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Review On High Voltage Circuit Breaker Failure Modes For Condition Monitoring

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Abstract

High voltage circuit breakers (HVCBs) play a critical role in power systems owing to their role of protecting and isolating short circuit faults. The reliable operation of these critical components is significantly affecting resiliency, and stability of power systems. Preventive maintenance (PM) and condition-based maintenance (CbM) are widely applied maintenance polices in power networks to extend HVCB lifetime and to avoid failures. An imperative step towards implantation of any diagnosis or prognostic approach via CbM is to understand whether failures are originating from aging or from random processes. This paper presents a review on the failure modes of HVCBs and discusses their causes and effects along with typical failure patterns. The prominent major failure modes (MaFs) and the proper diagnosis signals for HVCBs are discussed in this paper. This knowledge is then used to identify more precisely the applicability of diagnostics and prognostics approaches and to outline further development options.

Keywords: high voltage ciruit breaker, random failure, aging failure, reliability

1. Introduction

Once a short circuit fault happens in the power grid, or when otherwise a power line switching is required, high voltage circuit breakers (HVCBs) have been employed for these purposes. Accordingly, any improper performance of these critical components results in a dramatic decrease on availability, reliability, and resiliency in power networks. A change of the health state properties of HVCBs may result from different stresses and affect the performance of the equipment. Therefore, various maintenance policies are applied to extend the lifetime and increase the reliability of HVCBs such as time-based maintenance (TbM) and condition-based maintenance (CbM). While TbM refers to do maintenance activities within a predefined time schedule, CbM stands for evaluation of the condition of the HVCB using recorded signals through offline/online monitoring tools (Razi-Kazemi et al., 2013). The latter is dealt with to use this information for diagnosis as well as prognosis of the HVCB. CBs have been recognised as an electromechanical component that is susceptible to different malfunctions which result in a variety of causes for a certain failure.

Many research activities addressed this subject from different perspectives. In (Razi Kazemi and Niayesh, 2020), a comprehensive overview on the condition assessment of HVCBs, diagnostic signals and failure statistics of the CBs has been provided. In (Razi-Kazemi et al., 2014), coil current as a diagnostic signal for trip/close coil has been deeply investigated. The impact of installation of the online monitoring system on total maintenance cost and reliability of power system has been quantified in (Razi-Kazemi and Lehtonen, 2017). A great insight into the CB failure statistics has been provided in CIGRE 510 (501A3.06, 2012), based on the failure statistics on 251’090 CB-yrs within 2004-2007 from 26 countries. The other valuable effort is presented in CIGRE 725 (Working Group A3.29, 2018) to explain thoughtfully the aging procedure of all switching components including of the CBs. (Janssen et al., 2014) compares three failure statistics of the CBs. (“IEEE Guide for the Selection of Monitoring for Circuit Breakers,” 2019) provides a failure mode and effect analysis to determine the proper diagnostic signals for CBs through IEEE std C37-10-1-2000. (Balzer and Drescher, 2004) evaluates the failure frequency coming from disturbance statistics of equipment.

A deep understanding of equipment ageing can help to proactively implement an asset performance management approach to reduce the probability of failure, and to manage the risk of equipment failure. This paper presents a procedure for a better lifetime management for HVCBs. In addition, it has been attempted to provide a better understanding of the failure modes dealt with the aging. This paper has been mostly established based on review of well-known reports, i.e., CIGRE 725, CIGRE 510 and IEEE std C37-10. At the end, the some signals which could have highly link with predominant failure modes have been suggested.

This paper has the following structure: Failure patterns of CBs are reviewed in section 2. Then, the aging mechanism, and the degradation of CBs along with prominent major failure modes are discussed in Section 3. In section 4, a connection amongst major failures, causes and key components is provided. Section 5 addresses the proper diagnosis signals for CbM. The information presented in this paper is helpful to understand better the critical components of CBs for future improvement in design, and for implementation of CbM techniques.

2. Failure patterns

Understanding the failure patterns/characteristics (how failures develop over time, e.g., expressed by a failure rate) in HVCBs is an imperative step towards to implementation of the most efficient maintenance policy and monitoring system ("IEEE Guide for the Selection of Monitoring for Circuit Breakers," 2019).

Figure 1 presents different failure patterns for HVCBs.

