IEEE Guide for Diagnostics and Failure Investigation of Power Circuit Breakers

Sponsor

Switchgear Committee
of the
IEEE Power Engineering Society

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Abstract: Procedures to be used to perform failure investigations of power circuit breakers are recommended. Although the procedure may be used for any circuit breaker, it is mainly focused on high-voltage ac power circuit breakers used on utility systems. Recommendations are also made for monitoring circuit breaker functions as a means of diagnosing their suitability for service condition.

Keywords: diagnostics, failure investigation, power circuit breaker

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Introduction

(This introduction is not part of IEEE Std C37.10-1995, IEEE Guide for Diagnostics and Failure Investigation of Power Circuit Breakers.)

This guide was prepared by the Quality and Reliability Working Group of the HVCB Subcommittee of the Switchgear Committee of the IEEE Power Engineering Society.

Work on this guide began in 1990 with the purpose of developing guidelines that could be used by utilities and industrial users alike in the process of investigating failures as well as in monitoring and diagnostics of the power circuit breakers.

Many papers have been written and numerous conferences have been held regarding reliability, maintenance, and diagnostics of power circuit breakers. The subject of monitoring and diagnostics is evolving rapidly. This guide attempts to bring together the current knowledge and techniques on these subjects into one comprehensive document.

This guide is in two parts. The first part describes a procedure to investigate and analyze circuit breaker failures. The second part describes diagnostics and monitoring of the circuit breaker functions as an aid to improve and extend circuit breaker service life. The annexes contain information on advanced diagnostics, diagnostic tests, and basic design and application of circuit breakers.

The Standards Committee on Power Switchgear, C37, which reviewed and approved this standard, had the following personnel at the time of approval:

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IEEE Guide for Diagnostics and Failure Investigation of Power Circuit Breakers

1. Overview

1.1 Scope

This guide recommends procedures to be used to perform failure investigations of power circuit breakers. Although the procedure may be used for any circuit breaker, it is mainly focused on high-voltage ac power circuit breakers used on utility systems.

Recommendations are also made for monitoring circuit breaker functions as a means of diagnosing their suitability for service condition.

1.2 Purpose

The purpose of this guide is

a) to provide a methodology by which the most probable cause of any particular circuit breaker failure may be determined;
b) to provide sufficient guidelines and promote uniformity in the analysis of circuit breaker failures;
c) to provide guidance for systematic and uniform data collection so that valuable facts are not lost or destroyed;
d) to encourage cooperative efforts by users and manufacturers during failure analysis;
e) to encourage consistency of nomenclature and compatibility with similar efforts by other organizations such as CIGRE (International Conference on Large Voltage Electric Systems), EEl (Edison Electric Institute), IEC (International Electrotechnical Commission), NEMA (National Electrical Manufacturers Association), and AEIC (Association of Edison Alluminating Companies).

1.3 Organization

This guide is divided into two main parts as follows:

Part I: Failure investigation

Part II: Diagnostics

Annexes provide information on advanced diagnostics, diagnostic tests, and circuit breaker basic design and application.

2. References

ANSI C37.06-1987, American National Standard for Switchgear—AC High-Voltage Circuit Breaker rated on a Symmetrical Current Basis—Preferred Ratings And Related Required Capabilities.[1]

ANSI C37.11-1979, American National Standard Requirements for Electrical Control for AC High-Voltage Circuit Breakers rated on a Symmetrical Current Basis or a Total Current Basis.

IEEE Std 100-1992, The New IEEE Standard Dictionary of Electrical and Electronics Terms (ANSI).[2]

IEEE Std 1325-1996, IEEE Recommended Practice for Reporting of Power Circuit Breaker Field Failures.[3]

IEEE Std C37.04-1979 (R1988), IEEE Standard Rating Structure for AC High-Voltage Circuit Breakers rated on a Symmetrical Basis (ANSI).

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

IEEE Std C37.010-1979 (R1988), IEEE Application Guide for AC High-Voltage Circuit Breakers rated on a Symmetrical Current Basis (ANSI).

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 C37.012-1979 (R1988), IEEE Application Guide for Capacitance Current Switching for AC High-Voltage Circuit Breakers rated on a Symmetrical Current Basis (ANSI).

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

3. Definitions

3.1 ancillary equipment: Auxiliary or accessory equipment (e.g., thermometer, liquid level gauge, pressure gauge) (see also IEEE Std 100-1992).

3.2 circuit breaker downtime: Time from the discovery of the failure until the breaker is returned to service.

3.3 contributing cause: A cause that, of itself, may not result in failure.

3.4 control circuit failure: Failure attributed to the inability of the electrical control circuit to perform its function.

3.5 defect: Imperfection in the state of an item (or inherent weakness) which can result in one or more failures of the item itself or of another item under the specific service or environmental or maintenance conditions for a stated period of time.

3.6 diagnostic tests: Comparative tests or measurements of one or more of the characteristic parameters of a circuit breaker to verify that it performs its functions.

NOTE — The result from diagnostic tests can lead to the decision of carrying out overhaul.

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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, USA.

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

[3] As this standard goes to press, IEEE Std 1325-1996 is approved but not yet published. The draft standard is, however, available from the IEEE. Anticipated publication date is December 1996. Contact the IEEE Standards Department at 1 (908) 562-3800 for status information.

3.7 electrical failure (of a circuit breaker): Failure attributable to the application of electrical stresses to the main circuit of the circuit-breaker.

3.8 examination: An inspection with the addition of partial dismantling, as required, supplemented by diagnostic tests in order to reliably evaluate the condition of the circuit breaker.

3.9 failure: Termination of the ability of an item to perform its required functions.

NOTE — The occurrence of a failure does not necessarily imply the presence of a defect if the stress is beyond that originally specified.

3.10 failure analysis: The logical, systematic examination of an item or its diagram(s) to identify and analyze the probability, causes, and consequences of potential and real failure. (see IEEE Std 100-1992)

3.11 failure cause: The circumstances during design, manufacture, or use which have led to failure; *syn:* root cause. (see IEEE Std 100-1992)

3.12 failure detection: Examination to determine the position, evidence, and type of failure.

3.13 failure mode: The manner in which failure occurs; generally categorized as electrical, mechanical, thermal, and contamination.

3.14 focused tests: Tests performed to identify a particular area of failure.

3.15 forensic engineering: The application of engineering knowledge to questions of law affecting life and property.

3.16 initiating cause: A cause that directly leads to the failure.

3.17 in-service inspection: Visual periodic investigation of the principal features of the circuit breaker in service, without dismantling. This investigation is generally directed toward pressures and/or levels of fluids, tightness, position of relays, pollution of insulating parts; but actions such as lubricating, cleaning, washing, etc., that can be carried out with the circuit breaker in service, are included.

NOTE — The observations resulting from inspection can lead to the decision of carrying out overhaul.

3.18 major failure (of a circuit breaker): Failure of a circuit breaker that causes the termination of one or more of its fundamental functions, which necessitates immediate action.

NOTE — A major failure will result in an immediate change in system operating condition; e.g., the backup protective equipment being required to remove the fault, or will result in mandatory removal from service for non-scheduled maintenance (intervention required within 30 min).

3.19 mechanical failure: (of a circuit breaker):Failure other than an electrical failure.

3.20 minor failure: (of a circuit breaker):Any failure of a part or a sub-assembly that does not cause a major failure of a circuit breaker.

3.21 monitor: Continual or periodic testing with comparison to observe or determine trends.

3.22 overhaul: Work done with the objective of repairing or replacing parts that are found to be out of tolerance by inspection, or test, or examination, or as required by equipment maintenance manual, in order to restore the component and/or the circuit breaker to an acceptable condition.

3.23 repair: Work done to restore the component or the circuit breaker to condition for operation.

3.24 servicing: Planned servicing of the circuit breaker including lubricating and replacing minor parts.

Part I Failure investigation

4. Procedure for the investigation of circuit breaker failures

A failure investigation shall begin by determining if the failure was catastrophic, operational, or minor in order to decide what course of action to follow.

a) *Catastrophic failures*. A failure of the circuit breaker in which physical damage has occurred to power current carrying or high-voltage isolating elements. Catastrophic failures require
   - Exercise of extreme caution to minimize risk to personnel and other system equipment
   - Collection of physical data and photos to aid in analyzing the failure
   - Clean-up, and repair or removal and replacement of the failed circuit breaker to restore service

b) *Operational failures*. A failure of the circuit breaker in which a lack of basic function occurs such as, a change of state occurs when not commanded, a change of state does not occur when commanded, the circuit breaker is locked in position due to a lack of some critical parameter or an alarm is activated to warn of impending lack of basic function. An operational failure requires
   - Caution to determine if it is safe to approach the circuit breaker
   - Checking of troubleshooting features to diagnose the source of the failure
   - Repair of the circuit breaker to restore service

c) *Minor failures*. A minor failure requires
   - Checking of troubleshooting features to diagnose the source of the failure
   - Repair or scheduling of repairs of the circuit breaker to prevent future lack of function

4.1 Immediate action

a) If there has been any personnel injury and/or continuing fire, call for medical emergency help.
b) Provide first aid as needed.
c) Evacuate the immediate area.
d) Electrically, pneumatically, etc. Isolate failed equipment as dictated by equipment condition.
e) Do not try to operate failed equipment. Isolate from HV source. Before removing auxiliary power, verify status of all relay targets.
f) Extinguish fire with caution or let it burn out. Cold water on hot porcelain can cause it to fracture. Prevent fire from spreading.
g) Be aware of hazards of arced SF_6 gas and by-products, PCBs, asbestos, and other toxic materials that could be present.
h) Secure the area. Wait a few minutes. Do not immediately approach failed equipment because there may be high pressures, voltage, charged springs, excessive thermal, or mechanical stresses in the equipment.
i) Visually inspect failed equipment from a safe location to assess the situation.
j) Follow established safe working procedures for isolation, grounding, etc., and practices regarding environment protection and spill control, etc.

4.2 Investigation

a) Take good quality photographs of everything before any disassembly or moving of parts. Photographs showing an overview from all angles as well as photographs showing close details will assist in documenting visual evidence. If disassembly is required, photograph each step, with an information card appearing in the photo. Consider backup recording by video camera. Tape record all observations.
b) Determine the position of all relays, targets, and counter readings before removing control voltages, if possible. Record also by photography, if possible.
c) Interview observers or tape record as soon as possible.

d) Obtain station oscillograms, sequence of events, and logs and fault recordings.
e) Take samples of oil, gas, air, etc.
f) Call the manufacturer and determine if the manufacturer wishes to be represented during failure investigation. Determine if a consultant is required to assist in analysis of failure.
g) Think through a failure sequence first and then look at the evidence.
h) All parts should be saved until the investigation is complete. Avoid a hasty cleanup.
i) Determine events immediately preceding, immediately succeeding, and simultaneous with failure.
j) Acquire/review manufacturer's engineering information, drawings, and test reports on other “special releases/ reports.”
k) Investigate each subsystem thoroughly (tripping subsystem including latch energy sources, linkages, etc.; main current contact path and movement, arcing contacts, nozzles, etc.; fluid subsystems (gas, air, and liquid); (i.e. investigation on a system and subsystem basis).
l) Review maintenance records to see if there has been any recent or repeating type activity. Often failures result from parts disturbed during maintenance procedure.
m) Open breaker access, inspect internals, and disassemble as necessary. Try to avoid disassembly until experts arrive.
n) Inspect circuit breaker (external). Look for sticking parts, arc marks, burning, eroded metal, molten metal, signs of excessive pressure, etc., leakage of fluids [smoke (gas) or oil (liquid)].
o) Determine the position of all operating mechanism parts including auxiliary switch contacts, props, latches, linkage, pressure switches, valves, and control power breakers. Disconnect supply source switches before releasing mechanism stored energy.
p) If a failure was explosive, determine distances parts travelled, sizes of parts, which parts, etc. Map location of exploded/propelled items. Inspect parts for arc marks etc. before beginning clean up, etc. Make pictures, movies, videotapes, drawings, etc. as appropriate.

4.3 Investigation flow chart

In many situations, it may be desirable to perform selected tests. Figure 1 has been developed as a guide to aid in the determination and investigation of a failure.

The two starting points for this flowchart are

a) Circuit breaker failure.
b) Routine tests that show deviation from past history. Routine tests cover such tests as those listed in table 3.

The paths in the flowchart lead to scrapping or returning to service. Prior to returning to service, it may be desirable to perform selected tests to verify suitability for service.

Based upon the external observations (see table 2) or the presence of obvious damage, selected tests may be performed as suggested in table 3. From their results, a hypothesis of failure can be developed. This may be confirmed through internal inspection and teardown as deemed appropriate.

