Equipment Monitoring Selection as a part of Substation Automation

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INTRODUCTION

Monitoring has generally been applied to specific and individual pieces of substation equipment rather than as complete substation monitoring systems. This document and the references attempt to show a greater benefit from using a value based, risk management logic to select monitoring appropriate for the specific circumstances and based on sound engineering and economic judgment.

Principles described can be used for the selection of monitoring for components or equipment on power systems as well as in numerous other situations.

This paper builds on research and concepts developed in a Canadian Electricity Association (CEA) sponsored report. CEA Project No. 485T1049 “On-line condition monitoring of substation power equipment - utility needs”, published in January 1997 was produced by BC Hydro (D. F. Peelo project leader, D.G. Short, D.R. Eden); Ontario Hydro (J. Meehan, C. Yung); TransAlta Utilities (W. Bergman). [1]. The report defines many of the utility monitoring needs as guidance for utilities, manufacturers of original equipment and third party vendor schemes.

A subsequent presentation based on the CEA research (W. Bergman), “A value based methodology for selecting on-line condition monitoring of substation power equipment.” at the EPRI, Substation Equipment Diagnostics Conference V, New Orleans, LA, February 17 - 19, 1997 showed a methodology to be used with the CEA report to make value based monitoring decisions. [2].

This contribution shows how the link between failure causes and required monitoring can be developed. It shows how the risks associated with equipment functional failure can be quantified and how monitoring can be shown to be of economic value if applied appropriately.

PURPOSES OF MONITORING

Monitoring can be used for many purposes. The most obvious is to determine the condition of the equipment. Recognize that monitoring can take many forms including manual inspections (periodic visual inspections), continuous monitoring with a change in status/condition alarm as the only output (low level alarm), periodic automated monitoring (connection of portable analysis instruments (dial-up computer analysis) or continuous on-line monitoring (full time measurement of parameters to assess condition while in service).

Monitoring should be applied when a cost/benefit value results from it’s use over alternatives without monitoring.

Monitoring can provide benefits in at least the following areas, each of which should be considered in the evaluation. Inclusion of all existing visible or intangible costs and all expected benefits allows for a more accurate assessment of the value of monitoring.

Application Issue	Application Benefits & Advantages
operational status	• determine operational ability of equipment • determine operational status of equipment
failure prevention	• evaluate condition of equipment, detect abnormal conditions and initiate action to prevent impending failure
maintenance support	• evaluate condition of equipment and initiate maintenance only when degraded condition requires maintenance • assist with maintenance planning • judge condition of a larger population of similar/identical equipment
life assessment	• evaluate condition of equipment to determine anticipated remaining life • detect abnormal conditions
optimize operation	• evaluate functional condition of equipment while extending or maximizing duties imposed on equipment (generally at conditions other than nameplate loading) • control the effects of loading regardless of equipment condition • optimize operation of equipment on system (ex. circuit breaker controlled switching)
commissioning verification tests	• confirm correct installation conditions and adjustments • evaluate condition of equipment and improve effectiveness and efficiency of verification/acceptance testing • automate collection and preservation of baseline condition data and characteristics
failure analysis	• provide information on prior condition of equipment after a failure has occurred
personnel safety	• prevent unsafe conditions to personnel
environment safety	• prevent unsafe conditions to environment

Table 1

BASIS OF SELECTING MONITORING

The proposed basis for selecting monitoring for any specific equipment component or combination(s) of components or systems requires an understanding of:

- failure mechanisms, their characteristics and appropriate monitoring devices to observe the deteriorating condition
- failure effects
- failure criticality
- the principles of risk assessment
- appropriate economic support for the application of monitoring

A value based decision regarding the appropriate application of monitoring will be achieved by including these items.

Failure Modes and Effects Analysis (FMEA)

Failure Modes and Effects Analysis (FMEA) is a technique aimed at examining how failures are displayed, their causes and the effects of failures on a component or system. A FMEA, performed at the design stage or after equipment is in service, can support implementation of monitoring. The chosen monitoring should warn against identified impending failure causes and indicate equipment condition.

Similarly, a failure modes and effects analysis including criticality, sometimes referred to as a FME(C)A, can identify failure modes and their causes, as well as their effects and criticality specific to the failed equipment or to the power system functions. Monitoring is then selected on the basis of its ability to identify equipment condition and warn of impending failures or deficiencies with sufficient time to take appropriate operating or maintenance action.

