

IEEE Guide for the Selection of Monitoring for Circuit Breakers

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Abstract: Direction is provided for the selection of monitoring and for diagnostic parameters to be used with high-voltage circuit breakers (i.e., above 100 V). Guidance on appropriate parameters to be considered for monitoring applied to various circuit breaker technologies is also provided.

Keywords: failure characteristics; failure modes and effects analysis (FMEA); failure modes, effects, and criticality analysis (FMECA); failure rate; high-voltage circuit breakers; monitoring; online condition monitoring; risk assessment

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Introduction

(This introduction is not part of IEEE Std C37.10.1-2000, IEEE Guide for the Selection of Monitoring for Circuit Breakers.)

This first issue of this guide, IEEE Std C37.10.1-2000, provides guidance in the selection of monitoring for high-voltage circuit breakers. Monitoring for a particular circuit breaker is very dependent on the circuit breaker technology, age of the circuit breaker, details of the specific application, and the risks associated with the various failures possible with the circuit breaker and its many associated power or protection and control and other support components.

This guide is not intended to provide guidance on the monitoring of protection and control circuits and devices used with circuit breakers, even though such circuits and devices can have a significant effect on the overall performance of circuit breaker functions.

NOTE—This guide makes no attempt to address the many possible protection and control failure modes. These failure modes are dependent on the technology of the protective devices as well as on the manner in which they are applied on the power system. IEEE Std C37.10.1-2000 does not address the subject of software used in protective, control, or monitoring devices and systems.

Several methodologies are introduced. A methodology termed failure modes and effects analysis (FMEA) is presented to assist identification of significant failure modes and their causes. The concepts of risk assessment are introduced. The subsequently derived priority and economic analysis determines when and where monitoring is warranted.

The selection of monitoring for circuit breakers should be based on logical engineering and economic principles. Appropriate monitoring can be selected by considering failure modes and their effects on the circuit breaker and on the power system, the degree of risk or criticality associated with the failure, and the economics associated with each type of failure. Monitoring can be used to reduce or replace some inspections, optimize maintenance, enhance availability of the circuit breaker, improve safety to human and environment, and derive information on the condition of a specific circuit breaker (or information from several circuit breakers can be extrapolated to a larger population of identical circuit breakers).

Considerably more information can be gained by combining various signals than from an individual signal.

More advanced monitoring systems may include diagnostic analysis using tools such as artificial intelligence. These may relate recent monitoring data to historic monitoring data and provide engineering conclusions or actions required. Systems may be further enhanced by remote access through supervisory control and data acquisition (SCADA) or use of telephone dial-up systems. Eventually, it is presumed that systems will become integral to substation automation development.

Readers of this guide are advised of ongoing standards development work now underway that will provide useful supplementary guidance.

The IEEE Substations Committee is the draft stages of developing Draft Standard for Substation Integrated Protection, Control, and Data Acquisition Communications. The communication requirement for devices used to monitor substation equipment is a rapidly changing area.

The IEC is in the draft stages of producing IEC 60300, Dependability Management—Part 3-13: Application guide—Project risk management.

The IEEE Transformer Committee is developing similar guidance for selecting monitoring for transformers.

Monitoring of predominant failure causes and remedying them may also significantly reduce minor failure causes from occurring.

NOTE—Many of the techniques discussed in this guide could have application with many other types of components.

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IEEE Guide for the Selection of Monitoring for Circuit Breakers

1. Scope

This guide provides direction for the selection of monitoring and for diagnostic parameters to be used with high-voltage circuit breakers (i.e., above 1000 V). It provides guidance on appropriate parameters to be considered for monitoring applied to various circuit breaker technologies.

This guide will lead a user through an analysis of circuit breaker performance and application expectations. The analysis includes a failure modes and effects analysis (FMEA) of the circuit breaker and associated components, an analysis of the risks associated with failure of the specific application, and a discussion of the items to be considered in a cost-benefit study to justify application of monitoring in its many forms. Monitoring is dependent on the technology of the circuit breaker and monitoring available at the time of application. FMEA as well as failure modes, effects, and criticality analysis (FMECA) are methods of reliability analysis intended to identify failures that have significant consequences affecting the system performance in the considered application.

NOTE—The examples shown are for illustrative purposes only. Numeric and financial values shown are solely for the purpose of showing that values can be assigned if so chosen. Actual circumstances will dictate values, costs, and expenses to be used in the quantifying of risk, economic evaluation and justification, and the ultimate selection of monitoring. The specific circuit breaker technology employed will also either restrict or broaden opportunities for monitoring.

