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A Step Towards Circuit-Breaker Diagnostics Interoperability

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SUMMARY

Diagnostics are an integral part of a circuit-breakers (CB) life. A variety of test and diagnostic tools are often used with custom software and interpretation rules. However, there is a gap between available diagnostics data and a user friendly asset management tool. To bridge this gap, existing data needs to be properly structured to facilitate integration of any type of diagnostics. This data structure will also facilitate the future to standards or guides.

The key is interoperability between diagnostic tools and asset management systems which involves the exchange of information and the proper use of information so exchanged. Exchange of information requires syntax level compatibility which is achieved by protocols. Proper use of the information is more complex and requires semantic compatibility as well as common understanding.

The simplified diagnostic process consist in physical parameters measurements which are transformed by a specific diagnostic method into condition indicators. The latter compared to the thresholds, can turn into a symptoms. These feed the decision support tool in order to obtain a diagnosis or health index. In this model, the integration of information is executed at the interpretation level. Current diagnostic methods generally hide important information such as basic measurement and only provide the final results. In contrast, nowadays systems are rather oriented in the direction of more open architecture and basic measurements are accessible in order to form distributed applications.

An attempt is made in this paper to define a coherent dictionary at the level of physical measurements and algorithms in order to enable interoperability between heterogeneous diagnostics. Furthermore, it is discussed on how to improve CB diagnostics using data acquired by different diagnostic tools at different moments in time. This could be referred as "distributed diagnostics in space and time".

This paper reviews common CB diagnostic data and proposes a way to organize it into a structured system allowing for comprehensive integration.

KEYWORDS

Circuit Breaker, diagnostics, monitoring, condition indicator, interoperability

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1. INTRODUCTION

Diagnostics are an integral part of a circuit-breakers (CB) life. A variety of test and diagnostic tools are often used with custom software and interpretation rules. However, there is a gap between available diagnostics data and a user friendly asset management tool. The end users have to deal with multiple diagnostics software, often proprietary, which are not directly compatible with one another.

The actual diagnostic process consist in physical parameters measurements which are transformed by a specific diagnostic method into condition indicators. The latter compared with specified values (thresholds), provided by international standards or by the CB manufacturer, can turn into symptoms. These feed the decision support tool in order to obtain a diagnosis (i.e. information on equipment condition or failure mode) or health index (which combines known information relating to the assets age, design, operating environment, operating duty and physical observations of the condition) [1]. The diagnosis are often about one aspect of the CB condition. For example: tests for insulation integrity, timing for mechanical integrity, and measurement of dynamic or static resistance for contact wear, etc. [1]. Current diagnostic methods generally hide important information such as basic measurement and only provide the final results. In this model, the integration of information is weak and is executed at the interpretation level. The end users often use custom databases or systems to store the results and reports.

To bridge the gap between available diagnostics data and a user friendly asset management tool, the existing data needs to be properly structured to facilitate integration of any type of diagnostics. This data structure will also facilitate the future transition to standards and guides. The key is interoperability between diagnostic tools and asset management systems which involves the exchange of information and the proper use of information so exchanged. Exchange of information requires syntax level compatibility which is achieved by protocols. Proper use of information is more complex and requires semantic compatibility as well as a common understanding.

The digital substation concept and the application of IEC 61850 requires that formal data models be precisely defined. IEC 61850-90-3 [2] is well elaborated for data related to transformers but contains very little relevant information on switchgear diagnostics. One of the goals of CIGRE WG A3.43 is to clearly define all possible CB condition indicators based on what is already available and to develop a new data structure which can then be adopted by IEC related committees [3].

2. CONDITION INDICATORS FOR MV AND HV SWITCHGEAR

The ultimate condition assessment of switchgear would be obtained by an exhaustive internal inspection, requiring the dismantling of the switchgear. In this case one would gather complete and precise information about its real condition. However, this kind of intervention should be avoided, especially for SF_6 CBs due to high cost, environmental risks, and the possibility of errors during CB reassembling.