A simple example is shown for a failure mode with several failure causes

Failure Mode	Failure Cause	Inspection or Maintenance Task	Monitoring schemes
- fails to provide required interrupter insulating gas properties	- loss of SF6 gas density	- measure gas pressure and temperature monthly - replace gasket and seals every five years	- continuously measure gas temperature and pressure, convert to gas density; advise at limits - measure gas density directly
	- extreme low ambient temperature	- maintain thermal insulation and heater circuits	- monitor interrupter & ambient temperature, heater current

Fig. 1 – Example of Failure Mode, Failure Cause, Task and Monitoring

Risk Assessment

Risk can be defined as the product of the probability of an event occurring and the consequences if that event should occur. Risk can be quantified using a matrix of these products. Using a ranking system such as shown in fig 6, risk can be ranked from highest to lowest. In this case numbers 1 to 4 are high priority, numbers 5 through 9 are medium priority and numbers 10 through 20 are low priority. In this manner, any issue such as utility financial impact, customer impact, safety, environment, legal or other issues can be ranked in the criticality assessment. Evaluations sometimes refer to risk as criticality.

Risk Matrix

(Risk ≡ probability of an event occurring × consequences if that event should occur)

Consequence	**Probability**				
ranking	**1 Frequent**	**2 Probable**	**3 Occasional**	**4 Remote**	**5 Improbable**
1 Catastrophic	**A**	**A**	**A**	**B**	**B**
2 Critical	**A**	**A**	**B**	**B**	**C**
3 Moderate	**A**	**B**	**B**	**C**	**C**
4 Negligible	**A**	**B**	**C**	**C**	**C**

Fig. 2 – Risk Matrix

Level of Risk	**Description of Risk**
A	High risk
B	Moderate risk
C	Low risk

Fig. 3 – Levels of Risk

Assistance in quantifying descriptions of probability levels, consequential impact and resulting risk levels are provided in reference [3]. These numeric or text descriptors must be tailored to the specific user's circumstances.

Reliability Centered Maintenance

Reliability Centered Maintenance (RCM) employs FMEA and risk assessment techniques and as such it's use is directly applicable. RCM is directed at selecting maintenance tasks that are directly related to failure causes that have a high criticality. The same methods can be directed to selecting monitoring which is directly related to advising condition or impending failure information.

Reliability Centered Maintenance is a technique aimed at identifying the most appropriate inspection and maintenance tasks in order to preserve functional reliability. It can be a logic aimed at components or at defined systems. The steps of RCM implementation should included:

- define RCM system boundary and interface(s)
- define functional and reliability requirements of RCM system
- use failure modes and effects, (criticality) analysis (FMEA or FMECA), to identify the failure modes, their possible and probable causes, the system and component effect(s) of that failure and the "criticality" involved. Criticality is viewed in the concept of risk i.e. being made up of consequences of an event factored with the probability of the event. Therefore risk identification is an integral part of RCM.
- assign inspection and maintenance tasks which are directed to preventing the identified failure causes in accordance with the criticality identified. The inspection and maintenance tasks must be appropriate, effective, efficient and economic. The inspection or maintenance task also takes into consideration the broad range of breakdown (run-to-failure), preventative and predictive maintenance tasks as well as inspection tasks while considering the failure characteristic of the devices, components or system.
- collect applicable information to continuously improve the RCM maintenance program through appropriate feedback of information. Refinement of the maintenance triggers is a goal of this phase of RCM. As-found condition, periodic inspections and most of all, on-line condition monitoring are aids to refining knowledge of the equipment condition.

Manual inspection can trigger appropriate maintenance if a failure characteristic can be observed and a predictable pattern recognized. Continuous condition monitoring is the only effective choice if the failure characteristic can not be identified by routine inspection or the failure development time is shorter than the inspection period. Inspection and maintenance are only appropriate if it is effective at preventing failure. Some failure characteristics are not predictable in advance or identifiable with routine inspection or maintenance. Continuous monitoring can be justified on the basis of knowing equipment conditions as well as providing maintenance triggers. These considerations need to be factored into the selection of on-line condition monitoring as the solution of choice or in some cases the only available solution.

Economic or Value analysis

When all analysis is said and done, it still comes down to a value assessment, which must show an economic benefit to applying monitoring.

