Condition Monitoring of High Voltage Circuit Breakers: Past to Future

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Abstract— **High voltage circuit breakers (HVCBs) play a critical role on providing the desired reliability, and resiliency in power systems. In order to extend their lifetime and predict the failures, various maintenance policies could be applied on these critical components. Amongst these strategies, condition-based maintenance (CBM) provides a satisfactory agreement with future smart environment. This paper aims to provide an insight into the relevant developments in this subject and to explore the viable visions compatible with future research stream. Accordingly, three directions, i.e. diagnostic signals, intelligent modelling and using monitoring data in asset management have been addressed in this paper. It presents challenges dealing with real-time assessment of the diagnostic signals relating to measurements, and analyses. Subsequently, the issues associated with using artificial intelligent (AI) and Machine learning for providing intelligent algorithms have been discussed. Finally, the connection between the monitoring data and the asset management approach is investigated. The latter is looking for the subjects including remaining lifetime estimation, prioritization, and health index definitions. This paper has attempted to make a bridge from past to future research trends in the failure diagnosis of HVCBs.**

Index Terms—**Circuit breaker (CB), condition monitoring, fault diagnosis, maintenance, future trend, visionary paper.**

I. INTRODUCTION

HIGH voltage circuit breakers (HVCBs) have been recognized as the critical components owing to their role in protection and switching. Therefore, any failure in these components could highly influence the reliability and resiliency of power systems. Many failures, even explosion, have been reported dealing with the non-perfect operation of the CBs [1], and [2]. As the CBs are comprised of various mechanical and electrical components such as damper, latch, spring and coils, the failures could be of different origins [3]. In addition, various maintenance policies could be applied to avoid the failures and extend the lifetime of these assets.

CBs consist of three main sections, i.e. control section, operating mechanism, and the interruption chamber [3]. In addition, they are conventionally categorized based on the arc quenching medium into the air, minimum oil, SF_6 and vacuum CBs. While SF_6 CBs are widely used in high voltage level,

vacuum CBs are employed in LV and MV power networks due to some restrictions. Some researchers have recently focused on SF_6 alternatives giving rise to global environmental effects [4], [5]. Furthermore, regarding the fast growing renewable energy sources, and employing high voltage DC networks (HVDCs) for transmission, some efforts are devoted to develop the hybrid DC CBs to provide a forced current zero crossing for mechanical CB using power electronic layout within acceptable operation time [6], [7].

Inspection and maintenance have been practically preformed through various policies to extend the lifetime of the CBs and avoid the failures. The main maintenance strategies are time-based maintenance (TbM), condition-based maintenance (CBM) and reliability centered maintenance (RCM). TbM or preventive maintenance refers to preforming some activities within a predefined time-interval to prevent the component failures. As the inspection interval is determined irrespective to the condition of the components, it is possible that a part experiences a serious problem prior to the next inspection. Therefore, this policy might result in the cost increase without any reliability improvement in some cases. The next inspection time, and the required activities could be determined based on the condition of the CBs through recording some signals such as the number of operations, coil current (CC), timing test and other diagnostic parameters in CBM, also called predictive maintenance. RCM stands for the implementation of the CBM regarding the importance of the CBs in the power systems and allocating the budget on critical part of the network [8]–[11].

Amongst different maintenance strategies, CBM could be more compatible with future smart environment due to the use of diagnostic signatures. This paper aims to expose the challenges of the CBM, the developed solutions, relevant researches as well as the future achievable visions. The main step toward implementation maintenance strategies for HVCBs is to understand failure modes, the origin of the failures, and using suitable diagnostic signals. Accordingly, Section II has been devoted to provide an insight into the failure statistics dealing with main components of the CBs. Having identified the trend of origin of the failures, the rest of the paper is organized to precisely scrutinize the challenges and visions through three directions

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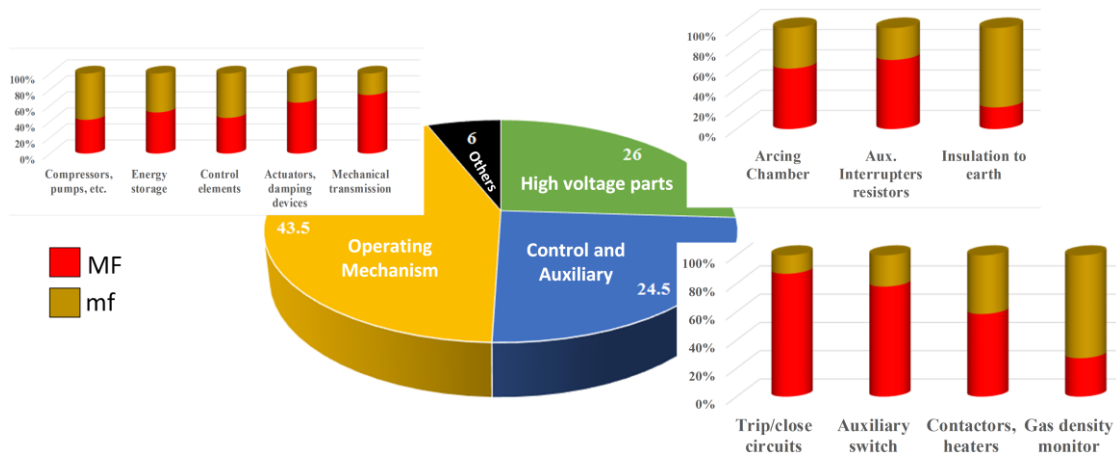
Figure 1. Percentage of failures related to the subassembly and component responsible [12].

including diagnostic signals, intelligent modelling and using monitoring data in asset management. In the first direction, diagnostic signals and the relevant efforts have been discussed to point out the challenges and new visions. Section III addresses data gathering and intelligent modelling to evaluate the applicability of the recent and emerging concepts such as artificial intelligent (AI) and machine learning in the context of CBM. The last direction explained in IV presents some challenges and viable visions from power systems point of view such as using monitoring data for lifetime estimation, failure rate reduction, budget management of online monitoring (OLM) systems, and aging tracking algorithms.