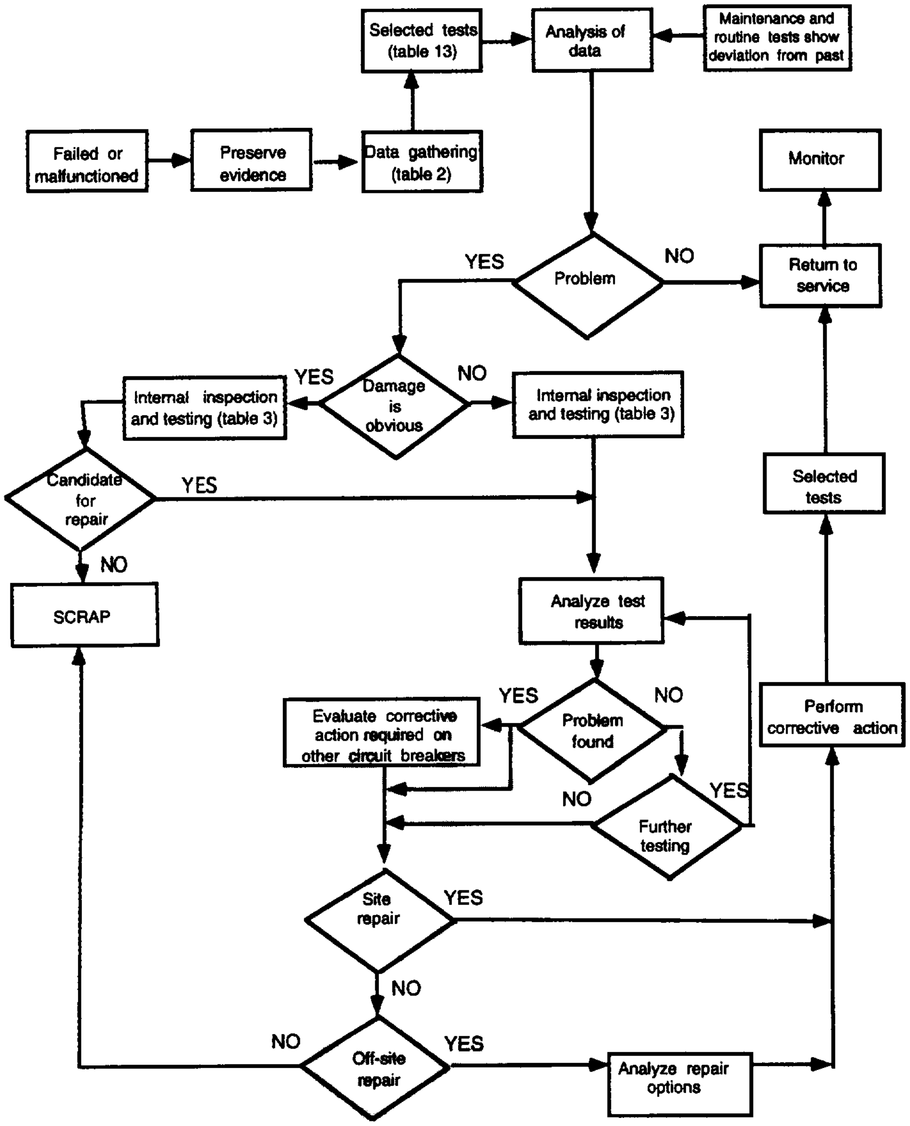

Figure 1— Suggested investigation flow chart that forms the basis for this guide

4.4 Recommended plan of action

4.4.1 Failure investigation

a) Determine if the circuit breaker was in a long-term static position or if it had recently changed state when the failure occurred or was initiated.

b) If the failure was during a static position
   1) Determine where the initial breakdown occurred.
   2) Determine whether the insulating fluid (gas or liquid) systems were fully charged and full.
   3) Determine whether the paths to ground were in specified condition, i.e., gas and air dry; minimum external contamination; no conducting paths to ground.
   4) Determine whether there were any voltage stresses that could have exceeded the nameplate levels, i.e., lightning; switching surges or other transients.

    5) Look at maintenance records for clues.
    6) If the breaker failed while open, check for condition of the grading capacitors that would cause unequal voltage distribution across the breaks.
    7) Determine if other system events occurred recently or at the time of failure.
- c) If the failure appeared to be initiated during interruption
    1) Read oscillographs and digital fault recordings if available.
    2) Determine whether the operating voltage and system short-circuit level was within the nameplate rating of the switchgear.
    3) Determine whether the breaker has capability of switching capacitors if it was used for that purpose.
    4) Check the pressure interlocks for adjustment and proper functioning.
    5) Verify that all mechanisms are in the same position. Look for broken parts of mechanism or valve gear as well as for evidence of pumping if all mechanisms are not in the same position.
    6) If a circuit breaker opened and failed several seconds or minutes later, consider the possibility that it opened, dumped insulating fluid by a valve failure or other means and then failed dielectrically.
    7) Determine whether there was any lightning in the vicinity. If so, consider the possibility that the circuit breaker was opening due to a lightning stroke or shield failure and failed due to a subsequent lightning stroke.
    8) Look at maintenance records for clues
    9) Check condition of resistor switches, resistors, and grading capacitors for any malfunction that would cause unequal voltage distribution across the breaks.
- d) If the failure appeared to be initiated during closing
    1) Read oscillographs and digital fault recorders if available.
    2) Determine whether the system momentary current was within the nameplate rating of the circuit breaker.
    3) Determine whether the breaker was fully closed.
    4) Look at the maintenance records for clues.
- e) A review of the above results will probably give direction to the troubleshooting staff.

4.4.2 Summarizing failure analysis

- a) In summarizing the failure analysis, indicate the sequence of events that caused the failure. If possible, give the time the events occurred and backup data.
- b) State the most probable cause of failure.
- c) State any preventive measure that may prevent future failure occurrences.

4.4.3 Summary

- a) Gather data per 4.2.
- b) Review records of oscillographs and operations, including weather, and any voltage and current transient information on system and related circuit breaker operations.
- c) Review application vs. ratings.
- d) Review maintenance records.
- e) Prepare sequence of events from the time all systems were normal until failure.
- f) Propose all possible failure sequences.
- g) Determine most likely cause.
- h) Determine if other similar equipment has had similar experiences, or could have similar failures in the future.
- i) Determine corrective action plan.
- j) Determine which parts are damaged and what damaged them.
- k) Inspect similar type circuit breakers and determine if all parts are present and no foreign parts are present.

5. Data collection

5.1 General approach

Cooperation at all levels of the participating organizations should facilitate the investigation at the site and improve the accuracy of the diagnosis.

It is important that the manufacturer be informed of the equipment failure, especially when it is under warranty and always if there is injury or major equipment damage. The manufacturer will probably be expected to supply information such as the factory test data, inspection history, and internal construction drawings, and investigation support. If at all possible, do not remove or disassemble until the manufacturer has visited or concurred.

Any significant failure and all failures that involve personal injury will probably be involved in litigation. Well documented records of all observations including photographs are critical to a factual recording. Nothing should be trusted to memory.

Development of a team concept may be helpful for the final analysis of data. It is suggested that the team include representatives of the user and manufacturer/repair facility. This may facilitate the work and may also eliminate any considerations of bias in the final diagnosis.

5.2 Preparation

Some preparation prior to travelling to the site will aid site investigation. Failure investigations at the site are similar to detective work; a knowledge of the subject, a sense of curiosity, and objectivity is vital.

A quick review of information that might be available in a file regarding the subject circuit breaker may prove to be valuable before travelling to the site. Some items may also be taken to the site. Table 1 is a suggested checklist of various items.

5.3 Immediate investigation

Timeliness of an inspection of the failed circuit breaker is very important. Data could be destroyed because of movement of the circuit breaker or changes in the system configuration; therefore, data collection and tests should proceed as quickly as possible.

Work crews are almost always on-site before investigators. Their standing instructions should be to follow the outline discussed in clause 4, and to bypass failed equipment rather than to “clean it up.” Someone in the work crew should be appointed to preserve evidence and to follow 4.2. However, it is not always practical to cease restoration of service until the investigators arrive on-site. Thus, instructions should be given to operating personnel for restoration of service consistent with minimum negative impact on failure investigation work. If possible, all work should cease on the circuit breaker until the investigators have a chance to look at the circuit breaker, take photographs, notes, and perform tests that will assist future analysis.

Oscillograms, digital fault recorders, sequence of events recordings, and printouts should be reviewed.

Familiarity with the site, circuit breaker and general area is important. Personnel familiar with the operation and maintenance of the circuit breaker should be part of the investigation team.

A complete investigation of each circuit breaker subsystem ensures a thorough investigation.

Table 1— Suggested checklist of preparation items

____	Circuit breaker instruction manuals—includes such items as outline and schematic drawings, descriptions of components, and factory photographs.
____	Test reports (factory and field)
____	Any prior written reports or notes about previous failures
____	Routine inspection reports
____	One line diagram of station
____	Relaying scheme
____	Records of maintenance work which may include reports on past problems
____	Camera (video, 35 mm including close-up lens), film, flash, batteries
____	Tape measure, calipers (Vernier)
____	Protective clothing, safety glasses, safety shoes, hard hat, gloves
____	Binoculars
____	Magnifying glass
____	Tape recorder, tape and batteries
____	Flashlights
____	Oil sample bottle and syringes
____	Gas sample bottles
____	Plastic bag(s) to protect evidence
____	Plastic tag(s) to identify evidence
____	Records of relay targets
____	Oscillographic, digital fault recordings or sequence of events records
____	Identification of personnel who may have been present
____	Information of system operating conditions
____	Trouble reporting form
____	Work permit

It is better that at least two individuals initially inspect the circuit breaker. Two people can support one another and discuss the various findings and the immediate “next step” at the site.

Items that may be of importance include conditions and events at the time of the failure, physical inspections of the circuit breaker following failure, and electrical conditions of the circuit breaker following failure. Table 2 is a suggested checklist of observations.

5.3.1 Electrical tests

Safe work methods and practices should be observed. Before performing any tests, precautions should be taken to assure that the circuit breaker is isolated from the power system and has been properly grounded and any necessary safe work permits have been issued. Table 3 is a suggested checklist of electrical tests. It is recommended to consult the manufacturer's instruction manual.

5.3.2 Tests of insulating medium

These should include chemical analysis of gas, moisture content, and dielectric withstand test. Check the polychlorinated biphenyls (PCB) content.

Table 2— Suggested checklist of general observations

External conditions	Recorded data
___ time of day	
___ "no lights" call (power out)	
___ storms or lightning in area, general weather conditions	
___ temperature	
___ unusual sounds, odors, sights	
___ debris expelled from circuit breaker	
___ dead animals in area	
___ evidence of animal contact (animal may not be dead)	
___ foreign objects in area	
___ parts—visual	
___ evidence of vandalism	
___ interview of witnesses or station operators present when unit tripped or failed	
___ load interrupted	
___ system disturbances—both local and remote	
___ switching configuration in station at time of event	
___ previous, subsequent or concurrent switching operations	
___ location of surge arrestors	
___ signs of arcing or damage (metal erosion) to substation bus, insulators, steel structures	
___ movement of circuit breaker on its base	
Main tank	**Recorded data**
___ bulged	
___ cracked	
___ leaks	
___ evidence of overheating	
___ oil level	
___ gaskets or seals, leaks, expulsion, etc.	
___ gas temperature	
___ presence of arc marks, eroded metal, molten metal	
___ air or gas valves—open or closed	
___ air pressure	
___ gas pressure	
Bushings	**Recorded data**
___ signs of arcing—phase to phase or phase to ground	
___ leaks	
___ broken porcelain	
___ holes in cap	
___ pollution	
___ tracking	
___ oil level	
___ gas pressure	

Operating mechanism	**Recorded data**
___ linkages, loose, bent, corroded, broken	
___ spring condition	
___ pressure in air reservoir, normal—low	
___ hydraulic “pre-charge” pressure	
___ sludged hydraulic fluid	
___ control valves—open or closed	
___ corrosion in air or hydraulic system	
___ piping, leaks	
___ oil level in dashpots	
___ blown fuses	
___ breaker position, open or closed	
___ counter reading	
___ loose bolt/nuts securing the operating mechanism to the breaker	
___ control cabinet condition	
Protective relay targets	**Recorded data**
___ all targets that dropped/indicated	
___ all targets that should have dropped but did not drop	
Operation of	**Recorded data**
___ oscillograph	
___ sequence of events recorder	
___ digital fault recorder	
___ fault recorder	
___ annunciator	
___ blown fuses	
___ operation counter	
___ operation of other breakers on the system	
___ gas pressure	

5.4 Subsequent investigation

- Review the application of the circuit breaker. (See IEEE Std C37.010-1979 for guidance.)
- Review maintenance records.
- Determine available fault current. The oscillograms, digital fault recordings, and the sequence of events recordings printouts may assist in determining the actual fault current and fault duration.
- Check the system TRV at the expected short-circuit current level to be sure the TRV falls within the rating of the circuit breaker. Calculate the prospective transient recovery voltage and rate of rise of recovery voltage in accordance with methods documented in ANSI and IEEE standards, e.g., IEEE Std C37.011-1979.

Table 3— Electrical and other tests

Field tests
-Auxiliary power supply voltge
-Contact resistance
-Insulation resistance
-Power factor
-Starting & running currents of motors
-Opening & closing coil resistances
-Timing test with motion analyzer
-Value of closing resistors
-Value of opening reistors
-Value of grading resistors
-Value of grading capacitors (capacitance, power factor)
-Insulation & resistance of bushing current transformers
-Insulation power factor (all paths)
-Contact wear/erosion
-Oil or gas quality
Other tests
Operating mechanism
-Calibration and scaling of safety valves
-Calibration of pressure gauges
-Calibration of pressure switches
-Free movement of mechanism
-Fluid in dashpots
-Compressor interstage pressures, oil level
-Moisture levels in air, oil, and gas systems
-Lubrication

NOTE — These are tests that are common. (Review the manufacturers instruction book for values and testing intervals.)