Condition indicators provide indirect but essential information required for a proper CB lifecycle management. They include both measured quantitative values during maintenance or by monitoring systems as well as observed qualitative values during periodic inspections. The CB condition indicators can be divided into two groups: condition indicators related to age (corrosion, mechanical strength and integrity, tightness, insulation, current carrying capacity, accessories, etc.) and condition indicators related to switching operation history (performance during the operation, dynamic electrical and mechanical integrity, contact wear, dielectric integrity of medium, etc.). The first group is mostly based on data acquired in continuous monitoring (e.g. trending or alarms on gas pressure or temperature, etc.) or periodic testing and inspections (e.g. visual observations, gauges reading, insulation integrity, PD, contact resistance, etc.). The second group is based on data obtained during switchgear operations. It could be done while the equipment remains in service or off duty. The basic indicator in this group is the history of operations i.e. the number and nature of switching operation (normal/fault condition) and derived cumulative I^2t for estimating contact wear. Several condition indicators are related to timing of operation, e.g. requirements for simultaneity of poles and series connected interrupter units defined in IEC 62271-100 [4], break times, make times, arcing times, pre-arcing times, etc. Other important condition indicators related to electrical performance of CB could be detected during normal operations such as restrike/re-ignition occurrence, multiple prestrikes occurrence in one interrupter, long delays between prestrikes within one pole, etc.

In this paper we will elaborate on the second group of condition indicators mentioned above.

3. PROPOSED DATA STRUCTURE FOR A CB SWITCHING OPERATION

There is a need to structure the data relative to CB operations. A data structure is proposed with an objective of containing all relevant data related to a given CB operation. It must be easily encoded, stored and exchanged between systems, devices and users. So exchanged data can be combined in many ways: gather the data about one operation from different sources, assembly the data from many operations of one CB, comparing the data from different CB, etc. This structure facilitates all kind of analysis: calculations of condition indicators, statistical analysis, modeling, publishing and reporting, etc. It is scalable i.e. can accept any new type of information or evolution (new version) of existing information. This structure is called a sequence of event (SE) which is representative of all data relative to a CB operation.

The SE is composed of a header and a sequence of events. The header contains information such as the date and type of switching operation (close/open), basic information such as position in the substation, application, CB model, number of interrupters, use of controlled switching, pre-insertion resistors, etc., as well as grid data such as voltage and current phase angle, voltage value in p.u., inrush current in p.u. and nominal current. Ideally, the date and time of the switching operation is stamped with high precision. For example the system IRIGB has a precision of 1 ms and a 61850 event could be tagged with 1 µs of precision.

The main part of SE is a list of a data structures describing the operation of the CB. Indeed, the CB operation follows a predetermined sequence of events of mechanical and electrical nature (Fig. 1, Table 1). If the CB operates off duty, the electrical events do not occur. The sequence is predetermined by the mechanical events and, to a lesser extent, by electrical network condition (mainly voltage and current waveforms). For example, the prestrike will occur when the contacts are close enough and instantaneous voltage exceeds the withstand voltage across them.

