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Developing a Quantitative Reliability-Centered Maintenance (QRCM) Model for High Voltage Circuit Breakers

Ali A. Razi-Kazemi

Research Centerer, Hitachi Energy, Baden-Dättwil. E-mail: Aliasghar.Razikazemi@hitachienergy.com

High voltage circuit breakers (HVCBs) are recognized as critical components in power systems due to their essential protective function. To extend the lifespan of these components and prevent failures, various maintenance strategies, such as time-based maintenance (TbM) and condition-based maintenance (CbM), have been implemented by power utilities. To optimize these maintenance strategies given the available resources, a quantitative modelling approach is crucial. This paper introduces a Quantitative Reliability-Centered Maintenance (QRCM) framework for HVCBs in air-insulated substations (AIS). The proposed model is developed using failure data from established sources, including CIGRE 510 and IEEE C37. It identifies the distribution of failures across key components and major failure modes. With this information, random and aging failure modes are quantified using Weibull distribution. The model is then simulated using a reliability block diagram (RBD), incorporating stochastic methods, i.e. discrete event simulation (DES) and Monte Carlo simulation to provide a robust quantitative analysis.

Keywords: High voltage circuit breaker (HVCB), Reliability Block Diagram (RBD), Quantitative Reliability-Centered Maintenance (QRCM), Asset management.

1. Introduction

High voltage circuit breakers (HVCBs) are essential components in electrical power systems, ensuring the safe and reliable operation of the grid. Failures of these components can result in significant disruptions, costly repairs, and potential safety hazards. Therefore, maintaining their reliability is of utmost importance (Razi-Kazemi A. A., et.al. (2020), (2019), (2016)). Traditionally, power utilities employ various maintenance strategies, such as time-based maintenance (TbM) and condition-based maintenance (CbM), which may not fully address the complexities and specific needs of HVCBs (Rudsari. F, et. al (2019)).

To address these challenges, this paper proposes a Quantitative Reliability-Centered Maintenance (QRCM) model specifically designed for HVCBs. The QRCM model integrates quantitative data analysis with reliability-centered maintenance (RCM) principles to optimize maintenance schedules, enhance reliability, and reduce operational costs. By leveraging historical performance data, failure modes, and criticality assessments, the QRCM model aims to provide a systematic and data-driven approach to maintenance decision-making.

The ultimate goal of this paper is to present a probabilistic framework through reliability block diagram (RBD) model based on CIGRE and IEEE datasets for HVCBs in air-insulated substations (AIS) to enable us quantitatively evaluate availability of the system. In response to this, the key components of the HVCBs are identified, and the main resources of failure and maintenance statistics are discussed. Finally, the RBD model is proposed and illustrated through a case study. This model facilitates the simulation of various what-if scenarios and criticality assessments to optimize maintenance policies.

2. Asset Review: High Voltage Circuit Breakers

To conduct reliability analyses on HVCBs, it is imperative to first understand the

operational interrelationships among their various components. The reliability of a system cannot be improved or accurately evaluated without a thorough comprehension of each component's function and its influence on the overall system performance.
The key functions of the HVCBs are as follows (CIGRE WG A3.29):

• Withstand voltages in open position (between contacts)
• Withstand voltages to earth
• Operate on command
• Carry the nominal current
• Carry and withstand the short circuit current (in closed position)
• Remain in open or closed position (unless operated)
• Interrupt short circuit currents
• Switching of the load current

Under normal conditions, the CB carries the rated current and manages sections of the high-voltage network. In the event of a short circuit, the CB is the primary protection device. If the short-circuit current is not promptly cleared, backup protection systems will trip, causing outages in larger network sections, including overhead lines, busbars, and substations.

Depending on if the tank of the interruption chamber is grounded, CBs can be divided into the live tank breaker (LTB), dead tank breaker (DTB) and CBs used in gas insulated switchgear (GIS). The focus of the paper is on the AIS LTB CBs (See Fig. 1).

3. Key Components and Functions

From reliability viewpoint, the CB components can be broken in four distinct groups as shown in Fig. 1 and explained as follows:

• *Component at Service Voltage*

This includes the actual CB body including any tanks, interrupters, conductors, bushings, support structure.

• *Kinematic Chain*

This includes the mechanical transmission elements between the operating mechanism and the component at service voltage.

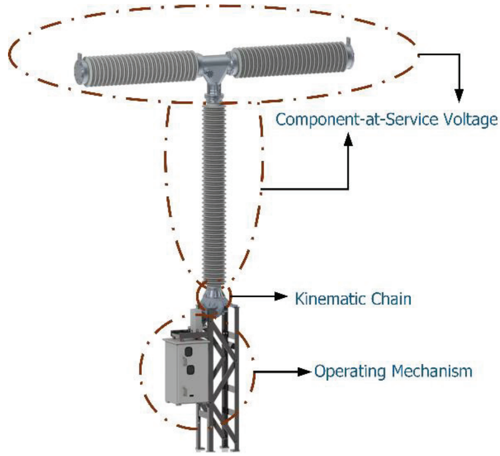

Fig. 1. The main components of the LTB CB.

