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***Abstract*— This paper presents a practical approach to evaluation of the operational health and reliability of circuit breakers in substations. Motivated by the recent failure surveys conducted by CIGRE working groups, circuit breaker condition data, obtained by monitoring critical parameters such as operational timings, tank gas pressure and temperature, mechanism traveling time and speed, etc., is used to evaluate the proposed health index. The proposed measure would help identify the transmission lines available for switching actions from the circuit breaker reliability view point. The proposed health index also provides a valuable input for substation maintenance personnel. The applicability of the proposed methodology is explored and validated using the actual circuit breaker condition data collected in the field.**

I. INTRODUCTION

The large penetration of renewable resources such as wind and solar created incentives to use transmission line switching for economic dispatch efficiency and also to control sudden changes in power flows and mitigate critical contingencies caused by the generation variability [1]-[4]. As an important implementation concern of switching actions, circuit breaker (CB) reliability has to be evaluated. The switching actions are being executed using CBs at both ends of the line and reliable CBs are the key to the switching implementation success.

Reliability of the system CBs can be ensured with the timely replacement and maintenance activities [5]. Due to a huge number of CBs in the system, with different operational characteristics, ages, and aging mechanisms, industry experts have come to an agreement that the time-based maintenance (TBM) programs cannot be adequate for management of CB annual maintenance resources any longer [6], [7]. The condition-based monitoring and maintenance (CBM) is thus desirable to be able to recognize the need for maintenance of various CBs in the system where and when necessary. This can not only lead to a more cost-effective maintenance and asset management decisions, but also could ensure an acceptable measure of CB reliability over time, making them available for operation in the anticipated day-to-day transmission switching plans and also clearing the unavoidable faults [8]-[11].

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Condition monitoring of CBs have been widely researched in literature. Depending on the type of deterioration impacts, the analysis is concentrated on vibration [12], [13], contact wear-and-tear [14]-[16], digital modeling for sensor techniques [17], or gas pressure in the operating chamber [18], [19]. Partial discharge tests are also among the approaches significantly focused on estimating the CB deterioration and dielectric properties [20], [21]. Automated approaches for CB monitoring, specifically the CB control circuitry, have been also broadly investigated in [22]-[24]. Expert system for the automated fault diagnosis has been utilized in [22]. Signal processing techniques and the expert systems are employed in [23]. Wavelet analysis to extract the features, and mobile agent software technology has been brought to play in [24]. An architecture for a flexible processing of monitored control circuit signals is introduced in [25]. Data mining approaches to provide the decision support for CB maintenance management on the basis of condition monitoring data are employed in [26].

According to the recent failure surveys conducted by CIGRE Working Group, CB failures are mostly found to be initiated due to the malfunction of operating mechanism and control circuit, and in that order compared to other CB subassemblies [27]-[29]. 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%). The recognized major failures in the 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 [28].

Inspired by the recent CB failure surveys, this paper proposes a practical approach to measure the health properties of the CBs using the condition monitoring data. The paper is organized as follows. After the Introduction, Section II describes the employed technology for CB condition monitoring and data requirements. Section III is devoted to introduce the proposed methodology for CB health evaluation. A numerical analysis is conducted in Section IV, and the conclusions are provided at the end.

II. Circuit Breaker Condition Monitoring

A. CB Monitoring Technology

The monitoring technologies currently available in the market are able to monitor several critical parameters of CB operations which can be helpful in detecting any potential failures. These parameters may be concerned with the interrupter wear, integrity of the gas systems, CB mechanical parts, electrical control system and auxiliaries. There are several sensors that are used in these technologies, mounted where necessary to be monitored such as CB tank, mechanism, or control circuit, in conjunction with a modular microprocessor to perform the monitoring tasks. An example use of this monitoring technology is given in [30]. In this example, the approach is for the user to ignore the monitored data over time until an alarm has happened and is being reported. The data is then analyzed and the decision is made to either change the alarm settings or initiate thorough maintenance investigation.

B. Monitored Signals/Features

The monitoring technology under study is fed with various inputs which can be helpful in the reliability and health analysis of the breakers in power systems. The coil connections not only help to detect when the CB is being operated, but also ensure the coil continuity. Monitored signals of the auxiliary contacts are helpful in distinguishing the close, open, and close-open operations. The inputs concerning the phase currents are mainly used to assess the interrupter wear. Parameters extracted out of the travel sensor enable monitoring the breaker timing behavior over time. There are also sensors reflecting the temperature conditions of tank, mechanism, or cabinet temperature. The pressure input along with that of the temperature provides the possibility for monitoring of SF_6 gas density. The runtime and number of starts associated with the mechanism charging motor are monitored through the motor voltage inputs. The monitoring technology introduced in [30] continuously evaluates several conditions listed in Table I. The monitored parameters range over the coil continuity, temperature, SF_6 gas pressure, and leak rates. It also keeps track of coil energization, mechanism, and reaction times, contact speed, and total travel and interrupter wear increments with every single operation of the breaker. As soon as one parameter falls out of the desired thresholds, an alarm is generated as an indicator of either caution or problem states depending on how far a specific parameter is compared with the desired value. To serve as an example, a group of monitored signal parameters covering the CB operation timings is demonstrated in Fig. 1 for a CB close operation. The above mentioned CB parameters are collected over time, but are ignored until an alarm occurs. The monitored data would then be analyzed and a specific maintenance plan would be decided in response. This view mostly based on the corrective thinking of maintenance, however, does not give a clue on the overall quantitative health and reliability of the breaker over time which can be further helpful in investment decisions either on the replacement or other preventive maintenance plans. This paper strives to propose an approach to evaluate the overall operational health and reliability of the breakers using the monitored signals by the at hand technology. This index would also help in other operational decisions in power systems including the reliable implementation of transmission line switching and system topology control scenarios.