This guide provides advice on what parameters can be monitored to derive information about the condition of a circuit breaker. Use of techniques, such as those in CEA Project No. 485T1049 (1997)¹, provides more information on combining appropriate signals to derive greater information than either signal alone would provide.

Circuits associated with the operation of the circuit breaker, which might include auxiliary contacts, X and Y relays, lockout switches, and so on, are included in this guide. External control circuits are not included in the scope of this guide. This guide is not intended to provide guidance on the monitoring of protection and control circuits, although they can have a significant effect on the overall circuit breaker functions.

NOTE—This guide makes no attempt to address the many possible protection and control failure modes. These failure modes are dependent on the technology of the protective devices as well as on the manner in which they are applied on the power system. This issue of the guide does not address the subject of software used in protective, control, or monitoring devices and systems.

¹Information on references can be found in Clause 2.

2. References

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

CAN/CSA-Q634-91, Risk analysis requirements and guidelines.²

CEA Project No. 485T1049 (1997), On-line condition monitoring of substation power equipment—Utility needs.³

IEC 60812:1985-07, Analysis techniques for system reliability—Procedure for failure mode and effects analysis (FMEA).⁴

IEEE Std C37.10-1995, IEEE Guide for Diagnostics and Failure Investigation of Power Circuit Breakers.⁵

IEEE Std 493-1997, IEEE Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems (*IEEE Gold Book*TM).

NOTES

1—Appendix J and Appendix N of IEEE Std 493-1997 contain summaries of the more comprehensive documents in Annex C—Beierer et al. [B6]⁶, CIGRE [B5]⁷, CIGRE [B8], and Diagnostic techniques [B9].

2—IEEE Std 493-1997, Appendix J, “Summary of CIGRE 13.06 Working Group World Wide Reliability Data and Maintenance Cost Data on High Voltage Circuit Breakers Above 63 kV” by C. R. Heising, A. L. J. Janssen, W. Lenz, E. Columbo, and E. N. Dialynaas (*IEEE-IAS Industrial Application Conference*, October 2–5, 1994, Denver, Colorado, 94CH34520, pp. 2226–2234).

3—IEEE Std 493-1997, Appendix N, Transmission Line and Equipment Outage Data, Part 3, “Transmission Equipment Reliability Data from Canadian Electricity Association” by D. O. Koval (*IEEE Transactions on Industry Applications*, vol. 32, no. 6, Nov./Dec. 1996, pp. 1–9).

3. Definitions

For the purposes of this guide, the following terms and definitions apply. *The Authoritative Dictionary of IEEE Standards Terms* [B12] should be referenced for terms not defined in this clause.

3.1 continuous monitor: Monitoring installed for uninterrupted consecutive sampling or observing circuit breaker condition. Sampling, calculation, or processing time may not yield real-time results. Ability to monitor some characteristics may only be possible when the circuit breaker operates.

NOTE—The monitored circuit breaker can be in the energized or de-energized state, with manual, or automatic on-line, periodic, or continuous monitoring.

²CSA publications are available from the Canadian Standards Association (Standards Sales), 178 Rexdale Blvd., Etobicoke, Ontario, Canada M9W 1R3 (<http://www.csa.ca/>).

³CEA publications are available from Canadian Electricity Association (CEA), Research & Development, Suite 1600, One Westmount Square, Montreal, Quebec, Canada, H3Z 2P9 (<http://www.canelect.ca>).

⁴IEC publications are available from the Sales Department of the International Electrotechnical Commission, Case Postale 131, 3, rue de Varembe, CH-1211, Genève 20, Switzerland/Suisse (<http://www.iec.ch/>). IEC publications are also available in the United States from the Sales Department, American National Standards Institute, 11 West 42nd Street, 13th Floor, New York, NY 10036, USA.

⁵IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA (<http://standards.ieee.org/>).

⁶The numbers in brackets correspond to those of the bibliography in Annex C.

⁷CIGRE publications are available from the International Council on Large Electric Systems, 21, rue d’Artois, 75008, Paris, France (<http://www.cigre.org/>).

3.2 diagnostic analysis: Application of tools such as artificial intelligence (including expert systems, neural nets, and fuzzy logic) to analyze the outputs from periodic or continuous monitoring. These tools may relate present or recent data to historic information. They can, however, provide engineering conclusions based on the measured values.