The application of monitoring should be value-based, i.e. it usually should be of recognized economic benefit. Monitoring can reduce costs of inspection and maintenance, allow greater utilization of equipment capacity, allow continue operation in critical times with impaired condition, and assist in making equipment end-of-life replacement decisions. All existing direct and indirect costs associated with these topics must be included to recognize the full potential of a monitoring application. Capital and ongoing monitoring costs must also be included of course.

The following table lists some costs involved in inspection, maintenance and failure remedial work associated with substation power equipment. While not complete for every situation, it will provide guidance in determining a significant portion of the costs. Knowing the full cost of maintenance is vital to identify 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. Many owners generally have only a partial appreciation of the full cost of maintenance and underestimate their full maintenance costs, perhaps including portions with general operations. Some of those activities would not be performed if it wasn't for maintenance purposes.

Inspection Costs Considerations	**Maintenance Costs Considerations**	**Failure Resolution Considerations**
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 & inputting data	reporting & inputting data	reporting & 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 and supplies, machinery and instrumentation	vehicles, materials and supplies, machinery and instrumentation	vehicles, materials and supplies, machinery and instrumentation
	spare parts	spare parts and spare 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 for initial and final restoration, 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
	possible damage to facilities required by maintenance access	damaged equipment, damage to adjacent facilities, equipment & facilities rebuild
		apportioned cost of “system spares”, purchase of replacement equipment or components
		outage costs (loss of revenue, customer cost of un-supplied energy, overtime, etc.)
		diagnostics and failure investigation
		“in” and “out” costs of failed equipment and replacement equipment, transportation
other costs ???	other costs ???	other costs ???

Table 2 - Inspection, Maintenance and Failure Resolution Costs

The listed items are to be considered as representative example items which need to be modified in accordance with the specific situation.

In addition to direct inspection and maintenance benefits there can be significant benefits in terms of increased capacity, ability to continue operation with equipment in an impaired state, improved human and environmental safety, and improved future application of both equipment and monitoring.

Root Cause Failure Analysis

A monitoring (or maintenance) program is not complete unless there is action taken to verify that information derived from monitoring in fact correlates with actual equipment condition and that when failures occur the monitoring provided appropriate information. Root cause failure analysis is an integral part of continuous improvement in an equipment monitoring program. Monitoring can only be effective in indicating the cause(s) of failures when there is a fundamental understanding of the root cause of the failure. This contribution will establish the need to perform additional monitoring, maintenance or redesign.

Monitoring programs which fail to continuously correlate the results of ongoing equipment and system performance with actual failure causes forego an opportunity in reliability improvement or operation and maintenance efficiency/effectiveness. Understanding the root cause of failures is fundamental to assigning the most appropriate monitoring scheme.

Failure Statistics

Competition and re-regulation of the electric utility industry have tended to restrict the sharing of equipment performance information to the detriment of the industry as a whole. Never the less, there are several valuable sources of equipment performance data. [3,7,8,9,10]. Equipment operators and owners are encouraged to maintain equipment performance and failure data correlated with actual service conditions.

SOURCES OF MONITORING DATA

Direct application of specific monitors

Many direct and specific monitoring devices and systems are available for application to specific pieces of equipment or even to entire substations. Occasionally, these schemes match the value based monitoring requirements of the specific application. Usually they provide a portion of the requirements or they provide much more than is required on a value basis.

The challenge is to apply the appropriate degree of monitoring as determined by specific circumstances.

Use of Available Signals and Data

The monitoring scheme that makes the most cost effective use of available parameters should be selected. Usually monitoring can be enhanced by combining parameters or signals.

Much information can be learned from data that is already available in some form at substations. Current and voltage transformer outputs, digital relay interrogation for fault magnitude and interrupting time, event timing, control input and outputs, and temperature data can be made available. The combination of this data can be the basis of a much more comprehensive substation monitoring system than some schemes previously considered.

Several simple examples taken from the "CEA Project No. 485T1049 On-line Condition Monitoring of Substation Power Equipment - Utility Needs" are shown in fig. 4 & 5. Note that several monitoring schemes share common parameters.