6. Failure analysis

6.1 General

Prior to analyzing the failure, it is imperative that all the investigations, data collection, and tests are performed. See clauses 4 and 5. When analyzing a failure, it is important to determine the sequence of events. Fault recorders, oscillographs and/or sequence of events recorders, if available, can help determine if a fault occurred, the number of faults, breaker operation, and the time of events. Analyzing the protective relay targets, annunciators, SCADA logs, breaker operations and interviewing witnesses can provide information to determine the sequence of events.

Once sufficient data has been gathered from the on-site and off-site investigations, several hypotheses should be developed using the scientific method. A hasty analysis may lead to a bad diagnosis. It is recommended that data be thoroughly studied before interpretations are finalized. In-service failure sometimes results in mechanical damage and electrical failure. The energy available from the power system can cause both to occur. One must use caution in reporting cause and effect.

These hypotheses should be tested against the data and the performance of other system components. This may be done through peer group discussions and data verification. Any information found incorrect should be replaced, if possible, with correct information. Studies, appropriate laboratory experiments and factory simulations could be initiated to test the accuracy of each hypothesis.

If the assembled data does not support a proposed hypothesis, a revised hypothesis should be developed and retested. Unsupportable hypotheses should be discarded.

6.2 Operating mechanism failures

A majority of circuit breaker failures are due to a failure of the operating mechanism.

Failure of the operating mechanisms are usually of the following type:

a) Failure in the closed position
b) Failure to close
c) Failure to close properly
d) Failure to stay closed, i.e., unintended trip
e) Failure in the open position
f) Failure to open
g) Failure to open properly
h) Failure to stay open, i.e., unintended close

Failure of the mechanism in the closed position could involve a failure to prepare for the next opening operation, such as failure of the motor to charge the closing springs. Inadequately charged closing springs would be indicated by the failure of the spring charged flag going from “discharged” to “charged,” but may not be noticed until an opening operation is attempted.

Failure to close or failure to stay closed, i.e., unintended trip, could be due to defects in the latches, the close coil, the anti-pump relay, the auxiliary switches, or other control scheme components.

A leak in the air storage tank of the pneumatic system or in the accumulator of the hydraulic system could cause excessive motor operation and circuit breaker lockout.

Failure to close properly, at the correct speed, or failure to stay closed, could be due to low pressure, weak springs, high friction in moving joints, improper latches operation, or higher than rated short-circuit current.

Failure to open or failure to stay open, i.e., unintended close, could be due to defects in the latches, shock absorbers, the trip coil, the auxiliary switches, or other control scheme component.

Failure to open is frequently from a slower than required opening speed usually caused by low operating pressure, weak or broken springs, or by excess friction in the moving joints.

The failure modes are as numerous as the types of designs. Obvious things would be broken mechanical parts, incorrectly manufactured parts, excessively worn parts, excessive corrosion, inadequate lubrication, gummy lubrication, incorrect adjustment, and things of this sort. The forensic analyzer should study carefully the manufacturer's schematics and drawings relating to the operation of the particular mechanism, considering the role of each part involved. After some study, a best fit scenario explaining the reason for failure shall be developed. Not all mechanical failures are attributed to the mechanism. There are a few that could be caused by jamming of the main contacts or contact rods, bell cranks, etc.

Apart from complete failure to operate, trouble can also develop in the latch system resulting in failure to latch (e.g., breaker will not stay closed). Latches are usually spring return and may use “bumper stops” for bounce control. These are often carefully balanced mechanical systems having narrow wear limits. Sometimes the extra vibration from high-speed reclosing will result in extra latch bounce and failure to latch.

Visual inspection of springs, linkages, supports, and pivots can be made to look for major defects. A mechanical no-load operation, during which the times from coil-energizing to contact-making and breaking are recorded, is required for an accurate assessment of the health of the mechanism.

The compressor, including wearout or valve problems, may contaminate the air system and eventually prevent duty cycle. Excessive recirculation could even cause air to become hot enough to ignite oil vapors.

Pressure switches, gages, or safety valves may leak or have loose settings and could allow operation at a time when the mechanism will not have adequate speed.

Air leaks may drag the compressor system down and affect the ability of the circuit breaker to operate.

Hydraulic leaks may drag the pump system down and affect the ability of the circuit breaker to operate.

Lubrication, including incorrect application or lack of lubrication, may cause excessive binding of mechanical components including linkages and latches. Excessive mechanical stresses caused by binding can lead to destruction of mechanism components or even to interrupter failure.

Mechanism components become loose due to excessive vibration or shock during operations. Components are damaged due to incorrect adjustments or changing adjustments or settings on mechanical components. Large amounts of energy are used in the stored energy mechanisms.

6.3 Failures due to degradation of external solid insulation

This is the primary outdoor insulation used for most circuit breakers is porcelain. Degradation of porcelain insulators occurs under very heavy contamination due to industrial pollutants such as fly ash, iron laden slag, automotive emissions or salt-fog. These modes of failure are countered by spray cleaning the porcelain surfaces or by applying protective coatings to the weathersheds to prevent accumulation of pollutants on the porcelain surfaces. These coatings must be replaced periodically.

Analysis of this type of failure is aided by the arc marks and puncture trails.

6.4 Failures due to voltage transients

Voltage transients that exceed the breaker capability do occur on high-voltage power systems. Some of the sources of voltage transients on the system are as follows:

a) Lightning
b) Switching
c) Physical contact with a higher voltage system
d) Repetitive intermittent short circuits
e) Forced-current zero-current interruption
f) Resonance effects in series inductive-capacitive circuits

An excessive voltage transient may initiate the failure. The diagnosis will then require detailed knowledge of the system conditions and the circuit breaker state (closed, open, closing, or opening) at the time of failure. Oscillographs made at the time of failure would also be informative. If the circuit breaker had been opening at the time of failure, a subsequent lightning stroke or a voltage transient produced by the switching operation may have resulted and induced the failure.

Failure analysis for these conditions is often possible because of the availability of automatic fault recorders. More sophisticated monitoring systems that are under development may provide much better information.

6.5 Failures due to misapplication

Operating circuit breakers in systems that exceed the circuit breaker capabilities can lead to the circuit breaker failure. Some of these system conditions are due to normal system growth or other unforeseen additions, e.g., capacitors, reactors, etc. as follows:

a) System short-circuit current exceeding the circuit breaker rating
b) System TRV exceeding the circuit breakers rating
c) Operating voltage above the circuit breaker rated voltage
d) Load current in excess of circuit breaker rated continuous current
e) Frequent operation
f) Change in reclose duty cycle
g) Installation of shunt capacitors, shunt reactors or series capacitors
h) Application of a general purpose breaker for a definite purpose duty
i) Ambient temperature beyond the circuit breaker operating range

Failure analysis for these conditions is aided by calculation of system fault current, prospective transient recovery voltage, its rate of rise, a knowledge of system operating conditions, system configuration, and the analysis of fault recorder or monitor records.

6.6 Resistors, capacitors, current transformers

Some of the circuit breaker failures originate from the failure in its accessories such as opening and closing resistors, grading and TRV control capacitors, and instrument current transformers. These accessories usually fail violently, causing damage to the breaker interrupter, etc. Sometimes it is difficult to determine if the accessories failed first or as the result of another failure.

a) Post-insertion opening resistor failures and pre-insertion closing resistor failures can be caused by improper operation of resistor switches, overheating of the resistor due to an excessive number of rapid closings and openings, moisture infiltration, or defective resistors.
b) Breaker capacitor failures have occurred due to moisture infiltration, leakage of oil, and infiltration of SF_6 into the capacitor and defective capacitors.
c) Current transformer failure may be due to defective current transformers or moisture infiltration or to open circuiting of the secondary.

6.7 Failures due to animals

Animals remain a source of occasional failures from line-to-line or line-to-ground. When these failures are in substations and close to circuit breaker bushings, they can cause damage.

Analysis of the animal remains and fault recorded should pinpoint the failure condition.

6.8 Other causes of failures

a) Foreign objects in breaker
b) Burrs or sharp edges causing corona and dielectric breakdown

Analysis of failures due to manufacturing or maintenance errors is ordinarily possible because the errors may have been significant defects such as the screwdriver left in a breaker or the sharp edges on shields are not removed. They are often found near the main fault damage.

6.9 Internal dielectric and interrupter failures

6.9.1 Single-pressure SF_6, puffer, circuit breakers

In addition to causes described in 6.1 through 6.8, single pressure SF_6 circuit breakers can fail for the following reasons described in 6.9.1.1 through 6.9.1.5.

6.9.1.1 Failures due to loss of SF_6

Loss of SF_6 sufficient to cause failure should be rare for high-voltage circuit breakers that use on-board pressure and temperature compensated pressure switches to alarm or trip breakers before a dangerous condition is reached. Obviously a massive failure of the gas containment system can be too fast for pressure switches to detect. A failure of the pressure relief rupture disc, for example, will cause the pressure to drop much faster than a pressure switch can respond.

6.9.1.2 Failures due to degradation of the SF_6

Degradation of SF_6 can consist of addition of water vapor, air, or other gases, including the decomposition products of SF_6.

The presence of water vapor in SF_6 that has been subjected to arcing or corona can quickly degrade many types of solid insulation.

Liquid water on the surface of a solid insulator can seriously reduce the dielectric strength of the insulator by combining with the free fluorine, lower fluorides of SF_6, and metallic fluorides produced by arcing. The metallic fluorides are normally produced by heavy arcing at the contacts and appear as dark powders in the arcing compartment. The metallic fluorides, except silver fluoride, are insulators when dry. However, they will quickly combine with water vapor or liquid to form very strong fluoridic acids, which are very good conductors.

Ice does not have any measurable effect on the dielectric strength of solid insulators in SF_6; however, the presence of ice is not desirable because its rapid thawing may cause liquid water to form on the insulator. This occurrence, combined with the arc products described above, will degrade the insulation.

Failure analysis for the presence of water, as either vapor, liquid, or solid, cannot be determined after an arcing failure. Monitoring or periodic checking of moisture content prior to the failure is the only way to show that excessive quantities of water were present.

Air can reduce the dielectric strength of SF_6 significantly for concentrations higher than 20%. Air has an even greater effect on interrupting performance.

6.9.1.3 Failures due to SF_6 gas liquefaction

Most of the conditions under which SF_6 can cause failure are detailed in 6.9.1.1 and 6.9.1.2. The remaining issue is what happens when the temperature drops so low that the SF_6 starts to liquefy. For most single-pressure breakers this occurs at –30 °C to –40 °C. When some of the SF_6 gas condenses as a liquid the density of the remaining gas is reduced. The dielectric strength of SF_6 in almost all applications is directly proportional to the gas density; therefore, the dielectric strength of the internal insulation system is reduced.

Breakers suitable for temperatures colder than the liquefaction temperature of SF_6 may utilize an SF_6-gas mix.

Failure analysis of this condition will require records of prior measurements of gas density and the log of these measurements over a long enough period to assure that the gas density at temperatures above the liquefaction point is known. Then, density and dielectric strength at the time of failure can be estimated.

6.9.1.4 Failures due to degradation of Internal solid insulation

Solid insulation in single-pressure circuit breakers is generally selected to resist the environment that includes arced SF_6. Some of the cast resin insulators are not resistant to tracking in the SF_6 atmosphere. All glass fiber reinforced insulation is subject to tracking unless the glass fibers are thoroughly sealed away from the arced gas. Similarly, quartz-filled casting resins are subject to tracking in arced SF_6. Some special protective coatings have been developed to protect materials containing quartz and they have proven to be very effective.

When analyzing failures, deep or eroded carbon tracks on the insulators are easily found and point clearly to a failure mode, i.e., materials or coatings that were not effective.

6.9.1.5 Interrupter failures

a) Unacceptable tolerances of the arcing contacts, main contacts, and nozzle could cause failures.
b) If the position vs. time, i.e., velocity, of the interrupter is not within tolerance, the interrupter may fail. Failure analysis will center on arcing damage, pre-failure, and post-failure measurement of breaker travel.
c) Insufficient gas pressure build-up and gas flow in the gas compression piston could cause failures.
d) Excessively worn contacts and nozzles could also cause interrupter failure.

6.9.2 Two-pressure SF_6 circuit breakers

The discussion in 6.9.1 is equally valid for failures of two-pressure SF_6 circuit breakers.

Two-pressure SF_6 breakers have several additional failure modes compared to single pressure circuit breakers. The high pressure compartments of the breaker are operating at high enough density so that liquefaction occurs at room temperatures. Heaters shall be used to maintain the gas density at lower temperatures. This introduces the problems of a circulating gas system that requires frequent operation of the gas compressor.

Two-pressure breakers have many more seals and connections that could cause failures.