II. TREND OF ORIGINS OF FAILURES IN HVCBS

An imperative step toward the implementation of an effective condition assessment approach is to identify the failure modes and the origin of the failures over time. It provides a great insight into the main concerns for more attention, and further research to realize the effective diagnostic signals. Failure statistics have been published in literature based on various viewpoints and historical data [11]-[17]. Reference [13] presents an extensive study of SF_6 and minimum-oil CB failures in Swedish and Finnish transmission systems including 1546 breakers with a total operating history of 16384 years. It has been indicated that the CBs with higher operating frequency (more than 50 operations per year) have been more vulnerable to failures. In [14], the failures of 8600 HVCBs (with rated voltages higher than 100 kV) including minimum oil, air blast and SF_6 with about 6800 failures have been investigated to identify the failure rate trend and optimum time of maintenance. It has been reported that 40%, 30% and 24% of the origin of failures are dealt with the operating mechanism, high voltage and secondary and auxiliary circuits of SF_6 CBs, respectively. In addition, it has been deduced that the aging problem could not be detectable up to 15 yrs.

In addition to these surveys, three reliable worldwide comprehensive surveys have been conducted by CIGRE since 1970 to scrutinize the failure origins. The first survey is comprised of 77892 CB-years from 102 utilities of 22 countries [15]. The second survey has been limited to the single-pressure SF_6 CBs with various operating drive mechanism including 70708 CB-years from 132 utilities of 22 countries [16]. The last survey has been conducted in the years 2004-2007 including 281090 CB-years from 83 utilities from 26 countries [12]. It is indicated that about 60%, 6% and 36% of maintenance philosophies are dealt with TbM, CBM and combination of those, respectively. CBs are generally divided into three main parts, i.e. operating mechanism, high voltage parts as well as control and auxiliary. Figure 1 presents the influence of these main parts and their sub-sections on the major and minor failures (MF, mF) [12],[17]. The origin of about 50% of failures is the operating mechanism, then control and auxiliary circuit (about 25%) and high voltage part (about 25%). As shown in Figure 1, the main parts include sub-sections with different portions of the total failures. While, it is indicated that the trip/close circuits and auxiliary switch are the origins of more than 6% of MF in the control and auxiliary part, about 50% of MF in the high-voltage part has been reported from the interruption chamber due to the erosion in the contacts, and misalignment of contacts. Furthermore, malfunction in damper, energy storage and mechanical transmission system are the most origins of the MF failures in the operating mechanism [12].

In addition, it is revealed that the technology of the operating mechanism is changing toward the spring drive mechanism: from a portion of 40% in the early days to 60% these days owing to the lower failure rate in comparison with the other mechanisms. While aging, erosion, and deterioration have been reported as the most important reasons of MF (about 50%), design faults, manufacturing faults, and incorrect maintenance together are reported as the causes of 15% MF. The comparison amongst results of three worldwide surveys indicates an improvement of the reliability of CBs from 1.58 to 0.30 MF per 100 CB-year [12].

The surveys reemphasize that the operating drive mechanism, the high voltage part and finally the control section are the most origins of the MF in CBs, respectively.
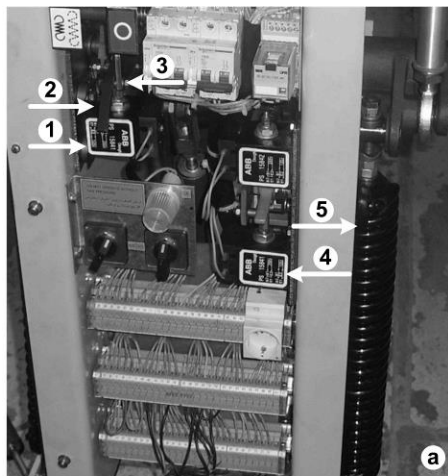
① Close Coil ② Latch ③ Armature ④ Trip Coil
⑤ Opening Spring

(a): a control section and drive mechanism
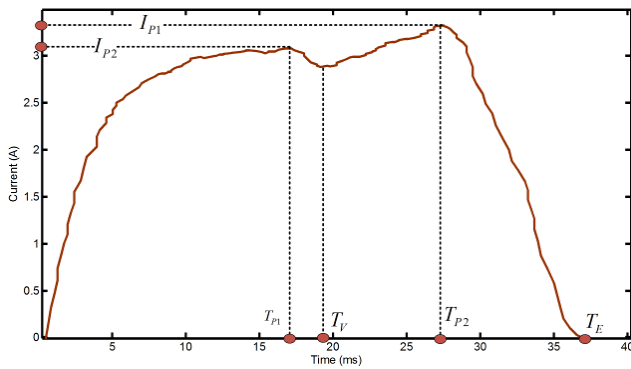
(b): a recorded trip coil current

Figure 2.Trip/close coil and related current and diagnostic features [18]

Therefore, the effective diagnostic signals are those that can reflect the condition of the mentioned failure origins. More information about the failure modes and the origins are available in [17].

