IEEE Guide for the Selection of Monitoring for Circuit Breakers

Sponsor

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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.

[1]Information 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*™).

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.

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[2]CSA 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).

[4]IEC publications are available from the Sales Department of the International Electrotechnical Commission, Case Postale 131, 3, rue de Varembé, 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.

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

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

[7]CIGRE 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.

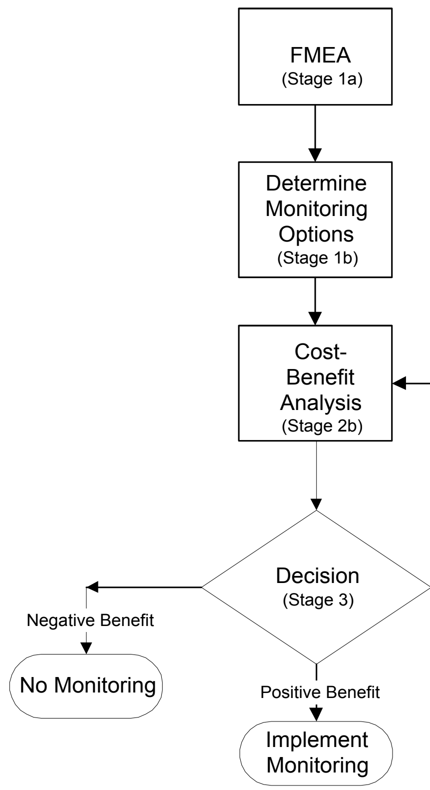


Figure 1—Monitoring decision process flow diagram

“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].

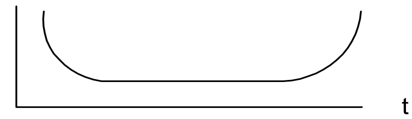
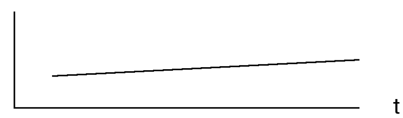
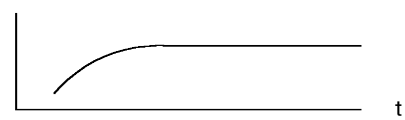
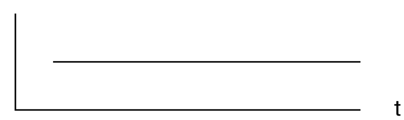
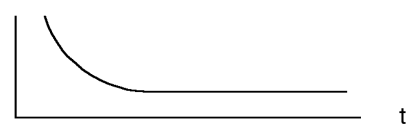
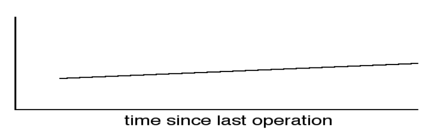
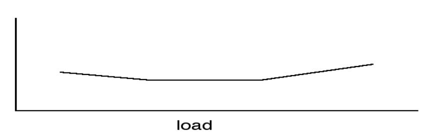
An FMEA is used to develop an understanding of what can fail, its effect on the functional system, and what characteristic can be monitored to observe the condition of a circuit breaker (or other devices).

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 19[8] 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.

[8]The 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).

[a]The 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-alarming 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	

[a]The 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 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	

[a]The 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 5—Generic listing of circuit breaker FMEA: Circuit breaker opens, but fails to interrupt [a]

Failure mode	Failure effect	Failure cause	Failure characteristic	Monitoring options	User score
Opens but fails to interrupt	Fault or load current is not interrupted, and the circuit breaker interrupter has a major failure	Oil contamination	Slowly over time	Oil dielectric	
		Low gas pressure or density (air or SF_6)	Slowly over time	Gas pressure or density as appropriate for ambient temperature	
		Loss of vacuum	Instantaneous or gradual	Periodic vacuum integrity overpotential test	
		Insufficient contact opening	Instantaneous or gradual	Monitor contact travel	
		Arc chute failure	Slow or sudden mechanical failure, heater failure, contamination, or connection failure	Visual inspection, partial discharge monitor, and heater or temperature monitor	
		Puffer failure	Slow or sudden	—	
		Mechanical failure	Slow or sudden	Monitor mechanism position and auxiliary contacts with respect to current flow and opening signal	
		Misapplication or other situation beyond circuit breaker capability	Developing system generally changes with reconfigured system or new switching duty Interruption under improper system application conditions	Monitor system fault level and conditions, especially during short circuit interruption and breaker operation Periodic review of system fault levels Power system disturbance recorder (including oscillographs and digital fault recorders)	

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Table 6—Generic listing of circuit breaker FMEA: Circuit breaker opens, but fails to maintain open contact insulation[a]

Failure mode	Failure effect	Failure cause	Failure characteristics	Monitoring options	User score
Opens but fails to maintain open contact insulation	Breaker fails to provide required dielectric isolation of contacts immediately after the opening operation	Loss of vacuum	Instantaneous or gradual	Periodic vacuum-integrity overpotential test	
		Mechanism does not travel complete distance	Out of adjustment because of excessive operations, or else, it jams and breaks suddenly	Full travel indication	
		Loss of gas pressure	Instantaneous or gradual	Gas pressure monitor	
		Too many operations in a time period	Slowly over time	Monitor number of operations over time period	
		Dielectric stress exceeds the circuit breaker capability	—	Monitor system voltage conditions, especially during short circuit interruption and breaker operation	
		Lightning	—	—	

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Table 7—Generic listing of circuit breaker FMEA: Circuit breaker opens without command[a]

Failure mode	Failure effect	Failure cause	Failure characteristics	Monitoring options	User score
Opens without command	Circuit is unintentionally interrupted with possible safety and economic damage issues	Trip latch not secure	Slowly over time	Change in current over time or change in speed to trip	
		Stray current in trip circuit (such as from transients, caused by switching surges on adjacent wiring)	Short circuit in some location of the circuit breaker control wiring causing current to flow in the trip coil	Monitor current in trip coil	
		Ground on trip circuit	Inadvertent ground on trip circuit	Monitor trip circuit for grounds	
		Self-protective feature of some circuit breakers (some airblast breakers)	Usually gradual loss of pressure	Monitor trend in operating stored energy	
		Loss of voltage on undervoltage trip	—	Monitor voltage in undervoltage trip supply circuit	

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Table 8—Generic listing of circuit breaker FMEA: Circuit breaker fails to close on command[a]

Failure mode	Failure effect	Failure cause	Failure characteristics	Monitoring options	User score
Fails to close on command*	Breaker does not close the circuit to conduct current	Defective close coil or solenoid	Fails suddenly without advanced indication	Monitor close coil circuit for possible increase in close current, or monitor closing time	
		Loss of stored energy	Can be quick or slow over time	Monitor spring position, air pressure	
		Inappropriate lubrication	Fails gradually and may be activity related	Monitor timing between main contacts and close coil current	
		Control circuit failure	Sudden or gradual	Monitor control circuit Monitor close coil current and auxiliary contact timing (on non-current-carrying contact)	

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Table 9—Generic listing of circuit breaker FMEA: Circuit breaker closes, but fails to conduct current[a]

Failure mode	Failure effect	Failure cause	Failure characteristics	Monitoring options	User score
Closes but fails to conduct current	Breaker does not close the circuit to conduct current in one or more poles	Contacts burnt away (electrically eroded)	Contacts eroded after interrupting beyond duty fault	Power system disturbance recorder (including oscillographs and digital fault recorders) in primary current circuit	
		Mechanical linkage to contacts broken	Linkage breaks after last operation or during closing operation	Monitor primary current start during change of state of operating mechanism	
		Loss of overtravel preventing full contact closing	Contact arcing and erosion	Monitor contact travel and over travel	

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Table 10—Generic listing of circuit breaker FMEA: Circuit breaker closes without command[a]

