Real-Time Life-Cycle Assessment of High Voltage Circuit Breakers for Maintenance using Online Condition Monitoring Data

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***Abstract*—Life-cycle assessment of high voltage (HV) circuit breakers (CB) in transmission systems, if efficiently done, can lead to an optimal decision on when, where, and how to perform maintenance activities. This paper elaborates a new approach on the identification of CB's deterioration/recovery states, i.e., the so called life-cycle assessment, using its control circuit condition monitoring data. Reliability-oriented performance indices, which can assess the condition of different physical parts of an HV CB in real time, are introduced first. Then, a quantitative methodology to define the probability of the CB falling into each class of deterioration/recovery states i.e., healthy, vulnerable, troubled, and failed, is proposed. Using this approach, maintenance decisions can be effectively made on different parts of an HV CB, the impact of maintenance can be quantified, and system-wide maintenance optimization with respect to the condition-based differentiation of CBs can be made possible. Field condition monitoring data recorded at different time intervals during the CB operation is utilized to evaluate the applicability and effectiveness of the proposed approach.**

***Index Terms*—circuit breaker (CB); condition monitoring data; high voltage; life-cycle; maintenance; reliability.**

NOMENCLATURE

D_i, F, M_i	Deterioration state *i*, failed state, and maintenance state *i* in the CB deterioration state diagram.
$f_{B_k}^{t_i}(t)$	Probability distribution assigned to the timing parameter *i* of the monitoring signals for the k^{th} CB in the system.
FP_O^{AB}, FP_C^{AB}	Failure probability of the AB contacts of the CB in its opening and closing operations.
FP_C^{CC}, FP_O^{TC}	Failure probability of the CB close coil and trip coil in its closing/opening operations.
FP_O^{FT}, FP_C^{FT}	Failure probability of the CB free traveling time in its opening and closing operations.
FP_O^{MT}, FP_C^{MT}	Failure probability of the CB mechanism traveling time in its opening and closing operations.
FP_{CB}^{O}, FP_{CB}^{C}	The CB overall failure probability in opening and closing operations.
$P_{B_k}^{t_i,D_j}$	Probability of the timing parameter *i* being in the deterioration state D_j for the k^{th} CB.
$P_O^{t_i,D_j}$	Probability of the timing parameter *i* being in the deterioration state D_j for the CB opening operation.
$P_{O/C}^{AB,D_i}$	Probability of AB contacts of CB, falling in deterioration state D_i once opening/closing.
$P_C^{CC,D_i}, P_O^{TC,D_i}$	Probability of CB close and trip coils in deterioration state D_i once closing/opening.
$P_{CB,O/C}^{D_i}$	Probability of the CB, as a component, falling into the deterioration state D_i in its opening/closing operations.
t_i	The signal timing parameter *i*.
$\sigma_k^{\min}$	Minimum acceptable threshold for the signal timing parameter *k*.
$\sigma_k^{D_i,\max}$	Maximum threshold for the signal timing parameter *k* to stay in deterioration state D_i.
μ, σ	The mean and standard deviation.

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I. INTRODUCTION

WITH the present economic constraints in the power industry, it seems desirable to optimize system planning and operation policies. Maintenance is, generally, considered a significant expense by the global utility industry due to the need to perform it frequently to maintain the availability of various important system components [1]. In response to an optimal resource allocation for maintenance, the power industry has been gradually changing from time-scheduled maintenance to *maintenance as needed*. The attention, hence, has shifted to real-time assessment of the critical components [2]-[6].

High Voltage (HV) Circuit breakers (CBs) are among those components which not only appear in great numbers, but also play a strategic role in the successful operation of power systems. CBs are crucial to fault clearing performance. CBs are also considered the key to make reconfiguration schemes and operational switching actions feasible [7]-[11]. Hence, CBs should be optimally maintained to keep them operating reliably.

Research on the condition based monitoring of CBs has seen a tremendous growth during the past decade as the increasing deployment of monitoring systems and smart sensors in substations took place worldwide. The condition based assessment approaches can be categorized into two main groups: system-oriented and component-oriented.

In the former, the CBs are classified based on their role and criticality in the system overall performance. The CBs with major impacts on system reliability are identified in [13] as the most critical for frequent maintenance. Likewise, CB criticality from the system overall security perspectives is addressed in [14], [15]. Quantitative and qualitative system-wide prioritization analysis is pursued in [16], followed by economic assessments in [17] for optimal maintenance of HV CBs.

In the latter, different approaches for assessing the status of individual CBs are introduced. Depending on the type of deterioration impact, the analysis may be focused on vibration [18], [19], contact wear-and-tear [20], [21], digital modeling for sensor techniques [22], or gas pressure in the operating chamber [23], [24]. Partial discharge tests are also among the other approaches mostly focused on estimating the CB dielectric properties, requiring significant expert knowledge and statistical analysis [25], [26]. Automated approaches for CB monitoring have also been broadly investigated in [27], where signal processing techniques and expert systems are employed to perform the CB fault detection. Wavelet analysis is used in [28] to extract the features, and mobile agent software technology is introduced in [29] as an architecture for flexible processing of monitored signals. The use of state diagrams in deterioration, inspection, and maintenance modeling, either through the Markov approaches or Monte Carlo Simulations, has been explored [30]-[32]. References [33] and [34] correlated the CB monitoring signals to reliability considering the CB failure probability as an indicator of its performance, but no effort has been yet made in utilizing the CB monitoring signals to distinguish its deterioration/recovery states as time progresses.

This paper is devoted to meeting the following objectives: a) calculating the overall failure probability of different CBs in the system in real time using the condition monitoring signals, b) deriving the probability of the CBs being in its various degradation states at any time of interest, and c) defining a reliability-oriented correlation between the monitored signals of the CB control circuit and the degradation status over time.