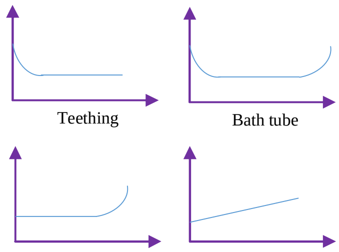

Fig. 1. Failure pattern for HVCBs (y: # failure rate vs x: lifetime of the CBs)
(IEEE Guide for the Selection of Monitoring for Circuit Breakers, 2019; Balzer and Drescher, 2004).

As outlined in the Figure 1, the patterns could be as follows:

- *Teething*: infant mortality followed by a constant or slowly increasing failure rate: this is a common pattern during the early life and warranty period of products;
- *Wear out*: Constant or gradually increasing failure rate with time followed by a pronounced wear-out region: Examples of this pattern could be erosion of the contacts, or grease quality over operations;
- *Aging*: Gradually increasing failure rate with no identifiable wear-out region: It can be like contact erosion, and damper issue;
- *Bath-tube*: Infant mortality followed by a constant or gradually increasing failure rate and then a pronounced "wear-out" region. It refers to total situation of the CBs including all major failure modes.

Aging refers to a change of the properties of the CBs resulting from different stresses. Therefore, it is not necessarily a matter of the age or operation time. Accordingly, the following sections target to identify the prominent failure modes, stresses, and aging mechanisms. In the next step, the connection between the aging, failure modes and key components is presented.

3. HVCB failure modes and ageing phenomena

3.1. Prominent failure modes

HVCB failures can be clustered into major failure modes (MaF) and minor failure modes (MiF). While MaF result in an immediate outage of the circuit breaker and a respective change in power system condition, MiF are defined to only change a functional characteristic of the HVCB without leasing to an immediate outage. Regarding the importance of MaF, this paper investigates these failure modes only. The key functions of HVCBs and failure modes that are linked to these functions are presented in Table 1. The total of 11 MaF, which has been labelled as MaF group (MFG), can be generally categorized into three principal groups which are related to 1) failure of the opening operation, 2) failure of the closing operation, and 2) failure of the insulation. Table 1 has been established based on a mix information from CIGRE 510, CIGRE 725, and IEEE std. C37. MaFs could have different contributions on the CBs as shown in Figure 2 (501A3.06, 2012). As it can be comprehended, the most predominant MaFs are comprised of MFG 6 (28.20%), MFG 7 (25.2 %), and MFG 5 (16.4%), i.e., fails to close on command, locking, and fails to close on command, respectively. Accordingly, the rest of the paper has focused on these critical MaFs for further investigations.

Table 1. The connection between the functions of the CBs and failure modes.

Key Functions	Failure modes (MaF)	MFG#
Withstand voltages (across contacts) in open position as well as during opening/closing operation	Fails to provide insulation between phases (Breakdown between pole during closing, open as well as in open, and close)	1
	Fails to provide insulation across the interrupter external (in open or during close and open operation)	2
	Fails to provide insulation across the interrupter internal (in open or during close and open operation)	3
Withstand voltages to earth	Fails to provide insulation to ground (breakdown to earth in the closed position, during closing operation, open position, during opening operation)	**4**
Operate on close/open command	Fails to open on command	**5**
	Fails to close on command	**6**
	Locking in open or closed position (alarm has been triggered by the control system)	**7**
Carry the nominal/short circuit current	Fails to conduct continuous or momentary current (while already closed)	8
Keep the open or closed position	Opens without command	**9**
	Closes without command	10
Interrupt short circuit currents	Opens but fails to interrupt	11

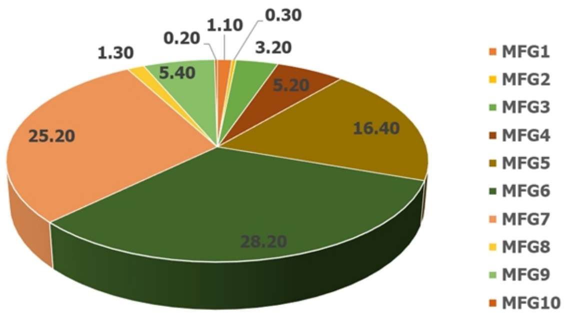

Fig. 2. Distribution of the MaFs in HVCBs, CIGRE 510 (501A3.06, 2012).