Failure mode	Failure effect	Failure cause	Failure characteristics	Monitoring options	User score
Closes without command	Circuit is unintentionally closed with possible safety and economic damage issues	Stray current in close circuit (such as from transients caused by switching surges on adjacent wiring)	Short circuit in some location of the circuit breaker control wiring causing current to flow in the close coil	Current in close coil	
		Ground on close circuit	Inadvertent ground on close circuit	Monitor close circuit for grounds	
		Pilot valve not secure	Air leakage or pilot valve not holding	Air pressure leaving pilot valve; monitor air compressor run time and pressure	
		Spring release mechanism worn	Wears slowly over time to point where it does not hold securely	Movement of release mechanism	
		Vibration of circuit breaker	Usually sudden failure	Improper application or vibration isolation	

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Table 11—Generic listing of circuit breaker FMEA: Circuit breaker fails to conduct continuous or momentary current (while already closed)[a]

Failure mode	Failure effect	Failure cause	Failure characteristics	Monitoring options	User score
Fails to conduct continuous or momentary current (while already closed)	Breaker does not conduct current with resulting thermal damage to contact assemblies	High-resistance contacts	Gradual increase in contact resistance during operation	Infrared monitoring of contact temperature	
		Ablation of contacts	Gradual increase in contact resistance during operation	Infrared monitoring of contact temperature	
		Broken or missing contacts; parts in current carrying circuit; bolted joints, sliding, rolling, or moving main contacts; spring failure	Increase in contact resistance with damaged continuous current carrying contact assembly	Infrared monitoring of contact temperature	
		Loss of over travel and contact closing force	Gradual or relatively sudden failure	Infrared monitoring of contact and connection and temperature	

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Table 12—Generic listing of circuit breaker FMEA: Circuit breaker fails to provide insulation[a]

Failure mode	Failure effect	Failure cause	Failure characteristics	Monitoring options	User score
Fails to provide insulation *	Short circuit on power system or unintentional energization of components	Loss of dielectric medium	Gradual leakage rate over time	Gas pressure or density Fluid level	
		Loss of dielectric integrity of oil	Gradual leakage rate over time	Periodic test of oil condition	
		Loss of vacuum	Sudden or rapid	Periodic vacuum-integrity overpotential test	
		Moisture in SF_6 gas	Gradual	Monitor SF_6 density and moisture	
		Loss of compressed air dielectric	Gradual increase in compressed air dew point, relative humidity, or ppm water content Sudden mechanical damage to interrupter envelope	Monitor compressed air water content and temperature or relative humidity of compressed air Trend periodic insulation resistance and dielectric tests	
		Damaged interrupter from external acts	—	Station security monitor	
		Excessive accumulated interrupted amperes	Gradual	Monitor interrupted amperes and breaker operations	
		Wear-generated particles in interrupter	Gradual	Monitor partial discharge?	

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Table 13—Generic listing of circuit breaker FMEA: Circuit breaker fails to provide insulation to ground[a]

Failure mode	Failure effect	Failure cause	Failure characteristics	Monitoring options	User score
Fails to provide insulation to ground	Phase-to-ground fault on the power system with possible safety and economic damage; interruption required to power system	Wildlife contact	Immediate on contact	—	
		Lightning strike	Instantaneous	—	
		Mechanical damage to insulation	Gradual or sudden	—	
		Water infiltration	Immediate on path	—	
		Contaminated bushings	Immediate on path	—	
		Flashover caused by system transient event	Sudden failure, but synchronized with power system transient event	Power system disturbance recorder (including oscillographs and digital fault recorders)	
		Excessive temperatures of insulating materials	Slow	Monitor ambient air or component temperature(s)	

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Table 14—Generic listing of circuit breaker FMEA: Circuit breaker fails to provide insulation between phases[a]

Failure mode	Failure effect	Failure cause	Failure characteristics	Monitoring options	User score
Fails to provide insulation between phases	Phase-to-phase fault on the power system with possible safety and economic damage; interruption required to power system components	Wildlife contact	Immediate on contact	—	
		Lightning strike	Instantaneous	—	
		Ionization of surrounding insulating air caused by unusual service conditions	Instantaneous	Partial discharge monitoring	
		Water infiltration	Immediate on path	Partial discharge monitoring	
		Foreign material	Immediate on path	Partial discharge monitoring	

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Table 15—Generic listing of circuit breaker FMEA: Circuit breaker fails to provide insulation across the interrupter—external[a]

Failure mode	Failure effect	Failure cause	Failure characteristics	Monitoring options	User score
Fails to provide insulation across the interrupter—external	Circuit is unintentionally closed with possible safety and economic damage issues; may result in a major failure of circuit breaker interrupter	Wildlife contact	Immediate on contact	—	
		Lightning strike	Instantaneous	—	
		Water infiltration	Usually slowly, however, immediate failure on establishing leakage path	—	
		Ionization of air during over duty fault	Instantaneous	System monitoring	
		Excessive voltage applied to breaker	Usually quickly	System monitoring	
		Dirt or pollution	Gradual	—	
		Deterioration of interrupter exterior surfaces caused by partial discharge	Gradual	Monitor partial discharge activity	
		Flashover of OPEN interrupter caused by system transient event	Suddenly but synchronized with power system transient event	Power system disturbance recorder	
		Ionization of surrounding insulating air caused by unusual service conditions	Instantaneous	Partial discharge monitoring	

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Table 16—Generic listing of circuit breaker FMEA: Circuit breaker fails to provide insulation across the interrupter—internal[a]

Failure mode	Failure effect	Failure cause	Failure characteristics	Monitoring options	User score
Fails to provide insulation across the interrupter—internal	Circuit is unintentionally closed with possible safety and economic damage issues; major failure of circuit breaker interrupter	Loss of dielectric density	Gradual over time	Gas density	
		Loss of dielectric integrity of oil	Gradual over time	Periodic test of oil condition	
		Loss of vacuum	Usually sudden or rarely gradual	Periodic vacuum integrity overpotential test	
		Excessive voltage applied to breaker	Gradual or sudden	System monitoring	

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Table 17—Generic listing of circuit breaker FMEA: Circuit breaker fails to contain insulating medium[a]

Failure mode	Failure effect	Failure cause	Failure characteristics	Monitoring options	User score
Fails to contain insulating medium *	Loss of insulating medium to environment (see also insulation failure effects)	Failure of seals, gaskets, corrosion, erosion, and porcelain rupture disk	Generally slowly over time but can be rapid	Monitor insulating medium level (liquids), density (SF_6), or pressure (air blast)	

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Table 18—Generic listing of circuit breaker FMEA: Circuit breaker fails to indicate condition or position[a]

Failure mode	Failure effect	Failure cause	Failure characteristics	Monitoring options	User score
Fails to indicate condition or position *	Operation of power system with a circuit breaker that is incapable or has reduced capacity to perform its functions	Failure of insulation gas density switch	Gauge indication becomes stuck	Monitor gas density variation as ambient temperature cycles to ensure density variation is appropriate	
	Defective closed, opened, or stored energy indicator, causing operator to undertake inappropriate actions	Stuck, broken, or defective indicator	Generally, during a single operation; could be gradual mechanical deterioration over time	Monitor indication with signal to open and close circuit, primary current, control circuit current, and stored energy charging system operation	
		Auxiliary contacts, linkage, or wiring	Possible erratic operation; may be sudden	Monitor indication with signal to open and close circuit, primary current, control circuit current, and stored energy charging system operation	

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Table 19—Generic listing of circuit breaker FMEA: Circuit breaker fails to provide safety in operation[a]

Failure mode	Failure effect	Failure cause	Failure characteristics	Monitoring options	User score
Fails to provide for safety in operation *	Hazard to personnel	Overpressure of porcelain interrupter Defects in porcelain	Sudden failure of pressure regulator supplying high-pressure air to interrupter chamber	Pressure relief valve monitoring	
		Overpressure of pneumatic or hydraulic fluids, spring charging system	Sudden failure of charged energy control device	Monitor circuit breaker stored energy device condition remotely	
		Failure of interlocks	Sudden or over time	Monitor indication with signal to open and close circuit, primary current, control circuit current, and stored energy charging system operation	
		Loss of gas and need to isolate	Sudden or over time	Monitor gas pressure/ density	
		Improper filling or adding liquid versus gas dielectric medium	—	Monitor gas pressure/ density	

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NOTES

1—Table 2 through Table 19 are only representative FMEA charts. They are not 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.

