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

Payman Dehghanian, *Member, IEEE*, Yufan Guan, *Member, IEEE*, and Mladen Kezunovic, *Life Fellow, IEEE*

***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. 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 indicators, 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 distinction 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 (HV), 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 kth CB in the system.
$FP_O^{\mathrm{AB}}, FP_C^{\mathrm{AB}}$	Failure probability of the AB contacts of the CB in its opening and closing operations.
$FP_C^{\mathrm{CC}}, FP_O^{\mathrm{TC}}$	Failure probability of the CB close coil and trip coil in its closing/opening operations.
$FP_O^{\mathrm{FT}}, FP_C^{\mathrm{FT}}$	Failure probability of the CB free traveling time in its opening and closing operations.
$FP_O^{\mathrm{MT}}, FP_C^{\mathrm{MT}}$	Failure probability of the CB mechanism traveling time in its opening and closing operations.
$FP_{\mathrm{CB}}^{O}, FP_{\mathrm{CB}}^{C}$	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 kth 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.
$P_{O/C}^{\mathrm{AB},D_i}$	Probability of AB contacts of CB, falling in deterioration state D_i once opening/closing.
$P_C^{\mathrm{CC},D_i}, P_O^{\mathrm{TC},D_i}$	Probability of CB close and trip coils in deterioration state D_i once closing/opening.
$P_{\mathrm{CB},O/C}^{D_i}$	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.

Manuscript received February 28, 2018; revised June 13, 2018 and August 20, 2018; accepted October 26, 2018. Date of publication October 29, 2018; date of current version February 20, 2019. Paper 2018-PSEC-0159.R2, presented at the 2018 IEEE/IAS 54th Industrial and Commercial Power Systems Technical Conference, Niagara Falls, ON, Canada, May 7–10, and approved for publication in the IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS by the Power Systems Engineering Committee of the IEEE Industry Applications Society. *(Corresponding author: Payman Dehghanian.)*

P. Dehghanian is with the Department of Electrical and Computer Engineering, George Washington University, Washington, DC 20052 USA (e-mail: Payman.Dehghanian@ieee.org).

Y. Guan and M. Kezunovic are with the Electrical and Computer Engineering, Texas A&M University, College Station, TX 77843 USA (e-mail: carling@tamu.edu; kezunov@ece.tamu.edu).

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Digital Object Identifier 10.1109/TIA.2018.2878746

I. INTRODUCTION

THE Smart Grid initiative was introduced in the Energy Independence and Security Act of 2007, which sparked the imagination and debate of what that effort should entail [1]. The fact is that the current electric power transmission and delivery infrastructure, which is one of the most complex man-made systems to date, was not originally planned to meet the requirements of a smart electricity grid as defined by an NETL study [2].

1) Enabling informed participation by customers.
2) Accommodating all generation and storage options.
3) Enabling new products, services, and markets.
4) Providing the power quality for the range of needs in the 21st century economy.
5) Optimizing asset utilization and operating efficiently.

6) Addressing disturbances through automated prevention, containment, and restoration.
7) Operating resiliently against all types of hazards.

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 [3]. 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 [4]–[8]. High-voltage (HV) circuit breakers (CBs) are among those components that 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 [9]–[14]. Hence, CBs should be optimally maintained to keep them operating reliably.

Smart grid concept has introduced quite a few interesting ideas, one of which is the extensive deployment of smart sensors and monitoring technologies. The widely deployed monitoring infrastructure could be very informative at the component level. In the case of CB, data captured in real time can be translated into vital information on the component's health and reliability. The new knowledge about the component health and condition can eventually be provided to the maintenance experts and system operators. Monitoring of the protective components, including transmission CBs, supports achieving more reliable control and protection of power systems, and ensures the electric safety as well. Finally, reliable and healthy components of the power system enable successful implementation of the future smart grid applications, such as power system topology control. 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 [15] as the most critical for frequent maintenance. Likewise, CB criticality from the system overall security perspectives is addressed in [16] and [17]. Quantitative and qualitative system-wide prioritization analysis is pursued in [18], followed by economic assessments in [19] 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 [20], [21], contact wear-and-tear [22], [23], digital modeling for sensor techniques [24], or gas pressure in the operating chamber [25], [26]. Partial discharge tests are also among the other approaches mostly focused on estimating the CB dielectric properties, requiring significant expert knowledge, and statistical analysis [27], [28]. Automated approaches for CB monitoring have also been broadly investigated in [29], where signal processing techniques and expert systems are employed to perform the CB fault detection. Wavelet analysis is used in [30] to extract the features, and mobile agent software technology is introduced in [31] 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 in [32]–[34]. Efforts in [35] and [36] correlated the CB monitoring signals to reliability considering its failure probability as an indicator of the performance, but no effort has been yet made in utilizing the CB monitoring signals to distinguish its deterioration/recovery states as time progresses.