For most two-pressure breakers gas liquefaction occurs at –30 °C to –40 °C for the low pressure insulating gas and at 5 °C to 15 °C for the high pressure interrupting gas.

The two-pressure SF_6 breaker with its gas compressor and gas filters, has the capability of purifying the gas under normal operating conditions. Under low temperature conditions, the breaker has the capability of concentrating the water from the gas at low temperature points in the gas system, where gas heaters are not present or not effective.

6.9.3 Bulk oil circuit breakers

In addition to causes described in clause 6.1 through 6.8, bulk oil circuit breakers can fail for the following reasons listed in 6.9.3.1 and 6.9.3.2.

6.9.3.1 Dielectric types of failures

a) Internal bushing deterioration by oil leakage, moisture/tracking
b) Water leakage into main oil tank
c) Tracking or related deterioration of operating rod
d) Loose and spitting joints
e) Carbonization of the oil

6.9.3.2 Interruption types of failures

a) Deteriorated arcing contacts or baffle chambers
b) Evolving fault
c) Binding mechanism
d) Inoperative tank heaters
e) Control malfunction including interlocks
f) Opening without a full close cycle
g) Pumping or related pilot valve failures

6.9.4 Vacuum circuit breakers

In addition to the causes described in clauses 6.1 through 6.8, vacuum circuit breakers can fail for the following reasons:

a) Dielectric breakdown across the open contacts due to loss of vacuum in the interrupter or to other reasons
b) Inability to interrupt current due to loss of vacuum in the interrupter or to other reasons
c) Inability of the compression springs to maintain specified force on the closed interrupter contacts

6.9.4.1 General

When a failure does occur, diagnosis by the user can proceed as follows:

a) If the failure is clearly outside the vacuum interrupter, the user may be able to determine the cause without the assistance of the manufacturer,
b) If the failure is suspected to be inside the vacuum interrupter, then the assistance of the manufacturer is essential, since sophisticated test methods and a detailed knowledge of the internal construction of the interrupter, which only the manufacturer possesses, are required for the detection of internal defects. The user should make no attempt to open the vacuum interrupter since this action could destroy important diagnostic information.

6.9.4.2 Failure of dielectric medium

Dielectric failures can be grouped as

a) External to the interrupter; or
b) Internal to the interrupter

External failures will be similar to those in other types of circuit breakers that can involve bushings, standoff insulators, and insulating tie members. Since vacuum interrupters require only a comparatively small interrupting gap, they are very compact with short external insulation distances. Therefore, the vacuum interrupter is typically not exposed directly to outdoor weather conditions, but is mounted inside of some other enclosure, such as a metal box filled with air or a tank filled with some other insulating medium.

In some applications at higher voltages, the vacuum interrupter is encased in an insulating coating, such as epoxy or urethane, to improve its external voltage withstand ability.

A dielectric failure of an external insulating element can be diagnosed by the user although the assistance of an insulation expert or of the manufacturer may be advisable. The failure usually leaves easily observable clues pointing to the element that failed. However, the initiating cause of failure may be more difficult to determine.

A material weakness or surface contamination may have initiated the failure. Careful tests of the insulation by a materials expert may be useful to find such material flaws or the evidence of contamination.

If a dielectric failure is suspected to have occurred inside the vacuum interrupter, then an ac voltage withstand test may be performed according to the manufacturer's instructions. External insulation shall be cleaned of any contamination, using a dry cloth, before performing this test.

6.9.4.3 Failure to interrupt

Failures to interrupt are very unusual with vacuum circuit breakers applied within their rating, since the interruption process in vacuum is very efficient and long lived.

The possible causes of a failure to interrupt are

a) Improper application, for example:
   1) Short-circuit current higher than rated
   2) Open-circuit voltage higher than rated
   3) Transient recovery voltage faster than rated
b) Loss of vacuum (leak allows gas or fluid to enter)
c) Broken parts inside the vacuum interrupter
d) Slow operating speed
e) Failure of the mechanism to hold the contacts open
f) Excessive contact wear beyond normal life
g) Voltage breakdown outside the interrupter caused by contamination which fails dielectrically when recovery voltage is applied

A failure to interrupt sometimes does not present externally visible evidence. Since the interrupting contact gap inside vacuum interrupters is much smaller than in other types of interrupters, the arc energy released is also much smaller. At currents that are a small fraction of the interrupter's rating, it is possible for arcing to continue for tens of cycles, and even a few seconds, without breaking the vacuum envelope or causing visible damage. Even at the interrupter's rated short-circuit current, a failure to interrupt with very long arcing times of many cycles may only crack the ceramic envelope. Moreover, if internal arcing damage is small, the interrupter may be able to continue to function after a failure and present no evidence that a failure has occurred.

Inspecting a vacuum interrupter for the cause of a failure to interrupt is limited to the following two possible actions on the part of the user:

a) Inspecting for obvious cracks or suspicious marks that could indicate a break in the vacuum envelope, or
b) Performing some basic tests on the vacuum interrupter including:
   1) An ac voltage withstand test across a vacuum interrupter whose contacts are in the open position can indicate, if a low value is observed, the presence of internal damage or a break in the vacuum envelope
   2) A dc resistance test through the closed interrupter in a circuit breaker can indicate, if a high value is observed, the presence of either external damage, such as weak or broken contact pressure springs, or internal damage, such as deformed or changed contacts.

If an internal failure is suspected, the user should make no attempt to open the interrupter. The user should, instead, contact the manufacturer who can perform sophisticated tests to look for the presence of internal gas or for small leaks. The user should also request that the manufacturer take X-ray photographs to look for physical changes of the internal parts. Ultimately, the manufacturer should cut open the interrupter and be able to interpret the physical internal evidence and test internal parts to look for defects or metallurgical changes in the contacts.

CAUTION — Valuable data for problem diagnosis and corrective action formulation can be lost if the user attempts to open a vacuum interrupter.

6.9.4.4 Failure of the operating mechanism

Failure of the mechanism in the closed position could involve a failure of a contact pressure spring to provide full force on the interrupter contacts. These springs, although usually located on each pole unit, can be considered a part of the mechanism. Inadequate contact force can result in problems in carrying current through the interrupter, by either excessive heating due to a high contact resistance or even welding closed, especially if a high short-circuit current occurs.

6.9.5 Air magnetic circuit breakers

In addition to causes described in 6.1 through 6.8, air magnetic circuit breakers can fail for the following reasons.

6.9.5.1 Dielectric types of failures

a) Composite bushing tracking
b) Arc chute tracking due to deterioration
c) Contaminated insulators
d) Loose and spitting joints
e) Failure to re-install phase barriers

6.9.5.2 Interruption types of failures

a) Puffer device failure at low currents if arc does not go into chute
b) Contact or arc chute lack of maintenance
c) Mechanism hang up or slow operation due to binding
d) Disconnected or incorrectly connected blow out coils

6.9.6 Air blast circuit breakers

In addition to causes described in clauses 6.1 through 6.8, air blast breakers can fail for the following reasons.

6.9.6.1 Dielectric types of failures

a) Low insulating gas pressure
b) Low air pressure (particularly with breaker open)
c) Wet air
d) Grading capacitor failure
e) Contaminated insulators
f) Loose and spitting joints

6.9.6.2 Interruption types of failures

a) Pumping due to either controls or pilot valve problems
b) Interlock failure
c) Breaker timing outside of limits
d) Breaker resistor switch outside of timing limits
e) Resistor failures

f) Mechanism opening without blast
g) Air line failures during interruption

6.9.7 Minimum oil circuit breakers

Deterioration of gaskets allow contamination of interrupter chamber or loss of oil which can lead to interrupter failures. Some interrupters rely on gas pressure in the interrupter to improve re-strike performance.

In addition to causes described in clauses 6.1 through 6.8 minimum oil circuit breakers can fail for the following reasons.

6.9.7.1 Dielectric failures

a) Grading capacitor failure
b) Moisture ingress into operating chamber
c) Contaminated external insulating surfaces
d) Degradation of insulating oil due to carbonization and/or water intrusion
e) Operation at duties beyond rating

6.9.7.2 Interruption types of failures

a) Breaker opening speed outside of limits
b) Re-strikes on capacitive switching
c) Binding in operating mechanism or operating linkages
d) Degradation of internal solid insulation/interrupter disks
e) Degradation of oil due to carbonization and/or water intrusion
f) Loss of pressure on the interrupter

7. Failure modes and causes

The most common reported failure modes of circuit breakers are as follows:

a) Does not close on command
b) Does not open on command
c) Closes without command
d) Opens without command
e) Does not make the current
f) Does not break the current
g) Fails to carry current
h) Dielectric breakdown to ground
i) Dielectric breakdown between poles
j) Dielectric breakdown across contact gap - internal
k) Dielectric breakdown across contact gap - external
l) Lockout in open or closed position
m) Miscellaneous

The most common causes of failures of circuit breakers as reported by CIGRE [B15] are shown in the data below. This information is provided here to assist the user in performing circuit breaker diagnostics and to monitor the circuit breaker performance.

A majority of the above failure modes are related to a failure in the operating mechanism.

Operating mechanisms	**43–44%**
Compressors, pumps, etc.	13.6–18.7%
Energy storage	7.2–7.6%
Control elements	9.3–11.6%
Actuators, damping devices	5.1–8.9%
Mechanical transmission	1.4–3.8%
Electrical control & auxiliary circuits	**20–29%**
Trip/close circuits	1.5–10%
Auxiliary switches	2.1–7.4%
Contactors, heaters, etc.	5.4–7.6%
Gas density monitors	4.0–10.7%
High-voltage components	**21–31%**
Interrupters	9.4–14.0%
Auxiliary interrupters, resistors	0.6–1.3%
Insulation to ground	5.7–20.9%
Other causes	**5.4–6.8%**

It should be noted that the above data was reported for SF_6 single pressure circuit breakers placed in service between 1978 and 1992. The CIGRE report also refers to a previous study that included all types of circuit breakers. This study had reported that 70% of circuit breaker major failures were of mechanical origin—19% of electrical origin concerning auxiliary and control circuits and 11% of electrical origin concerning the main circuit.

Part II Diagnostics

8. Diagnostics

As an aid to diagnose the circuit breaker condition and to predict any impending failure, the user should consider monitoring the various circuit breaker features and functions.

Circuit breaker diagnostics will assist the user in predicting the working condition of the parts and in extending the maintenance intervals.

Circuit breakers can be furnished with some built-in monitors. Additional monitoring is possible. The quantity and complexity of additional monitoring will depend upon the type and rating of the circuit breaker, and its importance in the system and user's preferences.

Monitoring a circuit breaker requires some or all of the following actions on the part of the user:

a) Visual periodic observation of indicators, marks, gauges, indicating lights, etc., at the circuit breaker location, without any dismantling, or de-energizing, but may require opening mechanism cabinet doors.
b) Visual periodic observation of indicators and gauges, etc., at a remote location, without dismantling, de-energizing of the circuit breaker. This may require permanent connection of transducers, auxiliary contacts, etc.
c) Visual observation of indicators, gauges, etc., temporarily connected to the circuit breaker, e.g., pressure gauges.
d) Automatic recording, continuous or periodic at set intervals, of the circuit breaker's basic functions by using chart recorders, sequence of events recorder, fault monitors, etc. This may require the circuit breaker to be de-energized and partially dismantled or at least operated while in-service.
e) Installation of complex diagnostic systems, either permanently connected to each circuit breaker or as a plug-in device to be used periodically.
f) Diagnostic tests carried out externally, e.g., timing tests, contact resistance, insulation, power factor, etc. This may require the circuit breaker to be de-energized and partially dismantled or at least operated while in-service.
g) Inspection with de-energizing and partial dismantling, as required, supplemented by measurements, non-destructive tests, etc.
h) Analysis of pressure switch settings and operation. This may require the circuit breaker to be de-energized.

See annex A for monitoring techniques and diagnostic systems.

Tables 4A through 13 list some of the features and characteristics of the circuit breaker recommended for monitoring.

These tables include the following:

a) Characteristic to be monitored
b) Circuit breaker operating mode for monitoring
c) Parameters measured and derived information
d) Assessment of the circuit breaker condition based on the derived information
e) Typical benefit/effort analysis for a typical utility

Some of the characteristics are monitored continuously by means of gauges, mechanical indicators, or by means of relays, transducers, etc., connected to the circuit breaker control system. Remote indication is provided by transducers. Other characteristics require the circuit breaker to be de-energized and isolated or even dismantled.

Several characteristics such as power factor, resistances, etc., require the user to maintain records and observe the trend of the measured values for proper assessment of the circuit breaker condition.

Effort to provide a monitoring system includes the cost of necessary materials, design, and labor effort required and the ongoing cost of operating and maintaining the system(s) and depends upon several factors such as the type of circuit breaker, complexity of the monitoring system, quantity of circuit breakers involved, and their location. Effort to provide a monitoring system will vary among users.

Effort for the application of a monitoring system is defined as *Low* when the system can be provided without any significant design and labor effort on the part of the circuit breaker manufacturer or the user.

Effort for the application of a monitoring system is defined as *Medium* when it was judged that the design and labor effort was somewhere between *High* and *Low*.