After the introduction, Section II defines the problem statement. The proposed solution methodology is described in Section III. Numerical analysis using the field recorded monitoring data is demonstrated in Section IV, and related discussions are presented in Section V. Finally come the conclusions in Section VI.

II. Problem Statement

A. Background

In a classical model, the failure-repair process of a deteriorating device is commonly represented by a sequence of states of increasing wear, i.e., D_1, D_2, and so on, finally leading to the equipment failure (F) as depicted in Fig. 1a [30]-[32]. Deterioration is, however, a continuous process in time which is usually demonstrated in discrete steps solely for the purposes of easier modeling. Depending on the sequence of maintenance actions, the stages do not only show deterioration, but also show recovery via maintenance or replacement activity, i.e. if the CB is repaired/ replaced, the state may go from failed to working/

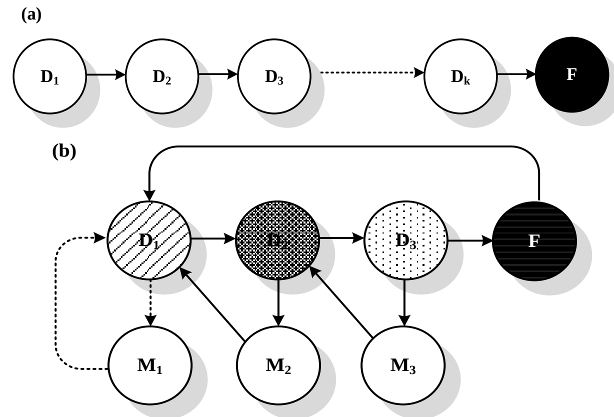

Fig. 1. (a) Classic state diagram for a deteriorating component over time; (b) 3-state deterioration/recovery state diagram with maintenance effects [30].

healthy states again. Maintenance effect can also be incorporated as demonstrated in the deterioration/recovery model in Fig. 1b for a 3-state deteriorating component. It is obvious, from Fig. 1b, that maintenance effect is to improve the component condition to that of the previous or healthy state through a replacement process. Further details on the topic are available in [30]-[32].

Once the deterioration/recovery state is known over time, one can not only differentiate various components of the same type in terms of maintenance consideration, but also can assign the proper preventive maintenance strategy based on the component condition. This could create considerable savings since maintenance can be done as needed, when and where necessary. The common approach to identify the deterioration/recovery state for a component (HV CB in this paper) is by taking the past duration of its operation into account, e.g. the second state is reached, on average, in three years of the component being installed and operated, the third in six, and so on. The problem with this approach is that the mean time of the CB falling in each deterioration/recovery state is usually obtained from a large amount of historical data from many of the CBs working under different operating environments, e.g., temperature, humidity, operation frequency, different voltage levels etc. The deviation among different CBs may impede the fair determination of the deterioration/recovery states. Moreover, the mean transition times between the states are generally uneven, may follow different distributions, and are commonly selected from the historical experiences or expert’s judgment [30]-[32], and increase the possibility of making wrong or inaccurate decisions. The operation frequency of the CB starting from its installation time may also be employed to decide on its replacement and inspection requirements as time elapses; however, it cannot be used to assess the deterioration/recovery status of the CB. It also gives no hints on the exact troubled area of the CB and, hence, does not assign any real-time criticality to different CBs system-wide. In response, this paper approaches the problem with the main focus on the CB monitoring signals of its control circuit. The goal is to find a linkage between the monitoring signals, deterioration/recovery states of various CBs, and maintenance state distinctions, accordingly.

B. Problem Description

Under a predictive maintenance model, the first question is concerned with differentiating the CBs maintenance needs in the overall system based on their deterioration/recovery levels and aging mechanisms. The need for maintenance is established through condition monitoring, which is the on-going inspection and surveillance of the CB operation to ensure its proper performance and to detect any abnormalities, indication of approaching a failed state. References [33], [34] have previously proposed a methodology utilizing the CB control circuit electrical signals to define several performance indices. It employs the timing instants captured when CB operates (either open or close) to reflect the condition of CB's sub-assemblies, e.g., trip coil, close coil, auxiliary contacts, etc. Although the approach has formulated the general framework, it has not been explored in the context of CB practical life-cycle assessments where the deterioration/recovery states of CBs are the focus of concern. This ignores the possibility of different types of maintenance practices in different time intervals and how differently they affect various CBs in the system.

In response, this paper further sets the specified tolerance of timing instants, determined from the CB monitoring signals coming out of its control circuit, into three distinctive bands each reflecting a different deterioration/recovery state. This would give a clearer definition of the healthy, vulnerable, and troubled states for a HV CB. Identification of the CB deterioration/recovery states, thus, can be achieved through continuously checking whether one or more of the timing signals have violated the accepted limits. An index of reliability, i.e., deterioration/recovery state probability, can be then calculated and updated as new monitoring data comes in. The proposed methodology is not the Markov process conventionally used in maintenance analysis of system components; instead, a new structure which gives the user a hint for Markov analysis is suggested. Particularly, the presented approach helps identify the probability of each HV CB sitting in various deterioration stages over its lifetime. This will be, in turn, helpful to more realistically find the optimum transition rates (e.g., inspection rate or maintenance rate) of a CB and facilitates using the Markov modeling and reliability analysis on that basis.