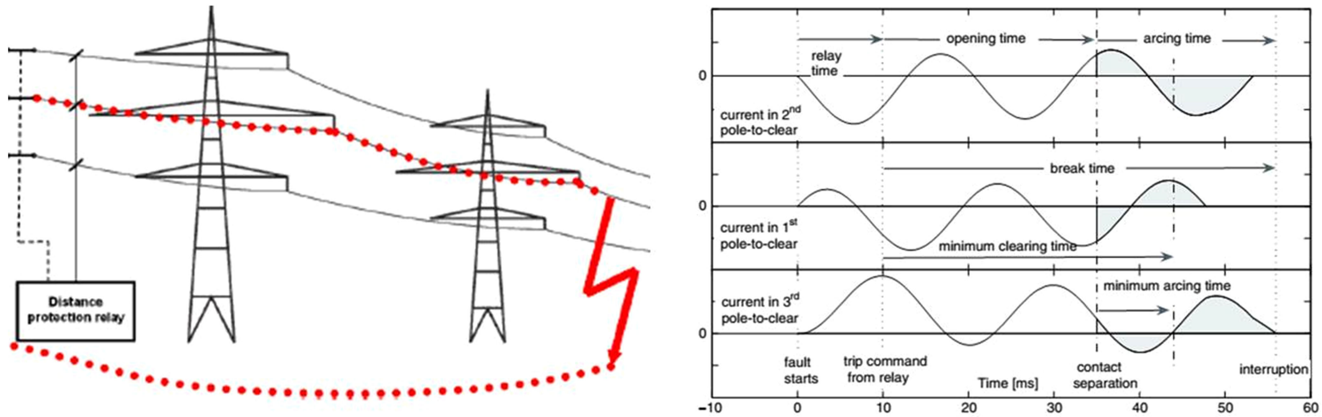
This paper is devoted to meeting the following objectives: first, calculating the overall failure probability of different CBs in the system in real time using the condition monitoring signals; second, deriving the probability of the CBs being in its various degradation states at any time of interest;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

Section II defines the roles and responsibilities of HV CBs in modern electric power transmission systems. Section III presents the problem statement. The proposed solution methodology is described in Section IV. Numerical analysis using the field recorded monitoring data is demonstrated in Section V, and related discussions are presented in Section VI. Finally, this paper is concluded in Section VII.

II. CB Roles in Electric Power Transmission Systems

A. Today: Switching Device for Fault Isolation and Clearance

In today's practice, CBs have a critical role in clearing the faults together with protective relays. As an example, the relays continuously monitor the currents and voltages, gathering the data and information from the instrument transformers (current and voltage transformers) on transmission lines. When a fault occurs, the associated short-circuit current is detected by the protective relays. The relays then initiate the CB operation in order to interrupt the fault current and clear the fault. The electric arc in a CB plays a key role in the interruption process and is often called a switching arc. Upon CB contact separation, the arc is extinguished in the interrupter(s) of each CB pole. Current interruption in each phase then happens at the first zero crossing point. The arc voltage and the current meet the zero crossing simultaneously as the arc is of resistive nature. The arc energy is quite low around current zero, and if the CB design is in such a way that cooling through the extinction medium is adequate, the current can be interrupted [37]. Depending on the type of the CBs considered, the device may not be prepared to interrupt the current at the first zero crossing following the contact separation. It takes a certain minimum time before the CB can actually interrupt the current, because sufficient cooling pressure of the extinction medium must be available and/or sufficient contact distance must be reached [37]. After the minimum arcing time has elapsed, the current can be interrupted at the first following current zero crossing. Crossing point takes place at the respective current zero states of each of the three phases (see Fig. 1).



(a) (b)

Fig. 1. (a) Faults in power systems. (b) CB three-phase current waveforms in the CB opening process to isolate the fault [37].