Effort for the application of a monitoring system is defined as *High* when the system requires a substantial design and labor effort, or if it requires the circuit breaker to be de-energized or partially disassembled. Cost is also considered to be high when the information obtained could have been indirectly derived from some other low cost system.

Effort for the application of a monitoring system is defined as *Extremely High* if circuit breaker must be moved to another location for test or elaborate field setup must be made.

Benefit is defined as *Low* when the derived information is essentially for statistics or to determine or observe trends, or it detects a condition that does not require an immediate action on the part of a user.

Benefit is defined as *Medium* when the derived information is judged to be somewhere between *High* and *Low*.

Benefit is considered as *High* when the derived information indicates a situation which, if not corrected, can lead to a major failure of the circuit breaker.

Note that the benefit vs. effort analysis shown in these tables is for a typical utility with a variety of circuit breakers, well established maintenance practices and a centralized control, and may not apply to all users.

The user should perform his own analysis and determine the extent to which circuit breakers should be equipped with the monitoring devices. The manufacturer may provide recommendations pertaining to monitored parameters.

A knowledge of historical reported failure modes together with the importance of the circuit breaker(s) on the particular system will assist the users in assigning value—Benefit/Effort—for the monitoring system desirable for their needs.

Table 4A —Diagnostics of all types of circuit breakers (mechanical features)

Characteristics to be monitored	Mode	Parameter measured & derived information	Assessment	Benefit/ Effort
Indicator status vs. mechanism position	I	Compare open/closed status indicators vs. mechanism position	Integrity of mechanism, linkages, latches and indicators to move main contacts to open/ closed status position correctly indicate position	H/L
Main contact status vs. trip close commands	0	Time from coil energization to main contact make or break	Operation of TC, CC, mechanism during open & close	H/H
Contact (main, resistor switch, auxiliary switch) position vs. time	0	Contact displacement & contact continuity vs. time	Strength of stored energy system; adequacy of lubrication Damper operation, contact bounce, mechanism friction	H/H
Contact adjustment	0	Dimension or position of contact or linkage part	Adequate contact engagement	H/H
Auxiliary contact status vs. trip close command	I	Time from coil energization to auxiliary contact make or break	Operation of TC, CC, mechanism during close/open operation	H/L

Letter symbols:

I	Circuit breaker energized and in service
O	Circuit breaker de-energized and isolated
L	Low
M	Medium
H	High
EH	Extremely High

Table 4B —Diagnostics of all types of circuit breakers (electrical current carrying features)

Characteristics to be monitored	Mode	Parameter measured & derived information	Assessment	Benefit/ Effort
Contact resistance	0	Resistance in μΩ of contacts and other parts of current path	Contact surfaces joint integrity and applied forces	H/H
Contact & conductor Temperature vs. current	0	Contact and conductor temperature rise	Contact and conductor condition Heat transfer media condition	H/H
Bushing terminal temperature	I	Relative temperature of bushing terminal	Bushing terminal temperature within specification Condition of bushing terminal	H/L

Letter symbols:

I	Circuit breaker energized and in service
O	Circuit breaker de-energized and isolated
L	Low
M	Medium
H	High
EH	Extremely High

Table 4C —Diagnostics of all types of circuit breakers (electrical insulating features)

Characteristics to be monitored	Mode	Parameter Measured & derived Information	Assessment	Benefit/ Effort
Voltage withstand of insulation	0	Voltage withstand or breakdown @ > specified voltage	Find contaminated or otherwise inadequate line-to-line and line-to-ground insulation	H/EH
Interrupter voltage withstand	0	Voltage withstand or breakdown @ > specified voltage	Find contaminated interrupter insulation and grading capacitor insulation	H/EH
Leakage current over standoff insulators	0	Leakage current	Detects cracked or contaminated insulators	H/H
Audible noise	I	Unusual audible noise, corona or vibration present	Arcing insulation or loose bushing	M/L
External corona test	0	Corona present	Insulation deterioration	L/EH
Internal corona test			Contacts damaged or not touching	
Bushing insulation	0	Capacitance, power factor	Capability of bushing insulation to withstand specified voltage Quality of bushing insulation	H/H
Breaker (tank) loss index	0	Power factor of entire breaker from all primary terminals to ground	Integrity of all line to ground insulation systems	H/H

Letter symbols:

I	Circuit breaker energized and in service
O	Circuit breaker de-energized and isolated
L	Low
M	Medium
H	High
EH	Extremely High

Table 4D —Diagnostics of all types of circuit breakers (control and auxiliary features)

Characteristics to be monitored	Mode	Parameter measured & derived information	Assessment	Benefit/ Effort
Closing power source and tripping power of source, recharging power source, heater power source	I	Voltage of sources	Adequacy of sources to supply closing and tripping power and to charge stored energy devices (pneumatic, hydraulic or spring) and power to heaters (if present)	H/L
Trip and close coil operation	0, I	Coil current magnitude and shape from source on operation	Integrity of coils, auxiliary switch contacts and wiring, plus stiffness of power source	H/M, if ‘O’ H/H, if ‘I’
Motor operation	I	Stored energy device; current drawn from source on operation	Integrity of motors, auxiliary switch contacts and wiring, plus stiffness of power source	H/M
Heater operation	I	Heater current drawn from source on operation	Integrity of heaters, auxiliary switch contacts and wiring, plus stiffness of power of source	H/L
Remote control operation	0, I	Remote controls produce desired operational results	Integrity & position of local/remote switch, wiring and communication channels	H/M(1) H/H(0)
Control circuit function	0	Determine that the control circuit functions in the manner intended	Control circuit is functioning correctly	H/M
Condition of trip and close latch/coils	0	Determine minimum voltage for trip and close coil/latch operation	Effort required to operate trip or close latch indicates condition of latch system	M/M

Letter symbols:

I	Circuit breaker energized and in service
O	Circuit breaker de-energized and isolated
L	Low
M	Medium
H	High
EH	Extremely High

Table 4E —Diagnostics of all types of circuit breakers (electrical switching features)

Characteristics to be monitored	Mode	Parameter measured & derived information	Assessment	Benefit/Effort
Interrupter performance	0	Current, arc voltage, transient recovery voltage and contact travel during switching operation	Integrity of interrupter, linkages and mechanism to interrupt current and open the power circuit	H/EH
Interrupter usage	0	Arc energy accumulated or amount of contacts eroded I^2t	Interrupter life expended or remaining	H/H

Letter symbols:

I	Circuit breaker energized and in service
O	Circuit breaker de-energized and isolated
L	Low
M	Medium
H	High
EH	Extremely High

Table 5 —Diagnostics of circuit breakers (special features of metal-clad circuit breakers)

Characteristics to be monitored	Mode	Parameter measured & derived information	Assessment	Benefit/ Effort
Mechanical interlock function	0	Circuit breaker open/closed status or change of status vs. circuit breaker position in cubicle	Prevention of closed circuit breaker from engaging or disengaging primary disconnects. Prevention of circuit breaker with charged springs from being withdrawn from cubicle	H/H
Breaker/switchgear rating installation Interference features	0	Breaker rating compared to switchgear cubical rating	Presence and proper operation of insertion interference features to prevent circuit breaker of one of rating from being installed in a different rated switchgear cubicle	H/H

Letter symbols:

I	Circuit breaker energized and in service
O	Circuit breaker de-energized and isolated
L	Low
M	Medium
H	High
EH	Extremely High

Table 6 —Diagnostics of circuit breakers (special features of air magnetic circuit breakers)

Characteristics to be monitored	Mode	Parameter measured & derived information	Assessment	Benefit/ Effort
Arc chute	0	Physical and magnetic properties of arc chute	Verify the integrity of all arc chute parts to control the arc by physical and/or magnetic means	H/H
Puffer	0	Air flow rate and volume on open operation and on open strokes of close/open operation	Proper operation of puffer to produce an air flow to interrupt the arc at low currents	M/H
Cooling fans (if present)	I	Operation, air flow	Adequacy of cooling	H/L

Letter symbols:

I	Circuit breaker energized and in service
O	Circuit breaker de-energized and isolated
L	Low
M	Medium
H	High
EH	Extremely High

Table 7 —Diagnostics of circuit breakers (special features of vacuum circuit breakers)

Characteristics to be monitored	Mode	Parameter measured & derived information	Assessment	Benefit/ Effort
Vacuum interrupter	0	Voltage withstand or breakdown at or > specified voltage	Presence of proper vacuum level, open gap dimensions, contact characteristics required to successfully withstand specified voltage and interrupt arcs	H/H
Contact condition	0	Main contact wear dimension	Change in contact dimension, contact gap, contact life, contact wear, closing and overtravel	H/H
Cooling fans (if present)	I	Operation, air flow	Adequacy of cooling	H/L

Letter symbols:

I	Circuit breaker energized and in service
O	Circuit breaker de-energized and isolated
L	Low
M	Medium
H	High
EH	Extremely High

Table 8 —Diagnostics or circuit breakers (special features of bulk oil circuit breakers)

Characteristics to be monitored	Mode	Parameter measured & derived information	Assessment	Benefit/ Effort
Oil volume	I	Level of oil in tank, Level of oil in bushings	Verify that enough oil is present	H/L
Oil quality	I	Oil power factor, Oil particle type & count, Dissolved & free water in oil, Withstand voltage of oil	Presence of proper oil quality required to successfully withstand voltage and interrupt arcs	H/L
Closing (opening) resistors (if present)	0	Resistance in Ω	Determine if resistance is within tolerance	H/H
	0	Insertion time in ms	Determine if insertion time between resistor switch closing (opening) and main contact closing (opening) is within tolerance	H/H
Current-carrying capacity	I, 0	Oil level, Tank temperature	Determines indirectly the ability of the circuit breaker to carry load current	H/L
	0	Varnish or carbon on contacts	Determine indirectly the ability of the circuit breaker to carry load current	H/H
Grading resistor (if present)	0	Resistance in Ω	Determine if resistance is within tolerance	H/H
Grading capacitors (if present)	0	Capacitance in pF	Determine if capacitance is within tolerance	H/H
Tank heater	I	Heater resistance & current	Determine that the heaters are of correct value and conduct the correct amount of current	H/L

Letter symbols:

I	Circuit breaker energized and in service
O	Circuit breaker de-energized and isolated
L	Low
M	Medium
H	High
EH	Extremely High

Table 9 —Diagnostics of circuit breakers (special features of live tank minimum oil circuit breakers)

Characteristics to be monitored	Mode	Parameter measured & derived information	Assessment	Benefit/ Effort
Oil volume	I	Level of oil in tank, Level of oil in bushings	Verify that enough oil is present	H/L
Oil quality	0	Oil power factor, Oil particle type & count, Dissolved & free water in oil, Withstand voltage of oil	Presence of proper oil quality required to successfully withstand voltage and interrupt arcs	H/L
Closing (opening) resistors (if present)	0	Resistance in Ω	Determine if resistance is within tolerance	H/L
Current-carrying capacity	0	Varnish or carbon on contacts	Determine indirectly the ability of the circuit breaker to carry load current	H/H
	0	Oil level, Tank temperature	Determine indirectly the ability of the circuit breaker to carry load current	H/L
Grading capacitor (if present)	0	Capacitance in pF	Determine if capacitance is within tolerance	H/H
Interrupter pressure	I	Pressure	Determine if pressure is within specified value	H/L
Grading resistor (if present)	0	Resistance in Ω	Determine if resistance is within tolerance	H/H

Letter symbols:

I	Circuit breaker energized and in service
0	Circuit breaker de-energized and isolated
L	Low
M	Medium
H	High
EH	Extremely High

Table 10 —Diagnostics of circuit breakers (special features of two-pressure SF_6 circuit breakers)

Characteristics to be monitored	Mode	Parameter measured & derived information	Assessment	Benefit/ Effort
SF_6 gas level (low pressure)	I	Pressure, Density (pressure and temperature)	Assesses ability to withstand voltage	H/L
SF_6 gas level (high pressure)	I	Pressure, Density (pressure and temperature)	Assess ability to interrupt current	H/L
Interrupter action	0	Pressure changes vs. time during switching operation	Assesses operation of blast valve and interrupter nozzle and contacts	H/EH
Moisture in SF_6	I	Measure water vapor in SF_6 in parts per million	Assesses level of H_2O in SF_6 which can affect voltage withstand and interrupting ability and corrosivity	H/L
Closing (opening) resistors (if present)	0	Resistance in Ω	Determine if resistance is within tolerance	H/H
	0	Insertion time in ms	Determine if insertion time between resistor switch closing (opening) and main contact closing (opening) is within tolerance	H/H
Voltage grading capacitors (if present)	0	Capacitance in pF	Determine if capacitance is within tolerance	H/H
Line to ground capacitors (if present)	0	Capacitance in pF	Determine if capacitance is within tolerance	H/H

Letter symbols:

I	Circuit breaker energized and in service
O	Circuit breaker de-energized and isolated
L	Low
M	Medium
H	High
EH	Extremely High

Table 11 —Diagnostics of circuit breakers (special features of two-pressure SF_6 circuit breakers)