3.2. Aging procedure and key components in HVCBs

Aging is a result of various stresses over the lifetime of the components in power systems. The stresses for HVCBs have been summarized as follows (working group a3.29, 2018, CIGRE 725):

- *Electrical stresses*

Open and close on load/short circuit current is the main task for HVCBs. In addition, they must withstand switching overvoltages as well as the lightning strikes. An electrical wear and degradation of the contacts over time is resulting form the arcing happening during operation. The temperature of the core of an arc can be about 20‘000 K and besides thermal damage, may also lead to an accumulation of by-products which can impact the dielectric capability of the insulating media. This contact wear is accumulated and increased by the number of operations under load. Accordingly, there is an inverse correlation between the total number of operations of the CBs (lifetime) and the accumulative short circuit interruption current. In addition, the nominal continuous current, which affect the temperature rise of the breaker could result in the degradation of several internal and external components.

- *Mechanical stresses*

HVCBs are the electromechanical equipment which are comprised of I) an operating mechanism including damper, spring, coils, rods, etc., and II) an interruption chamber including main contact, arcing contact, etc. Owing to the switching operations, vibrations are generated that can lead to different mechanical tensions. Such operations affect the wear on linkages, bearings, pins, etc., and on the moving parts of the mechanism and breaker (kinematic chain), in turn causing degradation of performance over lifetime.

- *Environmental stresses*

A CB can operate under various temperatures, humidity, rain, pollution, etc., which can affect the aging process. Environmental stresses can accelerate corrosion impacting seal integrity, linkage/mechanism performance, part failure, etc. Temperature can increase grease degradation/caking. Furthermore, moisture ingress can affect the insulation/arc extinguishing media, as well as the bushing insulators of CBs. It is worthwhile to mention that the sensitivities of the HVCBs to the stress factors are dependent on the design and characteristics of the breaker. To give an illustration, a breaker equipped with a spring-drive mechanism is less sensitive to the ambient temperature than a pneumatic-drive, which operates based on the high-pressure air. A breaker can be designed for a live tank, dead tank, or for a gas insulated substation (GIS). Another example is that MaFs related to live tank breakers are reported with a three times higher failure rate than dead tank and GIS (501A3.06, 2012). In addition, different applications lead to different stresses and respective failure rates in the field, as shown in Figure 3 (501A3.06, 2012). Although CBs used in the reactor and capacitor bank switching are interrupting only small currents (less than 1 kA), they can impose considerable stresses due to rapid transient recovery voltages and very frequent operations. As pointed out in (501A3.06, 2012) shown in Figure 3, CBs employed in these applications have the highest rate of MaFs, i.e., about 2.5 and 1 (1/100CBY) for shunt reactor and capacitor, respectively.

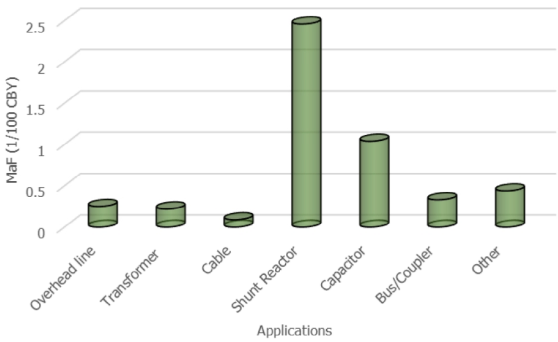

Fig. 3. Role of the application on aging procedure (501A3.06, 2012).

It is an imperative step to make a connection amongst failure modes, stresses, and subcomponents of CBs. Accordingly, from a reliability and diagnostics viewpoint, a breaker can be divided into the following key components:

- *Component at service voltage*

This category refers to the main body of CBs comprising tank, interrupter, conductors, bushings, and support structure.

- *Kinematic chain*

This category refers to mechanical linkage elements between the operating mechanism and the component at service voltage.

- *Operating mechanism*

This category refers to the mechanical parts required to generate the mechanical forces to move the contacts of the interrupter for closing and opening operations. These mechanisms can be hydraulic, pneumatic, or based on spring drives. The most frequently operating mechanism is the spring drive as well as hybrid hydraulic-spring (HMB) drives.

- *Electrical control and auxiliary circuits*

This category refers to the electrical circuit which processes an external signal to provide the proper action to run the CB.