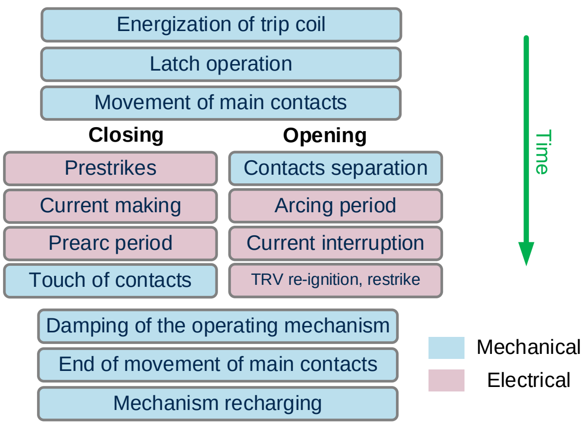


Figure 1. Overview of a CB operating sequence of events

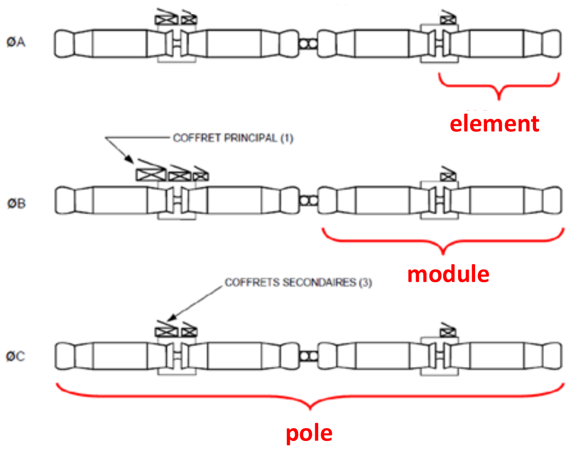


Figure 2. Top view of the CB, definition of a pole, module and element as per IEC 62271-100 [4]

The data structure describing an event is composed of event codes (Table 1), event position, event identification, and event value.

Event position express in which part CB the event occurs. Each event has a type of position: "Global", "By pole", "By module", and "By element" (Table 1 and Fig. 2). The element is also defined as making or breaking unit. The event related to trip mechanism (coil current) or event related to load current are evaluated by pole, which is coded for example as: *O.RM.B* for a latching operation of the tripping coil of phase B or for example *F.ECC.C* for current making in phase C. Some mechanical events are related to a whole module: for example *O.FCC.A.M1* means “end of movement of main contacts of module 1 in phase A”. Finally, many events are related to an interrupter or element, for example *F.PCA.B.M1.E2* means prestrike across contacts in module 1, element 2 in pole B. If multiple prestrikes occur we can identify them by successive numbering *F.PCA.B.M1.E2#1*, *F.PCA.B.M1.E2#2*.

Event value is a pair: event time and optionally event amplitude. Event time is referred to a special beginning event DEBUT which relative time is by convention zero and its absolute time corresponds to the date of operation. The event amplitude has a meaning only for some events, e.g. amplitude of restrike (*O.RM*) could be the amplitude of restrike transient current or for the event trip coil current saturation (O.SB) maximal value of coil current. The value is denoted by an equal sign: *O.RM.A.M1.E2 = 55 ms* means that restrike occurred at 55 ms from the beginning. The value could be the exact number or a distribution *F.MCA.A.M2.E1 = n(47.3; 0.9)* means that the timing test of CB gives for this element the average time of contact touch of 47.3 ms with standard deviation of 0.9 (*n* stands for normal distribution).

Table 1. Detailed list of events

Code[1]	Event description	Event type	Position type
DEBUT	Beginning of recording	N/A	Global
O.EB	Energization of trip coil	Mechanical	By pole
O.DME	Latch operation of trip coil	Mechanical	By module
O.FCP	End of movement of trip coil armature	Mechanical	By module
O.SB	Trip coil current saturation	Mechanical	By pole
O.MM	Beginning of movement of main contacts	Mechanical	By pole
O.DIR	Opening resistor insertion	Mechanical	By element
O.DPS	Beginning of gas blast in the interrupting chamber	Mechanical	By element
O.SCP	Instant of main contact separation	Mechanical	By element
O.CCPA	Current commutation from main contacts to arcing contacts	Mechanical	By element
O.SCA	Instant of arcing contact separation	Mechanical	By element
O.IA	Initiation of switching arc	Electrical	By element
O.DTC	Beginning of transient current in the primary circuit	Electrical	By pole
O.IC	Current interruption (arc extinction)	Electrical	By pole
O.PZN	Zero crossing of the natural 50/60 Hz current	Electrical	By pole
O.TTR	Initiation of transient recovery voltage (TRV)	Electrical	By pole
O.RL	Occurrence of a re-ignition	Electrical	By element
O.RM	Occurrence of a restrike	Electrical	By element
O.FB	Closing of auxiliary contact 52b	Mechanical	By module
O.OA	Opening of auxiliary contact 52a	Mechanical	By module
O.AFC	Beginning of damping in the operating mechanism	Mechanical	By module
O.FCC	End of movement of main contacts	Mechanical	By module
O.DRP	Beginning of steady-state operation	Electrical	By pole
F.EB	Energization of closing coil	Mechanical	By pole
F.DME	Unlatching of the operating mechanism	Mechanical	By module
F.FCB	Latch operation of closing coil	Mechanical	By module
F.SB	Trip closing current saturation	Mechanical	By pole
F.MM	Beginning of movement of main contacts	Mechanical	By module
F.DRD	Beginning of dielectric strength decrease between contacts	Electrical	By module
F.DPP	Beginning of the period of probable prestrikes	Electrical	By module