Characteristics to be monitored	Mode	Parameter measured & derived information	Assessment	Benefit/ Effort*
SF_6 gas level	I	Pressure Density (pressure and temperature)	Assesses ability to withstand voltage and to carry and interrupt current	H/L
Interrupter action	0	Pressure changes vs. time during switching operation	Assesses operation of puffer piston and interrupter nozzle and contacts	H/EH
Moisture in SF_6	I	Measure water vapor in SF_6 in parts per million	Assess level of H_2O in SF_6 that can affect voltage withstand and interrupting ability	H/L
Closing (opening) resistors (if present)	0	Resistance in Ω	Determine if resistance is within tolerance	H/H
	0	Insertion time in ms	Determine if the insertion time between resistor switch closing (opening) and main contact closing (opening) is within tolerance	H/H
Voltage grading capacitors (if present)	0	Capacitance in pF	Determine if capacitance is within tolerance	H/H
Line to ground capacitors (if present)	0	Capacitance in pF	Determine if capacitance is within tolerance	H/H
SF_6 gas/seal heater	I	Heater current Heater resistance	Assess condition of SF_6 gas & seal heaters	H/L

Letter symbols:

I	Circuit breaker energized and in service
O	Circuit breaker de-energized and isolated
L	Low
M	Medium
H	High
EH	Extremely High

Table 12 —Diagnostics of circuit breakers (special features of air blast circuit breakers)

Characteristics to be monitored	Mode	Parameter measured & derived information	Assessment	Benefit/ Effort
Low pressure air level	I	Pressure	Assesses ability to withstand voltage and to interrupt current	H/L
High pressure air level	I	Pressure	Determine that there is sufficient air to replenish low pressure level	M/L
Interrupter action	0	Pressure changes vs. time during switching operation	Assesses operation of blast valve and interrupter nozzle and contacts	H/EH
Moisture in air	I	Measure water vapor in air in parts per million	Assesses level of H_2O in air, which can affect voltage withstand and interrupting ability and corrosivity	H/L
Closing (opening) resistors (if present)	0	Resistance in Ω	Determine if resistance is within tolerance	H/H
	0	Insertion time in ms	Determine if the insertion time between resistor switch closing (opening) and the main contact closing (opening) is within tolerance	H/H
Voltage grading capacitors (if present)	0	Capacitance in pF	Determine ability to distribute voltage among series interrupters	H/H

Letter symbols:

I	Circuit breaker energized and in service
O	Circuit breaker de-energized and isolated
L	Low
M	Medium
H	High
EH	Extremely High

Table 13 —Diagnostics of circuit breakers (special features of current transformers associated with circuit breaker) (free standing or bushing type)

Characteristics to be Monitored	Mode	Parameter measured & derived information	Assessment	Benefits/ Effort
Leakage current	O	Leakage of current	Detects cracked or contaminated insulation	M/EH
Pressure buildup	I, O	Increase in pressure	Gassing current transformer	H/L
Oil quality	I	Oil power factor, oil particle type and count dissolved & free water, withstand voltage of oil	Presence of proper oil quality required to successfully withstand voltage	H/L
External corona test Internal corona test	0	Corona present	Insulation deterioration contacts damaged or not touching	L/EH
Oil volume	I	Low oil level	Verify that enough oil is present	H/L
SF_6 gas level	I	Pressure	Assesses ability to withstand voltage	H/L
Capacitance	O	Insulation integrity	Capacitance within specification	H/H
Power factor	O	Insulation integrity	Power factor within specification	M/H
Ratio	O	Turns ratio	Ration of primary current to secondary current within specification	H/H
Excitation current	O	Turn to turn insulation integrity	Excitation current within specification	H/H

Letter symbols:

I	Circuit breaker energized and in service
O	Circuit breaker de-energized and isolated
L	Low
M	Medium
H	High
EH	Extremely High

Annex A Advanced diagnostics

(Informative)

Techniques for advanced diagnostics include the following:

A.1 Diagnostics by signature analysis

Signature analysis technique 1 (table A.1)

Signature analysis technique 2 (table A.2)

Signature analysis technique 3 (table A.3)

A.2 Diagnostics by direct measurement

Direct measurement technique 1 (table A.4)

Direct measurement technique 2 (table A.5)

Direct measurement technique 3 (table A.6)

In direct measurement technique 2, all monitoring is carried out via a computer which operates continuously to derive information and accomplish decision making. Computer monitoring is carried out:

a) Locally (at the circuit breaker) with restricted decision making capabilities
b) Centrally (in the substation control room) with major decision making capability, and
c) System control center by remote system access.

Direct measurement technique 3 includes all the measurements required in the direct measurement technique 2 (table A.5) in addition to those listed in table A.6.

Table A.1 —Signature analysis—Technique 1

Measured	Characteristics to be monitored	Parameters measured and/or derived information	Significance
• Trip coil current • Close coil current • Auxiliary contacts • Relay contacts • Motor currrent draw • Trip initiation • Close initiation	• Contact position; TC, CC currents; time • a, b, aa, bb, contacts • Relay contacts • Motor current	• Slow moving linkage • Look for change in respect to reference signature • Open coils; open resistors; auxiliary contacts; power loss • Contact bounce • a and b finger timing and analysis • Charging motor current draw • Check of anti-pump circuit	• Establish baseline signature • Breaker timing - sluggish TC, CC, latches and mechanisms. Lubrication problems in linkage/ mechanisms. Coil characteristics changed • Detect change in adjustment of aux-sw or aux-switch contacts • Prediction of close and trip coil currents. Failure to trip or to close on command.
• Breaker Control Voltage	• Breaker control voltage vs. time	• Integrity of breaker control supply; breaker control voltage profile	• Detect need for adjustment of battery charger • Detect battery problem • Detect effects upon operation of compressors and other equipment • Supply circuit integrity

Table A.2 —Signature analysis—Technique 2

Measured	Characteristics to be monitored	Parameters measured and/or derived information	Significance
• Vibration bursts on each pole • Vibration burst in control cabinet	• Acceleration vs. time	• Time and frequency domains—vibration signatures, envelopes,and power spectra of events taking place on each pole and in control cabinet • Timing of events at poles (e.g., start of motion, impact upon shock absorber/overtravel stop, tailspring pickup, (potential) contact make/part) • Timing of events in control cabinet (relays, solenoids, valves) • Look for change in reference envelope and spectra shapes	• Establish baseline signatures • Condition of circuit breaker on first operation • Slow relays, valves, latches • Slow breaker closes/opens • Delayed breaker closes/opens • Malfunctioning shock absorbers • Changes in overtravel, stop clearances • Breaker timing—sluggish TC, CC, latches, and mechanisms. Lubrication problems in linkage/ mechanisms. Interrupter damage • Stuck or broken valves

Table A.3 —Signature analysis—Technique 3

Measured	Characteristics to be monitored	Parameters measured and/ or derived information	Significance
• Dynamic resistance	• Resistance vs. time graph • Voltage drops and currents are recorded during operation, when circuit breaker is not in service	• Look for change in respect to reference resistance plot • Timing of contacts having another contact or resistor in parallel • Shorting or arcing contacts or contact resistance abnormalities	• Identify resistance/timing problems with aux. contacts, main contact, closing resistor, or parallel circuits • Establish baseline resistance for continuous and arcing contacts and determine need for replacement

Table A.4 —Direct measurement—Technique 1

Measured	Characteristics to be monitored	Parameters measured and/ or derived information	Significance
• I^2t	• Interrupted current and time	•ΣI^2t pet phase • Contact erosion	• Whether to replace/maintain arcing contacts

Table A.5 —Direct measurement—Technique 2

Measured	Characteristics to be monitored	Parameters measured and/or derived information	Significance
• Travel of grounded and of the insulated operating rod	• Actual contact travel	• Comparison of mechanical motion intra and inter phases • Distance, contact velocity, acceleration	• Establish baseline for maintenance • Whether circuit breaker is within manufacturer's specifications for contact travel • Indirect indication of proper operation of blast valve
• Voltage (line to ground) at both sides of circuit breaker	• Voltage vs. time	• Whether voltages are out of phase or are in phase • Synchronization between breaks of the same pole • Synchronization between different poles • Out of phase conditions following closes, opens	• Whether or not to close the circuit breaker (synchronized,…) • Statistical review of circuit breaker TRV
• Pressures in both high and low pressure gas systems • Temperatures in both high and low pressure gas systems	• Pressure and temperature continously	• Quantity of gas in circuit breaker • Gas leakage	• Whether pumping is within the manufacturer's specifications • Leakage from or between high and low pressure volumes • Compressor capability/ condition • Circuit breaker leak rate to atmosphere
• Current through trip coil and close coil	• Trip and close coil continuity	• Whether circuit breaker is ready to operate	• If current exceeds threshold, then the circuit breaker is in good condition, ready to operate
• Running time of compressor	• Gas compressor monitoring	• Compressor pump-up time	• Whether total number of hours running time signals need for maintenance
• Air pressure in high pressure reservoir tank	• Air pressure	• Air compressor pump-up time • Accumulated life	• Compliance with manufacturer's specifications • Maintenance information • Circuit breaker leak rate
• Dew point of water in the gas (ppm by volume)	• Quantity of moisture in the gas	• Whether quantity of moisture is within manufacturer's limits	• Corrosion, reduction of dielectric strength • Source of moisture • Limits on extremely cold temperature operation
• Change in high pressure gas system caused by one operation • Mechanical motion of contacts	• High pressure gas pressure • Contact travel	• Whether blast valve operates within manufacturer's specifications	• Short-time change in high pressure gas pressure • Sticky, leaking valve
• Current flow through circuit breaker during arcing • Arcing time	• Current and time	• I^2 and $\Sigma I^2 t$	• Contact wear
• Temperature in equipment cabinet	• Temperature	• Whether temperatures are within design requirements of the equipment	• Condition of heaters and a.c. supply circuit • Capability of circuit breaker mechanism to operate in real-time ambient

Table A.6 —Direct measurement—Technique 3

Measured	Characteristics to be monitored	Parameters measured and/ or derived information	Significance
• Travel of lift rod (linear motion transducer at top of track (external), on lift rod	• Actual contact travel	• Comparison of mechanical otion intra- and inter-phases • Distance, contact velocity, acceleration	• Establish baseline for maintenance • Whether circuit breaker is within manufacturer's specifications for contact travel and velocity
• Current through trip coil and close coil	• Trip and close coil continuity	• Whether circuit breaker is ready to operate	• If current exceeds threshold, then circuit breaker is in good condition, ready to operate
• Current and voltage through compressor motors	• Current vs. time • Voltage vs. time following initiation	• Frequency of motor operation • Duration of motor operation • Performance of motor • Supply circuit condition	• Detect leaky storage vessel • Detect malfunctioning compressor (compressor not building up needed pressure) • Detect motor problems (e.g., bearings, field)
• Battery charger dc voltage	• Voltage vs. time	• Recovery time following operation of circuit breaker	• Detect need for adjustment of battery charger • Detect battery problem • Detect effects upon operation of compressors and other equipment
• Ambient temperature	• Temperature vs. time	• Base input for assessing performance of system and its components	• Detect effects upon operation of compressors and other equipment • Modify characteristics in “performance envelope”

Annex B Diagnostic tests

(Informative)

Diagnostic tests have been commonly carried out to assure the continuing availability of a circuit breaker.

Two general types of diagnostic tests are carried out by maintenance personnel. The first is done without removing the circuit breaker from service. Often auxiliary systems can be checked for proper function. For example they can reduce air pressure for a pneumatic mechanism until the compressor starts and also check to see that the compressor stops at the proper pressure.

The second type of a diagnostic test is made with the circuit breaker out of service where essentially all the manufacturers recommended tests can be performed. These tests would cover essentially all the characteristics listed in tables 1 through 8 as well as those dynamic characteristics that can only be measured during operation with the mains energized.

Typical test methods include opening and closing with travel or timing devices to indicate proper dynamic travel. Static position will ordinarily be measured with standard rules or with special gauges supplied by the manufacturer. Such gauges normally include steps to indicate the adjustment limits. The measured position, travel, and perhaps contact penetration are generally specified as a dimension with reasonable tolerances. For linear dimensions greater than 1 in (25 mm) the dimension will generally be stated in inches, plus or minus one smallest division of the rule. Linear dimensions greater than 1 in or 2 in (25–50 mm) are seldom specified with a percentage tolerance. In general angular dimensions are not specified, except for right angles.

B.1 Mechanical operation

Manual mechanical operation with a jack is carried out to measure contact motion, stop settings, auxiliary switch operation, and the operation of valves or resistor contacts. This test also permits measurement of contact penetration or start of shock absorber motion. Interpretation of the results of these tests would rely on comparison with the manufacturer's instruction book and with any historical records maintained by the maintenance personnel.

Mechanical operation is carried out with normal operating mechanism at full speed but circuit breaker isolated from the power system and de-energized. This test can show any characteristics that must be measured under dynamic conditions. This test would permit measurement of energy use from the stored energy mechanism. It would show contact speed as a function of time and position, which is a critical indication of proper operation. Interpretation of these test results would of course rely on comparison with the manufacturer's instruction book but it would depend much more on a historical record that would permit estimation of remaining life, such as contact wear. Small variations in speed or travel can be indicators of deterioration of the circuit breaker operation and could permit estimates of remaining life.