When all the CB poles are interrupted, the fault is cleared. The time between the instant of energizing the trip coil (TC) of the CB and the current interruption in all phases is called the *break time* (see Fig. 1) [37]. The CB technology must be able to operate reliably and withstand the high thermal energy of the arc before current zero crossing. Malfunctions in any part of the CB (mechanical, operation mechanism, electric circuit, etc.) may be an impediment to the successful operation of the CB when needed. CBs mal-operation in the fault clearing and isolating the faulted sequences may impose a significant risk to electric safety due to high fault currents, exposed faulted conductors, or other unsafe conditions due to damaged insulation. This calls for a wise and comprehensive maintenance management of CBs system-wide.

B. Future: Switching Device for Power System Topology Control Applications

CBs are expected to operate reliably and quickly all the time. Reliable operation of transmission CBs is the key for implementation of every-day switching actions or power system topology control commonly known as transmission line switching. With an increased use of renewable energy resources, sudden changes in power flows and probable contingencies caused by generation variability may lead to disastrous consequences. Such interruptions are not desirable and attempts should be made within the realm of power system operation, protection, and control to prevent and mitigate such contingencies in a timely and cost-effective manner. Power system topology control by means of transmission line switching is regarded as a promising solution to mitigate such contingencies and emergencies. As illustrated in Fig. 2, system overloads and overvoltage conditions can be well tackled by temporarily switching a transmission line out of service. Transmission switching technology is also acknowledged as a tool for network loss reduction, system congestion management, security enhancement, and reliability improvement [9]–[11]. Furthermore, power system topology control through transmission line switching is recognized as an effective approach for achieving either higher grid economic efficiency or improved reliability by exploiting the existing grid infrastructure. Switching or de-energizing a transmission line requires isolation of the sources feeding the line, which involve operating several CBs. Mal-operation of any of these CBs is an impediment to the successful execution of switching operation and realization of the anticipated benefits.

Fig. 2. Topology control applications in electric power transmission systems.

The suggested system architecture for the future topology control solution is illustrated in Fig. 3, which consists of various analytics divided into two main groups.

1) Topology control optimization, including various optimization algorithms suggesting the optimal topology and the associated line switching plan.
2) Support data analytics, which mainly employ processing of the substation data to evaluate the performance and condition of CBs, support identification of cascade events due to relay mis-operation, and relaying setting coordination evaluation under the proposed topology switching.

As shown in Fig. 3, the components of the system require data from various data sources: modeling data tools, market/planning tools, energy management systems (EMS) tools (topology processor and state estimator), and substation event-triggered

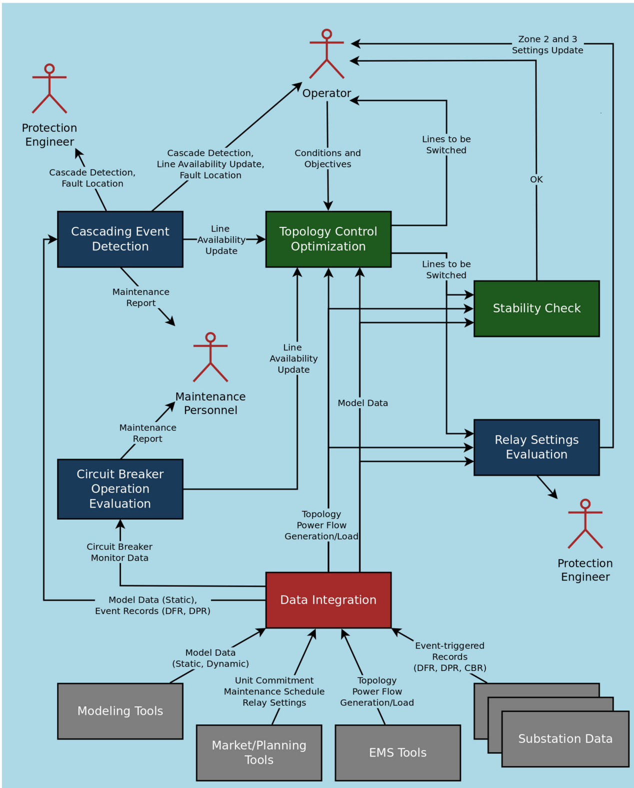


Fig. 3. System architecture for the future application of topology control.

data. The data analytics provide support functions to the use of optimal topology algorithms. In the day-to-day practice, several worthwhile considerations have to be incorporated into the solution design and implementation.

1) Data integration and historical data archival.
2) Topology processor/state estimator outputs and substation based analysis.
3) Security and reliability constraints under the switching optimization framework.
4) AC feasibility and stability check on the proposed switching plans.
5) Relay settings coordination evaluation accounting for relay setting changes due to network topology changes.
6) And eventually applying the switching decisions using the associated CBs.