C. CB Condition Monitoring and Data Requirements

According to the recent surveys conducted by CIGRE Working Group, HV CB failures are mostly found to be initiated due to the malfunction of operating mechanisms and control circuits, and in that order compared to other CB sub-assemblies [35]-[36]. Aging, wear, and corrosion are also reported as the most common causes of major failures in HV CBs. As a result, the control circuit part of the CB is selected for the condition assessment using the associated monitoring signals. There are portable monitoring devices, available in the market, which are designed to gather and display the control circuit signals, i.e., both analog and/or digital waveforms [37]-[40]. A CB monitoring (CBM) infrastructure for the main sake of acquisition and automated analysis of the condition monitoring data is introduced in [27]. Once triggered via the operator action in the control house, a relay, or a control device, an initiate signal is sent to CB control circuit to start its operation either opening or closing. The initiate signals are then referred to the trip or close coil through the auxiliary contacts and control relays to energize the coils. This, in turn, creates a coil current. The coil current is measured across a shunt that is placed in series with the coils. In fact, monitoring of coil currents provides insights into the condition of both the coil and operating mechanism. The coil current activates a plunger leading to movement of the operating mechanism. The stored energy is used then to move all the CB mechanical parts and open/close the main interrupting contacts.

As the CB opens/closes its main contacts, the CB auxiliary (52a) and (52b) contacts change the state. The A and B contact signals (52a and 52b) indicating the voltage across auxiliary switches are monitored which signify the CB status either opening or closing. Any observed inconsistency may indicate a wrong cable connection or a problem with the operating mechanism. Y coils (52Y) are used to prevent multiple-close attempts in a close operation [27]. Trip and close coil (TC or CC) current as well as the A and B contact (52a and 52b) voltage signals are the most important signals monitored which are employed in the analysis of this paper to investigate the aging and deterioration level of CBs. Usually, abnormal behavior of signal waveforms implies an existing problem or developing failure. Since the difference between transitions of auxiliary contacts indicates the relative speed of CB operation, any changes in the signals may sense a deteriorated contact mechanism, a binding between the contacts leading to a slow CB operation, etc [27]. The excessive noise during the contact transition indicates a dirty auxiliary contact; the excessive voltage drop of DC voltage indicates a battery problem and so on. Signal processing modules are developed to extract the timing of the close operation. These timing instants should occur within the manufacture specified tolerance bands to ensure that the CB is functioning properly. The events representing the change in the signals need to occur in a specific order for a proper CB operation. An example in the case of CB closing operation is demonstrated in Fig. 2 and the associated timing parameters describing the sequence of breaker operations are introduced in Table I. Based on the preliminary research in [33] and [34], only timing parameters t_2-t_6 are selected for analysis in this paper, as tabulated in Table I.

The mal-functions in CBs may result from various parts and sub-assemblies such as interrupters, dampers and so on [35]. Due to criticality of control circuit in CB operations (both opening and closing) according to [35]-[37], the proposed methodology has specifically taken into account the control circuit signals for condition assessment of CBs since they are the only major source of monitoring data available in the utilities. In such cases, which is not rare in utilities today, this methodology helps in extracting the most relevant information from the control circuitry raw monitoring data, useful for the operator and maintenance personnel to make the best decisions.

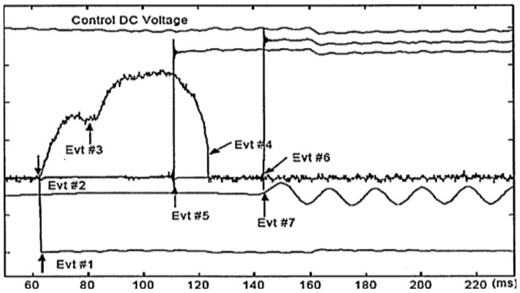

Fig. 2. Monitored coil current waveform during the CB close operation [27].

TABLE I
CB EVENTS AND THE CORRESPONDING SIGNAL TIMING PARAMETERS

Event	Event Description	Signal Parameter
1	Trip or close operation is initiated	t_1
2	Trip coil current picks up	t_2
3	Trip coil current dips after saturation	t_3
4	Trip coil current drops off	t_4
5	“b” contact breaks or makes (a change of status from low to high or vice vresa)	t_5
6	“a” contact breaks or makes	t_6
7	Phase current breaks or makes	t_7

III. PROPOSED FORMULATION

CB reliability analysis is approached in this paper in terms of failure probability. A practical approach is devised to assign the failure probabilities considering the monitoring signal parameters. In the first sub-Section, the probability distribution formation procedure for each timing signal parameter is proposed. Sub-Section B explores the condition assessment of CB and the associated sub-assemblies based on the assigned probabilities. And finally comes the solution methodology on how to set a correlation between the probabilities and the CB life-cycle deterioration/recovery states.

A. Probabilistic Treatment of the CB Signal Measurements

Conducting some on-line measurements via the CB monitoring devices, both for CB opening and closing operations, a set of data for each signal timing parameter can be recorded. A probability distribution can then be assigned to these timing measurements. According to the Central Limit Theorem (CLT), with the increase in the sample size (sufficiently large), the distribution of the random variables approaches the normal distribution irrespective of the shape of the original distribution [41]. Since the CB monitoring data is accumulated with time and the sample size will be large enough over time, normal probability distribution can be reasonably adopted. Besides, it is mathematically easier to deal with normal probability distributions. Hence, normal distribution is assumed in this paper for all signal parameters listed in Table I, as illustrated in Fig. 3 for parameter t_2. The proposed approach is, however, generic enough to accommodate different types of probability distributions as data may dictate in various applications. Note that in many practical cases, the methods developed using normal theory work quite well even when the distribution is not normal. To proceed with the methodology, three bands for every timing parameter are proposed each reflecting different deterioration/recovery levels of a CB, i.e.,