SF_6 circuit breaker

measured parameter →	*information yielded →*	*additional information yielded*
- interrupter gas pressure - interrupter gas temperature	interrupter gas density	interrupter gas density - gas leakage rate
with the addition of - time		- prediction of gas replenishment
- start of trip coil current - auxiliary switch “a” & “b” - time	- approximation of mechanism average operating speed	- closer approximation of mechanism average operating speed - indicator of interrupter “wear”
with the addition of - duration of trip coil current - primary current		

fig. 4 - Example combining of **SF_6** circuit breaker parameters

power transformer

- measured parameter →	*information yielded →*	*additional information yielded*
- top oil temperature - primary current	- winding simulated temperature	- modeled top oil and winding temperature compared to actual top and bottom oil temperature
with the addition of - tapchanger position - ambient temperature - top and bottom radiator temperatures		
-tapchanger operation counter	- approximation of tapchanger “wear” & maintenance interval	- closer approximation of tapchanger “wear” based on operation of diverter and reversing switches, frequency of operation
with the addition of - tapchanger position		- knowledge of wear on each selector and reversing switch and direction of tapchanges,
- tapchanger motor drive operating current		- knowledge of tapchanger mechanism operating time and condition
- time		- knowledge of time of day at each tap position
- power system voltage transformer load voltage		- check that tapchanger is adequately controlling transformer voltage

fig. 5 - Example combining of **transformer** parameters

An example for a single pressure SF6 circuit breaker with a spring mechanism is shown in figure A10 and examined in figure A11. An example of a transformer with a tapchanger is shown in figure A12 and examined in figure A13.

Power System Operating Centers / Energy Management Systems

The Energy management systems employed by most large electrical systems are capable of collecting huge amounts of data. Appropriate "data mining" techniques can be used to derive significant information without investing in unreasonable amounts of monitoring devices.

DATA INTEGRATION AND CONVERSION REQUIREMENTS

Electronic monitoring has and can make a tremendous amount of data available. More data is rarely of benefit. Automated or facilitated conversion of data to appropriate information is of immense value.

Integration of the many sources of data into system(s) with a common means of communications is essential. Automation (or sometimes automated batch processing) of the data conversion into useful and appropriate information should be the goal. This goal will require the close cooperation between equipment, protection & control, communications, automation and data processing skills. It requires participation by original equipment manufacturers (where available), users of equipment, manufacturers of monitoring devices and "systems integrators".

CONCLUSIONS

Understanding the condition of substation power equipment has an inherent value based on preventing failure, maximizing future operation of the equipment, appropriately scheduling and determining the extent of inspections and maintenance, providing for personnel safety and protecting the environment. Monitoring has a net value based on the differential between all costs and all benefits. On-line condition monitoring can be an effective, economic and efficient means of gaining the required understanding of equipment condition if the appropriate combination of parameters to be monitored, the appropriate monitor(s), and the appropriate degree of monitoring is matched with the value provided by the specific substation power equipment in the overall power system.

The challenge is to gather the combined talents of equipment manufacturers, users of equipment, manufacturers of monitoring devices and "systems integrators" to develop seamless, automated, delivery of operating and equipment condition information in an effective, efficient and economic manner.

Some of the CEA Project Team general conclusions relating to the direct application of on-line condition monitoring are listed below:

Knowledge of Equipment Condition

- Data is already collected on some equipment conditions which can be combined with additional sources to provide much more useful information.
- Much can be learned about the condition of equipment from combining parameters, many of which are already available in the substation.
- Condition monitoring contributes to improved equipment knowledge and performance.
- Condition monitoring identifies areas for equipment design changes.
- Monitoring information on a sample population can be extrapolated to a larger population of similar/identical equipment.
- Monitoring efforts must be directed where the greatest benefit can be realized.

Monitoring Implementation

- Current data collection is not integrated.
- Monitoring needs to provide operating and maintenance information by the use of "smart" data conversion to appropriate and useful information.

* New monitoring sensors are required for some applications.
* Implementation of condition monitoring within a utility requires a collaborative effort between equipment, maintenance, P&C, SCADA and communications engineering and software developer disciplines.
* A collaborative approach with all expertise would result in a more effective end product, i.e. manufacturers and utility users, protection and control, electronic sensor industry and data management and communication industries.