[1] The codes were originally defined in French, O stands for opening, F for closing, acronyms correspond to French original expressions

F.PIR	Prestrike related to closing resistor insertion	Electrical	By element
F.ECR	Current making in closing resistors	Electrical	By pole
F.MCR	Touch between closing resistor contacts	Mechanical	By element
F.PCA	Prestrike across arcing contacts	Electrical	By element
F.ECC	Current making in the primary circuit	Electrical	By pole
F.MCA	Touch of arcing contacts	Mechanical	By element
F.EPA	Extinction of pre-arc	Electrical	By element
F.MCP	Touch of main contacts	Mechanical	By element
F.FA	Closing of auxiliary contact 52A	Mechanical	By module
F.OB	Opening of auxiliary contact 52b	Mechanical	By module
F.AFC	Beginning of damping in the operating mechanism	Mechanical	By module
F.FCC	End of movement of main contacts	Mechanical	By module
F.DRME	Beginning of mechanism recharging	Mechanical	By module
F.FRME	End of mechanism recharging	Mechanical	By module
F.DRP	Beginning of steady-state operation	Electrical	By pole

The event can be evaluated by different physical measurements, e.g. coil current (*EB*, *DME*, *FCP*, *SB*, *O/FA*, *O/FB*), CB timing (*O.SCA*, *O.DIR*, *F.MCA*, *F.MCR*), load current (digital relay or fault recorder) (*O.DTC*, *O.IC*, *F.ECR*, *F.ECC*, *F.DRP*), Transient Electromagnetic Emissions (TEE) [5] (*O.RL*, *O.RM*, *F.PIR*, *F.PCA*), etc. Fig. 3 shows a few examples how to evaluate some sequence events from different measured oscillograms.

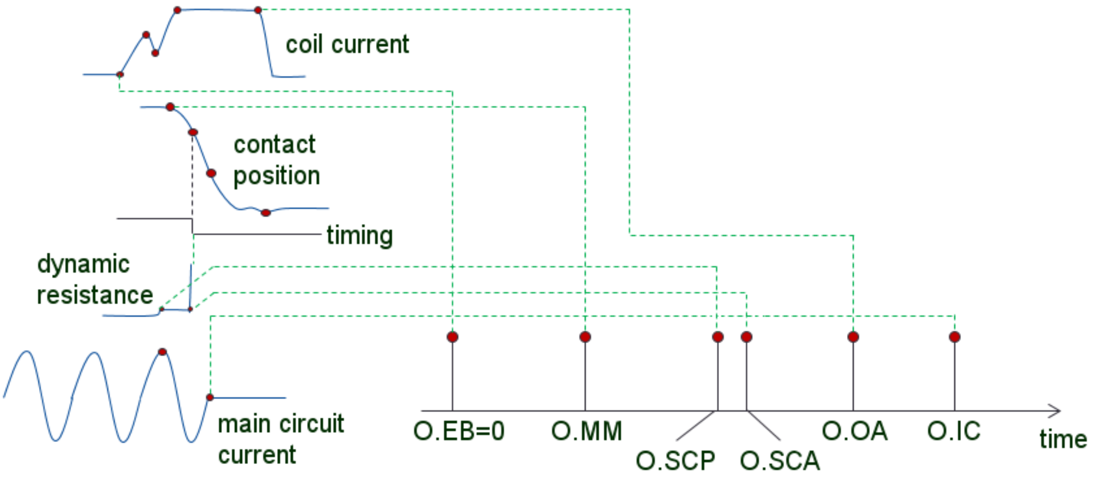


Figure 3. Elements of a SE on opening based on different physical measurements: coil current, load current and dynamic resistance with contact travel

The deviation (e.g. delay) of one mechanical event will eventually affect the remaining events. Modelling the course of the sequence based on known timing parameters and comparing it to the measurements (e.g. current making) would allow to find eventual discrepancies.