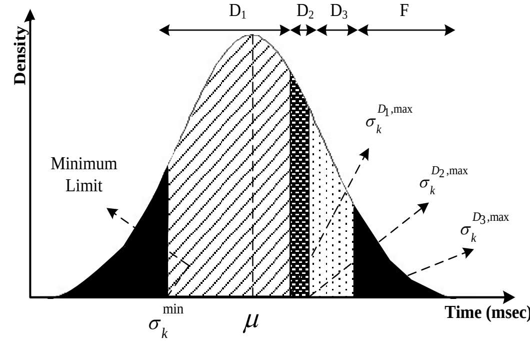

Fig. 3. Probability distribution and the bands assigned to timing parameter t_2.

healthy, vulnerable, and troubled states. If one new value of t_i falls in the health margin, then it indicates a proper operation of the breaker, reflected by that time instant t_i. Similarly, one new value of t_i may fall in the second band meaning that the associated parts of the CB respond with some delays and may be in the vulnerable deterioration state or may require maintenance. One new value of t_i could fall in the third margin span suggesting that the associated CB parts and sub-assemblies cannot respond correctly in time and may be in the troubled state; hence in a vital need of maintenance. If t_i falls out of the entire proposed margin spans, it can be concluded that there is something wrong going on associated with the close coil operation of the CB which is an indicative of the failed state. These limits may be different for different types of CBs, but are the same for the CBs of the same type in a substation. With the accumulation of monitoring data from the CBs of the same type in a substation with certain operational practices and geographical/operation conditions, these boundaries can be determined as the benchmark based on the historical data on the CB operation over time, operator expertise, expert systems and data mining approaches [39], [40]. Interestingly enough, similar limits for CB timing parameters can be automatically set around the values measured during the commissioning process and are, nowadays, being taken into account and supported by some monitoring devices of different vendors, in real world practices [42]. For instance, in the case of a vendor’s monitoring device, the set up begins by selecting the vendor’s breaker type followed by the mechanism type. By doing so, breaker specific default settings are recalled. The timing settings are defined through test operations while the monitoring device is in a special learning mode. The tool also allows the user to modify the default settings depending on the conditions of the CB. These boundaries are selected as the threshold sets for each type of CB in a substation and can help determine the wear condition of the CB when passes the desired thresholds [42].

In general, and according to the probability distribution assigned, the probability of a CB falling into each deterioration/recovery state margin with respect to the timing parameter t_i can be calculated in (1)-(4), respectively for the healthy, vulnerable, troubled, and failed states.

$$P_{B_k}^{t_i,D_1} = \int_{t=\sigma_k^{\min}}^{t=\sigma_k^{D_1,\max}} f_{B_k}^{t_i}(t)dt \qquad (1)$$

$$P_{B_k}^{t_i,D_2} = \int_{t=\sigma_k^{D_1,\max}}^{t=\sigma_k^{D_2,\max}} f_{B_k}^{t_i}(t)dt \quad (2)$$

$$P_{B_k}^{t_i,D_3} = \int_{t=\sigma_k^{D_2,\max}}^{t=\sigma_k^{D_3,\max}} f_{B_k}^{t_i}(t)dt \quad (3)$$

$$P_{B_k}^{t_i,F} = 1 - \sum_{j=1}^{3} P_{B_k}^{t_i,D_j} \quad (4)$$

These probabilities are used in the rest of the paper to define some performance indices for various subassemblies of a CB. Noteworthy is that the proposed approach can be employed in dealing with both the opening and closing operations of the HV CBs when assessing their conditions.

B. Reliability Performance of CB Subassemblies

Some CB sub-assemblies are to be monitored continuously (each time breaker operates) using the monitoring signals.

1) Performance of CB Trip Coil

As can be traced in Fig. 4, a sample representation of the trip coil current is demonstrated. The trip coil current signal, in general, should be fairly smooth except for a dip at the beginning and abrupt change at the moment the tail end of the waveform starts decaying. Once the trip initiate input is active, the coil current makes a gradual transition to a nonzero value at time "t_2". The time instant "t_3" corresponds to the time at which the operating mechanism starts moving using the trip coil energy. The coil current starts dropping down to zero at time "t_4". Possible abnormalities regarding the trip coil can be pointed out as the pickup delayed, dip delayed, drop-off delayed, etc. In the worst case, the aforementioned abnormalities may result in the CB not opening when it is supposed to. These abnormalities can be addressed by the probabilities $P_{B_k}^{t_2}$, $P_{B_k}^{t_3}$, and $P_{B_k}^{t_4}$ reflecting the timing parameters "t_2", "t_3", and "t_4". These time instants should be always kept within the margins to assure the proper operation of the trip coils. As a result, the performance index associated with the trip coil is defined as the probability that it will fail to operate properly, as demonstrated in (5).

2) Performance of CB Auxiliary Contacts

As the CB opens its main contacts, the status of the auxiliary "a" and "b" contacts is also changed as can be seen in Fig. 4.b. Some possible abnormalities regarding the operation of "a" and "b" contacts can be considered including the delay in transition, premature transition, unstable contacts, noise, and contacts bounce. The auxiliary contacts can properly operate only if the timings "t_5" and "t_6" fall within their tolerance span. The performance index reflecting the auxiliary contacts operation can be defined as the probability that the auxiliary contacts fail to operate properly, as introduced in (6).

3) Performance of CB Operating Mechanism

The time period between the instant at which the trip coil current (TC) rises, i.e., "t_2", and the instant at which the dip occurs, i.e., "t_3", is called the *free travel time* which reflects the performance of the trip latch mechanism. So, the timing parameters need to fall within the tolerance limits for the CB to exhibit a normal free travel time. The corresponding performance index is defined as the probability that free travel time is abnormal, as introduced in (7) in Fig. 4. The coil current also needs to correlate with the event of change of "a" or "b" contact. The time period between the dip and the change of the "a" contact for opening operation is the *mechanism travel time* whose normal value is ensured once the timings "t_3" and "t_6" fall in their corresponding tolerance limits. Any notable violation in these timings can be reported as the CB abnormal operation. So, the corresponding performance index is defined as the probability that the mechanism traveling time is abnormal, as formulated in (8) in Fig. 4.