2—These tables are a generic listing of circuit breaker failure modes, failure effects, failure causes, failure characteristics, and some monitoring options that are available. The listing is comprehensive, although there may be others that were either not identified at the time this guide was produced or that are applicable to new circuit breakers developed after this guide was developed.

3—Failure modes in bold font and indicated with an asterisk (*) are considered as predominant failure modes in this example analysis. Predominant failure modes can sometimes be considered to include most of the likely failure modes. A more rigorous FMEA would include all failure modes, whereas a less rigorous analysis including predominant failure modes only may be judged adequate for some situations.

4—For the convenience of users of this guide, a column has been added to score the relative importance of each monitoring option for the users' specific circumstances.

5—These tables attempt to establish correspondence among failure cause, failure characteristic, and monitoring option.

5—Be aware that a failure cause might have occurred during a previous operation and may not be apparent until the subsequent operation is requested.

6—Monitoring an action or characteristic may yield information that is not necessarily directly related to the root cause of a failure.

7—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 to the power system. Similarly, this guide does not address the issue of software used in protective, control, or monitoring devices and systems.

5.4 Risk assessment

After the effect of a failure is determined, the criticality or risk associated with that effect should be assessed. The risk assessment quantifies the importance of each failure effect (CAN/CSA-Q634-91).

Risk is formed from two factors: the probability of any event occurring and its consequence. Risk is high when an event is likely to occur, and it has serious results. Risk can be moderate if the probability is low and the consequences are high, when both are medium, or when the probability is high and consequences are low. Risk is low if both probability and consequences are low.

By evaluating the probability of an event happening and developing an idea of how serious the situation might be if it occurs, risk can be evaluated. High-risk items generally require action be taken to reduce the risk, whereas low-risk items may not need to have any action taken. In this assessment, action to be taken is implementation of condition monitoring, whereas in the area of maintenance, selection of appropriate maintenance tasks is undertaken. Obviously, manufacturers make these assessments based on the knowledge they have regarding the circuit breaker design and manufacture. The end user has application information not available to manufacturers and, therefore, is in a position to conduct an assessment appropriate to each situation.

Table 20 can be used to help quantify risk. Determine the level of probability that an event can occur and the consequences if that event does happen (regardless of how often it happens) to develop the level of risk that should be recognized. Consequences and probabilities can be quantified in the areas of financial impact as well as in the areas of safety, environmental, public, employee, or regulatory impact [CEA Project No. 485T1049 (1997) and CAN/CSA-Q634-91]. A complete analysis would consider the consequences and probabilities associated with risk in each of the areas of financial, safety, environmental, public, employee, or regulatory impact; and other areas of risk appropriate to the specific installation.

Table 20—Risk matrix

Risk matrix (Risk ≡ probability of an event occurring × consequences if that event occurs)				
	Consequence of an event occurring			
Probability that an event will occur	**I Catastrophic**	**II Major**	**III Moderate**	**IV Negligible**
1 - Frequent	A	A	B	B
2 - Occasional	A	A	B	C
3 - Infrequent	B	B	C	D
4 - Improbable	B	C	D	D
NOTE—Multiply chance of an event occurring times the consequence to obtain predicted risk.				

Another way of viewing risk is illustrated in Figure 2..

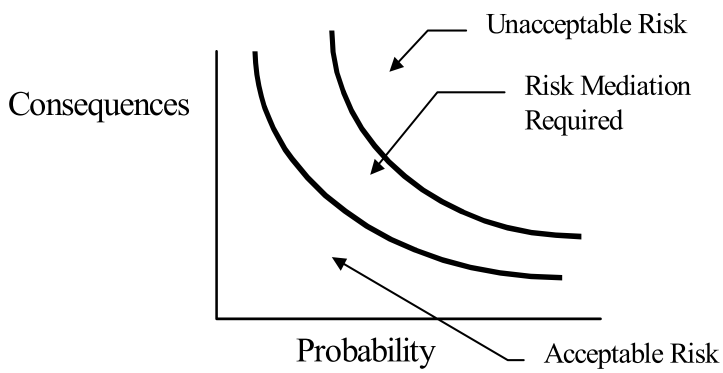

Figure 2—Graphic representation shows various levels of risk

Table 21 lists EXAMPLES only of how consequence and probability might be quantified. The consequence example uses a financial consequence. Other examples might include safety, environment, or public relations descriptions.

> The examples shown are for illustrative purposes only. Numeric financial values and consequential descriptions are strictly for the purpose of showing that values can be assigned if so chosen. Actual circumstances can 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 can also either restrict or broaden opportunities for monitoring.

Table 21—Risk or criticality ranking: Example

Rank	Level of risk or criticality
A	Highest risk, unacceptable, immediate action required to reduce risk
B	Major risk, not desirable, moderate action required to reduce risk
C	Moderate risk, acceptable with controls to mitigate risk
D	Minimal risk, acceptable risk without mitigating action

The examples of consequences shown in Table 22 are described in terms of financial, safety, and environmental consequences. These are examples for illustrative purposes only and should be customized for the specific circumstances. A user should insert values specific to their situation.

NOTE—The suggested process is for the user to identify and assess the importance to their enterprise and customers of the various levels of consequence for an event.

The examples shown in Table 23 are for illustrative purposes only. Numeric probability values are strictly for the purpose of showing that values can be assigned if so chosen. Actual circumstances can dictate probabilities to be used in the quantifying of risk, economic evaluation and justification, and the ultimate selection of monitoring. The specific circuit breaker technology employed may result in probabilities specific to that technology. These are examples for illustrative purposes only, they may not be appropriately grouped, and they should be customized for the specific circumstances.

Several sources of failure probability are listed in IEEE Std 493-1997, Beierer et al. [B6], CEA [B2], CIGRE [B5], CIGRE [B8], Diagnostic techniques [B9], and IEEE 100 [B12]. Table 23 has illustrative values for the sole purpose of assisting a user in ranking probabilities for use in quantifying risk. The probabilities identified in each level of probability are not equivalent and are intended only as a means of describing relative probability.

Such analysis can be done for each user of the technique, applying knowledge of probabilities and consequences suitable to the user's specific circumstances. As an example, only consider the case in which a circuit breaker is called on to operate 5 times per year and has a probability of failure to operate of 1 in 200 operations or a 0.5% failure rate. If the consequence of this specific failure to operate is expected to be $50 000 for all costs, including those of the utility and its customers, the expected annual cost of failure is $0.005 \times 5 \times \$50\,000 = \$1{,}250$.

Selection of monitoring might well be made on an FMEA and risk management basis only. It is also important to consider consequences in areas other than the financial example provided. Other areas, which may have significant importance to the user, are the environment, customer relations, legal or regulatory effect, safety, or customer power quality.

Six valuable sources of information for circuit breaker performance data are given in Beierer et al. [B6], CEA [B2], CIGRE [B5], CIGRE [B8], Diagnostic techniques [B9], and IEEE 100 [B12].

The expected cost of a loss is used to evaluate possible mitigation efforts, such as installing on-line monitoring of selected circuit breakers. The expected loss with and without on-line monitoring is one of the factors to be considered in the economic analysis.