III. 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. 4(a) [32]–[34]. Depending on the sequence of maintenance actions, the stages do not only show deterioration, but also show recovery via maintenance or replacement. Maintenance effect can be incorporated as shown in the deterioration/recovery model in Fig. 4(b) for a three-state deteriorating component. Apparently, maintenance effect is to improve the component condition to that of the previous or healthy state. Further details on the topic are available in [32]–[34].

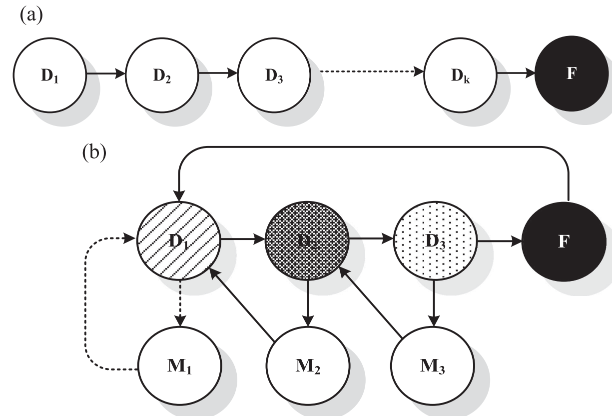


Fig. 4. (a) Classic state diagram for a deteriorating component over time. (b) Three-state deterioration/recovery state diagram with maintenance effects [32].

The common approach to identify the deterioration/recovery state for a component 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 historical dataset from many of the CBs working under different operating environments, e.g., temperature, humidity, operation frequency, voltage levels, etc. Deviation among different CBs may impede a 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 judgments [32]–[34], 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.

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 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. Natti and Kezunovic [35] and Kezunovic *et al.* [36] 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., TC, 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 from 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 an HV CB. 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.

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 (43%) and control circuits (29%), and in that order compared to other CB sub-assemblies [see Fig. 5(a)] [38], [39]. According to this international survey and as shown in Fig. 5(b), malfunctions in the CB operation mechanism takes the lead when it comes to CB *minor failures* (44%) following by the HV sub-assemblies (31%), such as arching chambers, auxiliary interrupters/resistors, and insulations. Aging, wear, and corrosion are also reported as the most common (almost 50%) causes of the major failures in CBs, followed by the design faults, manufacturing faults, and incorrect maintenance (15%). As illustrated in Fig. 5(c), the recognized CB major failures according to the internationally conducted surveys are found to be: the CB does not close on command (28.2%), locked CB in open or close operation (25.1%), and CB does not open on command (16.4%), respectively [38], [39]. As a result, the control circuit monitoring signals of the CB are used here for the condition assessment.

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 [40]–[43]. 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 TC or CC 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

