

IEEE Guide for the Selection of Monitoring for Circuit Breakers

IEEE Power and Energy Society

Sponsored by the
Switchgear Committee



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IEEE Std C37.10.1™-2018
(Revision of
IEEE Std C37.10.1-2000)

IEEE Guide for the Selection of Monitoring for Circuit Breakers

Sponsor

Switchgear Committee
of the
IEEE Power and Energy Society

Approved 5 December 2018

IEEE-SA Standards Board

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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 1000 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, IEEE C37.10.1™, monitoring, online condition monitoring, risk assessment

The Institute of Electrical and Electronics Engineers, Inc.
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PDF: ISBN 978-1-5044-5439-1 STD23487
Print: ISBN 978-1-5044-5440-7 STDPD23487

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Introduction

This introduction is not part of IEEE Std C37.10.1-2018, IEEE Guide for the Selection of Monitoring for Circuit Breakers.

The revised issue of this guide, IEEE Std C37.10.1-2018, 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, protection and control, and other support components.

This revised 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 C37.10.1-2018 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 humans 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 in the draft stages of developing a 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. 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 [ac](#)). 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.¹

¹[Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.](#)

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.²

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.

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

~~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.³²

CEA Project No.¹ 485T1049 (1997), On-line condition monitoring of substation power equipment – Utility needs.³

²¹Information on references can be found in Clause 2.

³²CSA publications are available from the Canadian Standards Association (~~Standards Sales, 178 Rexdale Blvd., Etobicoke, Ontario, Canada M9W 1R3~~) (<http://www.csa.ca/>).

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

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, Analysis, and Reporting of Power Circuit Breaker Failures. ~~Breakers~~^{5,6}

NOTES

~~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).~~

⁴~~IEC~~⁷~~CIGRE~~ publications are available from the International Electrotechnical Commission (<http://www.iec.ch>) and the American National Standards Institute (<http://www.ansi.org/>). ~~Council on Large Electric Systems, 21, rue d’Artois, 75008, Paris, France~~ (<http://www.cigre.org/>).

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

3. Definitions

For the purposes of this [document guide](#), the following terms and definitions apply. The ~~Authoritative Dictionary of IEEE Standards Dictionary Online Terms [B12]~~ should be [consulted](#) ~~referenced~~ for terms not defined in this clause.⁷

continuous [monitoring 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.

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.

[NOTE—See also: IEC 60812.](#)

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.~~

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

⁷[IEEE Standards Dictionary Online is available at http://dictionary.ieee.org.](http://dictionary.ieee.org)

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~~.

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.

failure pattern: *See:* failure characteristic.

periodic monitoring ~~monitor~~: The continuous ~~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.~~

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. Monitoring

4.1 Purpose of monitoring

The purpose of circuit breaker monitoring is to collect data for decision making.

4.2 Benefits of monitoring

Monitored data ~~Monitoring~~ can be used for the following actions: ~~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. Data acquisition, processing, and communicating

Key factors when considering the installation of a “circuit breaker on-line monitoring” system are the data acquisition, networking of information, and communication of the data to a remote site or office location. This part of the project often contributes to a significant amount of the total system cost. Also this technology is often the first to become outdated in the market. Often it is found that the products, services, and industries technical standards are outdated soon as they are introduced into the market.

6. Suggested components and operating conditions accessible for monitoring

6.1 Interrupter

The following interrupter components and operating conditions should be accessible for effective monitoring:

- a) Insulation medium status: Gas density and/or partial discharge, dew point measurement. Detect dielectric breakdown, corona, and degradation of SF₆ gas. Vacuum interrupters should be included, circuit breaker contact wear algorithms are common.
- b) Temperature rise: Detects loosening of joints, resistance rising, and overheating.
- c) Interrupter condition: Accumulated switching and interrupting current. Detect condition of arcing contacts and nozzles. Distinguish low level switching operations from higher current fault operations.

6.2 Control circuits

The following control circuit components and operating conditions should be accessible for effective monitoring:

- a) Trip circuit integrity using established methods: Detect open trip circuit and rising circuit resistance.
- b) Close circuit integrity using established methods: Detect close trip circuit and rising circuit resistance.
- c) DC control voltage: Voltage level, Detect abnormal control voltage.
- d) AC control voltage: Voltage level, Detect abnormal control voltage.

6.3 Operating mechanism

The following operating mechanism components and operating conditions should be accessible for effective monitoring:

- a) Mechanical quality– opening time: Detect mechanical and lubrication concerns
- b) Mechanical quality– closing time: Detect mechanical and lubrication concerns
- c) Mechanical quality– travel time: Detect mechanical and lubrication concerns
- d) Mechanical quality– stored energy: Detect loss or reduction in stored energy
- e) Mechanical quality– recharge time: Detect change in time of recharging
- f) Mechanical quality– total number of operations: Detect mechanical wear and system degradation
- g) Spring charging motor duration
- h) Hydraulic pump motor current, pump duration, frequency of pump starts
- i) Air compressor motor current, motor duration, frequency of motor starts

6.4 Accessories

The following accessory components and operating conditions should be accessible for effective monitoring:

- a) Control/mechanism cabinet heater operation: Detect loss of heater operation
- b) SF6 tank heater operation: Detect loss of heater operation, monitor heater resistance and current
- c) Cabinet door status, open/close time stamping

7. Methodology

7.1 General

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 [available](#) ~~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.