Table 22—Description of consequences: Example

Consequence of an event occurring (Financial, safety, and environmental examples are illustrated for example only. Additional areas of consequence could include social, regulatory, legal, public reputation, and political impact. Each user will have specific criteria for these areas of consequence.)
I—Catastrophic Financial and facility costs or exposure threatens the long-term survival of the organization. Any long-term impact on share value. Fatalities (as a direct result) or serious long-term health impact on — The public — Employees — Contractors An incident that causes long-term harm (*x* years or more). Ecological damage that endangers ecological processes or significant harm to humans.
II—Major Financial and facility costs or exposure cause a major impact on the organization. Any long-term impact on share value. Permanent impairment or serious injury or illness. An incident that causes significant ecological damage that can be controlled and lasts up to *x* years.
III—Moderate Financial and facility costs or exposure cause a moderate impact on the organization. Any short-term impact on share value. Recordable injury (restricted work, medical aid). An incident that causes noticeable but repairable damage, but where technology exists to mitigate the ecological damage over time.
IV—Negligible Financial and facility costs or exposure cause a minor impact on the organization. Minor injury / illness (first aid). An incident that causes short-term minor ecological impacts that can be repaired quickly or through natural processes.

5.5 Cost-benefit (economic) analysis

The following section describes some of the elements that might be included when developing a business case tailored to a specific situation. It is important to recognize that the examples are for illustrative purposes only. Numeric financial values are strictly for the purpose of showing that values can be assigned, if so chosen. Actual circumstances can 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 can also either restrict or broaden opportunities for monitoring.

Table 23—Descriptions of probabilities: Example

Probability of an event occurring
1—Frequent (possibility of repeated incidents) Current conditions indicate repeated future occurrences are possible for the system. Average probability of occurrences about 30% per year, with 9 occurrences likely in 30 years. Lowest probability greater than 10% per year. 1 to 3 misoperations in 10 operations.
2—Occasional (possibility of isolated incidents) Current conditions indicate isolated future occurrences are possible for the system. Average probability of occurrence about 3% per year, with 1 occurrence likely in 30 years. Lowest probability 1–10% per year. 1 misoperation in 30 operations.
3—Infrequent (possibility of occurring sometime) Current conditions indicate occasional future occurrences are possible for the system. Average probability of occurrence about 0.3% per year, with 1 occurrence likely in 30 years out of 10 similar systems. Lowest probability 0.1–1% per year.
4—Improbable (not likely to occur) Current conditions indicate only isolated future occurrences are likely for the system. Average probability of occurrence about 0.03% per year, with 1 occurrence likely in 30 years out of 100 similar systems. Lowest probability 0.01–0.1% per year.

This section is intended to help the users and owners of switchgear equipment consider and justify the implementation of monitoring and diagnostics programs based on the analysis of costs and benefits. The costs referred to in the risk assessment process are defined in greater detail, and the benefit of monitoring is compared to the nonmonitored situation. Economic analysis should consider direct and indirect costs and benefits. Use of a spreadsheet can assist in understanding the sensitivity of the business case to assumptions made during the analysis.

Costs are incurred in the operation, inspection, maintenance, and restoration of failed substation power equipment. One of the goals of monitoring and diagnostics schemes is to reduce these costs by more thorough inspections, more appropriate maintenance tasks and maintenance intervals, and lower failure rates. Monitoring is justifiable if a net benefit results from its application. It is prudent to review over time the benefits intended to be achieved with the benefits actually achieved and the costs incurred. The cost of monitoring should be related to equipment cost and its importance.

The analysis of costs and benefits is to facilitate better business decisions around operation, maintenance, utilization, and retirement of equipment. No monitoring scheme should be implemented without a supporting, full cost-benefit analysis, which includes much more than direct costs.

The analysis should include the following:

a) All existing costs of inspection, operation, maintenance, testing, failure restoration, outage costs, and risks (utility and customer) caused by equipment inspections, maintenance, and failures before implementation of monitoring schemes
b) All reduced costs of displaced or reduced inspection, operation, maintenance, monitoring, testing, outage costs, and risks (utility and customer) caused by equipment inspections, maintenance, and failure caused by monitoring schemes
c) All increased costs of operation, maintenance, inspection, monitoring, testing, training, outages, and risks (utility and customer) caused by equipment inspections, maintenance, and failure caused by monitoring schemes; monitoring maintenance and false alarms; cost of monitoring installation; cost to analyze data and information; communication facilities; and increased training for those installing, servicing, maintaining, and using monitoring systems
d) All benefits from increased operability and greater utilization, more appropriate timing and degree of maintenance, knowledge of the condition of a population of equipment from monitoring an individual equipment condition, increased safety adjacent to equipment with condition concerns, decreased risk exposure, and improved environmental protection

5.5.1 Inspection

Monitoring can often be used to supplement and reduce manual inspections. The decreased monitoring costs, including travel labor and vehicle time and expenses; disassembly, manual inspection, and time and expenses to reassemble; visual inspection; and reporting time, are to be evaluated against the cost of the automated or manual monitoring techniques. There is obvious risk in relying only on manual periodic inspection to detect impending failures if the failure development characteristic is much longer than the inspection interval. Conversely, some monitoring can be best served by periodic testing. Inspection costs are to include downtime costs to perform the inspection.

5.5.2 Maintenance

On-line condition monitoring also influences the maintenance program for substation power equipment.

Monitoring can be used to optimize the extent, timing, and specific maintenance activities to be performed. Similar calculations can be made for the costs and benefits associated with minor and major maintenance for each type of equipment, with and without monitoring installed.

Various power utilities and industrial power equipment owners have different maintenance programs. These programs are based on a number of factors, including time intervals or dates, type of equipment (MV, HV, oil, vacuum, SF_6), condition of equipment, age, brand and model of equipment, reliability, and criticality of application. Although historically the maintenance and inspection programs were primarily time-based, the trend is toward more sophisticated maintenance schemes.

5.5.3 Consequences of failure

A method of evaluating the value of monitoring is to consider the consequences of failure when monitoring is installed and when it is not installed. (An alternative is to consider only the reduction in failure, maintenance, and inspection costs when monitoring is installed.)

A methodology to assess the consequences of failure is included from the CEA on-line condition monitoring report [CEA Project No. 485T1049 (1997)]. Several of these considerations can also be applied to maintenance-caused outages as well as to the costs of inspections.

Consider the consequences of failure in terms of the degree of acceptability for a particular failure mode.

The value of on-line condition monitoring can be significant if the consequences are major (risk to personnel, prolonged outage, disruption to large sensitive customers, etc.). The consequences may also be significant in symbolic and pragmatic capital terms or in social terms (connection to a hospital or to a remote rural community subject to low ambient temperatures). In contrast, the value of on-line condition monitoring can be minimal if the consequences are minor. The consequences of failure are an integral part of the cost-benefit analysis [CEA Project No. 485T1049 (1997)].

To evaluate the benefit of on-line condition monitoring applied to prevent or reduce failures, the following information should be known for circumstances without monitoring and estimated for the following situations in which monitoring is being considered [CEA Project No. 485T1049 (1997)]:

a) Major (excluding explosive failures) failure rate (*MFR*) in [#failures/component/year]
b) Minor failure rate (*mfr*) in [#failures/component/year]
c) Explosive failure rate (*EFR*) [#failures/component/year]
d) Cost of repair for major, minor, and explosive failures (*CR, cr, ECR*) in [$/failure]
e) Cost of outages for major, minor, and explosive failures (*CO, co, ECO*) [$/hour]
f) Repair times for major, minor, and explosive failures (*RF, rf, RE*) in [hour/failure]

The above rates are average annual values. The costs can change from year to year because of changing failure trends, cost escalation, and so on. The cost of failure (*CF*) in dollars per component per year can be evaluated as

$$CF\left[\frac{\$}{\text{component/year}}\right] = MFR \times CR + mfr \times cr + EFR \times ECR$$
$$\times MFR \times CO \times RF + mfr \times co \times rf + EFR \times ECO \times RE$$

The total cost of failures (*TCF*) can be calculated for a type of component (type of breaker) as

$$TCF\left[\frac{\$}{\text{year}}\right] = CF \times (\text{\# of components of a given type})$$

It should be noted that *CF* can vary from year-to-year because of factors such as cost escalation and failure predictions. The above formula should be recalculated for all component (breaker) types to obtain the costs of failures of equipment.