Some elements of the SE can be considered as condition indicators themselves, other condition indicators related to timing of CB switching operation are evaluated based on this sequence of events by simple calculations. For example the simultaneity of poles on closing (IEC 62271-100 §5.101 [4]) can be expressed as Max_p *{F.MCA.p}* <= *"1/4 of a cycle"*, *p* = *A*, *B*, *C* or the simultaneity of series connected interrupters (elements) as Max_e *{F.MCA.A.M1.Ee}* <= *"1/6 of a cycle"* where *e* is a number of element in a module.

4. DIAGNOSTIC SOFTWARE

Hydro-Québec has developed specialized diagnostic software and database to store data from various CB diagnostics tools such as Transient Electromagnetic Emissions (TEE) based diagnostics [5], dynamic resistance tests, digital relay recordings and CB timing tests. The software allows for treatment of different recordings with different sampling rates with one common time base. Fig. 4 shows a combined analysis of coil current, load current and antenna signal (TEE). The arrows on the bottom indicates how closing time (*ct*) and insertion time (*it*) are evaluated: *ct = F.ECR - F.EB* and *it = F.ECC - F.ECR*. In this case the data was measured by different recorders which share a common trigger signal. In such a case the precise alignment (synchronisation) of recordings is easily obtained using known settings such as pre trigger and delay.

If the recorders are asynchronous, the resynchronisation of recordings could be done by precise time stamp (GPS, IRIGB, 61850) or sometimes by identifying common reference characteristics. For example the event "opening of auxiliary contact 52a" (*O.OA*) can be measured by coil current and directly by the state of the auxiliary contact. Then, it would be possible to resynchronise two distinct recorders if one measures the coil current and the other the state of the contact.

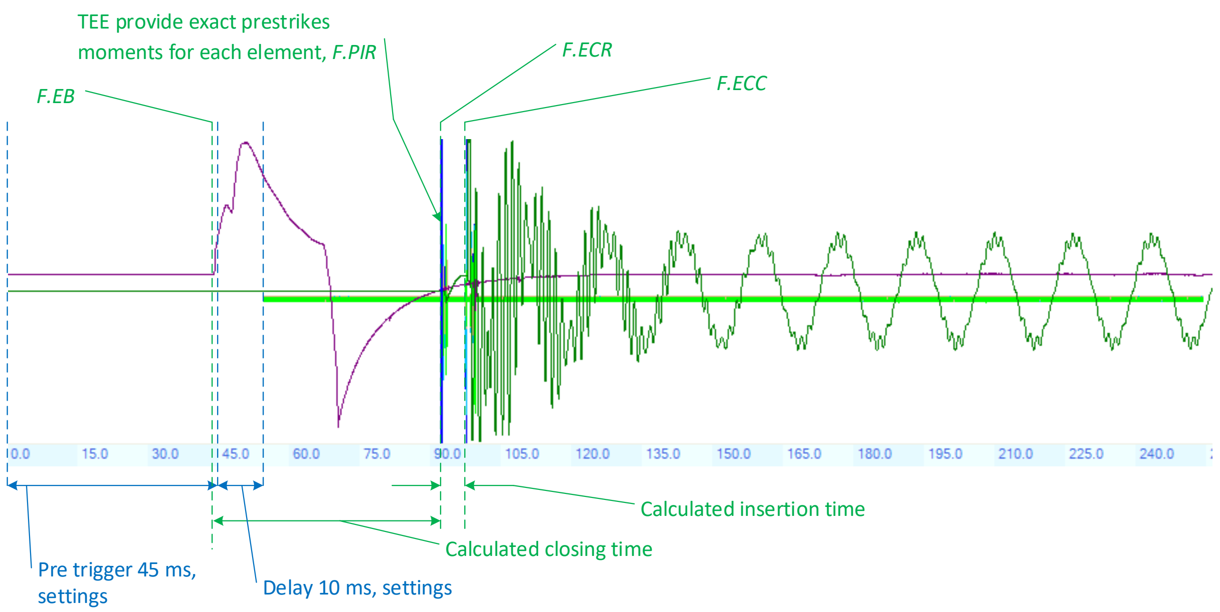


Figure 4. Combined measurements of coil current, load current and antenna signal (TEE) for a CB with closing resistor using different acquisition tools