7.2 Decision-making sequence

The [decision-making](#) process [for monitoring selection](#) 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.

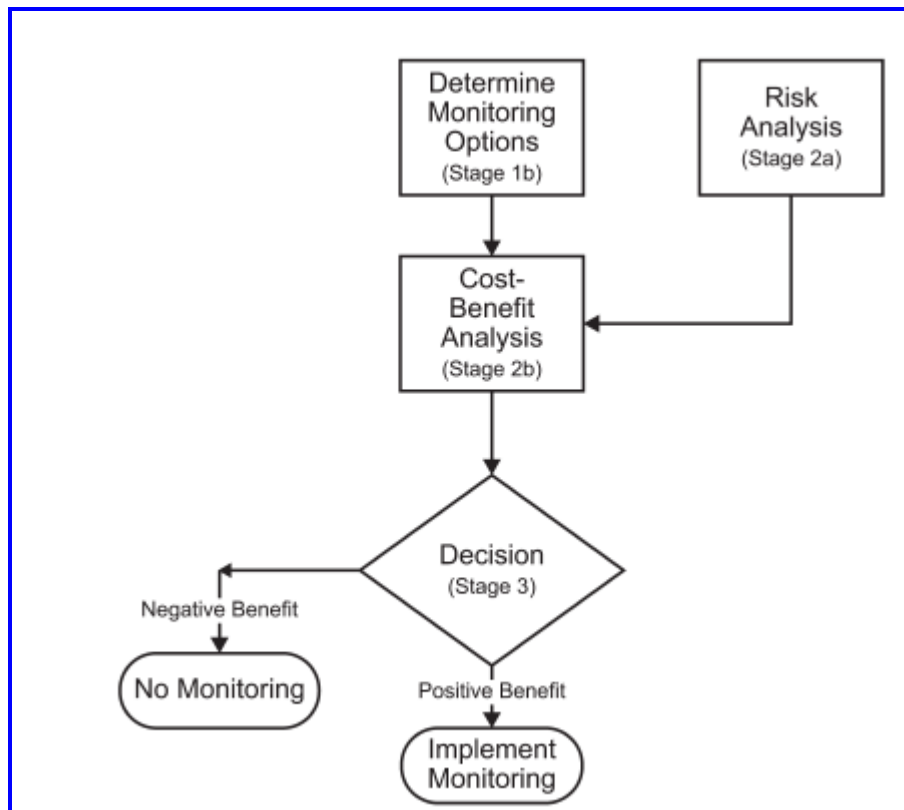
The process is described in the flow diagram of Figure 1.

7.3 Failure modes and effects analysis (FMEA)

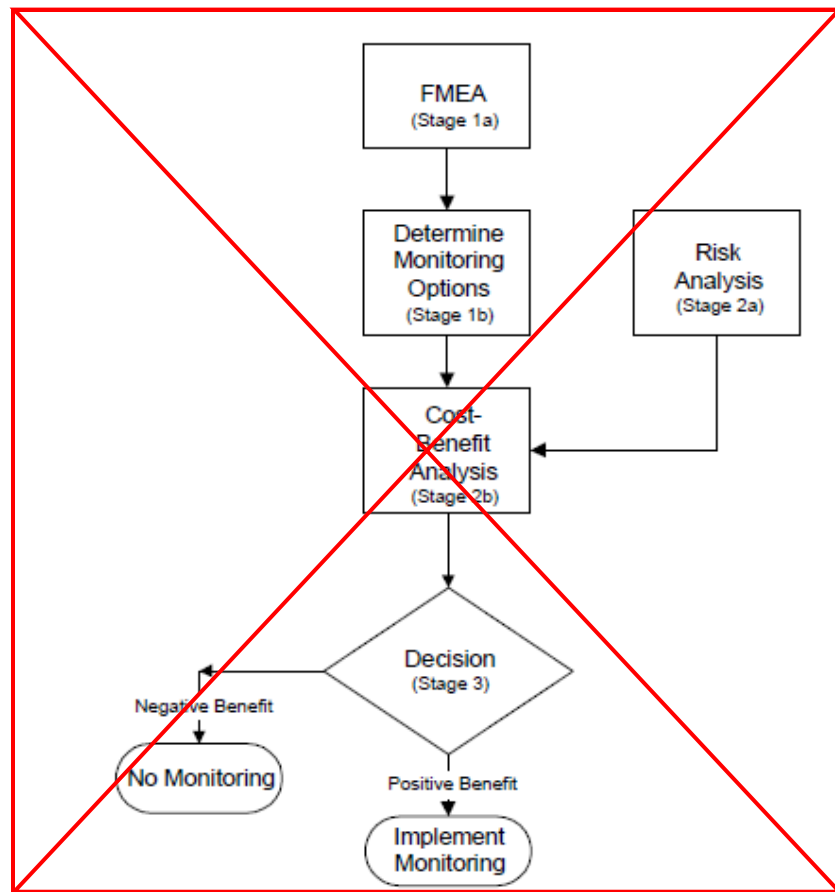
FMEA and ~~or~~ FMECA are methods of reliability analysis intended to identify failures that have significant consequences affecting the system performance in the considered application (~~see IEC 60812~~); ~~1985-07~~.