An example inspection and maintenance program with resulting failure rates is shown in Table 24.

In addition to Table 24, the following factors should be considered when performing a cost-benefit analysis [CEA Project No. 485T1049 (1997)]:

— Replacement cost of equipment (include purchase and installation costs)
— Damage to adjacent equipment (utility and customer) facilities, including the costs to replace and rehabilitate neighboring facilities
— Insurance premiums based on facility performance history

Table 24—Example inspection and maintenance program with resulting failure rates

Inspection costs	Maintenance costs (minor and major)	Failure resolution costs
Example	**Example**	**Example**
Monthly visual inspection of circuit breaker, record operations counter, compressed air pressure Diagnostic inspection—periodic contact resistance check, dielectric test, contact motion test every third inspection	Minor maintenance—every 3 years, external, including contact resistance, oil check, and lubrication Major maintenance—every 6 years, internal, contact maintenance, oil, interrupter, etc.	Major (excluding explosive failures) failure rate (*MFR*) in number of failures/component/year = 0.0089 Minor failure rate (*mfr*) in number of failures/component/year = 0.0782 Explosive failure rate (*EFR*) in number of failures/component/year = 0.0019 Cost of repair for major, minor, and explosive failures (*CR*, *cr*, *ECR*) in $/failure = $50K, $5K, $450K Cost of outages for major, minor, and explosive failures (*CO*, *co*, *ECO*) in $/hour = $1.5K, $0.1K, $5.7K/MWh Repair times for major, minor, and explosive failures (*RF*, *rf*, *RE*) in hour/failure = 24, 6, 144 h

— Replacement cost of appropriate equipment
— Costs of replacing equipment, including all labor and possible overtime rates, materials, supplies, vehicles, specialized machinery, contractor services
— Technical, engineering, and management support
— Outage costs incurred by the power system, including loss of energy sales opportunities, increased system losses during outage, reduced system reliability during outage
— Outage costs incurred by affected customers, including loss of production, damage to plant facilities, start-up costs and damage to facilities, production of less than commercial quality product during start-up, penalties for delivery disruption, loss of sales, missed opportunities, increased marketing costs
— Loss of revenue (utility and customer)
— Loss of reputation (utility and customer)
— Injury (utility and customer)
— Loss of life of equipment or plant (utility and customer)
— Problem cascading to major blackout
— Nonoptimal utilization of equipment remaining life

- Direct or indirect failure caused by intrusive inspection or maintenance without on-line condition monitoring
- Undiscovered equipment “common-type” problems that may spread within a specific equipment population
- Failure to meet electric supply contracts and potential liabilities
- Failure modes with environmental impact (utility and customer)
- Relative waste of resources using less-effective maintenance processes
- Interest and overhead charges on many of the above
- Costs of maintaining the monitoring systems
- Costs of responding to false alarms
- Cost of damage from undetected events that might have been detected with existing inspections and maintenance
- Increased costs for scheduling maintenance (maintenance driven by monitor output alone cannot be levelized)
- Cost of reading, storing, and analyzing data from monitors
- All reduced benefits caused by not realizing the calculated savings from a circuit breaker monitor-driven maintenance program; a user may have difficulty levelizing his maintenance workforce with a true circuit breaker monitor-driven maintenance program; all of the calculated savings may not be attainable

Table 25 lists some costs involved in inspection, maintenance, and failure work associated with substation power equipment. Although not complete for every situation, it can provide guidance in determining a significant portion of the costs. Identifying the full cost of maintenance is vital to identifying how much money is available for on-line condition monitoring. Often, a reduction of these full maintenance costs is required to justify implementation of monitoring schemes. Some power equipment owners might have only a partial appreciation of the full cost of maintenance and underestimate their full maintenance costs, perhaps including portions of the maintenance costs with general operational costs. Some of those “operations costs” would not be incurred if it were not for maintenance purposes. Similarly, the full costs of failure and of inspections is essential to providing the complete view of costs and benefits associated with monitoring.

On-line condition monitoring (or even off-line or periodic monitoring) can modify the above costs. Several possible benefits of such monitoring and diagnostic schemes are listed as follows:

- Improved electric service delivery reliability performance
- Knowledge and ability to remove equipment from service in a planned manner (albeit possibly with little planning time), rather than having it fail unexpectedly
- Knowledge and ability to make replacement decisions based on balancing outage time and duration, coordination with customers and other parts of the power system, and delivery of suitable replacement components or equipment.
- Knowledge and ability to increase the effective service (loading) of equipment in a short- and a long-term planned manner
- Positive effect on insurance premiums
- More appropriate timing and selection of maintenance

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Table 25—Inspection, minor and major maintenance, and failure resolution cost considerations

Inspection costs	Maintenance costs (minor and major)	Failure resolution costs
Example	**Example**	**Example**
Actual inspection labor	Actual maintenance labor	Actual failure analysis labor
Travel time and costs	Travel time and costs	Travel time and costs
Contractor services	Contractor services	Contractor services
Training time and costs	Training time and costs	Training time and costs
Reporting and inputting data	Reporting and inputting data	Reporting and inputting data
Analyzing results	Analyzing results	Analyzing results
Clerical support personnel	Clerical support personnel	Clerical support personnel
Technical and management support of inspection activity; corporate resource overheads and loading associated with the inspection function	Technical and management support of maintenance activity; corporate resource overheads, and loading associated with the maintenance function	Technical and management support of restoration activity, corporate resource overheads, and loading associated with the restoration function
Vehicles, materials, supplies, machinery, and instrumentation	Vehicles, materials, and supplies, machinery, and instrumentation	Vehicles, materials, and supplies, machinery, and instrumentation
	Spare parts	Spare parts and equipment
	Spare parts management, procurement, warehousing, delivery, interest	Spare parts and equipment management, procurement, warehousing, delivery, interest
	Consumable material and supplies	Consumable material and supplies
	Preparation of power system switching schedules and orders; issuing of safe work permits	Preparation of power system switching schedules and orders; issuing of safe work permits
	Power system switching effort, installation, and removal of workers' protective grounding	Power system switching effort, installation, and removal of workers' protective grounding
	Power system outage costs, e.g., increased losses, loss of revenue	Power system outage costs, e.g., increased losses, loss of revenue
Vehicles, materials, supplies, machinery, and instrumentation	Possible damage to facilities required by maintenance access	Damaged equipment, damage to adjacent facilities, and equipment and facilities rebuild
		Apportioned cost of "system spares," purchase of replacement equipment or components
		Outage costs (loss of revenue, customer cost of energy supply interruption, overtime, etc.)
		Diagnostics and failure investigation
		"In" and "out" costs of failed equipment and replacement equipment, transportation
Other costs?	Other costs?	Other costs?

Having completed this calculation, the present worth of the cost of failure over the expected life of the equipment can be derived. However, even if the failure is avoided by using monitoring equipment, some inspection and corrective maintenance is still required. The above calculation should then be repeated using the expected lower costs of inspection, repair, and repair times with monitoring, again deriving the present worth. The difference between the two present worth values is the avoided cost that can be achieved by the implementation of on-line condition monitoring. Monitoring can be justified if its present worth cost is less than the avoided cost (CEA Project No. 485T1049 (1997) and Bergman et al. [B1]).