The developed software implements a data structure based on a SE and underlying protocol to store, exchange, and use the data collected during a CB switching operation in order to evaluate more complex condition indicators based on long term statistics and trending as well as produce the reports. The advantage of applying the SE is that, once the events are processed from each recordings, there is no more need to store the individual data, such as travel curves, into the DB. Further exploiting of the results will be easier and more efficient.

The SE is encoded in xml format. This allows for any manipulation with any other data corresponding to CB operation. The xml files are very flexible and can be transformed and combined in many ways enabling any configuration and application.

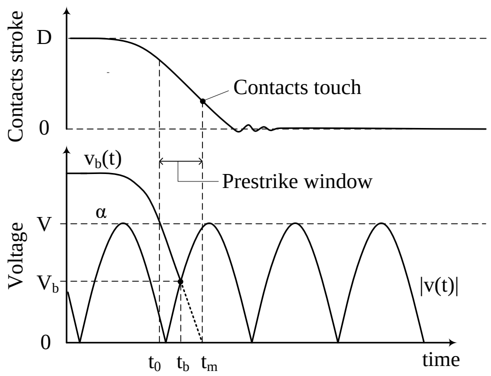
There are two other objectives: distributed monitoring and comprehensive analysis of data.

Distributed monitoring is a model where the data of many straightforward (simpler), standalone, specialized monitoring devices are combined. Each measures one type of signal and provides a partial SEs. The diagnostic software gathers these partial results, combines them into a more comprehensive SE that can be used for diagnostics or other analysis. For example, the SE will ensure that data collected from a coil current monitor installed in the CB control cabinet can be used in conjunction with data from a digital relay or fault recorder monitoring load current and voltage installed in substation building, with data from a TEE signal recorder installed in the vicinity of CB, with data from travel transducers installed in the CB mechanism, etc. Two requirements are to be fulfilled: the synchronisation between standalone recorders and algorithms for automatic calculation of all elements described in the SE (Fig. 3). The former will be achieved with implementation of 61850. The latter is under development.

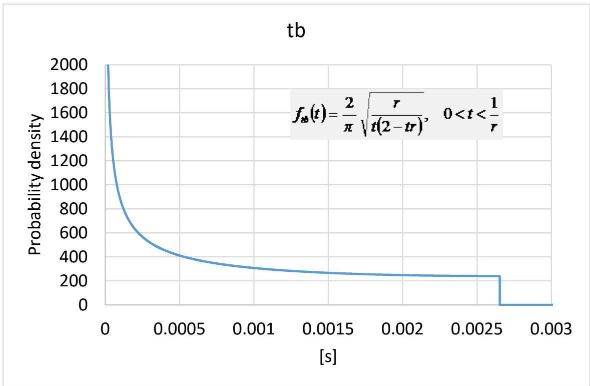
Comprehensive analysis of data aims to develop statistical models in order to retrieve as much information as possible using optimal data. One example of such modeling, still in development, is presented the section below.