III. MONITORING PARAMETERS, AND CHALLENGES

Various diagnostic signals could be employed to assess the condition of the CBs under offline / online conditions. In this direction, the most important diagnostic signals have been presented to point out the research stream, the challenges and the required conceivable future-researches.

A. Coil current

Figure 2 (a) illustrates the main components such as close coil, trip coil, latch, armature and spring drive mechanism for a 72.5 kV, SF_6 CB. The measured trip coil current and its diagnostic features are shown in Figure 2 (b). The current profile is characterized through some time- and current-based features. Once a CB receives the trip/close command, the trip/close coil is energized. Once the coil current reaches the pre-designed value (I_{P1} at T_{P1}), the armature inside of the coil moves up to hit the latch (at T_V). Subsequently, the energy stored in the operating mechanism (usually the charged spring(s)) is released to start the motion of contacts through the mechanical transmission linkage (T_{P2}, I_{P2}).

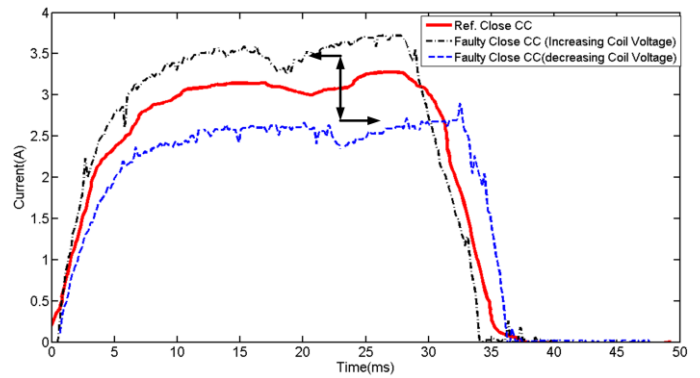Figure 3.The impact of coil supply voltage failure on CC [19]

Numerous efforts have addressed this signal to realize proper diagnostic features, provide a link between failures and the features, and to use this signal in the fault detection algorithms. In [19] and [20], the interaction between various failures resulting from malfunction in latch, control voltage and coil have been investigated. In [21] and [22], the appropriate diagnostic features of the coil current have been identified to apply for fault prediction. In [18], this signal along with the travel curve (TC) have been employed for fault detection in HVCBs. The problems in battery, degraded contacts and coil, and friction have been diagnosed using CC in [22], and [23]. Reference [25] employs CC signal for detection of the coil aging, core jamming and lack of core travel space. Timing features of CC signal have been utilized in [26] to improve the fault detection based on the vibration signals. One of the important challenges in diagnosis is identification of the threshold level of features from the normal (healthy) state to the faulty state, which has been addressed in [21] and [27] applying data mining and taking an probabilistic approach.

More precisely, the CC could track the failures in following sections: trip/close coil supply voltage, continuity of the coil, latch, and auxiliary switches. Once the station battery or any other source is not in good condition, the voltage applied on the control unit of CB can be lower or higher than the set value. This abnormality leads to shift up and left as well as shift down and right of CC signal for the cases of the higher and lower than normal supply voltage, respectively (See Figure 3). The continuity of the coil changes the resistance of the coil resulting from the aging process or malfunctions. This failure could have an influence on the CC profile. Furthermore, the latch operation can be imperfect due to the lack of lubrication or in case of a mechanical deterioration. The latch sluggishness is identifiable through its impacts on the CB operation time as well as on the CC waveform [19].

The advantages using this signal are the provision of valuable real-time information from the control section and, to some extent, from the operating mechanism. In addition, it could be employed for the timing test along with TC as explained later. Furthermore, the required measurement sensor (a simple current sensor or shunt resistor) is easy to implement and inexpensive. In addition, the complex post
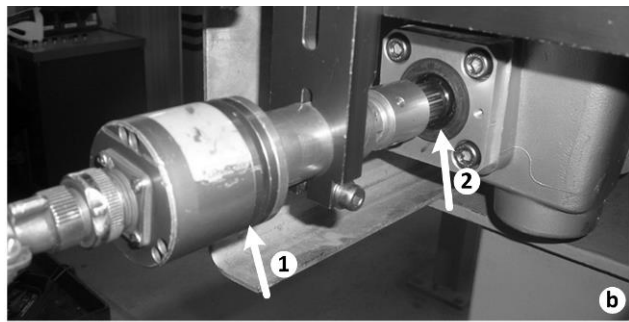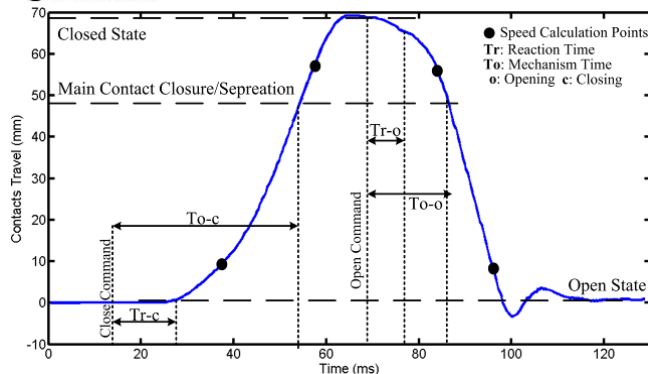
❶ Travel Curve Transducer
❷ Main shaft

Figure 4. The travel curve profile and the required transducer [28]

processing techniques are not required owing to simple CC profile as shown in Figure 2 (b). The CC covers only the failure modes happening in the control and auxiliary circuit. Consequently, it is not solely enough for a comprehensive condition assessment. In fact, it could reflect about 25% of MF.