Practices Associated with Monitoring

* The use of RCM and FME(C)A principles would assist in selecting and optimizing the most appropriate attributes monitored for any given situation and equipment.
* Scheduled maintenance alone is effective for certain failure characteristics that show gradual signs of impending failure.
* On-line condition monitoring is the only effective maintenance triggering method where scheduled maintenance is unable to detect or prevent failure.
* Centralized records of failure causes and remedies are needed. Because of proprietary information concerning specific data, a trusted holder of the records must be named.
* Data collection for substation equipment needs to be age-related.
* The greatest benefit will come from addressing equipment that has the highest risks associated with failure.
* Failure analysis is critical; use of standardized diagnostic and failure investigation guides is encouraged.
* The full cost and benefit of monitoring needs to be recognized and established when applying monitoring.

Monitoring Standards Required

* There is an urgent need for standards for on-line condition monitoring.
* No overall strategy appears to exist within utilities for the application of on-line condition monitoring to substation power equipment. Current on-line condition monitoring applications are implemented mostly on an ad hoc or experimental basis.

RECOMMENDATIONS

* A broad perspective such as:
    * Reliability Centered Maintenance (RCM), directed at preserving function and
    * Failure Mode and Effects Criticality Analysis (FMECA) techniques directed at identifying specific failure causes of functional failure modes,

  is suggested as a strategy for identifying and selecting condition monitoring opportunities.
* Research on failure causes and evolution must continue.
* Improved monitoring sensors are required.
* Individual on-line monitoring efforts need to integrate with the larger and longer term issues identified in the CEA and this report.
* Standardization of on-line condition monitoring systems and protocols is required.
* Optimize costs with a stepped or modular approach to on-line condition monitoring implementation. Optimize use of currently collected data.
* Future advances in on-line monitoring must be integrated into current systems.
* Expert systems need to be developed for on-line monitoring to translate data rapidly into recommended action.
* Form a user group from utilities and manufacturing groups to
    * Lobby for international standards for condition monitoring systems

* Develop common reporting systems
  * Develop a database of failures prevented by on-line monitoring
  * Provide education and training for condition monitoring systems
  * Develop a page on the World Wide Web devoted to sensors and monitoring schemes available for condition monitoring.
  * Advise existing and potential manufacturers of monitoring systems.
* Develop "expert rule base" for various sensor and equipment combinations.

ACKNOWLEDGMENT AND RECOGNITION OF OTHER'S WORK

CEA Project 485T1049 "On-line condition monitoring of substation power equipment - utility needs" January 1997

This report uses many of the above techniques to determine utility needs for substation power equipment monitoring. It also discusses the integration of monitor and existing signals to provide greater information to the utility. The report was prepared by BC Hydro (chaired by D. Peelo), Ontario Hydro and TransAlta Utilities with the input from Hydro Quebec and SaskPower. The report contains essential information, conclusions and recommendations for anyone involved with developing, selecting or applying or integrating on-line condition monitoring. (chaired by D. Peelo, BC Hydro)

"A value based methodology for selecting on-line condition monitoring of substation power equipment." EPRI Substation Equipment Diagnostics Conference V, 1997

A methodology is developed to determine which equipment should be equipped with selected monitoring devices to gain the greatest value. The methodology is based on the CEA report "On-line condition monitoring of substation power equipment - utility needs". (Adapted from CEA Project 485T1049 "On-Line Condition Monitoring of Substation Power Equipment - Utility Needs" January 1997, by W. Bergman on behalf of committee D. Peelo (chair), Dave Short, Dave Eden, John Meehan, and Cochrane Yung).

IEEE draft C37.10.1 "Guide for the Selection of Monitoring for Circuit Breakers"

This guide (draft) uses the above techniques to address the specific selection of monitoring for circuit breakers. It includes a description of circuit breaker failure modes and failure characteristics aligned with appropriate monitoring techniques. The methodology is transferable to other components. (chaired by W. Bergman, TransAlta Utilities).

CIGRE 13.09 Working Group on Monitoring of Circuit Breakers

This worldwide working group is preparing a publication on the application considerations, benefits and technical needs of condition monitoring of circuit breakers. Material from the above items has been shared with the CIGRE working group. (chaired by C.J. Jones, Reyrolle Switchgear).

REFERENCES

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[12] IEEE 1325-1996 “Recommended practice for reporting failure data for power circuit breakers”.
[13] ANSI/IEEE C57.117-1986 (Reaff 1992), “Guide for Reporting Failure Data for Power Transformers and Shunt Reactors on Electric Power Systems”.
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Addresses of Agencies & Societies

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