• *Operating Mechanism (OM)*

This includes the apparatus which provides the mechanical forces to move the contacts of the interrupter. These mechanisms are either hydraulic, pneumatic (Old OM generation), or spring drive.

• *Electrical Control and Auxiliary Circuits*

This includes the electrical circuit which processes an external signal to provide the proper action to activate the CB. This system also performs some monitoring functions to ensure the breaker can perform its function.

4. Asset Failure and Maintenance Field Data

Providing accurate failure and maintenance data is one of the most critical steps in developing a reliable model for components. Table 1 presents the potential references which provide a great insight into the failure statistics of HVCBs

Table 1. Sources used for failure and maintenance statistics.

Source	Document Title
CIGRE	Final Report of the 2004 - 2007 International Enquiry on Reliability of HV Equipment – TB 510 (W.G. A3)
	Final Report of The Second International Enquiry on

	High Voltage Circuit-breaker Failures and Defects in Service – TB 83 (Working Group 13.06 (2012))
	Circuit-breaker controls failure survey on circuit-breaker controls systems – TB 319 (Working Group 13.08 (1994))
Canadian Electricity Association	Yearly report within 5-yr time frame 2019, 2018, 2017, 2016 (Website)
IEEE	IEEE Std C37-10: IEEE Guide for Breaker Failure Protection of Power Circuit Breakers (IEEE C37.10 (2000))
Other	CIGRE, IEEE and IET Paper (R.E. T. M. Lindquist, et. al (2007))

The first CIGRE survey (1974-1977) analysed nearly 78,000 CB years in service, significantly influencing IEC testing standards. The second survey (1988-1991) covered almost the same number of CB years, focusing on single pressure SF6 circuit breakers. The third survey (2004-2007) included 56,000 CB years and expanded to cover disconnecting switches, earthing switches, instrument transformers, and gas insulated switchgear (GIS), for equipment with voltage ratings of 60 kV and above. The fourth CIGRE survey, conducted from 2014 to 2017 included 100,000 CB years, expanded its scope to include generator circuit breakers, high and medium voltage vacuum circuit breakers, and surge arresters, in addition to SF_6 CBs, disconnecting switches, earthing switches, instrument transformers, and GIS. This survey aimed to provide updated reliability data and compare it with previous surveys. The focus of this paper is on Major failure (MaF) which refers to an incident that causes the complete loss of the equipment's primary function, requiring significant repair or replacement.

The maintenance activities are dependent on the faulty sections, availability of the spares, the associated budget, etc. Therefore, the times can be different year-by-year. For example, Fig. 2 presents the MTTR for operating mechanism

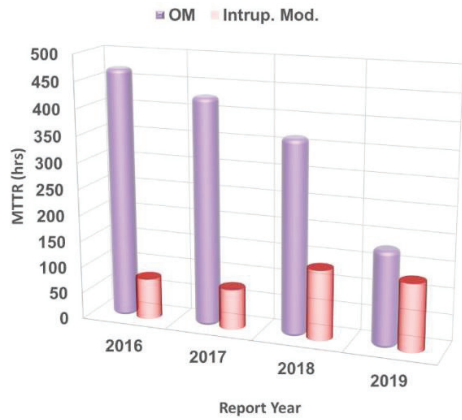

Fig. 2. Variations of the MTTR dealing with operating mechanism and interrupting module over years.

(OM) and interrupting module (Intrup. Mod.) within 2016 to 2019 based on information provided (Website). As it can be seen, the values are different over years. To address this, the maximum of the MTTR and median would be employed in this work.

5. RBD Model Developed for AIS LTB CBs

Fig. 3 presents the proposed RBD model for LTB SF_6 CBs. As it be seen, the breaker has divided into the five key components including interrupting chamber, insulation support, operating mechanism (OM), kinematic chain, control and auxiliary a long with the "other".

The first step in developing the RBD model is to establish a connection between the Modes of Failure (MaF) and the key components. Next, the contribution of the MaFs, which could be either random or aging failures, is identified. For aging failures, the Weibull distribution is employed. While the β value is assumed to be 2.5, the η value is estimated through Monte Carlo simulations with nearly 10,000 iterations. For illustration, Table 2 presents the list of MaFs, their contributions, ROCOF, failure types, as well as the β and η values for the Weibull distribution for the operating mechanism of a 100 kV-200 kV LTB CB. A similar approach has been applied to other key components.