Two examples of value analysis of monitoring costs and benefits are illustrated in Table A.1 and Table A.2. Be aware that these are only examples used to illustrate some cost/benefit analysis and comparisons. An electronic spreadsheet could be developed to include the many considerations for a specific or particular application.

Annex A

(informative)

Examples of circuit breaker monitoring analysis

NOTE—The following comparisons are examples only. The numbers and values are not from any valid source, but they are used to show how a cost-benefit analysis comparison can be made to choose or reject installation of monitoring. The business cases are examples only. Fictitious numbers have been used to show a process and how a business model can be used. All costs are on an annualized basis. The present value of these costs has not been calculated. Use of a spreadsheet eases calculation and permits sensitivity analysis.

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

It is important for the user to keep records to establish costs and performance representative of the specific application being analyzed. The analysis should be performed by type of circuit breaker and type of failure mode(s). It should consider the sources of most appropriate sources of data and information.

The user should consider the specific application of the circuit breaker. Two identical circuit breakers in substantially different duties may behave differently, which in turn would lead to different values assigned to monitoring.

Circuit breakers used for capacitor switching, arc furnace duty, or frequent switching of large motors may have a shorter life expectancy and a greater value for on-line condition monitoring.

Failure rate costs should be calculated for the major and minor failure rates. Maintenance costs should be calculated for the minor and major maintenance activities.

Monetary values show dollars and cents because some values are sufficiently small that they would not show if dollars only were shown. The cumulative effect of many small items is shown. The assumptions underlying the calculations may not support this accuracy.

The examples presented here were developed using a spreadsheet to calculate financial values using inputs shown in the input values column. As a result, many financial values are small amounts; however, the sum totals are relevant to the evaluation. The intent of the example is to illustrate the many components that go toward making the total comparison of capital, operation, and maintenance costs.

A.1 Example cost comparison with and without circuit breaker monitoring

Monitoring would not be economical on the basis of Table A.1. .

Table A.1—Example 1: Cost comparison with and without circuit breaker monitoring

Annual direct costs					
Annual inspection costs	**Input values**	**Annualized hours**	**Costs without monitoring**	**Annualized hours**	**Costs with monitoring**
Inspection hours/breaker without monitoring (per breaker hours, although four breakers in one station)	0.25	3.00	$111.00		
Number of annual inspections without monitoring	2.00				
Inspection hours/breaker with monitoring (per breaker hours, although four breakers in one station)	0.25			1.00	$37.00
Number of annual inspections with monitoring	4.00				
Travel time and costs (hours each way shared by four breakers)	1.00	6.00	$111.00	2.00	$37.00
Contractor services (hours)		0.00	$0.00	0.00	$0.00
Reporting and inputting data (clerical)		0.15	$4.16	0.00	$0.00
Analyzing results (maintenance staff)		0.10	$3.70	0.05	$1.85
Clerical support personnel		0.20	$5.55	0.05	$1.39
Vehicles, materials and supplies, machinery, and instrumentation (inspection and travel time @ light truck hourly rate)			$90.00		$20.00
Other costs?			$0.00		$0.00
Subtotal annualized inspection costs		**9.45**	**$325.41**	**3.10**	**$97.24**
Annual maintenance costs (major and minor)					
Annual inspection costs	**Input values**	**Annualized hours**	**Costs without monitoring**	**Annualized hours**	**Costs with monitoring**
Maintenance hours/breaker without monitoring (per breaker hours, although four breakers in one station)	8.00	2.00	$74.00		
Number of years between maintenance without monitoring	4.00				
Maintenance hours/breaker with monitoring (per breaker hours, although four breakers in one station)	8.00			1.00	$37.00
Number of years between maintenance with monitoring	8.00				
Travel time and costs (hours each way shared by four breakers)	1.00	0.50	$18.50	0.25	$9.25
Contractor services		0.00	$0.00	0.00	$0.00
Reporting and inputting data (clerical)		0.15	$4.16	0.00	$0.00

Table A.1—Example 1: Cost comparison with and without circuit breaker monitoring *(continued)*

Annual maintenance costs (major and minor) (*continued)*					
Annual inspection costs	**Input values**	**Annualized hours**	**Costs without monitoring**	**Annualized hours**	**Costs with monitoring**
Analyzing results (maintenance staff)		0.10	$5.55	0.05	$2.78
Clerical support personnel		0.20	$5.55	0.05	$1.39
Vehicles, materials and supplies, machinery, and instrumentation			$25.00		$12.50
Spare parts/maintenance @ $	$200.00		$50.00		$25.00
Spare parts management, procurement, warehousing, delivery, interest (@ xx% of parts/year)	10.00%		$5.00		$2.50
Consumable material and supplies @ $xx/maintenance	$100.00		$25.00		$12.50
Preparation of power system switching schedules and orders, issuing of safe work permit hours /maintenance @ xx hours/maintenance (maintenance rate)	0.50	0.13	$4.63	0.06	$2.31
Power system switching effort, installation and removal of workers protective grounding @ xx hours/ maintenance (maintenance rate)	1.00	0.25	$9.25	0.13	$4.63
Power system outage costs, e.g., increased losses, loss of revenue			$0.00		$0.00
Possible damage to facilities required by maintenance access			$0.00		$0.00
Other costs?			$0.00		$0.00
Subtotal annualized maintenance costs		**3.33**	**$226.64**	**1.54**	**$109.85**
Annual failure resolution costs					
Annual inspection costs	**Input values**	**Annualized hours**	**Costs without monitoring**	**Annualized hours**	**Costs with monitoring**
Failure rate (from user's source)	0.00100	0.0010			
Failure rate decrease with monitoring @ xx% previous rate	25.00%			0.0003	
Actual failure analysis labor (xx hours/failure maintenance hourly rate)	40.00	0.0400	$1.48	0.0100	$0.37
Travel time and costs @ 5 round trips of 0.25 hour each way		0.0000	$0.00	0.0006	$0.02
Analyzing results @ 10 hours/failure (engineer rate)		0.0100	$0.06	0.0000	$0.01
Clerical support personnel @ 4 hours/failure		0.0040	$0.03	0.0010	$0.01
Technical and management support of restoration activity, corporate resource overheads, and loading associated with the restoration function @ 100 hours/ failure		0.1000	$5.55	0.0250	$1.39

Table A.1—Example 1: Cost comparison with and without circuit breaker monitoring *(continued)*

Annual failure resolution costs (*continued*)					
Annual inspection costs	**Input values**	**Annualized hours**	**Costs without monitoring**	**Annualized hours**	**Costs with monitoring**
Vehicles, materials and supplies, machinery, and instrumentation			$0.10		$0.00
Spare parts and spare equipment @ $5 000.00			$5.00		$0.00
Spare parts management, procurement, warehousing, delivery, interest (@ 10% of parts)			$0.50		$0.00
Consumable material and supplies @ $10.00/maintenance			$2.00		$2.00
Power system switching effort, installation and removal of workers protective grounding @ xx hours/failure	1.00	0.00	$0.04	0.0003	$0.01
Power system outage costs, e.g., increased losses (@ $xxx.xx/occurrence)	$100.00		$0.10		$0.03
Damaged equipment, damage to adjacent facilities, and equipment and facilities rebuild @ $x xxx/failure	$500.00		$0.50		$1.25
Apportioned cost of "system spares," purchase of replacement equipment or components example 1 spare breaker of $100 000/25 breakers = $4 000.00/breaker	$5000.00		$5.00		$1.25
Diagnostics and failure investigation (@ xx hours/ investigation) (engineering hourly rate)	40	0.04	$2.22	0.01	$0.56
"In" and "out" costs of failed equipment and replacement equipment, transportation @ $ x xxx.xx/ occasion	$5000.00		$5.00		$1.25
Other costs?			$0.00		$0.00
Subtotal annualized failure resolution costs		**0.20**	**$27.57**	**0.05**	**$7.02**
Subtotal annualized direct inspection, maintenance, and failure resolution costs		**12.97**	**579.62**	**4.68**	**214.10**
Annual monitoring installation and operation					
Annual inspection costs	**Input values**	**Annualized hours**	**Costs without monitoring**	**Annualized hours**	**Costs with monitoring**
Monitoring capital cost (@ $xxx.xx)	$10000.00				$500.00
Expected life of monitoring (years)	20				
Installation labor (maintenance hourly rate)	16			0.80	$29.60
Installation labor (engineer hourly rate)	10			0.50	$27.75
Annual monitoring support xx hours/year (maintenance hourly rate)	2			2.00	$74.00
Annual monitoring support xx hours/year (engineering hourly rate)	4			4.00	$222.00