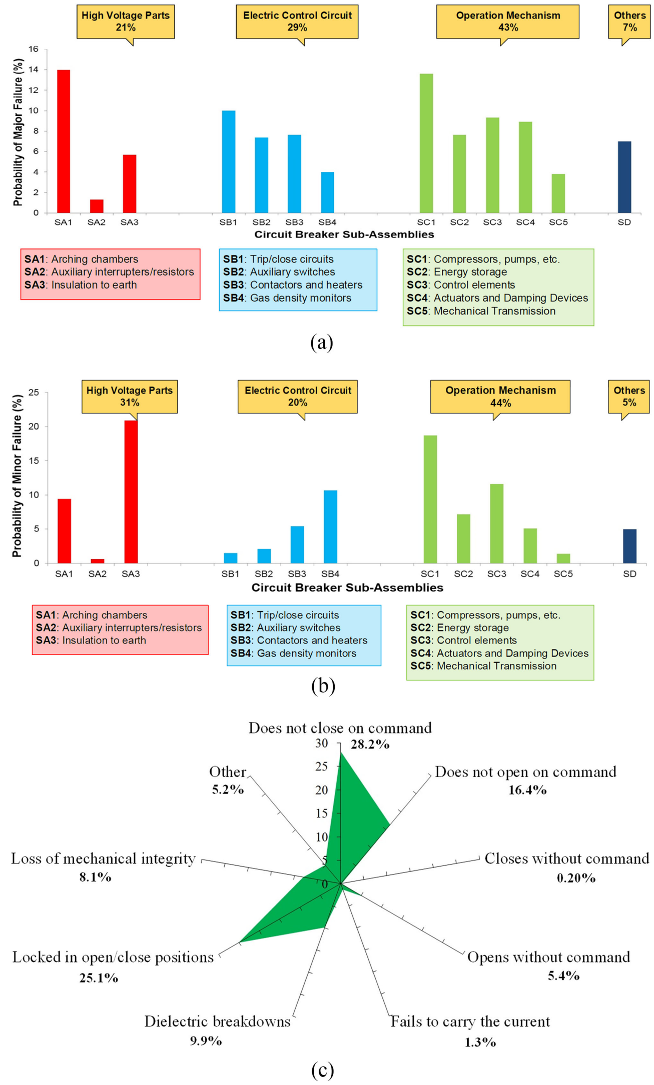


Fig. 5. CIGRE International survey on the probability of (a) *major failures* and (b) *minor failures*. (c) Critical modes (reasons) of major failures in CBs.

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 [29]. TC and close coil (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 CB's aging and deterioration. 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. [29]. 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

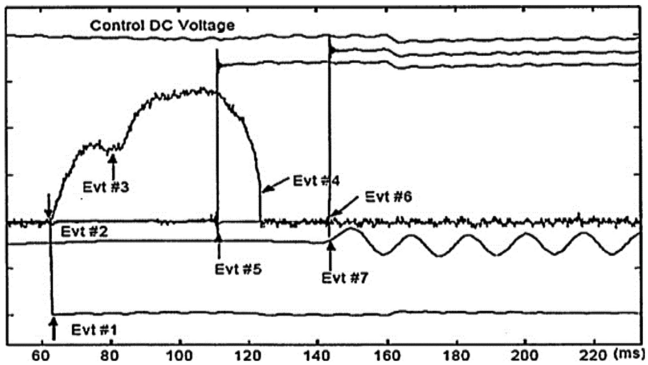


Fig. 6. Monitored coil current waveform during the CB close operation [29].

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

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. 6 and the associated timing parameters describing the sequence of breaker operations are introduced in Table I. Based on the preliminary research in [35] and [36], only timing parameters $t_2 - t_6$ are selected for analysis in this paper, as tabulated in Table I.

IV. PROPOSED FORMULATION

CB reliability analysis is approached in this paper in terms of failure probability. In Section IV-A, the probability distribution for each timing parameter is assigned. Section IV-B explores the condition assessment of CB and the associated sub-assemblies based on the assigned probabilities. And finally the solution methodology on how to set a correlation between the probabilities and the CB life-cycle deterioration/recovery states is described.

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 dataset for each signal parameter can be recorded. A probability distribution can then be assigned to these timing measurements. According to the central limit theorem, 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 [44]. Since the CB monitoring data is accumulated with time and the sample size will be large

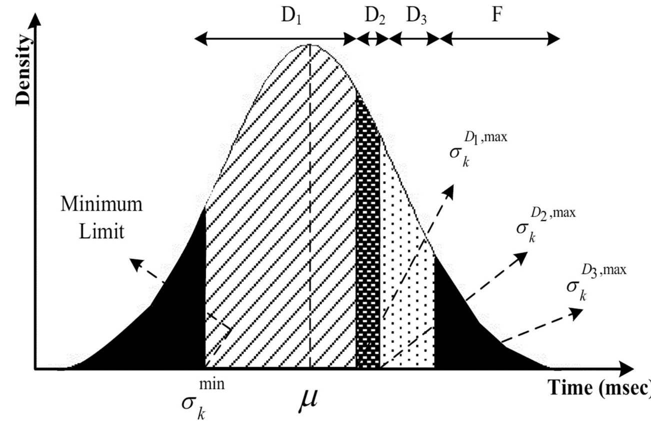


Fig. 7. Probability distribution and the bands assigned to timing parameter t_2.

enough over time, normal probability distribution can be reasonably adopted. Normal distribution is assumed in this paper for all signal parameters listed in Table I, as illustrated in Fig. 7 for parameter t_2. 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., 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 CB, 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 is an indicative of the failed state for the CC operation of the CB.

Based on the assigned distribution, the probability of a CB falling into each deterioration/recovery state margin with respect to the timing parameter t_i is assessed in (1)–(4), respectively for the healthy, vulnerable, troubled, and failed states.