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.

“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].~~



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Figure 1 – Monitoring decision process flow diagram

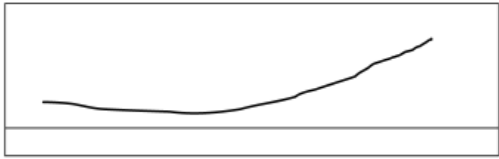
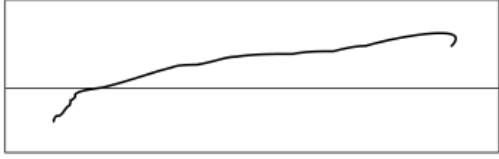
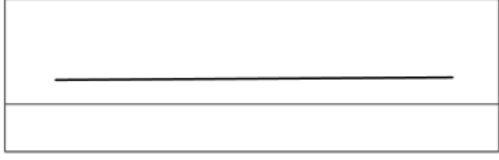
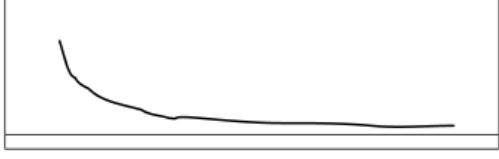
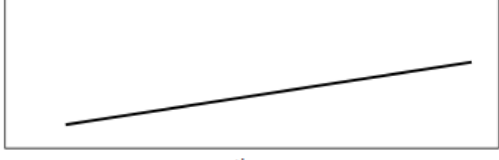
An FMEA is used to develop an understanding of what can fail, its effect on the functional system, and what characteristic can be monitored to observe the condition of a circuit breaker (or other devices).

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).

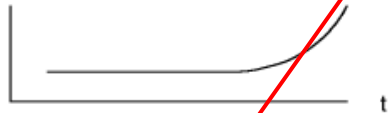
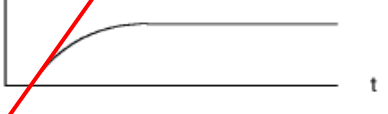
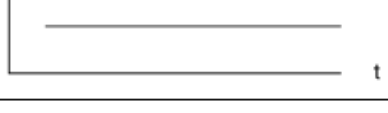
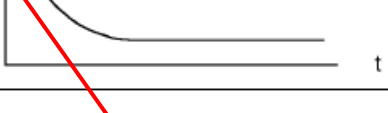
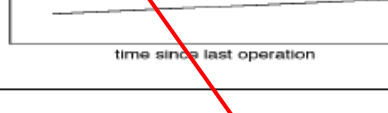
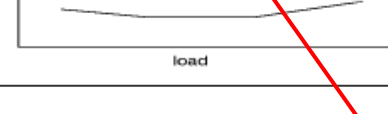
A description of circuit breaker functions leads to identification of failure modes. “A failure mode is the effect by which a failure is observed” (IEC 60812:~~1985-07~~). Failure causes for various technologies of circuit breakers can then be listed for each failure mode (IEEE Std C37.10-[2011](#) ~~1995~~). 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

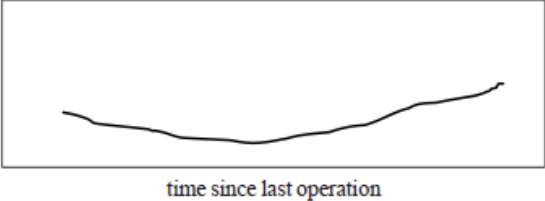
a) Infant mortality followed by a constant or gradually increasing failure rate and then a pronounced “wear-out” region (“bathtub curve”)	 time
b) Constant or gradually increasing failure rate with time followed by a pronounced wear-out region.	 time
c) Gradually increasing failure rate with no identifiable wear-out region.	 time
d) Low failure rate when new or overhauled, followed by a rapid increase to a relatively constant	 time
e) Relatively constant rate of failure at all ages	 time
f) Infant mortality followed by a constant or slowly decreasing failure rate	 time
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)	 time

(New)

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	

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

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	

(New)

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 20 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~~).

7.4 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.⁸

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.

NOTES

NOTE 1—Table 2 through Table 19 are only representative FMEA charts. They are not exhaustive complete for every circuit breaker and may not include all issues of importance to the user. The end user should consider many factors, including, as an example, the fault level at the circuit breaker compared with the circuit breaker interrupting rating and the consequence to the circuit breaker owner as well as to downstream customers.

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.