B.2 Insulation power factor

Measurement of insulation power factor consists of applying a 60 Hz ac voltage with a value up to its rated voltage to the insulation system in question and measuring the capacitance and parallel resistance. The power factor of the system is essentially a measurement of the leakage current through the equivalent insulation system resistance. The lower the leakage current, the lower the power factor and the better the insulation system.

Measurement of power factor has advantages over measurement of dc resistance (MΩ) of the insulation system. In the de test, good insulation in series with bad insulation will cover up detection of the bad insulation. Also, the power factor measurement does not vary due to the volume of the insulation system being tested. A negative power factor is an indication of tracking across the insulation system.

Another value of the power factor measurement is that it will detect voids in the insulation system that may be causing high partial discharges.

Insulation power factor may be measured by special bridge circuits or by the voltampere-watt method. The accuracy of measurement should be within ±0.25% insulation power factor and the measurement should be made at or near a frequency of 60 Hz.

It is very important that power factor measurement instrumentation be well shielded if it is used in a substation area where there may be a significant level of electrostatic interference. Using a higher frequency power supply may help solve the interference problem.

Values obtained at the time of the original tests are used as benchmarks to determine the amount of insulation deterioration on subsequent tests. Insulation power factor is best compared to these benchmark values when performing field tests. However, it is also possible to determine a degree of insulation conditions by comparing test results to other similar circuit breakers.

For more information on power factor testing of bushings, refer to IEEE Std C57.19.00-1995.

B.3 Insulating oil testing

B.3.1 Dielectric breakdown

The measure of the dielectric strength of an insulating liquid is the minimum voltage at which electrical flashover occurs between two metallic electrodes. A low dielectric strength indicates contamination of the liquid with such things as water, carbon, and/or other foreign matter. It should be noted, however, that high dielectric strength is no guarantee that the liquid is not contaminated, Tests on oil from failed circuit breakers are not indicative of the oil quality just before failure since carbon and debris from the failure will be suspended in the oil.

Two ASTM test methods are in common use in the power utility industry. The D-877 method uses 1 in diameter flat disc electrodes which are separated by a distance of 0.10 in (2.4 mm) and a rate of rise of 3 kV/s ±20% is applied to the test sample. The D-1816 method uses spherical electrodes with a spacing of either 0.08 in (2 mm) or 0.04 in (4 mm), a rate of rise of the test voltage of 1/2 kV/s ±20% and incorporates stirring of the liquid sample. The D-1816 test is more sensitive to moisture than the D-877 test.

B.3.2 Interfacial tension (ASTM D971)

The interfacial tension (IFT) of an oil is the force in newton/meter required to rupture the oil film existing at an oil-water interface. IFT is one of the earliest indications of the degradation of an oil. When certain contaminants such as soaps, paints, varnishes, and oxidation products are present in the oil, the film strength of the oil is weakened, thus requiring less force to rupture. For oils in service, a decreasing value indicates the accumulation of contaminants, oxidation products, or both. Acceptable limits for IFT vary with operating voltage. Refer to IEEE Std C57.106-1991 for acceptable limits.

B.3.3 Moisture content (ASTM D1533)

A low moisture content is necessary to obtain and maintain acceptable electrical strength and low dielectric losses in insulation systems. The presence of excessive moisture may not be evident from electrical tests. The presence of excessive moisture accelerates metal corrosion and shortens the life expectancy of cellulose insulation. The taking and handling of oil samples must be done with care to avoid misleading high reading. Refer to IEEE Std C57.106-1991 for acceptable limits.

B.3.4 Power factor

Oil power factor should be less than 0.5%.

B.3.5 Color

The color test compares the oil with standards of colored glass. The color of a new oil is generally accepted as an index of the degree of refinement. New oils are usually bright and clear. A change in color of an oil in service indicates contamination and/or deterioration during service. Clear oil (low color numbers) allows visual inspection of internal equipment components. Additional tests should be made on any oil with a color number over four to determine whether the oil is an operating hazard. ASTM method D1500 is available for laboratory testing, and D1542 is useful in the field. See IEEE Std C57.106-1991 for acceptable limits.

B.4 Applied voltage test (high potential)

This test basically stresses the major insulation of the circuit breaker. Also tested, however, is the insulation-to-ground of current carrying parts such as current transformers, bushings, resistors, grading capacitors, etc.

Normally, a source of 60 Hz ac, in the range of 65% to 75% of the factory applied voltage test values is used. The applied voltage level is determined by the BIL as found on the nameplate or factory test sheet. For more details, see IEEE Std C37.09-1979. The test voltages are given in ANSI C37.06-1987.

This test is a proof test that stresses the major insulation in a manner that is not consistent with operating stresses. It is also a test that does not lend itself to quantitative evaluation but introduces a finite risk for a destructive test failure on a circuit breaker that might otherwise be serviceable. Since power factor and insulation resistance tests provide quantitative measurements without the risk of damaging otherwise serviceable insulation, there is usually little justification for performing this test in field analysis.

Another question that often arises concerning this test is the possibility of substituting a dc source for the applied voltage. The use of dc is sometimes recommended on components with uniform insulation structures such as cable or bus work, since it allows the use of smaller power supplies and a somewhat quantitative evaluation by measurement of the leakage current. In some circuit breakers, the insulation structures are usually complex combinations of materials with widely varying electrical characteristics. These structures were designed for ac voltages, which divide according to the dielectric constraints of the individual components, while dc voltages divide according to the resistivity of the individual components. Without a detailed analysis of the complete insulation structure, it can never be stated for certain whether or not some part of the insulation may be overstressed by a dc applied voltage test. Also, with a dc source applied for a period of time, there is a tendency for foreign particles to line up and possibly reduce the dielectric strength.

Before using a dc test, contact manufacturer for advice

.

CAUTION — Warning for withstand testing of vacuum interrupters:

The application of high dielectric withstand test voltages across an open vacuum interrupter may produce X-rays. At normal operating condition, any X-ray generation will be orders of magnitude below background cosmic rays. At or above those voltages, used for withstand testing, the production of a measurable x-radiation level is possible. Therefore, the operator must take appropriate precautions as stated in the circuit breaker operator's manual, so as to avoid possible exposure to X-rays, such as:

- —standing at least 3 m from the interrupter, and
- —standing with the mechanism or metal barrier between the interrupter and the operator.

These precautions are also good practice during any high voltage testing to avoid accidental contact with energized parts.

B.5 Electrical resistance of current path

Electrical resistance of the current path of each pole of the circuit breaker is measured using at least a 100A DC source from terminal pad to terminal pad. The tested values should not exceed the values specified by the circuit breaker manufacturer.

The circuit breaker contact resistance varies with the type and voltage of the circuit breakers.

An increase in the contact resistance usually signifies loose joints and corroded or misaligned contact surfaces.

Annex C Circuit breaker design

(Informative)

C.1 Operating mechanisms

C.1.1 General

The purpose of the operating mechanism is to provide the driving energy to open and close the contacts of the circuit breaker at the required speeds. This function includes: acceleration, movement, in some cases overcoming the arc-generated back pressure, and deceleration at the end of the stroke. All circuit breaker operating mechanisms use some form of stored energy to accomplish opening. This is usually in the form of charged springs, but in some cases could be in the form of pressurized gas. Many circuit breaker mechanisms use charged springs for opening energy and some other form of closing energy. Solenoid close circuit breakers receive their energy externally from station batteries or AC station service through a rectifier. Below is a list of some types of generic operating mechanisms:

- spring open/spring close
- spring open/solenoid close
- spring open/hydraulic close

In the hydraulic system either a gas-charged hydraulic accumulator or spring accumulator may be used.

- spring open/pneumatic close (compressed gas closing energy)
- pneumatic open/spring close
- pneumatic and spring open/pneumatic close
- hydraulic open/hydraulic close

C.1.2 Working medium/stored energy

In the pneumatic cases, the energy is from compressed gas, and in the hydraulic cases, the energy is from either compressed gas accumulators or charged springs operating against a hydraulic piston.

In spring-operated mechanisms, the closing energy is stored in motor wound springs that are latched in the charged position until the circuit breaker is commanded to close. The opening energy is stored in two places—an opening spring or springs attached to the mechanism jack shaft, and the contact force springs that apply contact force on each interrupter. The mechanism is also latched in the closed position until the circuit breaker is commanded to open.

C.1.3 Latches

In the case of the spring open mechanisms, which is the large majority, there is a system of latches that holds a breaker in the closed position. Generally, this is like a mechanical amplifier with at least three stages of latching. There is a main latch that holds against the main opening spring. Second, there is the in-between latch, which holds the main latch. Then, finally, there is a trip latch, which holds the intermediate latch. The force restrained by the main latch is usually rather large, being several kilo Newtons. The intermediate latch may only have to hold the force of one-tenth of the main. And finally, the trip latch itself usually has to hold only a small force—tens of hundred Newtons. The purpose of this is to get the latch releasing energy down to a point that is easily managed by electromechanical devices of low energy. Obviously, with this type of setup, the further down the latching amplifier one gets, i.e., towards the low energy end, the more important the cleanliness, proper dimensions, lubrication, and freedom from corrosion become. For example, a very small amount of corrosion on the trip latch can restrain it from operating. On the other end, it takes a much larger amount of corrosion on the main latch.

C.1.4 Release valves in pneumatic or hydraulic operators

In the pneumatic or hydraulic systems, there generally is a pneumatic/hydraulic amplifier consisting of a main valve that is often hydraulically/pneumatically operated by a pilot valve, which is then operated by the closing or tripping coil. This is, again, to get the electromechanical energy requirement down.

C.1.5 Solenoids

Solenoid closed breakers are one case where the closing energy for a breaker is supplied by the station battery or ac station service operating through a rectifier. Although many of these circuit breakers are still in service, they are rarely produced any more due to extremely large electrical energy requirement.

C.1.6 Opening

Generally, the trip coil releases the small latch or pilot valve and from that point on, once the latch is released or pilot valve actuated, the motion is completed to full open. It is not necessary in most cases to maintain the tripping coil in an energized state through the entire opening operation. At the end of the opening stroke, dampers, usually of the hydraulic type, break the motion of the contact system so that it comes to a gentle stop and does not pound itself to death. In the closing stroke, usually a larger energy is required both to accelerate the contacts and also to overcome the opening springs. Of course, this does not apply in the pneumatic or hydraulic opened breakers where the opening is strictly by hydraulic or pneumatic means without springs.

C.1.7 Closing

The closing operation is mechanically similar to the tripping operation except the contacts are moving closed. The contact motion is slowed with dampers at the end of the stroke.

C.1.8 Auxiliary switches

In addition to the main contacts, there is a set of auxiliary contacts driven by the same means whether it be hydraulic, pneumatic or mechanical, which follow the motion of the main contacts. This is to provide control system intelligence on breaker position. Most breakers are designed to sit only in the fully open or fully closed state; therefore, intermediate position monitoring is not required.

C.1.9 Mechanism auxiliaries

There are auxiliaries to the mechanism that include the means for replacing the stored energy which, in the case of springs, may be a spring winding motor. With hydraulic/pneumatics, a hydraulic pump/air compressor is used. Normally there is a system for monitoring adequacy of stored energy for operating circuit breakers.

C.2 SF_6 circuit breakers

C.2.1 General description

This type of circuit breaker uses compressed sulfur hexafluoride gas (SF_6) for both interruption and dielectric withstand. Bushings typically are insulated with SF_6 at the same pressure as in the main tank. Interruption is accomplished by clean un-ionized SF_6 gas blown across the separating contacts and through the nozzle structure.

For applications in extremely low ambient temperatures, the circuit breakers are usually provided with tank heaters to prevent gas liquefaction. Alternatively, they may employ an SF_6-N_2 gas mix.

In the pure form and room temperature and pressure, SF_6 is a colorless, odorless, non-toxic gas that is heavier than air. When the gas has been exposed to electrical arcs, certain toxic by-products are generated. Care needs to be exercised by personnel who handle these arced gas by-products. In addition because the gas is heavier than air, it can displace the air and lead to asphyxiation if adequate ventilation is not present.

C.2.2 Typical ratings

SF_6 gas circuit breakers have been used since the early 1960s. They are used at voltages between 15.5 kV and 765 kV in two different major variations. The first variation is a two pressure system where SF_6 is stored at high pressure in a reservoir separate from the lower pressure main tank. During interruption, a valve is opened between the high pressure system and the lower main tank pressure allowing clean gas to flow across the contacts and nozzles. When the pressure in the high pressure becomes low, gas from the low pressure system is compressed into the high pressure system. An SF_6 gas compressor is used to move the gas back into the high pressure system. The second variation is a single pressure system. During interruption, the motion associated with the moving contact compresses gas between a cylinder and piston and forces the compressed gas across the main contacts and nozzles. Except during interruption, there is only one gas pressure in this type of circuit breaker. During closing the gas is not compressed.

C.2.3 Typical applications

SF_6 insulated circuit breakers are used in both indoor metal-clad and in outdoor substations including gas insulated substations for practically all types of applications.