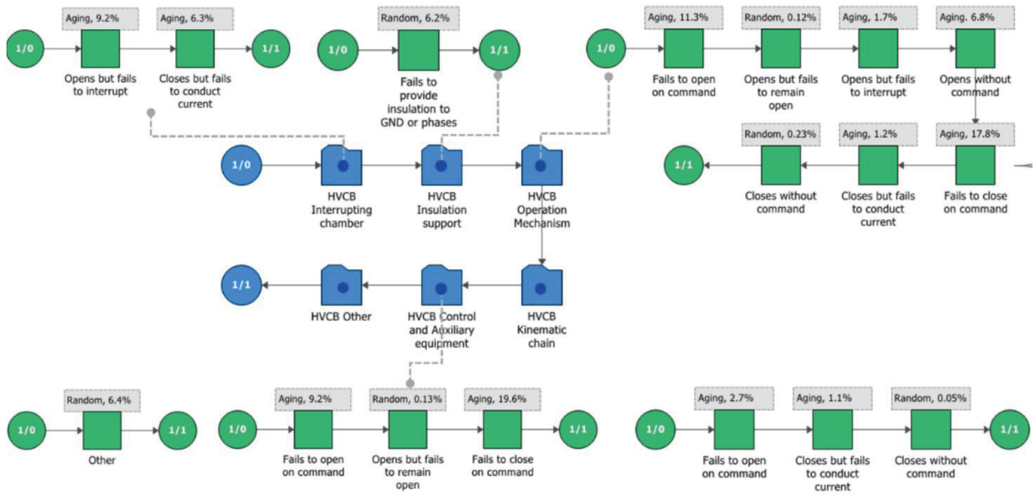

Fig. 3. The proposed RBD for LTB CB

Table 2. Input failure data for RBD of LTB 100 kV-200 kV_OM.

MaF	Contribu-tion %	ROCOF	Failure Type	Weibull Eta	Weibull Beta
MaF: Fails to open on command	11.28	0.00041736	Aging	45	2.5
MaF: Opens but fails to remain open	0.12	0.00000440	Random	225225	1
MaF: Opens but fails to interrupt	1.7	0.000063640	Aging	70	2.5
MaF: Opens without com-mand	6.82	0.000252340	Aging	56	2.5
MaF: Fails to close on command	17.8	0.0006586	Aging	35	2.5
MaF: Closes but fails to conduct current	1.2	0.000043660	Aging	90	2.5
MaF: Closes without com-mand	0.23	0.00000851	Random	117509	2.5

Another crucial factor in evaluating the reliability of components is the maintenance activities. Maintenance strategies include corrective maintenance (CM), time-based maintenance (TbM, referred to as preventive maintenance or PM here), condition-based maintenance (CbM), and inspections. For CM, the mean and median Mean Time to Repair (MTTR) are considered in this model. For PM and CbM, the model takes into account the maintenance intervals, MTTR, and the quality of maintenance, represented by the restoration factor (RF). It is used to model imperfect repairs. It quantifies how much a repair restores a component's condition:

- $RF = 1$: The component is as good as new after repair.
- $RF = 0$: The component remains in the same condition as before the repair.
- $0 < RF < 1$: The component is partially restored, with its age reset proportionally to the RF value.

This helps in accurately modeling the effectiveness of maintenance actions in reliability analyses. In addition, the repair resulting from maintenance has been categorised into type I and II. Type I Restoration assumes that repairs only address the wear and damage incurred since the last repair. The component's age is partially reset, reflecting only the most recent period of operation. Type II assumes that repairs address all accumulated wear and damage up to the current time. The component's age is more significantly reset, reflecting a more comprehensive restoration.

Table 3 provides the maintenance input for the model concerning the OM of a 100 kV-200 kV LTB CB. It is important to note that this information is generic and may vary between different utilities. In this table, FMG1 refers to all Modes of Failure (MaF) listed in Table 2, indicating that the maintenance activities are assumed to potentially impact all MaFs.

Table 3. Input maintenance data for RBD of LTB 100 kV-200 kV_OM

Grouped MA	MAs	Time Interval	MTTR	RF	PM restoration type I or II	Crew Size (# of people)
FMG1-Ins.- 1 yr	Ins1, ins2	1	1	0	-	2
FMG1-PM- 1 yr	PM 5, PM 6	1	1.2	0.7	I	2
FMG1-CBM- 1 yr	CBM3	1	1 (ins) 6 (PM task)	1	II	2 (ins) 2 (PM task)
FMG1-CBM- 3 yr	CBM2, CBM5	3	5 (ins) 15 (PM task)	1	II	0 (ins, online) 2 (PM task)
FMG1-CBM- 5 yr	CBM 1,4 ,6 7	5	4 (ins) 15 (PM taks)	0	-	2 (ins) 2 (PM task)
FMG1-PM- 20 yr	PM1, 2, 3, 4	20	15	1	II	2