4) CB Total Performance

In addition to the performance evaluation of the CB different sub-assemblies, an index to evaluate the CB overall performance is proposed. If none of the timing parameters, i.e., "t_2" to "t_6", which are extracted out of the control circuit monitoring signals via the signal processing techniques, is violated, one can conclude the CB operation in either opening or closing is troublesome. In other words, if any of these timings fall out of the corresponding tolerance limits, one can conclude there is failure of some kind. In response, the CB failure probability, i.e., the probability that the CB does not open properly, is estimated in (9) in Fig. 4. Similar discussions are valid for the CB closing operation whose derivations are formulated through (10)-(14) in Fig. 4.

C. CB Deterioration/Recovery Model

According to equations (5)-(14) describing the failure probability assessment of CB sub-assemblies, an approach to derive the life-cycle deterioration/recovery state probabilities of each CB subassembly is proposed next. The three CB subassemblies under study, i.e., CB trip coil, close coil, and contacts, are taken into consideration here. The performance indices associated with the CB opening/closing operations are elaborated in detail.

1) CB Trip Coil Deterioration/Recovery Level

The probability of a CB trip coil subassembly falling into the failed, troubled, vulnerable, and healthy states can be reached through (15)-(18), respectively.

$$P_O^{TC,F} = 1 - \prod_{i=2}^{4}\left(1 - P_O^{t_i,F}\right) \quad (15)$$

$$P_O^{TC,D_3} = 1 - \left(P_O^{TC,F} + \prod_{i=2}^{4}\left(\sum_{j=1}^{2} P_O^{t_i,D_j}\right)\right) \quad (16)$$

$$P_O^{TC,D_2} = 1 - \left(P_O^{TC,F} + P_O^{TC,D_3}\right) - \prod_{i=2}^{4} P_O^{t_i,D_1} \quad (17)$$

$$P_O^{TC,D_1} = \prod_{i=2}^{4} P_O^{t_i,D_1} \quad (18)$$

2) CB Auxiliary Contacts Deterioration/Recovery Level

Similarly, the probability of a CB auxiliary contacts falling into the failed, troubled, vulnerable, and healthy states can be

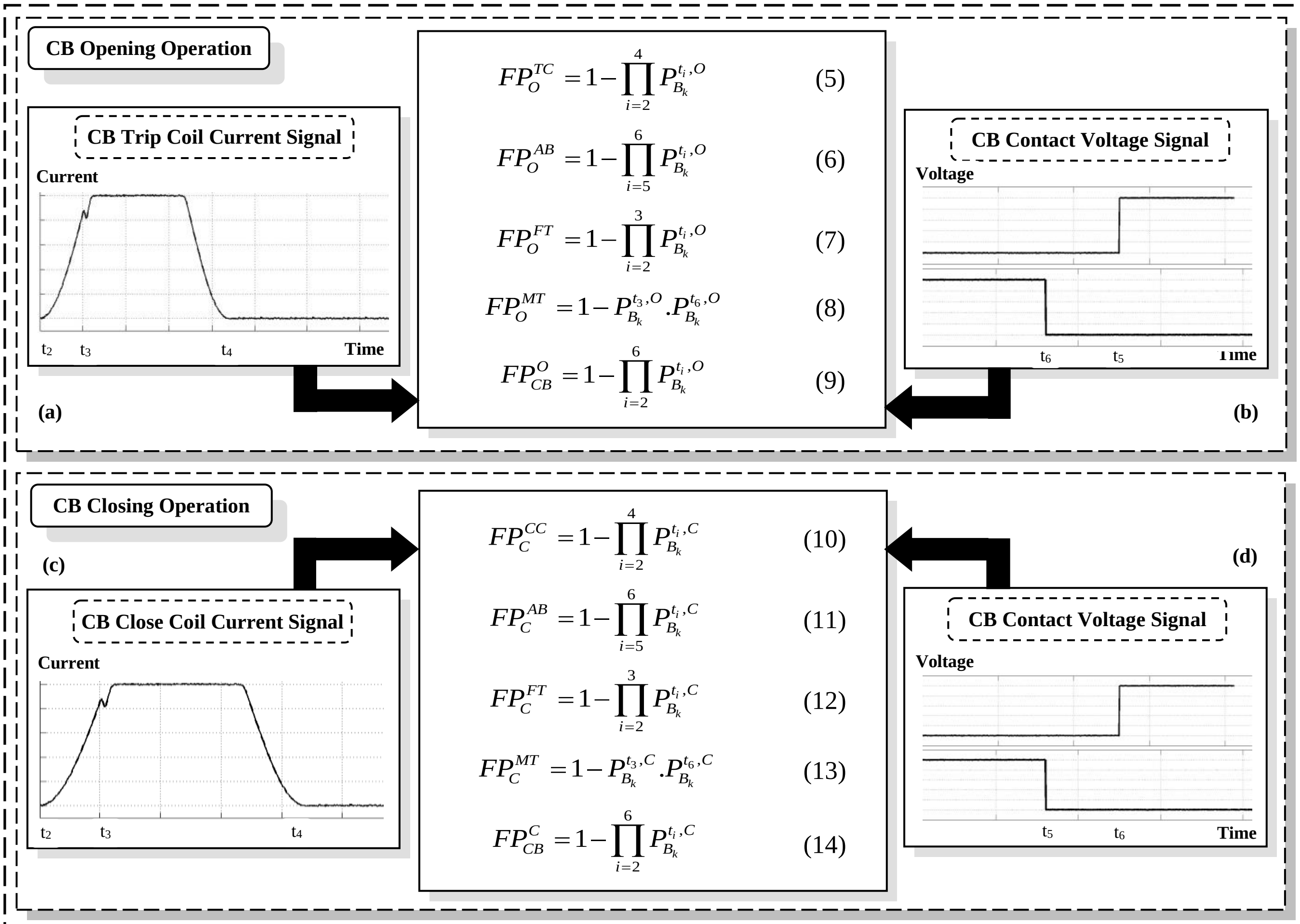

Fig. 4. General formulations for the failure probability estimation of CB subassemblies in both opening and closing operations.