B. Travel curve

TC refers to the motion of the contacts against time. It is captured via the transducer as shown in Figure 4. It indicates a close-open stroke-time characteristic. The operation speed is calculated based on two predefined points on the curve. In addition, some timing characteristics such as closing/opening reaction time (T_r) and mechanism time (T_o) could be obtained based on this curve. Accordingly, TC is applied for evaluation of the operation time of the CBs (called timing test) as well as malfunctions in the operating mechanism [20] and [28].

Realizing the correlation between the failures and the diagnostic features defined on TC is a prominent step toward proposing an intelligent fault detection algorithm. In this regard, comprehensive investigations have been performed in [20] and [29] to scrutinize the relationship between the failures in on/off switch, damper and trip/close coil on TC profile. In addition, in [30], this profile has been utilized to detect the oil leakage, the friction increase and oil-pressure increase in the damper. Similarly, the operating mechanism of a 12 kV CB has been simulated to evaluate the anomalies in the coil, opening spring, and oil buffer in [31].

In conclusion, TC is an appreciable signal in identification of the failures in the following sections of the CBs: the latch supply voltage, coil, damper, leakage/spring setting, contact failures, and pull rod failure [20] and [28]. The higher/lower
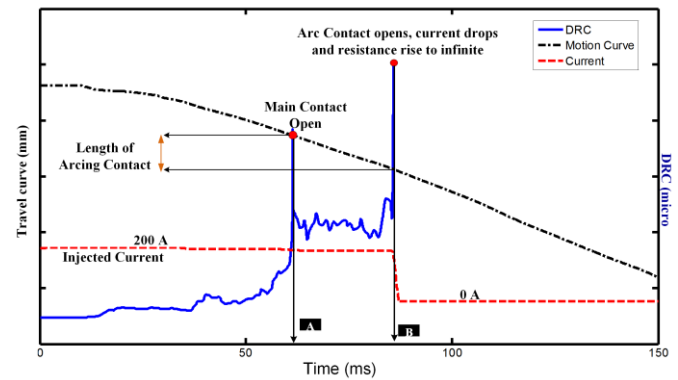

Figure 5. Dynamic resistance profile [32]

supply voltage leads to a faster/slower operation of trip/close coil. Consequently, these failures affect the timing characteristics of TC. Similarly, malfunction in the trip/close coil changes timing of the CBs. Accordingly, the fault could be identified based on the time-based features of TC. The tail of opening TC as shown in Figure 4 could reveal the anomaly in dampers. Once a failure happens in damper, the overshoot (over travel) and undershoot of the TC is changed in comparison with the healthy curve. Once a failure is resulted from improper setting of the spring drive mechanism or oil leakage in hydraulic drive mechanism, the speed and timing characteristics of TC are varied in comparison with the normal features. Consequently, with respect to the strong link between operating drive mechanism and TC, any malfunctions in this section could be detectable using TC [20] and [28].

The main advantage of TC is its ability for providing valuable information from the most origin of failures in CBs, i.e. operating mechanism. In addition, the complex post processing is not required for analysis of such a simple profile as shown in Figure 4. Furthermore, it is an important signal in coupling with dynamic resistance profile to identify the arc contact length. Moreover, this signal usually is available in data sheet released by Manufacturers for all CBs within the routine tests. Therefore, it could be employed as a fingerprint in the condition assessment methods.

The disadvantages using TC is the need for the installation of a transducer sensor leading to inapplicability of this method in online assessment for some CB designs [20] [28] [33]. In response to this, reference [28] has attempted to provide a correlation between auxiliary contacts and TC. It is indicated that there is a link between timing of auxiliary contacts and TC.

C. Dynamic Resistance Measurement

Arc and main contacts are deteriorated during the switching under normal and short circuit currents in the life cycle of the CBs. In order to evaluate the condition of the contacts without dismantling of CBs, dynamic resistance measurements (DRMs) have been suggested. In this regards, once a DC current is injected, the voltage across the breaker during the opening operation is recorded to find out the profile of the resistance versus motion as shown in Figure 5 [34] and [32]. For this purpose, a 200-A DC current is injected into the CB.

Once the CB starts to move (see motion curve), the dynamic resistance (DRC in Figure 5) increases owing to the increase of the current path length. The initial part of this dynamic profile stands for the main contact resistance. While the current is commutated from the main contact to the arc contact, a jump is observed in DRC owing to a high resistance material used in the arc contact. After a while, the current is interrupted. As it is demonstrated, in addition to the main and arc contact resistance, the arc contact length could be obtained through combination of the motion curve and DRC [32]. Once the main or arc contact is eroded or shortened the DRM profile changes in comparison with the healthy case. While the erosion increases the resistance, the shortening leads to a change at the separation time (A in Figure 5). Therefore, the malfunctions could be visible using DRM without any dismantling of the CBs.

In fact, similar to other diagnostic features, the correlation between failures and the features is an imperative diagnosis step. In response to this, the impacts of erosion in the fix and moving arc and main contacts as well as the broken fingers on DRM profiles have been scrutinized through simulation in COMSOL in [32]. Limitations to estimate the contact erosion in the early stages have been discussed in [35], where it has been shown that the early stage of contact erosion is not reflected in the dynamic resistance curves. In [36], the contact erosion has been calculated based on the defined diagnostic features on DRM profile. Furthermore, some new features have been defined in [37] based on the DRM profile. They have been verified by conducting some experiments based on five-erosion levels of the arc and main contacts.