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

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

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

$$P_{B_k}^{t_i,F} = 1 - \sum_{j=1}^{3} P_{B_k}^{t_i,D_j}. \tag{4}$$

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

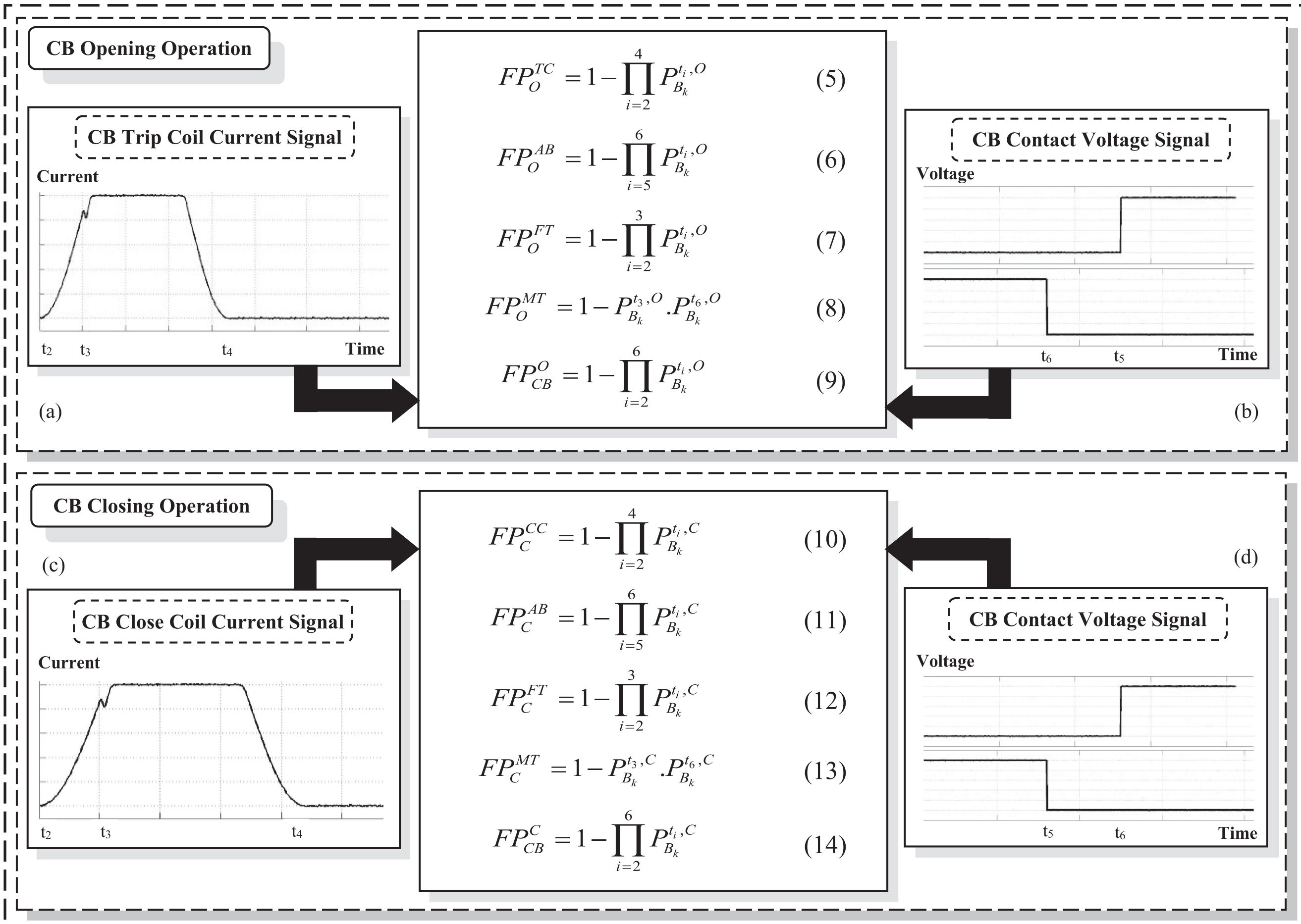


Fig. 8. General formulations for the failure probability estimation of CB sub-assemblies in both opening and closing operations.

B. Reliability Performance of CB Sub-Assemblies

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

1) Performance of CB TC: As shown in Fig. 8, a sample representation of the TC current is demonstrated. The TC 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 is active, the coil current makes a gradual transition to a nonzero value at time "t_2." The time instant "t_3" is when the operating mechanism starts moving using the TC energy. The coil current starts dropping down to zero at "t_4." Possible abnormalities regarding the TC can be the pickup delayed, dip delayed, drop-off delayed, etc. In the worst case, the above 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 TCs. The performance index of the TC is defined as the probability that it will fail to operate properly, as shown 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 shown in Fig. 8(b). Possible abnormalities regarding the operation of "a" and "b" contacts can be 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 failure probability of the auxiliary contacts is introduced in (6).