3.3 failure characteristic: (A) A description of the conditional probability of failure against operating age for an electrical or mechanical item; **(B)** The evolution of how a failure develops over time. *Syn:* **failure pattern.**

3.4 failure effect: A description of what actually happens when a failure mode occurs.

3.5 failure modes and effects analysis (FMEA): Analysis based on that defined component or subassembly level where the basic failure criteria (primary failure modes) are available. Starting from the basic element failure characteristics and the functional system structure, the FMEA determines the relationship between the element failures and the system failures, malfunctions, operational constraints, and degradation of performance or integrity. To evaluate secondary and higher-order system and subsystem failures, the sequences of events in time may also have to be considered.

NOTE—See also: IEC 60812:1985-07.

3.6 failure modes, effects, and criticality analysis (FMECA): A failure modes and effects analysis (FMEA) that also considers the criticality or risks associated with the effects of a failure.

3.7 failure pattern: See: **failure characteristic.**

3.8 periodic monitor: The noncontinuous, intermittent manual, or automated monitoring of circuit breaker condition at selected intervals. Periodic monitoring can be at very short, long, regular, or irregular intervals.

NOTE—The monitored circuit breaker can be in the energized or de-energized state, with manual, or automatic on-line, periodic, or continuous monitoring.

3.9 risk: The combined impact of the probability of an event occurring and the consequences of that event when it occurs.

NOTE—Failure, failure cause, monitor, catastrophic failure, major failure, mechanism failure, minor failure, failure mode, failure modes and effects analysis, and continuous monitor are defined in IEEE 100 [B12].

4. Purpose of monitoring

Monitoring can be used to

- a) Determine the condition of a specific circuit breaker
- b) Determine the condition of the circuit breaker support and control functions and facilities
- c) Optimize maintenance activity
- d) Develop an understanding of the condition of a larger population of circuit breakers in similar circumstances by examining a representative sample of the population
- e) Improve circuit breaker utilization
- f) Reduce circuit breaker failure rates
- g) Add to the circuit breaker body of knowledge available to determine the cause of failures after the fact
- h) Improve economics of equipment operation

5. Methodology

Several methodologies are introduced to assist a user with arriving at a monitoring selection based on the greatest reduction in failure rate, considering the risks of such failure and the cost benefit value introduced by the application of monitoring.

A methodology termed FMEA is presented to assist identification of significant failure modes and their causes. The concepts of risk assessment are then introduced. The subsequently derived priority and economic analysis then determines when and where monitoring is warranted.

5.1 Decision-making sequence

The process described in this guide is as follows.

Stage 1:

- a) Undertake an FMEA analysis to identify failure modes, causes of the failure modes, and causes of failure characteristics for the specific family of circuit breakers. This also indicates the most appropriate monitoring options.
- b) The FMEA identifies monitoring options that are available and appropriate to observe the condition of circuit breakers. This stage is described in the succeeding section and given in Table 2 through Table 19. The process for Stage 1(a) and Stage 1(b) would be to identify those elements in Table 2 through Table 19 that are important for the circuit breaker group in the analysis. A column is provided for adding the score from Stage 2(a) to Table 2 through Table 19.

Stage 2:

- a) Apply a risk assessment for the specific circuit breaker application. Conduct a risk assessment to quantify the risk associated with each specific circuit breaker failure mode (i.e., deterioration in functional capability or failure to functionally perform). This may indicate that monitoring should be applied almost regardless of cost. Typically, the risk assessment outcome will be used in conjunction with cost-benefit analysis. A risk matrix, as shown in Table 20, Table 21, Table 22, and Table 23, should be completed.
- b) Undertake the cost-benefit analysis as indicated in the last section and in Table 7. Annex A provides two specific examples.

Stage 3:

The decision to implement continuous or periodic monitoring may be unambiguously indicated from either risk assessment or cost-benefit analysis alone. In other cases, a balanced judgment may be more appropriate.

The process is described in the flow diagram of Figure 1.

5.2 Failure modes and effects analysis

FMEA or FMECA are methods of reliability analysis intended to identify failures that have significant consequences affecting the system performance in the considered application. See IEC 60812:1985-07.

The term *failure*, when used in the context of this guide and its companion standard IEEE Std C37.10-1995, is used to mean the “unsuccessful performance of function” regardless of cause, component, or device involved. Failure to perform the intended function(s) need not imply that the particular component failed, but that the component or system function was not satisfied. Functional failures are not necessarily caused by circuit breaker or component failure. External causes, including misapplication, should also be considered.