The main advantage using DRM is that it could provide helpful information associated with the condition of the arc and main contacts without any dismantling. The disadvantages are as follows: applicability only in offline mode of the CBs, need for TC for assessment of the arc contact length, sensitivity of the results to the injected current, and dependency of clarity of profile to operation speed of the CBs.

The implementation of this technique and its repeatability have been recently focused in many efforts. Reference [38]–[42] indicated that the measured resistance in this test is dependent on the injected DC current and opening velocity. The resistance decreases with an increase in the injected-current and decrease of the velocity. In addition, some efforts have been conducted to propose some methods rather than DRM to provide similar information in the real-time assessment. To give an illustration, in [43], the overlapping time and the contact speed for generator CBs have been identified based on high-frequency impedance of the breaker. Subsequently, the results have been compared with those obtained by DRM.

D. Energy

The estimation of remaining lifetime of the contacts based on mass loss calculated through energy during interruption/making of the currents has been recently
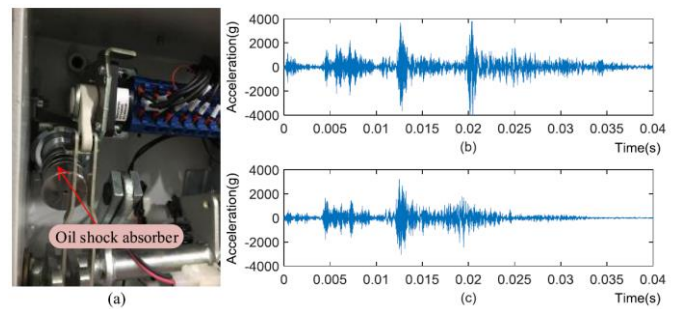

Figure 6: Samples of vibration signals (a: oil damper, b:healthy c: faulty) [53]

addressed in the diagnosis of the CBs. The main advantage of this approach is its applicability in real-time approach. It is somehow considered as an online version of the DRM.

A novel approach proposing an electric circuit design for real-time measurement of the arc voltage has been presented to predict the remaining lifetime of the CBs based on the energy in [44]. In this effort, the arc energy is calculated based on the recorded arc current using current transformer, and the arc voltage through the proposed online measurement system. Other investigations have been performed to inclusively reveal the relationship between the eroded-mass caused by short-circuit current interruption and different thermal stress indices such as transferred electrical charge, current squared, and arc energy in [45]. The mass loss is presented as a function of electrical parameters such as transferred electric charge, arc energy, or integral of current squared. These indices change regarding the erosion and aging of the contacts. In addition, it has been indicated that the change of morphology of the contacts changes the rate of erosion due to tendency of the arc to start from uneroded regions. Tungsten-copper contact materials are the main components of HVCBs. Reference [47] revealed that the arc ablation of these materials is predominantly resulted from the evaporation and splashing of copper component which has a low melting point, followed by the ablation and spallation of the tungsten skeleton structure. In [48], it is shown that the arc roots tend to be formed on larger copper zones and if the zones are not confined by tungsten area, the arc cross section expands resulting in a higher evaporation rate of copper areas.

The main challenges or disadvantages using energy for assessment of the interrupter wear is the low accuracy of the indices based on the transferred charge and integral of current squared owing to omitting the voltage. In addition, consideration of the voltage needs special measurement tool to record the arc voltage in a precise manner while withstanding the high voltage transients. Furthermore, comprehensive experimental tests are required to extend the energy based-index for all CBs [45].

E. Vibration

The vibration signal generated during the opening and closing operation of the CBs has gradually become the mainstream research owing to convenient data acquisition as well as its suitability for non-invasive and real-time evaluation, which could cover the most origins of the failures occurring in the operating mechanism of CBs [46], [49]–[52]. This signal

as shown in Figure 6 could reveal the anomalies in the mechanical section. Once a failure (such as in damper, rod, shaft, etc.) happens, the vibration signal changes in compassion with the healthy signal. To give an illustration, deformation of shaft, close coil, insulation pull rod, and damper of CB have been investigated based on the vibration signals in [51]. Similarly, in [53], the malfunction in damper and insulation push/pull rod have been identified using vibration. While the earlier is dealt with absorbing the residual energy and reducing the impact of mechanical collision during HVCB operating, the latter transmits the required energy from operating mechanism to the dynamic contact to perform closing and opening operation. To give an illustration, Figure 6 demonstrates the vibration signals resulting from failure in oil damper and the healthy signal of vibration. As it can be seen, the signal changes under faulty condition. As mentioned, the post processing techniques are necessary to precisely discriminate between healthy and faulty signals.

The main advantage of using vibration is the ability of real-time assessment of the most origins of failures. The main disadvantage of this method is the dependency of its accuracy on the number of sensors and the post processing techniques as discussed in IV-A. The reason lies in the fact that this signal is quite short in the time domain whereas the inherently highly nonlinear and non-stationary vibration signals are extremely wide in the frequency domain [53].

F. Future viable visions

The CC as an inexpensive, straightforward diagnostic signal and compatible with real-time assessment will play an important role in the future condition assessment approaches.