Time interval (per yr), MTTR (h)

6. Simulation Results

Considering the RBD model along with all the information provided in the preceding sections, the following assumptions have been hypothetically made for these simulations:

- Price for replacement of the OM: 100,000 CHF
- Price for replacement of the Interruption chamber: 50,000 CHF
- Price for replacement of the auxiliary and control unit: 5,000 CHF
- Price for pre hour Corrective Maintenance and repair after CBM: 100 CHF

It is noted that the interruption cost has not been concluded in this analysis. In addition, manpower cost has been about 100 CHF per person per hour. Furthermore, other alternatives of possible consequences of the events were not evaluated in the modelling. The Monte Carlo simulation was executed for 100,000 iterations over a total lifespan of 50 years using a Python code based on Discrete Event Simulation (DES). DES is a powerful technique used to model the operation of complex systems through a sequence of discrete events over time. This method enables the analysis of system performance, reliability, and maintenance strategies by simulating the interactions and behaviors of individual components within the system. DES is particularly effective for evaluating the impact of various maintenance policies, resource allocations, and operational scenarios on system reliability and availability. Table 4 presents different reliability indices for the breaker as well as the key components. The most contribution of the number of outages and therefore the costs would be for operating mechanism and auxiliary and control section.

To emphasize the critical role of the operating mechanism (OM), three prominent MaFs in OM—failure to open on command, failure to close on command, and unintended opening—have been considered for a more precise evaluation, as these are prone to aging. As shown in Table 5, failure to close on command contributes significantly to the number of outages, as well as to spare parts and repair costs.

Table. 4. Distribution of the different indices for the CB and key components

Indices	System	Aux.	OM	Ins.	Int.
Failures (1/yr)	0.1202	0.0124	0.1022	0.0008	0.0048
Unscheduled Downtime (h)	43.09732	0.0568	41.10811	0.0066	1.925809
Scheduled Downtime (h)	365.9278	176.0591	991.2171	100.5027	599.2998
Total Downtime (h)	409.0251	176.1159	1032.325	100.5093	601.2256
Availability	0.999067	-	-	-	-
Total Cost (CHF)	240723.1	7216.57	138330.9	10085.6	85089.98

Table. 5. Contribution of Major failure modes in OM

OM	Fails to open on command	Fails to close on command	Opens without com-mand
Failures (1/yr)	0.0332	0.0491	0.0199
CM Downtime (h)	18.12525	16.81314	6.169721
Inspections (#number)	49	49	49
Inspection Downtime (h)	49	49	49
Number of PMs	51.069	51.0531	51.0823
PM Downtime (h)	111.7829	113.095	123.7384
Number of CBM Inspections	74	74	74
CBM Inspection Downtime (h)	165	165	165
Number of CBM Repairs	0.0187	0.0304	0.0119
CBM Repair Downtime (h)	0.1752	0.3093	0.1164
Spare Costs (CHF)	5190	7950	3180
Repair Costs (CHF)	41110.05	40992.24	39908.61

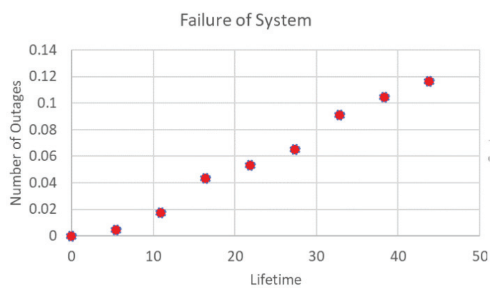

Fig. 4. Number of outages over lifetime of the breaker

Fig. 4 illustrates the trend in the number of outages over the lifetime of the CBs. As observed, the slope of the number of outages changes significantly following each overhaul, which occurs every 20 years. It is worth mentioning that the code allows for the simulation of various scenarios based on specific needs.

7. Conclusion

Developing a framework to quantitatively evaluate the reliability of CBs as critical components in power systems is of paramount importance. This paper outlines the procedure for developing a RBD for HVCBs. The breaker has been divided into key components to establish connections between them and their respective failure modes. Maintenance activities, including inspections, PM, CM, have been discussed in terms of MTTR, crew size, and restoration factors (RFs). The model has been developed based on the defined key components, associated MaFs, and maintenance actions through the RBD model. Both random and aging failure modes have been incorporated into the model using the Weibull distribution. A Monte Carlo simulation has been employed over DES using Python code for realization. As an example, the model has been demonstrated for a 100 kV-200 kV LTB. This framework offers a comprehensive approach to asset management, accounting for uncertainties within the power system and enabling more effective decision-making.

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