$$T' = T_{do}'\left(\frac{X_d' + X_s + X_t}{X_d + X_s + X_t}\right) = T_d'\left(\frac{X_d}{X_d'} \times \frac{X_d' + X_s + X_t}{X_d + X_s + X_t}\right) \text{ because } T_{do}' \cong T_d'\left(\frac{X_d}{X_d'}\right)$$

$$T = \frac{X_d'' + X_s + X_t}{\dfrac{X_d''}{T_a} + \dfrac{X_s}{\tau_s} + \dfrac{X_t}{\tau_t}} = \frac{X_d'' + X_s + X_t}{\dfrac{X_d''}{T_a} + X_s \times \dfrac{\omega}{(X/R)_s} + X_t \times \dfrac{\omega}{(X/R)_t}}$$

The reactances X_{d}'', X_{d}', X_{t}, and X_{s} are pu values on generator MVA base.

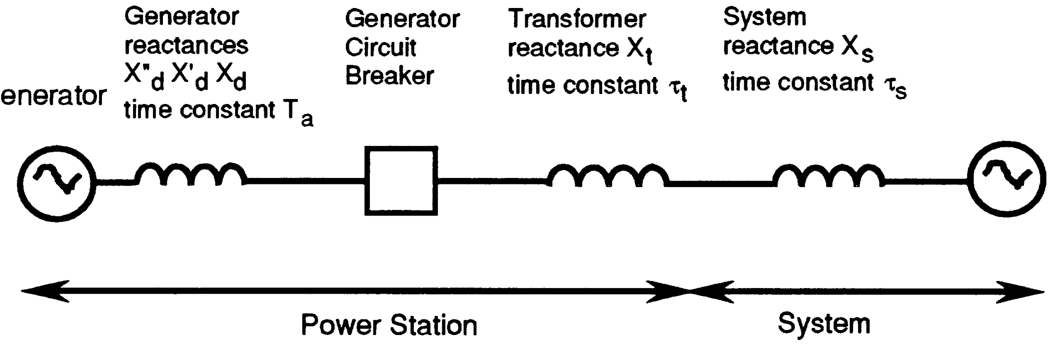


Figure A.4— Schematic diagram of power station (single-line diagram as in Figure 12)

For a 180 ° out-of-phase condition, δ is equal to 2. Under this condition for the phase with full asymmetry one-half cycle after current initiation, the peak current is 223 kA plus some percentage contribution from the auxiliary system. This current peak is considerably higher than the generator terminal fault peak short-circuit current of 181 kA (see Figure A.2). Such a high out-of-phase short-circuit current would damage the generator, taking into account that the mechanical forces increase as the square of the current. Consequently, the 180 ° out-of-phase condition must be avoided by appropriate relay protection.

For the 90 ° out-of-phase condition, δ is equal to the $\sqrt{2}$ with a voltage of $21\left(\frac{\sqrt{2}}{\sqrt{3}}\right)$ kV ; the out-of-phase asymmetrical peak current after one-half cycle is 158 kA, which is lower than the generator terminal fault peak short-circuit current.

The calculated out-of-phase current that must be switched at the primary arcing contact parting time for this example is 52 kA. The maximum current that would have to be switched for an out-of-phase condition is equal to 50% of the short-circuit current rating of the generator circuit breaker, in this case, 60 kA.

For a TRV calculation, the same considerations apply as in A.4. The TRV requirements are given in Table 9.

A.6 Continuous current application

The continuous current of the generator at the rated voltage of 21 kV is as follows:

$$\frac{588\text{ MVA}}{21\sqrt{3}\text{ kV}} = 16.2\text{ kA}$$

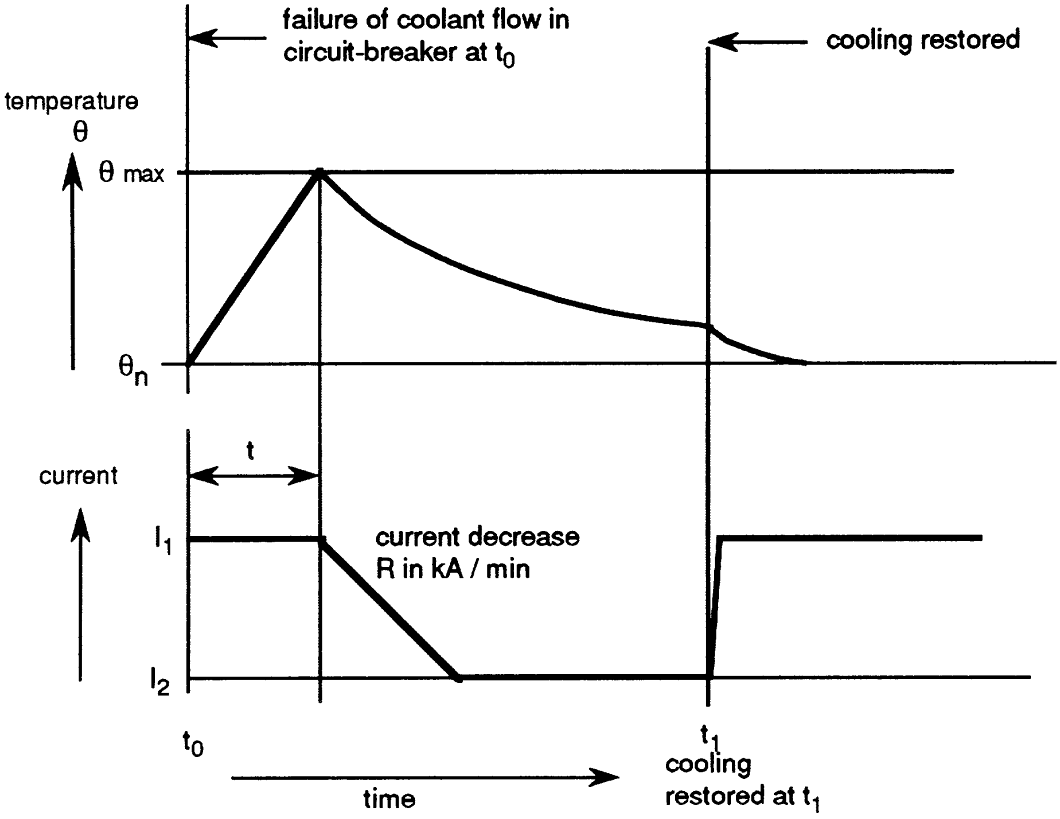
The generator circuit breaker in this example is forced-air-cooled. Figure A.5 illustrates the procedure for calculating the current rating of the generator circuit breaker when the forced-air-cooling fails.

With the forced-air-cooling in operation, the generator circuit breaker can carry the continuous current of the generator. If a failure occurs in the cooling system, the current must be reduced, starting after the time t, with a decreasing rate R in kA/min, in order that the temperature of the circuit breaker does not exceed the allowable hottest spot total temperature, θ_{max}. The allowable total temperature is limited by the materials used in the generator circuit breaker (see Table 2) so that there is no deterioration of any parts of the generator circuit breaker.

The temperature decreases due to the lower current, tending toward the allowable hottest spot temperature, θ_n. The cooling is restored at a time t_1, and the current is increased to the rated continuous current of the generator.

Consequently, the temperature decreases to the allowable hottest spot temperature, θ_n. This emergency procedure has to be established with the manufacturer.

A similar procedure is used when the cooling system is more complicated (e.g., the generator circuit breaker is water-cooled and the bus duct is forced-air-cooled). The emergency schedule contains, in such a case, the procedure for a failure in each of the cooling systems as indicated in Figure 1.



θ_{max} is the allowable hottest spot total temperature
θ_n is the allowable hottest spot temperature at rated current
t is the allowable time without reduction of rated current and without exceeding θ_{max}
I_1 is rated continuous current
I_2 is allowable current with failure of coolant flow

Figure A.5—Generator circuit breaker temperature and load current with loss of coolant

A.7 Generator circuit breaker electrical characteristics

The following are electrical characteristics of the generator circuit breaker selected in the example:

Rated maximum voltage	**21 kV**
Insulation withstand voltages:	
One minute dry	60 kV rms
Full wave impulse	125 kV crest
Rated continuous current	18 kA
Rated short-circuit current	120 kA