reached through (19)-(22), respectively.

$$P_{O/C}^{AB,F} = 1 - \prod_{i=5}^{6}\left(1 - P_{O/C}^{t_i,F}\right) \tag{19}$$

$$P_{O/C}^{AB,D_3} = 1 - \left(P_{O/C}^{AB,F} + \prod_{i=5}^{6}\left(\sum_{j=1}^{2} P_{O/C}^{t_i,D_j}\right)\right) \tag{20}$$

$$P_{O/C}^{AB,D_2} = 1 - \left(P_{O/C}^{AB,F} + P_{O/C}^{AB,D_3}\right) - \prod_{i=5}^{6} P_{O/C}^{t_i,D_1} \tag{21}$$

$$P_{O/C}^{AB,D_1} = \prod_{i=5}^{6} P_{O/C}^{t_i,D_1} \tag{22}$$

3) *CB Close Coil Deterioration/Recovery Level*

Probability of a CB close coil reaching the failed, troubled, vulnerable and healthy states can be calculated through (23)-(26), respectively.

$$P_{C}^{CC,F} = 1 - \prod_{i=2}^{4}\left(1 - P_{C}^{t_i,F}\right) \tag{23}$$

$$P_{C}^{CC,D_3} = 1 - \left(P_{C}^{CC,F} + \prod_{i=2}^{4}\left(\sum_{j=1}^{2} P_{C}^{t_i,D_j}\right)\right) \tag{24}$$

$$P_{C}^{CC,D_2} = 1 - \left(P_{C}^{CC,F} + P_{C}^{CC,D_3}\right) - \prod_{i=2}^{4} P_{C}^{t_i,D_1} \tag{25}$$

$$P_{C}^{CC,D_1} = \prod_{i=2}^{4} P_{C}^{t_i,D_1} \tag{26}$$

4) *CB Deterioration/Recovery State Probability*

Similar to the previous analysis, the probability of a CB, as a stand-alone component, transitioning into the failed, troubled, vulnerable, and healthy states can be calculated through (27)-(30), respectively. One can then differentiate the HV CBs in the system from the life-cycle viewpoint, since different CBs can have different probability distributions for each deterioration/recovery state.

$$P_{CB,O/C}^{F} = 1 - \prod_{i=2}^{6}\left(1 - \sum_{j=1}^{3} P_{O/C}^{t_i,D_j}\right) \tag{27}$$

$$P_{CB,O/C}^{D_3} = 1 - \left(P_{CB,O/C}^{F} + \prod_{i=2}^{4}\left(\sum_{j=1}^{2} P_{O/C}^{t_i,D_j}\right).\prod_{i=5}^{6}\left(1 - P_{O/C}^{t_i,F}\right)\right) \tag{28}$$

$$P_{CB,O/C}^{D_2} = 1 - \left(P_{CB,O/C}^{F} + P_{CB,O/C}^{D_3} + \prod_{i=2}^{6} P_{O/C}^{t_i,D_1}\right) \tag{29}$$

$$P_{CB,O/C}^{D_1} = \prod_{i=2}^{6} P_{O/C}^{t_i,D_1} \tag{30}$$

The CBs possessing higher probabilities associated with the troubled state would call for a major maintenance action and those of higher failure probability would be essentially in need of prompt part replacements. The proposed methodology can be applied for any other subassemblies of HV CBs. The proposed algorithm can be updated during time. Once the new monitoring data scan arrives, the associated timing values can be extracted employing the signal processing module. Then, the new probability distributions are assigned and the updated probabilistic indices can be calculated through (15)-(30). For the sake of clarity, a list of all parameters that are being monitored feeding the proposed analysis and the associated closed-form equations to assess the life-cycle status of CB subassemblies is presented in Table II.

IV. Numerical Analysis

A. Algorithm Uses of Recorded Condition Monitoring Data

To illustrate the applicability of the proposed methodology in real world practices, history of the signals coming from the control circuit of a 38 KV SF6 CB, containing samples for opening operation is documented and the associated timing parameters are extracted employing the signal processing tool previously developed in [27]. Detailed description of data sets and how the measurements are done can be found in [27], [34]. The tolerance limits for the signal timing parameters reflecting the deterioration/recovery thresholds are defined and demonstrated in Table III.

B. Application Considerations

We decided to use normal distribution as the assigned probability distribution to the extracted timing parameters.

$$f(t_i;\mu,\sigma^2)=\frac{1}{\sigma\sqrt{2\pi}}\exp\left(\frac{-(t_i-\mu)^2}{2\sigma^2}\right) \qquad (31)$$

The method is generic enough to accommodate different types of probability distributions as data dictates in various applications. Due to the space limit, only the signals for the CB opening operation have been studied in this paper for the sake of demonstration. Employing equations (15)-(18) and according to the defined limits and thresholds in Table III, the deterioration assessment is done for the CB trip coil, as illustrated in Fig. 5. As it can be observed in this figure, the CB trip coil is mostly in its failed state of deterioration since the associated failure probability is far more than that of the other deterioration/recovery states in all the observations recorded during the studied time interval. It reflects the fact that the CB trip coil is in a critical need to be repaired or replaced. Similar procedure can be pursued for the "a" and "b" contacts of the CB using equations (19)-(22). As demonstrated in Fig. 6, it can be concluded that the auxiliary contacts have been performing quite well during the first observations but are in the troubled state since the probability of this state overweighs the rest in the first few observations. It can also be traced that the probability of vulnerable state has gone ahead of that for the troubled state after a while, which reflects some maintenance practices done on the "a" and "b" contacts during the studied time interval. As a consequence, one may conclude that the CB contacts may call for minor maintenance activities to maintain their proper functionality.