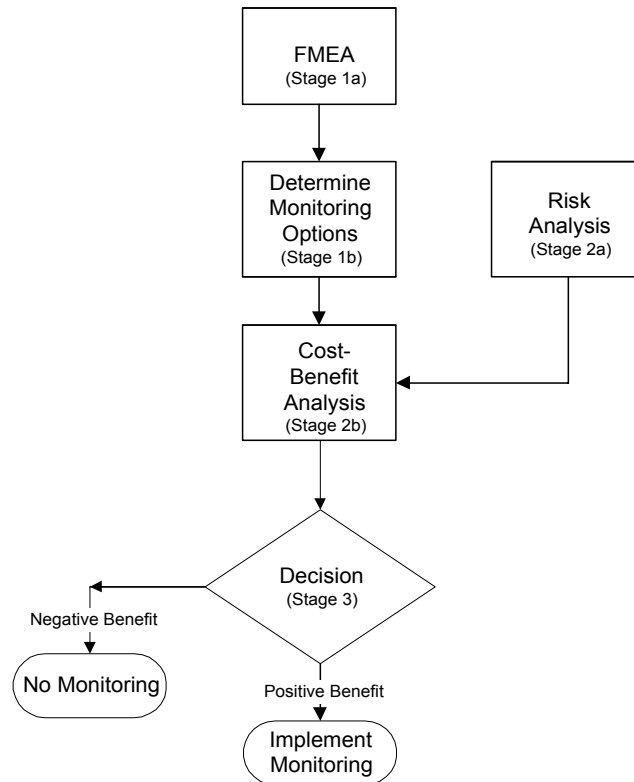


Figure 1—Monitoring decision process flow diagram

“The FMEA is based on that defined component or subassembly level where the basic failure criteria (primary failure modes) are available. Starting from the basic element failure characteristics and the functional system structure, the FMEA determines the relationship between the element failures and the system failures, malfunctions, operational constraints, and degradation of performance or integrity. To evaluate secondary and higher order system and subsystem failures, the sequences of events in time may also have to be considered” (IEC 60812:1985-07). Users of this guide are encouraged to make use of CEA Project No. 485T1049 (1997), Bierer et al. [B6], CIGRE [B5], and IEEE 100 [B12].

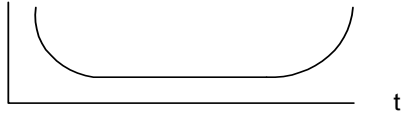
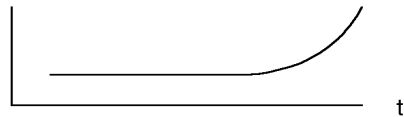
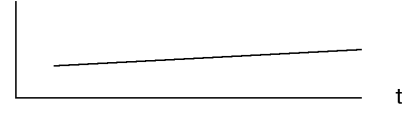
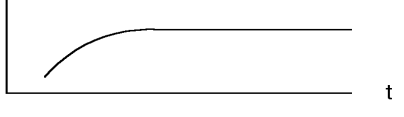
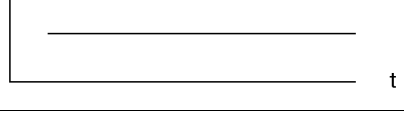
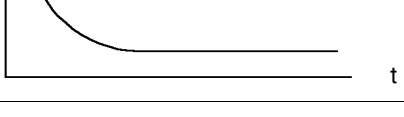
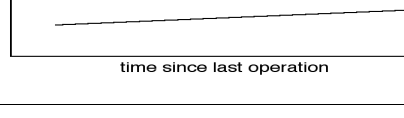
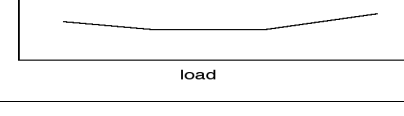
An FMEA is used to develop an understanding of what can fail, its effect on the functional system, and what characteristic can be monitored to observe the condition of a circuit breaker (or other devices).

This analysis derives the greatest value from being performed on a system basis rather than on a component basis. In this discussion, a power circuit breaker is considered a system. The circuit breaker becomes a component when applied in an electric power grid (system).