TC provides valuable information owing to the strong connection with the operating mechanism. However, the real time measurement of this diagnostic signal is infeasible in some breaker designs. Although some efforts like [28] or [43] have tackled the problem to realize a link between this signal and the online measurable signals, more investigations are necessary in future. It would be helpful to think about the new sensors for real-time measurement of the TC.

DRM could provide valuable evidence on the condition of the main and arc contacts. However, the main weak point of this approach is infeasibility in real-time assessment [42] [55]–[57]. Consequently, an online condition assessment method will be required to evaluate the status of the contacts encapsulated in an insulation medium. In this regard, although using energy-based method could be a solution, the main challenge would be the difficulty of the online measurement of the arc voltage. Therefore, the new methods based on different normalized-indexes, e.g. the integral of the arc current, could be developed for future online assessment of interrupter wear. In case of vibration signal, although many efforts have been conducted, it seems that still more work is necessary for de-noising and fault detection. The main weakness of this real-time signal is its strong dependency on inclusive post-processing in comparison to
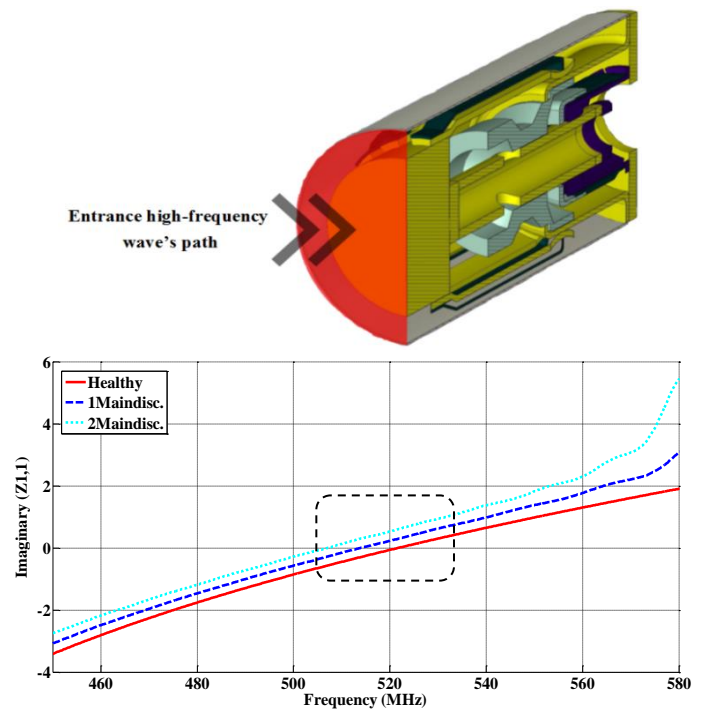

Figure 7. Using frequency response as a novel diagnostic signal [54]

simple profiles such as the CC, TC and, to some extent, DRM.

The main future challenge in selection of diagnostic signals is the constraints resulting from real-time and online approach. Therefore, it could be highly recommended to look for new non-invasive diagnostic methods. On this stream, some researchers have proposed some new approaches based on high-frequency concepts. To give an illustration, using frequency response has been recently suggested as a non-invasive diagnosis approach for CBs. A broadband micro-strip antenna has been employed as the new diagnostic sensor to evaluate the degradation of contacts through establishment of the correlation between the arc duration and signal energy and radiated wave in [49]. In another effort [59], the correlation between different working status of the CBs and the time-frequency characteristics of switching transient E-fields have been addressed to early predict the insulation defect of the HV CBs. In addition, references [54] and [60] have attempted to develop a frequency-based condition assessment approach. Figure 7 indicates how a frequency response is implemented to detect possible malfunction in contacts. As explained with more details in [54], the high-frequency wave is injected into the breaker. The input impedance has been recorded. Once a failure happens in the interruption chamber (e.g. finger breaking), the input impedance moves up resulting in the decrease of the resonance frequency. As shown in Figure 7, while the resonance frequency in the healthy case is 522 MHz, the losing of one and two fingers decreases it to 514 MHz and 507 MHz, respectively.

Although the attention to HVDC network and therefore HVDC CBs are increasing in these days, the proposed hybrid DCCBs are still in the research level. However, these hybrid

breakers will be requiring new condition assessment approaches in coming future.

Finally, in order to provide a comprehensive evaluation on progress of scientific researches on diagnosis of HVCBs, the last 20 years (2000-2020) efforts have been presented in Figure 8. It presents the statistics of researches associated with the researches coil current (CC), travel curve (TC), vibration, DRM and other methods. The trend indicates that real time approach and new signals have been investigated more.
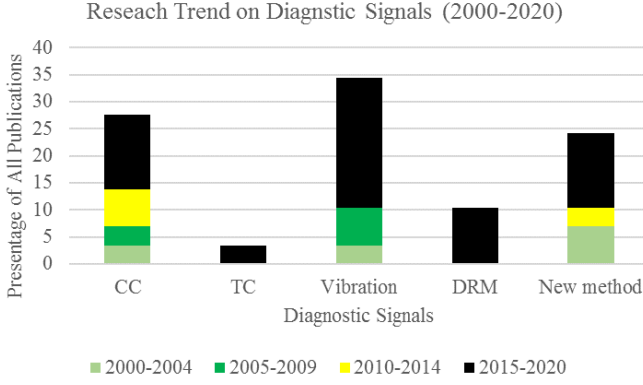

Figure 8. Research Stream since 20 years ago (2000-2020)

IV. DATA GATHERING AND INTELLIGENT MODELLING

All intelligent failure detection methods and life estimation algorithms are established based on data and reference curves. In fact, steps towards the fault detection are comprised of the obtaining of the diagnostic features, and making correlation between features and faulty and healthy cases to provide a condition assessment algorithm or one-step forward, a fault prediction approach. This section has been devoted to evaluate the role of artificial intelligent (AI) in hitherto and future research trend. The collected data from monitoring sensors in a substation or even in a network depending on available communication systems are investigated using AI techniques.