3) Performance of CB Operating Mechanism: The time period between the instant at which the TC current rises, i.e., "t_2," and the instant at which the dip occurs, i.e., "t_3," is called the *free travel time* that 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. 8. 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. 8.

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 from 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 response, the CB failure probability in opening operation is estimated in (9). Similar discussions are valid for the CB closing operation for which the derivations are formulated through (10)–(14) in Fig. 8.

C. CB Deterioration/Recovery Model

According to (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 sub-assemblies, i.e., CB TC, CC, and contacts, are studied here. The performance indices associated with the CB opening/closing operations are elaborated in detail.

1) CB TC Deterioration/Recovery Level: The probability of a CB TC subassembly falling into the failed, troubled, vulnerable, and healthy states is assessed in (15)–(18), respectively.

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

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

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

$$P_O^{\mathrm{TC},D_1} = \prod_{i=2}^{4} P_O^{t_i,D_1}. \tag{18}$$

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

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

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

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

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

3) CB CC Deterioration/Recovery Level: Probability of a CB CC in failed, troubled, vulnerable, and healthy states is calculated through (23)–(26), respectively.

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

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

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

$$P_C^{\mathrm{CC},D_1} = \prod_{i=2}^{4} P_C^{t_i,D_1}. \tag{26}$$

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 for each deterioration/recovery state.

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

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

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

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

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 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 using (15)–(30).

V. 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

TABLE II
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

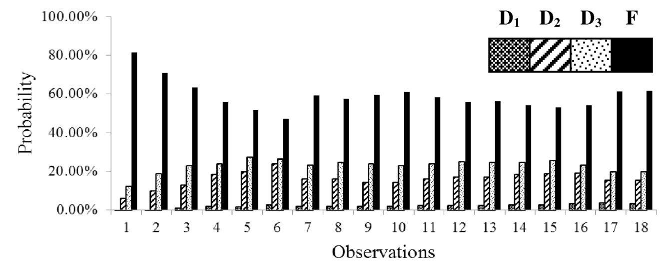


Fig. 9. Probability of the CB TC staying in each deterioration state.

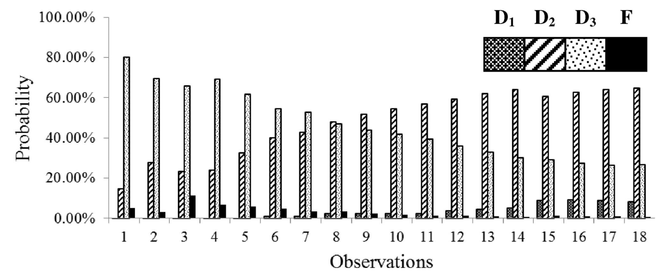


Fig. 10. Probability of the CB AB contacts staying in each deterioration state.

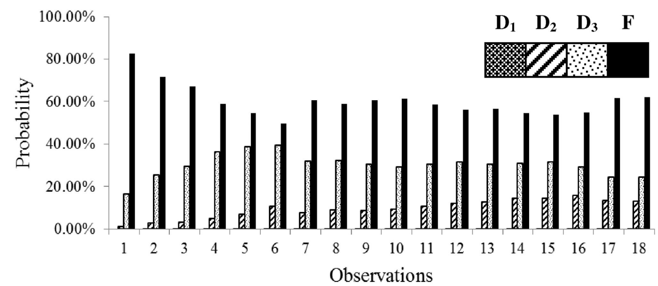


Fig. 11. Probability of the CB, as a component, in each deterioration state.

developed in [29]. Detailed description of datasets and how the measurements are done can be found in [29] and [36]. The tolerance limits for the signal timing parameters reflecting the deterioration/recovery thresholds are defined and demonstrated in Table II.

B. Application Considerations

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

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

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 are studied in this paper for the sake of demonstration. Employing (15)–(18) and according to the defined limits and thresholds in Table II, the deterioration assessment is done for the CB TC, as illustrated in Fig. 9. As it can be observed in Fig. 9, the CB TC is mostly in its failed state of deterioration since the associated failure probability is far more than that of the other deterioration or recovery states in all the observations recorded during the studied time interval. It reflects the fact that the CB TC 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 (19)–(22). As demonstrated in Fig. 10, 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. One may conclude that the CB contacts may call for minor maintenance activities to maintain their proper functionality.