A description of circuit breaker functions leads to identification of failure modes. “A failure mode is the effect by which a failure is observed” (IEC 60812:1985-07). Failure causes for various technologies of circuit breakers can then be listed for each failure mode (IEEE Std C37.10-1995). The effect of each failure mode can be developed, and the criticality or risk associated with each of the failure modes can then be analyzed. The “effect” is what happens to the circuit breaker when the failure cause manifests as a failure mode. The effect is the same for each circuit breaker, even though what happens to facilities (i.e., consequences) connected to the circuit might be different for each specific application.

The evolution of how a failure develops over time is known as the failure characteristic. Failures can occur very suddenly or over a long period of time. Failure characteristics vary with the types of devices and the physics and chemistry of the failure mechanism. For example, some known failure characteristics are shown in Table 1.

Table 1—Failure characteristics or patterns showing failure rate versus various parameters

a) Infant mortality followed by a constant or gradually increasing failure rate and then a pronounced “wear-out” region (“bathtub curve”)	
b) Constant or gradually increasing failure rate with time followed by a pronounced wear-out region	
c) Gradually increasing failure rate with no identifiable wear-out region	
d) Low failure rate when new or overhauled, followed by a rapid increase to a relatively constant level	
e) Relatively constant rate of failure at all ages	
f) Infant mortality followed by a constant or slowly increasing failure rate	
g) Failure rate associated with inactivity (failure caused because the circuit breaker is inactive for some time since the last operation), overloading or system stresses while in service, or environmental factors (e.g., corrosion)	
h) Load-related failure rates (e.g., higher or lower loading causes increased failure rate)	
i) Random failure rates	
j) Increased failure rate immediately after maintenance and then returning to one of the above patterns	
k) Decreased failure rate immediately after maintenance and then returning to one of the above patterns	

A more detailed understanding of the failure characteristic or pattern is important when selecting monitoring. Monitoring is more beneficial during circuit breaker life periods of higher expected failure probability and may be less beneficial during periods of anticipated lower failure rate. The failure pattern should be considered when using Table 2 to select monitoring.

Generally, more appropriate monitoring can be selected if the failure cause characteristic can be understood. Similarly, more appropriate maintenance may also be applied with this understanding. An example is reliability-centered maintenance where maintenance tasks are selected to prevent functional failure causes that are associated with higher risks. Reliability-centered maintenance analyzes failure modes and their effects on function and then assigns maintenance activity directly related to reducing the failures that are deemed most important. An understanding of failure characteristics also allows predictions to be made on the number of expected failures for future years. The accuracy of the predictive model is dependent on the volume of high-quality data and the use of the proper forecasting technique. It is recommended that the user acquire as much relevant data from sources such as IEEE, CIGRE, CEA, and other industry sources so that the predictions can be as accurate as possible. Application of this data with algorithms based on the failure cause produces future failure projections that can be significant when used in cost justification for the purchase of monitoring equipment.

A rigorous analysis might identify all of the circuit breaker functions and their failure modes, whereas a less-extensive analysis could concentrate on the predominant failure modes only. In many (but not all) cases, these predominant failure modes could cover most of the circuit breaker reliability concerns with significantly less effort.

A more complete FMECA can classify all “identified failure modes according to their detectability, diagnosability, testability, item replaceability, compensating and operating provisions (repair, maintenance and logistics, etc.) and any other relevant characteristics” (IEC 60812:1985-07).

5.3 Circuit breaker failure modes, failure characteristics/patterns, and monitoring parameters

Table 2 through Table 19⁸ identify several failure modes, possible effects, and some causes of the failure, with speculation on the failure characteristic and monitoring options.

The FMEA may be applicable to the entire circuit breaker or to individual poles of a circuit breaker. There is a benefit to a broad-based view in developing the FMEA. The circuit breaker is generally installed as part of an integrated system. Many external situations and circumstances are beyond the control or awareness of the circuit breaker manufacturer or application engineer and can have an impact on the circuit breaker functional performance.

Monitoring options can be applied on a continuous or periodic on-line basis, or on a periodic manual basis.

⁸The IEEE grants purchasers of this material permission to copy Table 2, Table 3, Table 4, Table 5, Table 6, Table 7, Table 8, Table 9, Table 10, Table 11, Table 12, Table 13, Table 14, Table 15, Table 16, Table 17, Table 18, and Table 19 for their use only. Under no circumstances are these copies to be shared or sold by purchaser. The IEEE reserves all other rights to the material.