Table A.1—Example 1: Cost comparison with and without circuit breaker monitoring *(continued)*

Annual monitoring installation and operation (*continued*)					
Annual inspection costs	**Input values**	**Annualized hours**	**Costs without monitoring**	**Annualized hours**	**Costs with monitoring**
Annual monitoring support xx hours/year (clerical hourly rate)	2	0.00		2.00	$55.50
Subtotal annualized monitoring costs		**13.31**	**$633.20**	**14.07**	**$1136.57**
Annual subtotal direct inspection, maintenance, and failure resolution with and without monitoring		**26.28**	**$1212.82**	**1.75**	**$1350.67**
Annual power systems cost					
Annual inspection costs	**Input values**	**Annualized hours**	**Costs without monitoring**	**Annualized hours**	**Costs with monitoring**
Cost/MWh	$20.00		$0.50		$0.13
Power delivery interruption (MW)	5				
Interruption duration (hours)	4				
Power system outage cost to customer = xx times utility loss of revenue	25		$12.50		$3.13
Subtotal power system costs			**$13.00**		**$3.25**
Annual subtotal with direct inspection, maintenance, and failure resolution costs with and without monitoring, including power system costs			**$1225.82**		**$1353.92**
Annual benefit (per breaker) with monitoring					**–$128.11**
			$ PER BREAKER		
Annual indirect costs (benefits, supervision, vacation, sick time + location expense and overhead)	**Rate**	**“Loaded” rate**			
Maintenance staff labor hourly rate	$20.00	$37.00			
Support staff labor hourly rate	$15.00	$27.75			
Engineering staff labor hourly rate	$30.00	$55.50			
Indirect costs (benefits, supervision, vacation, sick time + location expense) overhead multiplier	1.85				
Light truck hourly rate	$10.00	$10.00			
Maintenance truck hourly rate with tools/hour	$50.00	$50.00			
Contractor rate	$0.00	$0.00			

Notes to Table A.1:

1—Repeat analysis for each failure mode and failure cause.

2—Include costs of all maintenance tasks.

3—Include all risk (or criticality) costs associated with failures. Utility damage and repair costs, loss of revenue, and restoration of service costs are to be included. Customers' costs of "unsupplied energy" include business or process disruption, loss of product, facility damage, additional labor costs, waste or costs to return to commercial quality production, and penalties. Monitoring should be able to reduce the probability of an equipment condition progressing to the failure state by allowing prior removal from service. Consequences of the failure may also be reduced with the early warning of an impending failure. Reduction in probability or in consequence has the effect of reducing the cost of the failure risk, and is attributed as a benefit of condition monitoring.

4—Monitoring costs include the costs of selecting appropriate monitoring, engineering, purchase and installation, training, operational costs associated with data retrieval and analysis, maintenance, and troubleshooting of monitoring schemes.

5—Maintenance costs are reduced by condition monitoring triggering only appropriate maintenance tasks at the appropriate interval, thus, eliminating unnecessary maintenance and associated activities.

6—Include all costs associated with inspections (see Table 25).

7—Include all costs associated with failure resolution (see Table 25).

A.2 Example cost comparison with and without circuit breaker monitoring

Monitoring would be economical on the basis of Table A.2.

Table A.2—Example 2: Cost comparison with and without circuit breaker monitoring

Annual direct costs					
Annual inspection costs	**Input values**	**Annualized hours**	**Costs without monitoring**	**Annualized hours**	**Costs with monitoring**
Inspection hours/breaker without monitoring (per breaker hours, although four breakers in one station)	0.50	6.00	$277.50		
Number of annual inspections without monitoring	12.00				
Inspection hours/breaker with monitoring (per breaker hours, although four breakers in one station)	0.50			2.00	$92.50
Number of annual inspections with monitoring	4.00				
Travel time and costs (hours each way shared by four breakers)	1.00	6.00	$138.75	2.00	$46.25
Contractor services (hours)		0.00	$0.00	0.00	$0.00
Reporting and inputting data (clerical)		0.15	$4.72	0.00	$0.00
Analyzing results (maintenance staff)		0.10	$4.63	0.05	$2.31
Clerical support personnel		0.20	$6.29	0.05	$1.57

Table A.2—Example 2: Cost comparison with and without circuit breaker monitoring *(continued)*

Annual direct costs (*continued*)					
Annual inspection costs	**Input values**	**Annualized hours**	**Costs without monitoring**	**Annualized hours**	**Costs with monitoring**
Vehicles, materials and supplies, machinery, and instrumentation (inspection and travel time @ light truck hourly rate)			$120.00		$20.00
Other costs?			$0.00		$0.00
Subtotal annualized inspection costs		**12.45**	**$551.88**	**4.10**	**$162.64**
Annual maintenance costs (major and minor)					
Annual inspection costs	**Input values**	**Annualized hours**	**Costs without monitoring**	**Annualized hours**	**Costs with monitoring**
Maintenance hours/breaker without monitoring (per breaker hours, although four breakers in one station)	12.00	3.00	$138.75		
Number of years between maintenance without monitoring	4.00				
Maintenance hours/breaker with monitoring (per breaker hours, although four breakers in one station)	12.00			1.50	$69.38
Number of years between maintenance with monitoring	8.00				
Travel time and costs (hours each way shared by four breakers)	1.00	0.50	$23.13	0.25	$11.56
Contractor services		0.00	$0.00	0.00	$0.00
Reporting and inputting data (clerical)		0.15	$4.72	0.00	$0.00
Analyzing results (maintenance staff)		0.10	$6.48	0.05	$3.24
Clerical support personnel		0.20	$6.29	0.05	$1.57
Vehicles, materials and supplies, machinery, and instrumentation			$35.00		$17.50
Spare parts/maintenance @ $xx	$200.00		$50.00		$25.00
Spare parts management, procurement, warehousing, delivery, interest (@ xx% of parts/year)	10.00%		$5.00		$2.50
Consumable material and supplies @ $xx/maintenance	$100.00		$25.00		$12.50

Table A.2—Example 2: Cost comparison with and without circuit breaker monitoring *(continued)*

Annual maintenance costs (major and minor) (*continued*)					
Annual inspection costs	**Input values**	**Annualized hours**	**Costs without monitoring**	**Annualized hours**	**Costs with monitoring**
Preparation of power system switching schedules and orders, issuing of safe work permits hours / maintenance @ xx hours/maintenance (maintenance rate)	0.50	0.13	$5.78	0.06	$2.89
Power system switching effort, installation and removal of workers protective grounding @ xx hours/ maintenance (maintenance rate)	1.00	0.25	$11.56	0.13	$5.78
Power system outage costs, e.g., increased losses, loss of revenue			$0.00		$0.00
Possible damage to facilities required by maintenance access			$0.00		$0.00
Other costs?			$0.00		$0.00
Subtotal annualized maintenance costs		**4.33**	**$311.70**	**2.04**	**$151.92**
Annual failure resolution costs					
Annual inspection costs	**Input values**	**Annualized hours**	**Costs without monitoring**	**Annualized hours**	**Costs with monitoring**
Failure rate (from user's source)	0.00160	0.0016			
Failure rate decrease with monitoring @ xx% previous rate	25.00%			0.0004	
Actual failure analysis labor (xx hours/failure maintenance hourly rate)	50.00	0.0800	$3.70	0.0200	$0.93
Travel time and costs @ 5 round trips of 0.25 hour each way		0.0000	$0.00	0.0010	$0.05
Analyzing results @ 10 hours/failure (engineer rate)		0.0160	$0.10	0.0000	$0.03
Clerical support personnel @ 4 hours/failure		0.0064	$0.05	0.0016	$0.01
Technical and management support of restoration activity, corporate resource overheads, and loading associated with the restoration function @ 100 hours/ failure		0.1600	$10.36	0.0400	$2.59
Vehicles, materials and supplies, machinery, and instrumentation			$0.16		$0.00
Spare parts and spare equipment @ $5 000.00			$8.00		$0.00
Spare parts management, procurement, warehousing, delivery, interest (@ 10% of parts)			$0.80		$0.00