C.3 Bulk oil circuit breakers

C.3.1 General description

This type of breaker uses a large oil volume for both interruption and dielectric withstand. Bushings typically are either solid or oil filled and the mechanism is typically powered by a low pressure (about ten atmospheres) air compressor and tank. Interruption is accomplished by the arc established between the contacts, causing decomposition of oil and the resulting gasses extinguishing the arc through a system of baffles which are immersed in a large tank of oil.

C.3.2 Typical ratings

Bulk oil breakers were the technology for most high voltage breakers of all ratings up to 362 kV transmission applications prior to the introduction of air blast and SF_6 breakers, which gained momentum in the early 1960s. Although oil breaker maintenance was well understood, it had the disadvantages of high contact maintenance, potential oil fires from failures, relatively slow interruption, as well as a sensitivity to an evolving fault. There are still many thousands of these breakers in service, although few new breakers of this type are now supplied, particularly for transmission voltages.

C.3.3 Typical applications

Bulk oil circuit breakers are used in all applications for high-voltage interruption within their limitations.

C.4 Vacuum circuit breakers

C.4.1 General description

The internal components of a vacuum interrupter are shown in figure C.1. These include:

- A pair of butt contacts, one stationary and one moveable
- An insulating envelope made of ceramic or glass
- a metal shield for the condensation of metal vapor
- metal end plates as stationary supports and seals for the envelope, and
- a metal bellows to transit motion to one contact and maintain a vacuum seal

The ambient gas pressure inside of the interrupter is approximately 10^{-6} torr (0.133 mPa). To carry current, the contacts are butted together with several hundred pounds of force. To interrupt current, the contacts are rapidly separated to a gap of a fraction of an inch. An arc, formed upon separating the contacts, is supported by metal vapor from the contacts. This metal vapor quickly expands from the contact gap region and condenses on relatively cooler surfaces, specifically the metal shield that surrounds the contact gap. The shield is located coaxial with and inside of the insulating envelope, and thereby prevents the metal vapor from condensing on the insulating envelope, which would decrease its dielectric strength. As the current approaches zero, the metal vapor dissipates within microseconds, which restores the vacuum between the contacts and their ability to withstand the open circuit voltage of the power system.

Vacuum circuit breakers are mostly provided with spring-operated mechanism.

The small gaps required by vacuum interrupters to meet their dielectric withstand and current interrupting requirements result in short stroke, low energy mechanisms.

C.4.2 Typical applications

Vacuum circuit breakers are typically applied in both indoor metal clad switchgear and in outdoor substations. The small size of the vacuum interrupter has enabled manufacturers to design compact circuit breakers and switchgear.

For indoor application, switchgear designs are available that stack two circuit breakers, one above the other, to minimize floor space. In addition, retrofit versions of vacuum circuit breakers are available that fit into older switchgear that was originally designed for air magnetic circuit breakers.

For outdoor application, vacuum interrupters are always contained in an outside enclosure, since the compact design of the interrupter and the need to use smooth sided ceramic or glass envelopes makes the interrupter itself unsuitable to deal with water and contamination, where a long insulation creepage distance is required.

In addition to general purpose applications, vacuum circuit breakers are especially useful in many definite purpose applications where the special properties of vacuum interruption provide outstanding performance. Such applications include

- Arc furnace switching, where the long life of the vacuum interrupter is essential,
- Capacitor switching, including general purpose and back-to-back applications, and motor switching.

Surge suppression is sometimes required in applications where the insulation strength of the connected equipment is less than the circuit breaker rating.

C.4.3 Typical ratings

Vacuum circuit breakers are chiefly designed for medium voltages up to 38 kV and 200 kV BIL and up to 3000 A continuous current.

Higher system voltages are achievable by using two or more interrupters in series. At least one manufacturer has a retrofit design available that replaces the interrupters in an oil circuit breaker with 4 vacuum interrupters for a 145 kV rating. Higher currents are also achievable and available. Vacuum interrupters are also used in low voltage (600 V) contactors.

C.4.4 Typical maintenance checks

The manufacturer's instruction manual should be consulted for detailed checks and measurements to make acceptable values and suggestions on corrective actions. Typical checks are

a) Check for contact wear, especially if the circuit breaker operations counter shows a high number of operations. The location of a contact wear indicator or the measurement of contact position will provide a measure of the portion of contact life that remains. A small amount of contact material is eroded with each current interruption. While the interruption of many high fault currents will erode the interrupter contacts to the point where the interrupter can no longer operate properly, the interrupting life of vacuum interrupters is generally longer than other types of interrupters, and, moreover, the vacuum interrupter usually outlasts the mechanism.
b) Check contact wear springs for proper compression.
c) Check for loose or broken current transfer connections.
d) Check for vacuum integrity.
e) Check contact resistance.
f) Check for proper opening and closing times.
g) Check for proper closing over-travel and opening spacing. Mechanism wear in addition to contact wear can change these two dimensions that are of major importance. Contact wear indicators may be indicating a mechanism change as well as contact erosion so it may not be the contact wear causing loss of overtravel.

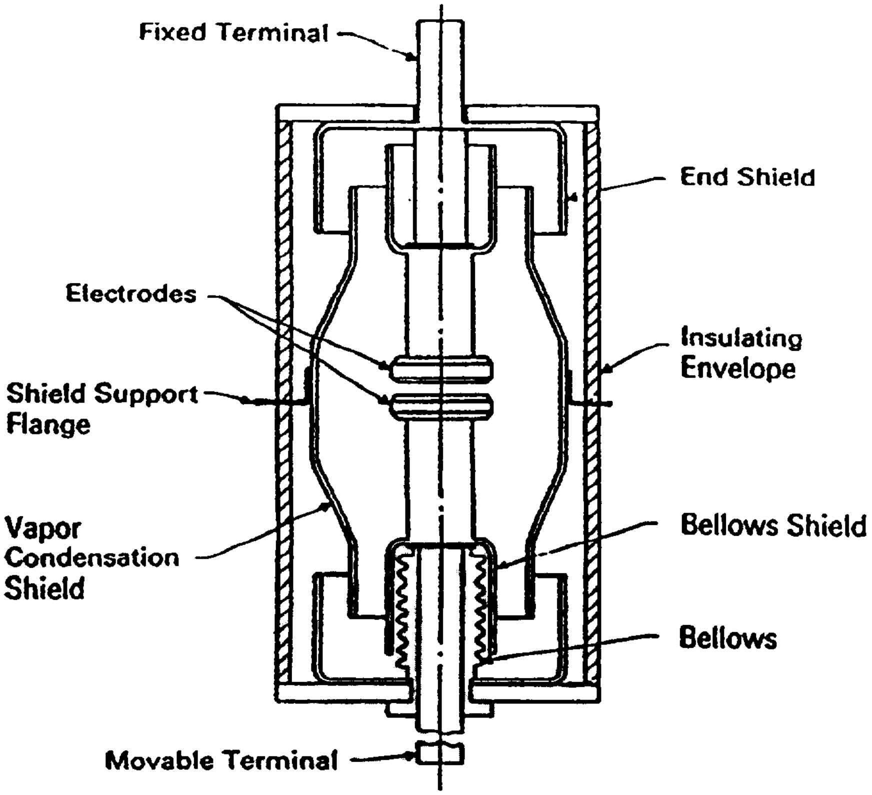

Figure C.1—A cross-section view of a typical vacuum interrupter

C.5 Air magnetic circuit breakers

C.5.1 General description

This type of breaker uses stored energy spring mechanisms, to operate the main contacts. Interruption involves the use of an arc chute for breaking up and cooling arc products, in a similar manner to low voltage breakers, although blow out coils are frequently used to accelerate the movement of the arc into the arc chutes. The breakers for medium voltage were large and weighed more than 1000 lb (455 kg). This type of breaker was in wide use before the more modem vacuum breakers. Typically, closing energy is supplied by closing springs charged by a motor or by solenoid. Arc chutes may contain asbestos.

C.5.2 Typical ratings

This concept involves arc chutes and some means of controlling the arc so that it is established in the arc chutes. In that location, the arcing current is reduced by increased circuit resistance and splitting of the arc so that after a current zero, the breaker gaps will successfully resist reignition. These concepts are presently applied in low voltage breakers and were applied in medium-voltage devices of the 4 kV, 7 kV, and 15 kV levels prior to the introduction of the more modern vacuum and SF_6 breakers in this class. The later technologies offer less maintenance, freedom from the large arc chutes, and a much more compact design.

C.5.3 Typical applications

Higher interrupting levels of low-voltage breakers, particularly those of continuous current exceeding 600 A and ac voltages of 440 and higher. Ratings in the medium voltage class covered all applications for interrupting levels.

C.6 Air blast circuit breakers

C.6.1 General description

This type of breaker uses high pressure air, [typically 40 atmospheres (4000 kPa)], to operate a quick opening mechanism as well as to provide insulation between line and load after opening. Interruption takes place by rapid mechanism opening coincident with an air blast to remove arc products and prevent re-ignition after a current zero. Typically, the breaker includes a compressor and dryer system for providing a stored air supply at about 150 atmospheres (15 000 kPa). Bushings typically are gas insulated, often SF_6 at about 4 atmospheres (400 kPa), and the interrupter is of a live tank design.

C.6.2 Typical ratings

This technology had been applied for medium voltage and high interrupting currents in the 1940s and 1950s. In the early 1960s the voltages were increased into the transmission class and eventually covered all interrupting ratings from 155 kV through 765 kV. Their application started to decline with the advent of the SF_6 puffers, in the late 1970s, due mainly to the maintenance requirements for the high pressure (2000 psi) air systems and the complex gasketing, as well as their high noise levels during interruption.

C.6.3 Typical applications

During their high popularity, they were applied in all transmission applications, particularly where their strong capacitor switching was desired and where sound levels were not critical. They are still applied in many generator breakers where interrupting levels and continuous currents must be high.

C.7 Minimum oil circuit breakers

C.7.1 General description

This type of breaker, when applied below 170 kV, normally now has one interrupter per pole with the highest voltages having up to six breaks. Minimum oil circuit breakers built in the 1970s would likely have two interrupter breaks per pole up to 170 kV. The interrupter breaker units are mounted on post insulators, which constitute the insulation of the pole to earth. The breaking units consist of an arc control device usually of the cross-blast type within an oil container. Units with more than one break are equipped with grading capacitors for voltage division across the breaks. The closing energy is provided by a motor-charged spring or by an hydraulic or pneumatic stored energy closing device. The closing mechanism is connected to the breaking units via a pull-rod system, link gears, and rotating insulators. The opening springs are charged during a closing operation so the breaker can never be closed without sufficient energy for an opening operation. The breaker is opened by release of the trip latch.

C.7.2 Typical ratings

The design of this breaker has operated over a wide range of voltage classes up to 765 kV and interruption ratings of 40 kA. The use of this style of breaker has diminished due to the advent of SF_6 breakers.

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Annex E Useful imperial—metric conversion factors

(Informative)

Area

1 circular mil = 5.067 075 E-04 square millimeters (mm^2)

Energy

1 British Thermal Unit (Btu) = 1.055 506 kilojoules (kJ)

1 kilowatt hour = 3600 kilojoules (kJ)

1 kilojoule = 0.947 813 3 Btu (international tables)

1 kilojoule = 0.277 777 7 watt hour

Velocity

1 miles per hour = 0.447 04 meter per second (m/s)

Force

1 pound-force = 4.448 222 newtons (N)

1 newton = 0.224 808 9 pound-force

Length

1 foot = 0.304 8 meter (m)

1 foot = 304.8 millimeters (mm)

1 inch = 25.4 millimeters (mm)

1 centimeter = 0.393 700 8 inch

1 kilometer = 0.621 371 2 mile

1 meter = 3.280 840 feet

1 millimeter = 0.039 370 08 inch

1 mil = 0.25 4 millimeters (mm)

Mass

1 oz (avoirdupois) = 28.349 523 grams (g)

1 pound (avoirdupois) = 0.453 592 37 kilogram (kg)

1 gram = 0.035 273 97 ounce (avoirdupois)

1 kilogram = 2.204 622 pounds

Pressure

1 atmosphere, standard = 101.325 kilopascals (kPa)

1 pound force per square inch (psi) = 6.894 757 kilopascals (kPa)

1 kilopascal = 0.009 869 23 atmosphere (standard)

1 kilopascal = 0.145 037 9 pound force per square inch (psi)

1 bar = 100 kilopascals (kPa)

1 inch of mercury = 3.386 39 kilopascal (kPa)

Temperature

Temperature Fahrenheit (t_F) to temperature Celsius (t_C)

$t_C = (t_F - 32)/1.8$

Temperature Celsius (t_C) to temperature Fahrenheit (t_F)

$t_F = (t_C \times 1.8) + 32$

Volume and Capacity

1 square inch = 645.16 square millimeters (mm^2)

1 cubic foot = 28.316 85 liters (L)

1 cubic yard = 0.764 555 cubic meters (m^3)

1 gallon (Imperial) = 4.546 092 liters (L)

1 gallon (U.S.) = 3.785 412 liters (L)

1 cubic centimeter = 0.061 023 76 cubic inch

1 liter = 0.219 969 1 gallon (Imperial)

1 liter = 0.264 172 0 gallon (U.S.)

1 cubic meter = 1.307 951 cubic yards

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