AI techniques, and machine learning are widely applied in the fault detection. Table I presents the trend of application of various approaches in diagnosis of HVCBs. It could be deduced that these methods are extensively dealt with the vibration signals. The main challenge dealing with this signal is its complexity. Therefore, the post-processing step for features extraction plays a significant role owing to the quite short time domain and the extremely wide frequency domain as well as the strong nonlinearity and non-stationarity of vibration signals. In fact, vibration signal includes abundant information of CB's mechanical conditions. Furthermore, the features of waveforms of this signal resulted from various failures may exist in different frequency components. Consideration of the noise in real-time assessment increases the complexity of the processing of vibration signal. The first step toward using vibration as a diagnostic signal is employing multi-scale decomposition methods such as

TABLE I
TREND OF INTELLIGENT DIAGNOSIS METHODS

Signals	Methods
Vibration	Energy entropy of Hilbert marginal spectrum (HMS), variational mode decomposition (VMD), [53] (2019)
	Wavelet, stacked auto encoder neural network [46] (2018)
	Current vibration signal entropy weight characteristic, grey wolf optimization-support vector machine (GWO-SVM), [49] (2019)
	Phase space reconstruction, Lyapunov exponent (LLE), correlation dimension (CD),Kolmogorov entropy (KE) [51] (2019)
	Empirical mode decomposition (EMD) energy entropy, multi-class support vector machine (MSVM) [61] (2010)
Vibration and Coil current	Wavelet packet, Multi-mapping [25] (2017)
DRM, Prediction purpose	Kernel partial least squares regression, prediction method [42] (2017)
All signals	Analytical hierarchy process (AHP), evidential reasoning (ER) [62] (2013)
TC, Prediction purpose	Maximum likelihood, interacting multiple models (IMM) [29] (2018)
TC and auxiliary contact	Neuro-fuzzy inference system (ANFIS) [28] (2015)
Coil current	Fuzzy-probabilistic analysis [63] (2014)
	Agglomerative Hierarchical Clustering (AHC), Data mining [21] (2015)
TC, Coil current	Neural network and support vector machine (SVM) [18] (2019)

empirical mode decomposition (EMD), empirical wavelet transform (EWT), wavelet packet transform (WPT), variational mode decomposition (VMD) for extraction of features. Subsequently, this signal can be transformed into several intrinsic mode functions. It can considerably restrict the accuracy of diagnostic approach.

The challenges or disadvantages associated with these methods are as follows: comprising of energy leakage, endpoint effect, modal aliasing, envelopment problem, adaptability, randomness of the decomposition levels affecting the robustness of diagnostic results, high computational complexity, which opposes with online monitoring, and consideration of high-frequency part of the signals [25][26][46][49]. The other challenge is the realization of time segmentation of a vibration signal to complete vector features, i.e. starting time and ending time of some major vibration events such as motion of the cam and collision of the moving contact.

Subsequent to the feature extractions, the next main step is to establish an effective classifier model. The point is that as the profile of the other diagnostic signals is not complex, the previous mentioned step generally does not require. However, the classification of features is applicable for all signals. As presented in Table I, the support vector machine (SVM), fuzzy based methods and back propagation neural network (BPNN) are commonly applied in the fault diagnosis of HVCBs. These methods are subjected to some disadvantages as follows: sensitivity to noisy data, dependency to training dataset, misjudgment of fault identification, and long time for training [25] [26].

The other thinkable point is providing a dynamic model for fault detection. To give an illustration, most researches are taking into account that all faults are known. However, recording all types of failures for the training of classifiers is unrealistic. Therefore, the diagnosis model needs to be flexible for identification of unknown faults.

The consideration of the mentioned challenges for improvement of feature extraction and classifier methods could be addressed in future research stream. Furthermore, the trend indicates that it is necessary to move from the feature extraction approaches into a further step, i.e. identification of the thresholds of the healthy and faulty cases to prepare an intelligent fault prediction approach. In this regard, a regression method has been developed to predict the degradation of the contacts in HVCBs in [42]. While in [18], SVM and neural network have been employed to identify the healthy and faulty domain of diagnostic features, reference [21] presented a probabilistic approach using clustering and data mining to intelligently discriminate between faulty and healthy diagnostic features. These algorithms are also applicable in model-aided approach [18][29][64][65] to use model-based CBs for evaluation of condition assessment.

It is worth mentioning that AI and machine learning techniques are helpful in discrimination between healthy and faulty situations and fault prediction. However, none of industrial tools has employed those for smart condition assessment. This is due to the lack of robustness of these methods, their dependency on training data sets and the variety of the CBs with regard to the operating mechanism, type, and different settings, which limits the generalization of the proposed algorithms. In fact, these tools have been stopped on reporting the diagnosis signals and condition assessment for own productions [66], [67].