A survey on HVCBs has been provided in (Working Group A3.29, 2018), CIGRE 725, as shown in Figure 4. As it can be seen, mechanical stresses (resulting from operations) are indicated as a strong influence on the ageing effects for all CB designs. In addition, water ingress is another key factor influencing the ageing of the CBs in the category of the environmental influence. Further factors such as mechanical stress due to mechanical loads, as well as environmental stress owing to the temperature, and media decomposition by-products/ improper or lack of maintenance are reported as important stresses for aging of CBs. Figure 4(b) reveals that highly influenced subcomponents in the category of components at service voltage are 1) making and breaking unit, and 2) main insulation to the earth. For the control section and operating mechanism, most relevant are 1) electrical components, and 2) gas density supervision, as well as 3) the damping device and mechanical transmission, respectively.

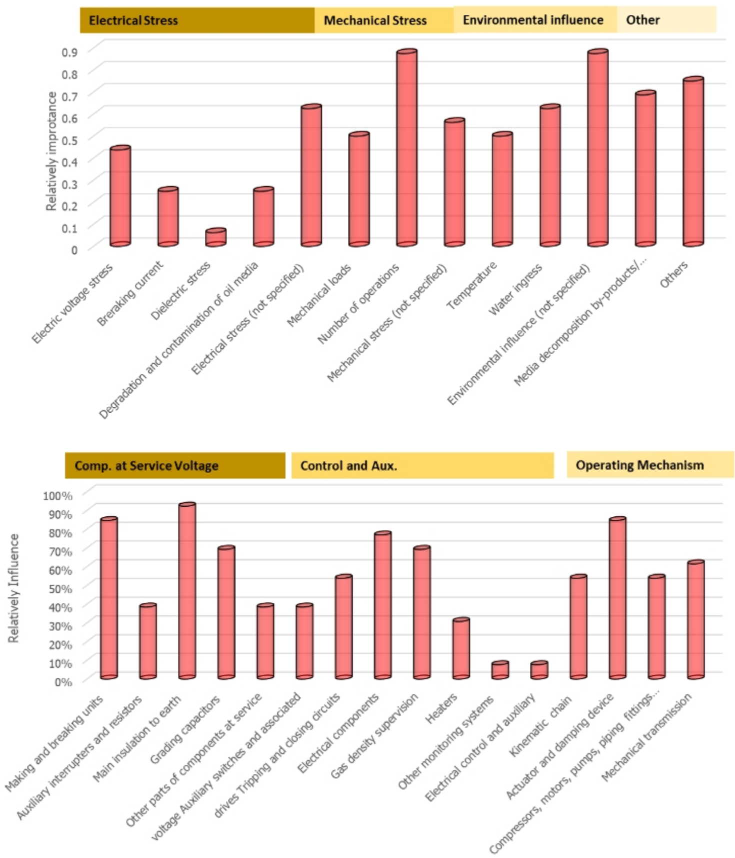

Fig. 4. Contribution of the stresses on the breaker (a) and affecting subcomponents (b), CIGRE 725.

3.3. Degradation in HVCBs

The above-mentioned stresses result into different degradation mechanisms in HVCBs, which can be categorized into the following clusters, see CIGRE 725:

- *Electrical degradation*

All degradation from this category have been linked into the "component in service voltage." It is comprised of the increase of contact resistance (owing to erosion of the contacts, worn-out silver plating coated onto the contacts, or deterioration of grease for lubrication of the contacts (if any)), electrical wear (wear of contacts and nozzles), loss of dielectric strength (owing to cracking or voiding inside of the insulators, or resulting from severe conditions such as rain, dust, contamination, etc.), and the reduced short-circuit capability (as a consequence of the degradation of the contacts or operating mechanism).

- *Mechanical degredation*

It includes the mechanical wear (due to the friction of the parts), fatigue (owing to repeated mechanical loading), relaxation (in real packing or O-ring, etc), loosening (owing to stress on the bolt), loose/sticking contacts (owing to mechanical deformation, etc.), and interrupting medium leakage (as a result of sealing problems)

- *Material degradation*

Material degradation includes corrosion (owing to water, moisture, and air), contamination, chemical reaction with by-products, grease degradation, and the increase of moisture.

In CIGRE 725, it has been indicated that the corrosion, wear, and fatigue are the most significant ageing phenomena in CBs. In addition, leakage is still a frequent problem for gas CBs and lubrication can be a big challenge in aging of the CBs.

4. Evaluation of the predominant MaF from aging perspective

As it has been outlined in Section 3.1, the prominent MaFs are as follows:

I. Does not operate on command (close/open)
II. Operates without command
III. Electrical breakdown

It is worthwhile mentioning that these MaFs are important from both, component, and system viewpoint, respectively. Occurence of these MaFs result into outage and consequential costs. Accordingly, it has been attempted to focus on these critical MaFs. Table 2 provides and analysis for these MaFs and links MaF with failure causes, failure patterns, and affected key components. To give an illustration, the MaF "operate without command" may be cause by vibration stresses from operation of a nearby breaker, which may be a random failure.