TABLE III
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%

One can likewise evaluate an overall deterioration/recovery level of a CB as a stand-alone component using (27)–(30). As can be seen in Fig. 11, the results demonstrate that the CB is constantly on the edge of failed state due to the abnormal operation of different sub-assemblies and high failure probability assigned. In this case, a major maintenance is in urgent need. Based on these performance probabilities, one can easily conclude on the overall deterioration/recovery status of the CBs, as tabulated in the *classical life cycle model* in Table III.

VI. 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 [32]–[34], [43].

1) 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.
2) 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.
3) 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.

TABLE IV
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

TABLE V
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

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.

4) 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.
5) 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.
6) 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 [33]–[35], 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 IV and Table V. It is obvious that the probability of successfully bringing the CB into a better working state following major maintenance actions is larger than that following the minor maintenance strategies. 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 IV, 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.

In the second case in Table V, 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.

The following points are worthy to note.

1) The calculated failure probability of the CB (more than 50%) reflects that some parts of the CB under study responsible for the tripping operation are not reliable enough and need maintenance. The failure probability index calculated in real time is different from the failure rate index (number of failures per year. Failure probability 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).
2) 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. This research 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.
3) Conducting the same procedure for every CB in a substation would lead to a distinction between different CBs across the system, which 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 [45]–[50].
4) A cost/benefit analysis to assess the economic aspect of the proposed approach should be conducted. The economic benefits of the proposed monitoring scheme should outweigh the costs of device installation and assessment of CB condition over time.

VII. CONCLUSION

A quantitative approach to assess the reliability status of HV CBs and its sub-assemblies in real time is proposed. Some advantages of contributions elaborated in this paper are given as follows.

1) The proposed methodology uses the field monitoring signals from the CB control circuit, which takes advantage of increasing deployment of smart sensors and monitoring devices in the system.
2) The presented approach allows a quantitative assessment of CB status leading to the classification into different deterioration/recovery states in real time.
3) 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.
4) 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.

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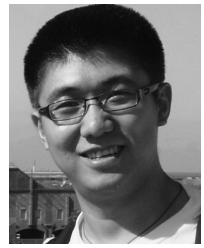
Payman Dehghanian (S'11–M'17) received the B.Sc. degree from the University of Tehran, Tehran, Iran, in 2009, the M.Sc. degree from the Sharif University of Technology, Tehran, Iran, in 2011, and the Ph.D. degree from Texas A&M University, College Station, TX, USA, in 2017, all in electrical engineering.

He is an Assistant Professor with the Department of Electrical and Computer Engineering, George Washington University, Washington, DC, USA. His research interests include power system protection and control, power system reliability and resiliency, asset management, and smart electricity grid applications.

Dr. Dehghanian is the recipient of the 2013 IEEE Iran Section Best M.Sc. Thesis Award in electrical engineering, the 2014 and 2015 IEEE Region 5 Outstanding Professional Achievement Awards, and the 2015 IEEE-HKN Outstanding Young Professional Award.



Yufan Guan (S'06–M'13) received the B.S. degree from Zhejiang University, Hangzhou, China, in 2007, and the Ph.D. degree from Texas A&M University, College Station, TX, USA, in 2013.

His research interests are alarm processing, substation automation, and artificial intelligence applications in power systems and electricity market operation.

Mladen Kezunovic (S'77–M'80–SM'85–F'99–LF'17) received the Dipl. Ing. from University of Sarajevo, Sarajevo, Bosnia, M.Sc. from University of Kansas, Lawrence, KS, and Ph.D. degrees in electrical engineering from University of Kansas, Lawrence, KS, in 1974, 1977, and 1980, respectively.

He has been with Texas A&M University, College Station, TX, USA, for 31 years, where he is currently a Regents Professor and an Eugene E. Webb Professor, the Director of the Smart Grid Center, and the Site Director of "Power Engineering Research Center, PSerc" consortium. He is currently the Principal of XpertPower Associates, a consulting firm specializing in power systems data analytics. His expertise is in protective relaying, automated power system disturbance analysis, computational intelligence, data analytics, and smart grids. He has authored over 550 papers, given over 120 seminars, invited lectures, and short courses, and consulted for over 50 companies worldwide.

Dr. Kezunovic is a CIGRE Fellow and an Honorary Member. He is currently a Registered Professional Engineer in Texas.