Table A.2—Example 2: Cost comparison with and without circuit breaker monitoring *(continued)*

Annual failure resolution costs (*continued*)					
Annual inspection costs	**Input values**	**Annualized hours**	**Costs without monitoring**	**Annualized hours**	**Costs with monitoring**
Consumable material and supplies @ $10.00/maintenance			$2.00		$2.00
Power system switching effort, installation and removal of workers protective grounding @ xx hours/ failure	1.00	0.00	$0.07	0.0004	$0.02
Power system outage costs, e.g., increased losses (@ $xxx.xx/occurrence)	$500.00		$0.80		$0.20
Damaged equipment, damage to adjacent facilities, equipment and facilities rebuild @ $x xxx/failure	$500.00		$0.80		$0.20
Apportioned cost of “system spares,” purchase of replacement equipment or components example 1 spare breaker of $100 000/25 breakers = $4 000.00/ breaker	$6000.00		$9.60		$2.40
Diagnostics and failure investigation (@ xx hours/ investigation) (engineering hourly rate)	80.00	0.13	$8.29	0.03	$2.07
“In” and “out” costs of failed equipment and replacement equipment, transportation @ $x xxx.xx/ occasion	$5000.00		$8.00		$2.00
Other costs?			$0.00		$0.00
Subtotal annualized failure resolution costs		**0.39**	**$52.74**	**0.10**	**$12.49**
Subtotal annualized direct inspection, maintenance, and failure resolution costs		**17.17**	**916.32**	**6.23**	**327.04**
Annual monitoring installation and operation					
Annual inspection costs	**Input values**	**Annualized hours**	**Costs without monitoring**	**Annualized hours**	**Costs with monitoring**
Monitoring capital cost (@ $xxx.xx)	$10000.00				$500.00
Expected life of monitoring (years)	20				
Installation labor (maintenance hourly rate)	16			0.80	$37.00
Installation labor (engineer hourly rate)	10			0.50	$32.38
Annual monitoring support xx hours/year (maintenance hourly rate)	2			2.00	$92.50

Table A.2—Example 2: Cost comparison with and without circuit breaker monitoring *(continued)*

Annual monitoring installation and operation (*continued*)					
Annual inspection costs	**Input values**	**Annualized hours**	**Costs without monitoring**	**Annualized hours**	**Costs with monitoring**
Annual monitoring support xx hours/year (engineering hourly rate)	4			4.00	$259.00
Annual monitoring support xx hours/year (clerical hourly rate)	2	0.00		2.00	$62.90
Subtotal annualized monitoring costs		**17.85**	**$1017.94**	**15.70**	**$1334.79**
Subtotal annualized direct inspection, maintenance, and failure resolution with and without monitoring		**35.02**	**$1934.26**	**21.93**	**$1661.83**
Annual power systems cost					
Annual inspection costs	**Input values**	**Annualized hours**	**Costs without monitoring**	**Annualized hours**	**Costs with monitoring**
Cost/MWh	$20.00		$1.60		$0.40
Power delivery interruption (MW)	10				
Interruption duration (hours)	4				
Power system outage cost to customer = xx times utility loss of revenue	25		$40.00		$10.00
Subtotal power system costs			**$41.60**		**$10.40**
Annual subtotal with direct inspection, maintenance, and failure resolution costs with and without monitoring, including power system costs			**$1975.86**		**$1672.33**
Annual benefit (per breaker) with monitoring					**$303.62**
			$ PER BREAKER		
Annual indirect costs (benefits, supervision, vacation, sick time + location expense and overhead)	**Rate**	**“Loaded” rate**			
Maintenance staff labor hourly rate	$25.00	$46.25			
Support staff labor hourly rate	$17.00	$31.45			
Engineering staff labor hourly rate	$35.00	$64.75			

Table A.2—Example 2: Cost comparison with and without circuit breaker monitoring *(continued)*

Annual indirect costs (benefits, supervision, vacation, sick time + location expense and overhead) (*continued*)	**Rate (*continued*)**	**“Loaded” rate (*continued*)**
Indirect costs (benefits, supervision, vacation, sick time + location expense) overhead multiplier	1.85	
Light truck hourly rate	$10.00	$10.00
Maintenance truck hourly rate with tools/hour	$50.00	$50.00
Contractor rate	$0.00	$0.00

Notes to Table A.2:

1—Repeat analysis for each failure mode and failure cause.

2—Include costs of all maintenance tasks.

3—Include all risk (or criticality) costs associated with failures. Utility damage and repair costs, loss of revenue, and restoration of service costs are to be included. Customers’ costs of “unsupplied energy” include business or process disruption, loss of product, facility damage, additional labor costs, waste or costs to return to commercial quality production, penalties, and so on. Monitoring should be able to reduce the probability of an equipment condition progressing to the failure state by allowing prior removal from service. Consequences of the failure may also be reduced with the early warning of an impending failure. Reduction in probability or in consequence has the effect of reducing the cost of the failure risk and is attributed as a benefit of condition monitoring.

4—Monitoring costs include the costs of selecting appropriate monitoring, engineering, purchase and installation, training, operational costs associated with data retrieval and analysis, maintenance, and troubleshooting of monitoring schemes.

5—Maintenance costs are reduced by condition monitoring triggering only appropriate maintenance tasks at the appropriate interval, thus, eliminating unnecessary maintenance and associated activities.

6—Include all costs associated with inspections (see Table 25).

7—Include all costs associated with failure resolution (see Table 25).

Annex B

(informative)

Examples of maintenance programs with and without monitoring

The following examples illustrate different maintenance programs for a bulk oil circuit breaker. They are provided as an example to indicate the possibilities for maintenance modifications available with monitoring. The inspection and maintenance tasks and intervals are illustrative only and are not intended to represent recommendations.

B.1 Example maintenance programs with and without monitoring

No monitoring

— Routine maintenance (external inspection of breakers)—every 2 weeks to 1 month
— Internal maintenance—every 2 to 10 years, regardless of the condition, age, brand, and so on

With monitoring

— Inspection (visual)—every 3 months
— Internal maintenance—condition based, expected to vary from every 1 to 17 years

B.2 Example maintenance programs with and without monitoring

No monitoring

— Diagnostic inspection—every 5 to 7 years, contact resistance check, dielectric test, contact motion test every third inspection
— Internal maintenance—no particular time interval only based on condition, scheduled when necessary

With monitoring

— Internal maintenance—condition based, expected to vary from every 3 to 12 years

B.3 Example maintenance programs with and without monitoring

No monitoring

— Inspection—every month, visual, operate the breaker if it did not operate in the last 3 months
— Minor maintenance—every 3 years, external, including contact resistance, oil check, lubrication
— Major maintenance—every 4 to 8 years, internal, contact maintenance, oil, interrupter, etc.

With monitoring

— Inspection (visual)—every 3 months
— Major maintenance—condition based, expected to be every 7 to 12 years

Annex C

(informative)

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