Table 2. The connection between the functions of the CBs and failure modes.

MaF	Causes	Pattern	Connected key Components
Dose not operate on command (open/close)	Open/shorted trip/close coil	Random	Cont. Aux.
	Nonsufficient lubrication of trip latch or trip mechanism	Aging	OM
	Loss of stored energy in OM owing to leaks, and breakage	Aging for hydraulic and pneumatic Random for spring drive OM	OM
	Control circuit failure	generally Random, Auxiliary contact: Aging	Cont. Aux.
	CB operation blocked	Random	Cont. Aux.
	Linkage failure between OM and interrupters	Aging/Random	OM
	Deformation of trip latch	Aging	Cont. Aux.
	External Circuit failures like wiring, battery, and relays	Random	-
Operates without command	Trip/close latch not secure	Aging	Cont. Aux.
	Stray current in trip circuit such as transients, caused by surges	Random	Cont. Aux.
	Ground on trip/close circuit	Random	Cont. Aux.
	Vibration of CBs	Random	Cont. Aux.
	Spring release mechanism worn	Aging	Cont. Aux.
Electrical breakdown	Moisture, contaminated bushing, mechanical damage, lightning stroke	Random	Com. At Ser. Voltage.

Different key components of CBs may follow various patterns of the failures as discussed in (Balzer and Drescher, 2004).

Figure 5 represents the results of evaluation of failure events on HV components of 4184 SF6 CBs with 3163 failures as well as 3473 hydraulic drives of same type with 1734 failures (Balzer and Drescher, 2004). It has been indicated that the teething is a common pattern in CBs, which refers to the higher probability of failure in the same year as maintenance activities are running. This framework usually would be covered through warranty time from companies. In addition, the hydraulic drive shows a wear out after 13 years.

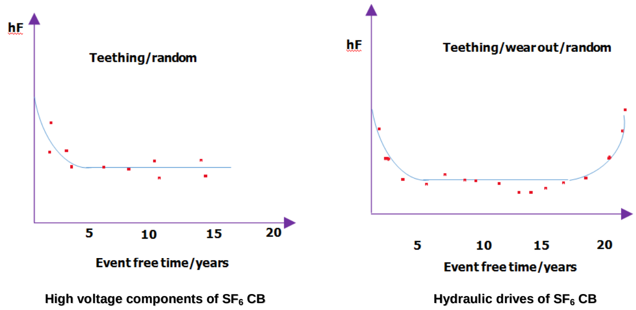

Fig. 5. Different failure patterns of the key components in CBs (Balzer and Drescher, 2004).

5. Suggested signals for CbM

CbM has been established based the recorded signals for diagnosis and further prognosis. In addition, the varieties of signals could be taken account for this purpose such as coil current, travel curve, motor current, etc. However, scheduled condition-based maintenance tasks are technically feasible if

1. It is possible to define a clear potential failure condition, and
2. The P-F interval is reasonably consistent, and
3. It is practical to monitor the item at intervals less than the P-F interval, and
4. The P-F interval is long enough for action to be taken to reduce or eliminate the consequences of the functional failure (Marius Basson, 2019).

Table 2 enables us to precisely select the more efficient diagnosis signals based on predominant MaFs and connected key component. List of the monitoring signals are presented in Table 3. SRM refers to static resistance measurement, which has been stablished based on calculation of the voltage drop across a CB in a close position over the DC injected current. DRM is like the SRM but during the open/close operation and provide a profile of resistance of the CB (Abdollah and Razi-Kazemi, 2019). However, both can be applied in offline state. In the case of condition assessment of the making and breaking unit the only online approach is based on the current based calculation of the energy. Travel curve (TC) which refers to the contact motion against time is an informative diagnosis signal for evaluation of OM (Rudsari et al., 2019). However, in some type of the CBs, it is not possible to apply it in the online state. One solution could be using vibration signal with considering to some difficulties such as sensitivity to location of sensor, and post processing approach (Yang et al., 2019). Depending on the type of the OM, monitoring of the current of the motor can be helpful for evolution of this section. Trip and close coil current (CC) is the other valuable signal for condition assessment of Aux. Cont. Section (Razi-Kazemi, 2016).