An emerging concept coupled with intelligent approach is digital twins (DT), which could provide a new paradigm for fault diagnosis and remaining lifetime estimation of HVCBs. DT is a proactive bi-directional approach between real world and virtual world. Once a change is detected in the physical asset or its environment, a learning model has been employed to define simulation scenarios to explore which and how the model parameters need to be modified to mirror the observed-behavior. A DT is a digital holistic emulation of a physical system or assembly using integrated simulations and service data from multiple sources across the product lifecycle. This information is continuously updated and is visualized in a variety of ways to predict current and future conditions [68][69]. In case of the CBs, it could be possible to define a dynamic learning model based on some diagnosis signals such as CC, vibration, TC along with temperature, gas pressure of the interrupter, and number of operations as variables controlling the parameters of the dynamic aging model of the CB. Furthermore, it is possible that a CB has not received any command for a long time. Once this CB operates, the diagnostic features can indicate an improper operation in the first shot. However, it works well in the next operation. Therefore, the dead-time of the operation (idle time of the CB)

could be involved in this dynamic model, as well.

V. APPLICATION OF MONITORING DATA IN SYSTEM LEVEL

In addition to challenges dealing with the component level, diagnosis raw data and monitoring data could be applicable in the system level. An approach is to employ monitoring data beyond condition assessment purposes. The data acquired from maintenance activities during inspections, and overhaul in the substations are recorded in the maintenance centers. Once the components are equipped with online monitoring systems (OLM), the data are available locally or in a monitoring center depending on the communication infrastructure in the power network.

The installation of OLM, and establishment of a link between data and deterioration process could be considered as the main challenges in this context. The applicability of CBs with low failure rate to equip with an expensive OLM is of importance for power network manager. Although a simple response is the risk of failures in CBs is high, it is necessary to make a tie between monitoring data and failure rate to provide a precise insight into the influence of monitoring on aging of CBs.

In [10], and [70], a connection has been established between the monitoring data and aging procedure as shown in Figure 9. The model has been established through a combination of discrete Markov model and signals obtained from OLM systems. Markov chain model quantifies the aging process within discrete states. In addition, the maintenance activities could be involved in the model to determine the lifetime extension of the component. As shown in Figure 9, once a CB operates, the diagnostic features, e.g. timing features of CC, are captured in real-time. Subsequently, regarding the calculated wear-out index (WI), the condition of the CB (normal, alarm, emergency), required maintenance activity (minor maintenance, major maintenance, no-maintenance), and the new state (new normal state or previous state) are determined. The proposed link between monitoring of the CB and aging procedure has been applied for prioritization of the CBs for equipping with OLM systems [10]. As the installation of OLM systems on all CBs is neither economically nor technically feasible, the prioritization approach for selection of critical CBs in power system has been addressed in [8], [9], and [71]. To give an illustration, a qualitative-quantitative approach has been presented in [8], and [9] for prioritization. While the qualitative approach including age, switching frequency, operating drive mechanism, and quenching medium has been included using decision-making method, the interruption cost has been considered as the quantitative side in this model. The deterioration process of CBs could be quantified using monitoring data through real time life-cycle assessment [72]. The remaining lifetime of the CBs could be estimated through a hybrid approach for prognostics of CBs, which integrates deterministic and stochastic operation through piecewise deterministic Markov processes [73]. In addition, the maintenance action could be intelligently determined using monitoring data [74].

The implementation of OLM systems on CBs has been remaining a main concern due to the limitation of the maintenance budget, and the cost of OLMs. Although some above-mentioned efforts have been addressed this vision, more research is required to provide a link between the monitoring data and lifetime estimation and aging.
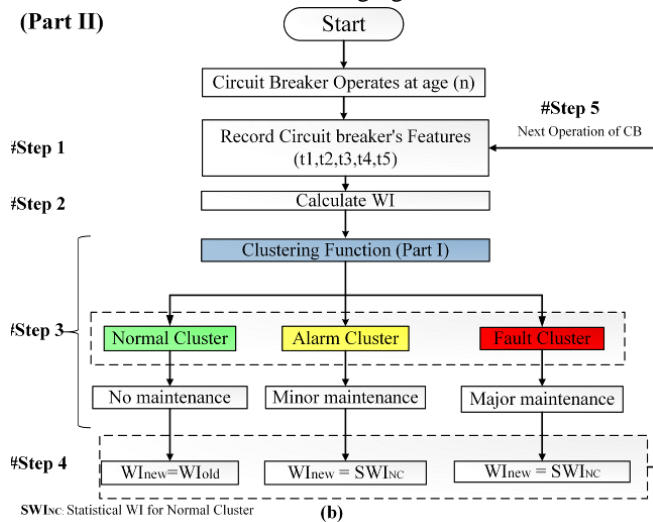

Figure 9. Using the monitoring data in aging procedure [10]

VI. CONCLUSIONS

This paper presented the efforts on the condition assessment of HVCB form past to present. In addition, it has been attempted to provide viable visions for future research streams in this context. Various failure statistics have been reviewed to understand the failure modes and their origins. It is indicated that the trend of failure of CBs is decreasing and still the main origins of the failures are the operating mechanism, high-voltage part, and control part, respectively. The challenges in the main diagnostic signals, i.e. coil current, travel curve, DRM, energy, and vibration have been presented to determine more required future research. In addition, some new developed approaches based on the frequency response have been presented. The role of AI has been clarified in the future research in identification of the thresholds of state transitions. The methods are subjected to some advantages and disadvantages such as robustness of diagnostic results, sensitivity to noisy data, and misjudgment of fault identification. In addition, a proactive bi-directional approach between real-world and virtual world, called DT, leading to a dynamic model could be considered as an emerging concept in this subject. From power system point of view, it is discussed that the monitoring data could be applied in modelling of the aging process.

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