One can likewise evaluate an overall deterioration/recovery level of a CB as a stand-alone component with the aid of the proposed approach using equations (27)-(30). As can be seen in Fig. 7, the results obtained for the CB under study demonstrate that the CB is constantly on the edge of failed state due to the abnormal operation of different subassemblies and high failure probability assigned. In this case, a major maintenance is in urgent need. Based on these performance probabilities, one can easily get to a conclusion regarding the overall deterioration/recovery status of the CB, as tabulated in the *classical life cycle model* in Table IV.

Table II
Summary of the Required Signals, Proposed Analysis, and Related Formulations

CB subassembly	Signals Monitored	Deterioration/Recovery Status	Equation
Trip Coil	Trip Coil Current Signal	Healthy	(18)
		vulnerable	(17)
		Troubled	(16)
		Failed	(15)
Auxiliary Contacts	Contacts Voltage Signal	Healthy	(22)
		vulnerable	(21)
		Troubled	(20)
		Failed	(19)
Close Coil	Close Coil Current Signal	Healthy	(26)
		vulnerable	(25)
		Troubled	(24)
		Failed	(23)
CB in General	Trip coil current Close coil current Contacts voltage	Healthy	(30)
		vulnerable	(29)
		Troubled	(28)
		Failed	(27)

Table III
CB Deterioration Level Thresholds for Signal Timing Parameters

Event	$\sigma_k^{\min}$	$\sigma_k^{D_1,\max}$	$\sigma_k^{D_2,\max}$	$\sigma_k^{D_3,\max}$
t_1	0.00	1.00	1.50	2.00
t_2	13.6	16.1	17.4	18.6
t_3	26.4	30.9	33.2	35.4
t_4	28.7	33.7	36.2	38.7
t_5	22.4	27.4	29.9	32.4

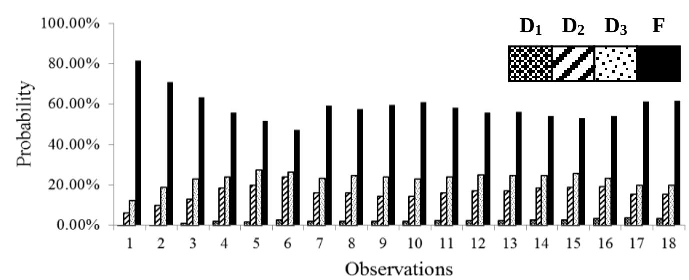

Fig. 5. Probability of the CB trip coil staying in each deterioration state.

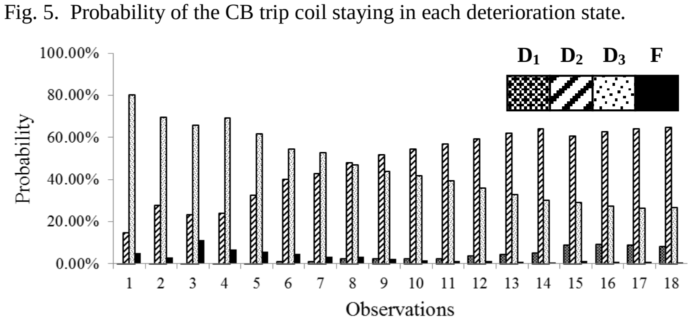

Fig. 6. Probability of the CB AB contacts staying in each deterioration state.

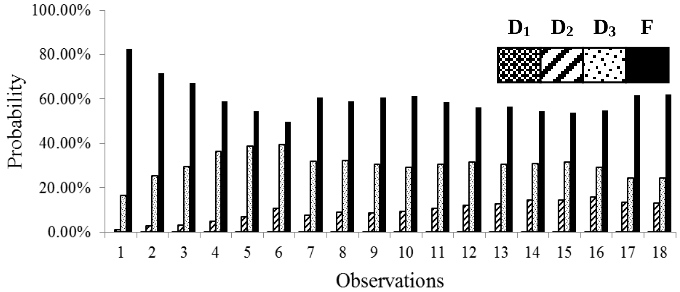

Fig. 7. Probability of the CB, as a component, in each deterioration state.

TABLE IV
CB DETERIORATION LEVEL THRESHOLDS FOR SIGNAL TIMING PARAMETERS

Deterioration/Recovery State	D_1	D_2	D_3	D_4
$P_{CB,O}^{D_i}$	0.28%	13.21%	24.40%	62.11%

V. DISCUSSION ON THE IMPACTS OF MAINTENANCE

Maintenance has considerable impact on improving the deterioration/recovery condition of a component. Consequently, one may be interested in investigating the effects of maintenance on the CB deterioration/recovery status in the context of the proposed methodology. In this regard, the following considerations are made [30]-[32], [40]:

- CB, as a component, is assumed to have four deterioration/recovery states, introduced earlier, where in the vulnerable state, the CB will still work properly. The objective is to keep the CB at least working in vulnerable state, and look for timely maintenance.
- In the troubled state, the CB could still work but on the edge of failure. In the failed state, the CB may or may not work as expected; the open/close operations are not reliable at all and a large operation delay may exist.
- There are three types of maintenance states assigned: minor for vulnerable condition, major for troubled condition, as well as failure repair (replacement) for failed condition. Take into account that these are all among the preventive maintenance considerations and not the corrective maintenance actions, which are commonly done on the CB after it fails.
- Maintenance should not turn the CB into a worse state, i.e., maintenance activities are assumed to be judiciously applied with no drawbacks. So, the states can be only *recovered/ improved* via maintenance/repair.
- Minor maintenance will only bring the CB into the prior deterioration/recovery state; for instance, troubled state to vulnerable state, but will not lead to the healthy state directly from the troubled deterioration. However, the major maintenance can bring CB to a healthy state.
- Minor and major maintenance have very small impact on turning the failed CB into a healthy state since a replacement has to be considered if aiming so.