Table 2—Generic listing of circuit breaker FMEA, failure characteristics, and monitoring options^a

Failure mode	Failure effect	Failure cause	Failure characteristic	Monitoring options	User score
* Failure modes in bold font and indicated with an asterisk are predominant failure modes, i.e., this failure mode covers most cases. Failure modes indented below those with an asterisk are a subset of the predominant failure modes.	This column describes what can happen when the failure mode occurs, i.e., the effect by which a failure is observed.	This column describes the possible causes of the failure mode.	This column suggests the developing characteristic of the failure cause, i.e., the manner over time in which the failure develops.	This column offers monitoring options. Monitoring may be implemented as continuous or periodic on-line, periodic off-line, or periodic manual monitoring. The breaker may be in the energized or de-energized state.	Enter a user score from 5.1, Stage 2(a).

^aThe IEEE grants purchasers of this material permission to copy Table 2, Table 3, Table 4, Table 5, Table 6, Table 7, Table 8, Table 9, Table 10, Table 11, Table 12, Table 13, Table 14, Table 15, Table 16, Table 17, Table 18, and Table 19 for their use only. Under no circumstances are these copies to be shared or sold by purchaser. The IEEE reserves all other rights to the material.

Table 3—Generic listing of circuit breaker FMEA: Circuit breaker fails to open on command ^a

Failure mode	Failure effect	Failure cause	Failure characteristic	Monitoring options	User score
Fails to open on command *	Breaker does not open the circuit to interrupt current	Open or shorted trip coil	Fails suddenly without advanced indication	Monitor trip coil continuity or impedance	
		Inappropriate or inadequate lubrication of trip latch or trip mechanism	Operating time of trip latch may increase over time Energy to trip latch may increase over time	Monitor trip coil energy consumed or current and voltage drop during time for circuit breaker to operate, or monitor the time for the circuit breaker to operate	
		Loss of stored interrupting energy due to leaks, slippage, and breakage	Pneumatic- and hydraulic-actuated mechanisms generally lose energy over at least several minutes Spring-actuated mechanisms may suddenly fail or may have less sudden loss of energy	Monitor stored energy pressure or position of stored energy springs	
		Control circuit failure	Control circuits generally fail suddenly. Auxiliary contacts generally change relationship with the main contacts; gradually, however, they may also suddenly fail	Monitor control circuit continuity and dc voltage at circuit breaker and controls Monitor trip coil current and auxiliary contact timing (on noncurrent carrying contact) Periodic insulation testing	

Table 3—Generic listing of circuit breaker FMEA: Circuit breaker fails to open on command (continued)^a

Failure mode	Failure effect	Failure cause	Failure characteristic	Monitoring options	User score
Fails to open on command *	Breaker does not open the circuit to interrupt current	Circuit breaker operation blocked	Legitimate blocking caused by loss of circuit breaker function Incorrect blocking caused by monitoring or alarm failure, incorrect settings, or operation of initiating transducers	Self-monitoring and self-alarms of monitoring scheme Trending of monitored parameters	
		Mechanism linkage failure between operating mechanism and interrupters	Generally, linkages either go out of adjustment over a number of operations or break suddenly during an operation	Monitor primary current interruption during change of state of operating mechanism Monitor timing sequence between operating mechanism and interruption	
		Trip latch surface wear, deteriorated bearings, or deformation of trip latch flat surfaces	Operating time of trip latch may increase over time Energy to trip latch may increase over time	Monitor trip coil energy (current and voltage drop) and time for circuit breaker to operate	
		Mechanism cabinet below required temperature	Probable lowering temperature over several hours	Monitor mechanism temperature or mechanism heater current and ambient temperature	
		External circuit failure, including wiring, battery, and protection devices	Slowly over time or failure only apparent with attempted operation	Monitor station battery voltage at circuit breaker, continuity of trip circuitry, self-monitoring of electronic primary and backup protection devices	

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Table 4—Generic listing of circuit breaker FMEA: Circuit breaker opens, but fails to remain open^a

Failure mode	Failure effect	Failure cause	Failure characteristic	Monitoring options	User score
Opens but fails to remain open	Circuit breaker opens and then closes again	Mechanism failure, loss of “hold open” energy (e.g., loss of air pressure on air blast circuit breaker requiring air pressure to hold contacts open)	Gradual failure of X or Y relay timing resulting in sudden “pumping” of circuit breaker	Monitor mechanism position and auxiliary contacts with respect to current flow and opening signal	
	Circuit breaker opens and then repeatedly closes and opens	Failure of antipumping scheme	Usually fails as part of the opening operation. May not fail with every opening operation	Monitor number of operations over time period Monitor X and Y relay timing	

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