With respect to the prominent MaFs in Table 2 and the available signals in Table 3; the best suggestion for CbM would be using vibration signal along with TCs, which could cover most of origins of the MaFs.

Table 3. The connection between the functions of the CBs and failure modes

Monitoring Signals	Connected Comp.	Online/Offline
SRM	Making/breaking Unit	Offline
DRM	Making/breaking Unit	Offline
Monitoring of the interruption current	Making/breaking Unit	Online
TC	OM	Online/offline
Vibration	OM	Online
CC	Aux. Cont.	Online
Motor current	OM	Online

Summary

This paper presented a review on MaFs in HVCBs as the critical components in power systems based on released statistics in CIGRE 510, CIGRE 725, and IEEE C37.10. It was tried to provide helpful information dealing with prominent MaFs, the stresses and degradation in HVCBs and how they are linked to key components within a framework. It has been revealed that the prominent MaFs for HVCBs are "does not operate on command", "operate without command" and "electrical breakdown". Furthermore, it has been pointed out that corrosion, wear, and fatigue are the most significant ageing phenomena in CBs. In addition, it was indicated that accumulated mechanical stresses (number of operations) have the highest influence on the ageing for all CB designs. Finally, it has been derived that most aging phenomena are happening in the operating mechanism and in the contacts of the interruption chamber. At the end, the proper signals for condition assessment of the CBs were suggested to be vibration, TC and CC with respected to the ability in monitoring of the prominent MaFs. This information is helpful to find the optimum diagnosis signals and further development of HVCBs.

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References

Abdollah, M. Razi-Kazemi, A. A. 2019. Intelligent Failure Diagnosis for Gas Circuit Breakers Based on Dynamic Resistance Measurements. IEEE Transactions on Instrumentation and Measurement 68(9), 3066-3077.

Balzer, G. Drescher, D. 2004. Evaluation of Failure Data of HV Circuit-Breakers. CIGRE.

IEEE Std C37.10.1. 2019. IEEE Guide for the Selection of Monitoring for Circuit Breakers. 1-61.

Janssen, A. Makareinis, D. Solver, C. E. 2014. International surveys on circuit-breaker reliability data for substation and system studies. IEEE Transactions on Power Delivery, 29(2), 808-814.

Marius B. 2019. RCM3: Risk-based Reliability Centered maintenance. Industrial Press Inc., U.S.

Razi Kazemi, A. A. Niayesh, K. 2021. Condition Monitoring of High Voltage Circuit Breakers: Past to Future. IEEE Transactions on Power Delivery 36(3), 740-750.

Razi-Kazemi, A. A. 2016. Circuit breaker condition assessment through a fuzzy-probabilistic analysis of actuating coil's current. IET Generation, Transmission and Distribution 10(1), 48-56.

Razi-Kazemi, A. A. Lehtonen, M. 2017. Aging failure model of circuit breakers equipped with condition monitoring systems. International Transactions on Electrical Energy Systems 27(12), 1-9.

Razi-Kazemi, A. A. Vakilian, M. Niayesh, K. Lehtonen, M. 2013. Priority Assessment of Online Monitoring Investment for Power System Circuit Breakers-Part I: Qualitative-Quantitative Approach. IEEE Transactions on Power Delivery 28(2), 928-938.

Razi-Kazemi, A. A. Vakilian, M. Niayesh, K. Lehtonen, M. 2014. Circuit-breaker automated failure tracking based on coil current signature. IEEE Transactions on Power Delivery 29(1), 283–290.

Rudsari, F. N. Razi-Kazemi, A. A. Shoorehdeli, M. A. 2019. Fault Analysis of High-Voltage Circuit Breakers Based on Coil Current and Contact Travel Waveforms Through Modified SVM Classifier. IEEE Transactions on Power Delivery 34(4), 1608–1618.

WORKING GROUP A3.29. TB 725, 2018. Ageing High Voltage Substation Equipment and Possible Mitigation Techniques. CIGRE.

WORKING GROUP 501A3.06. TB 510. 2012. Final Report of the 2004–2007 International Enquiry on Reliability of High Voltage Equipment, Part 2-SF_6 Circuit Breakers. CIGRE.

Yang, Q. Ruan, J. Zhuang, Z. Huang, D. Qiu, Z. 2019. A New Vibration Analysis Approach for Detecting Mechanical Anomalies on Power Circuit Breakers. IEEE Access 7, 14070-14080.