5. EXAMPLE OF SEQUENCE OF EVENTS APPLIED TO CB DIAGNOSTICS ANALYSIS (PRESTRIKE CHARACTERISTICS AND MECHANICAL SCATTER)

Prestrike times (*F.PCA*) can be retrieved from load current waveforms and can be used for non-intrusive, in service approximating CB timing characteristics. The simplified modeling of prestrike times is depicted in Fig. 5a, where t_0 is instance when the CB's dielectric strength is equal to the peak voltage between the contacts on closing, *tb* (time to breakdown or making) is a period from t_0 to the moment when the instantaneous voltage equals the instantaneous dielectric strength (voltage withstand) on closing and t_m is time to mechanical contact touch (*F.MCA*). *tb* is a function of phase angle (α) of voltage and the RDDS (r) [6]. Then we have $F.PCA= t_0+tb(\alpha, r)$



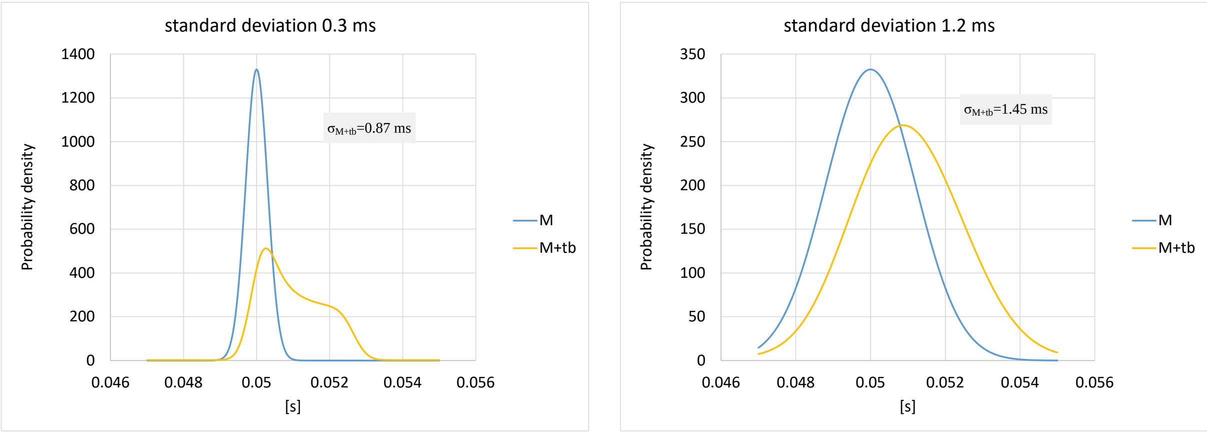
(A)



(B)

Figure 5. (A) Prestrike time determination during a closing operation, (B) probability density of a function *tb* (time to breakdown)

Considering that angle α follows a uniform distribution ($\alpha = u(0, \pi)$), which is the case if there is no controlled switching, the function *tb* is a statistical distribution with a density of probability as presented in Fig. 5b. The time t_0 depends on the mechanical scatter of the CB which is usually modelled by a normal distribution. Then prestrike time is calculated by the summation of the two distributions: $F.PCA = N(\mu_M, \sigma_M)+tb(u(0, \pi), r)$, where μ_M, σ_M are mechanical parameters which could be evaluated by traditional timing tests and r is the rate of decrease of dielectric strength (RDDS) of the CB, its nominal relative value at 60Hz being 377 (ω). The absolute value of RDDS is its relative value times the peak voltage across CB contacts. Fig. 6 compares the two scenarios: a CB with low scatter (σ=0.3 ms) and a CB with more important mechanical scatter (σ=1.2 ms). In the 2nd example, the impact of prestrike time is small (standard deviations of the original mechanical distribution and the resulting distribution are comparable). For both cases it would be possible, based on prestrike recordings to calculate the mechanical distribution i.e. the scatter of the circuit breaker with the CB in service.



(A) (B)

Figure 6. Distribution function of prestrike time (*tb*) for RDDS 1p.u. (A) σ=0.3 ms (B) σ=1.2 ms

6. CONCLUSION

A comprehensive data structure with underlying protocol is proposed to store, exchange and analyse any data gathered during a CB operation.

A distributed system for monitoring CBs with simple sensors or monitoring devices contributing to a common data structure is possible.

Data interoperability for heterogeneous data analysis (from different systems) in a common and coherent environment is ensured.

Models are described on how to apply this data structure to evaluate condition indicators and statistical analysis.

This data structure is aimed to be eventually implemented in IEC 61850.

This research is ongoing. Further development and applications are expected.

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