Taking the above assumptions into account and assuming the data presented in [31] and [33], the effects of different maintenance policies on the HV CB in different deterioration/recovery states can be quantified as demonstrated in two case studies in Table V and Table VI. It is obvious that the probability of successfully bringing the CB into a better working state following major maintenance actions is larger than following the minor maintenance.

As noted earlier, maintenance attempts are devoted to keep the CB being at least in the vulnerable state (i.e., the sum of probability of the D_1 and D_2 states to be larger than 85% after maintenance) before any other action is taken. In the first case in Table V, the analysis shows that the CB is very likely to be in a faulted situation. Even after a major maintenance, the total probability of D_1 and D_2 is 42.61% which implies that a repair is in an urgent need.

TABLE V
EFFECTS OF MAINTENANCE ON THE CB DETERIORATION/RECOVERY: CASE I

	Deterioration/Recovery State Probability			
	D_1 (%)	D_2 (%)	D_3 (%)	F (%)
Before maintenance	0.28	13.21	24.40	62.11
Minor maintenance	9.53	21.04	10.43	59.00
Major maintenance	35.99	6.62	7.41	49.98
Failure repair	99.00	0.91	0.08	0.01

In the second case in Table VI, the numerical results demonstrate that the CB is in its pretty good working state with a very small possibility of having damages. A minor maintenance could bring the CB into a state with a 90.5%, as the total probability of D_1 and D_2. However, a major preventive maintenance, which may cost more than ten times of the minor one, will only improve the overall reliability performance a bit better [31]. Thus, one could make a conclusion that the proposed model will not only identify the cause of deterioration in a timely manner, but it could also suggest an optimized economic maintenance solution.

TABLE VI
EFFECTS OF MAINTENANCE ON THE CB DETERIORATION/RECOVERY: CASE II

	Deterioration/Recovery State Probability			
	D_1 (%)	D_2 (%)	D_3 (%)	F (%)
Before maintenance	20	60	15	5
Minor maintenance	62.00	28.50	4.75	4.75
Major maintenance	88.00	7.85	2.00	2.15
Failure repair	99.20	0.78	0.02	0

The following points are worthy to note:

- The calculated failure probability of the CB (more than 50%) reflects that some parts of the CB under study responsible for the trip operation are not reliable enough and need maintenance. The failure probability index calculated here in real time is different from the failure rate index (number of failures per year) commonly used in system reliability analysis. Failure probability used here reflects the CB condition at any given time. As a result, the two indices are different in unit and order of magnitude (failure rate is usually a very small value).
- Historical records are initially used to get an estimate of the CB reliability index as proposed in this paper. Such data may be acquired during time and with the operation of the CB by the monitoring devices. The probability distribution will then be updated as new data arrives.

This gives a dynamic update of the CB failure probability in real time as time passes.

- The proposed approach can capture the CB failures mainly related to the operation timing parameters that can be recognized by the control circuit monitoring signals. Some mechanical failures in the release and operating mechanisms as well as contact overheating, dielectric breakdowns, nozzle damages, incorrect assembly after maintenance, etc. may not affect the timing of the switching operation. Moreover, sudden mechanical breakdowns, corrosion, leaks, and a wide variety of different wear and tear processes may be very difficult to detect. The research done in this paper helps where the control circuit signals are the only or major source of monitoring data available in the utilities, which is not rare in practice today. This also highlights the need for more comprehensive research for a wise and comprehensive asset maintenance management.
- Conducting the same procedure for every CB in a substation would lead to a reasonable differentiation of CBs maintenance scheduling and asset management practices. Making such a distinction between different CBs throughout a power system would definitely open new opportunities for cost-effective asset management decisions. This will also help maintaining a reliable power grid and ensuring that the state-of-the-art technologies for power grid resilience against natural disasters and severe disruptions can be effectively practiced in real-world applications [43]-[48].
- It may be of interest to conduct a cost/benefit analysis to assess the economic aspect of putting the proposed approach in practice in the future. The gained economic benefits of the proposed monitoring scheme should outweigh the costs of device installation, fault detection, and assessment of CB condition monitoring over time.

VI. Conclusion

A quantitative approach to assess the reliability status of HV CBs and the subassemblies in real time is proposed. The followings are some advantages of contributions elaborated in this paper.

- The proposed methodology uses the field monitoring signals from CB control circuit, which takes advantage of increasing deployment of smart sensors and monitoring devices in the system.
- The presented approach allows a quantitative assessment of CB status leading to the classification into different deterioration/recovery states in real time.
- The real-time deterioration/recovery states differentiate the status of all the CBs in the system, which in general, is a helpful and reliable criterion for root-cause analysis and maintenance prioritization as time elapses.
- Deterioration-based distinction helps in improving the system-wide maintenance scheduling and asset management practices to answer where, when, and how to perform the maintenance tasks on the system CBs.
- While only monitoring of CBs is considered in this paper, the same concept can be easily extended to other power system assemblies such as power transformers, bushing insulators, lightning arresters, etc.
- The most critical prerequisite for reliability and maintenance analyses on HV CBs is past historical records. Hence, developing and employing a data gathering structure is an imperative.
- It may be of interest to conduct a cost/benefit analysis in the future to assess the economic aspect of putting the proposed approach in practice.

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