III. Proposed Methodology

A. Concept Development

The CB operational health index (HI) is formulated using the concept of a hyper-ellipse inscribed within the hyper-box, introduced in this sub-section.

Assume a vector x_m (m = 1, 2… k) reflecting one monitored parameter over time (m is the number of monitored inputs) whose values are restricted between upper and lower limits $X_m^{\max}$ and $X_m^{\min}$, respectively. If a value hits such limits in any CB operation experience or in any sample arrival of monitoring data, it implies a critical condition which represents a problem. In addition to these limits, which are regarded as the trouble limits, upper and lower alarm limits $A_m^{\max}$ and $A_m^{\min}$, respectively, are also proposed to be included for the vector x_m, as can be seen in a two-dimensional demonstration in Fig. 2(a). For a k-dimensional vector space, a hyper-box can be formed by the alarm and trouble limits, as illustrated in Fig. 2(b) for the two-dimensional case. The vector g_m is the difference between the trouble and the alarm limits and are proposed as follows for both upper and lower limits:

$$g_m^{\max} = T_m^{\max} - A_m^{\max} \qquad \forall m = 1,2,...,k \tag{1}$$

$$g_m^{\min} = A_m^{\min} - T_m^{\min} \qquad \forall m = 1,2,...,k \tag{2}$$

TABLE I
CB Monitored Parameters

Travel time	Total travel
Contact velocity	Breaker current
Reaction time	Coil continuity
Coil energization time	SF6 gas pressure
Interrupter wear	Tank/Mech./Cabinet Temperature
Trip count	Motor operation

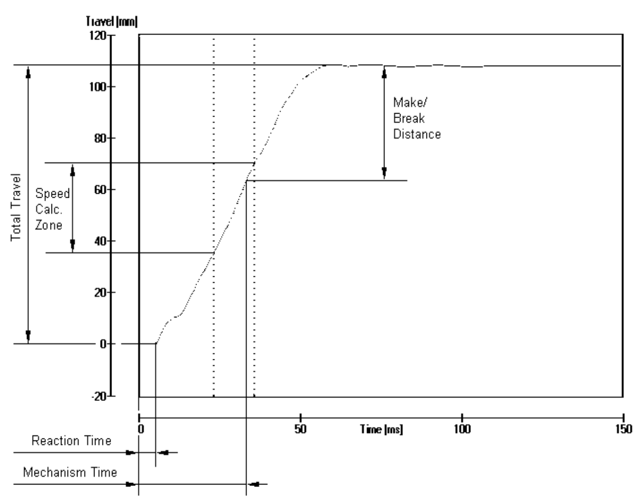

Fig. 1. Monitored timing parameters for the CB close operation [30].

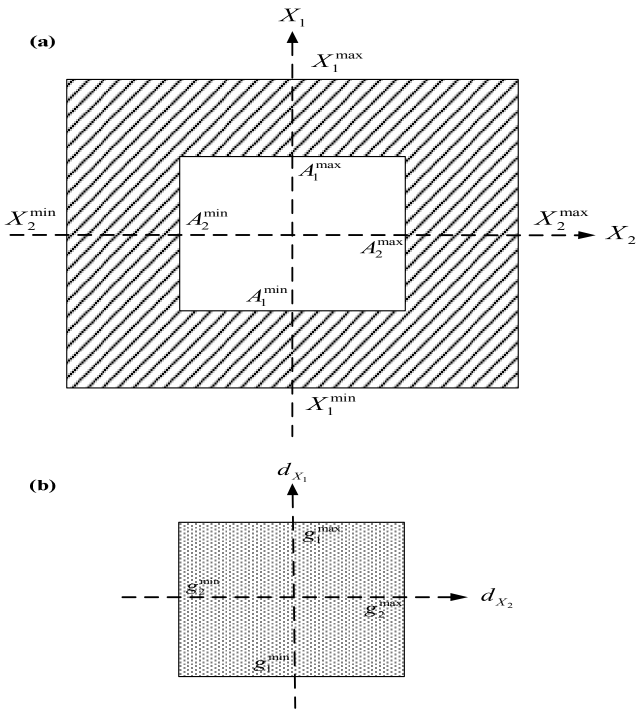

Fig. 2. Two-dimentional example of the hyper-box assigned for every monitored paramter of the breaker.

Also, the d_{X_m} is the limit violation vector of x_m beyond the alarm limit for both upper and lower levels, as defined in (3). The way it works is when any of the components of the vector x_m exceeds the trouble limit, the corresponding limit violation vector d_{X_m} lies outside the hyper-box and is considered as troubled observation.

$$d_{x_m}^{\max} = \left[x_m - A_m^{\max} \right] \qquad if \;\; x_m > A_m^{\max} \quad \forall m = 1,2,...,k \tag{3}$$

$$d_{x_m}^{\max} = 0 \qquad if \;\; x_m < A_m^{\max} \quad \forall m = 1,2,...,k \tag{4}$$

$$d_{x_m}^{\min} = \left[A_m^{\min} - x_m \right] \qquad if \;\; x_m < A_m^{\min} \quad \forall m = 1,2,...,k \tag{5}$$

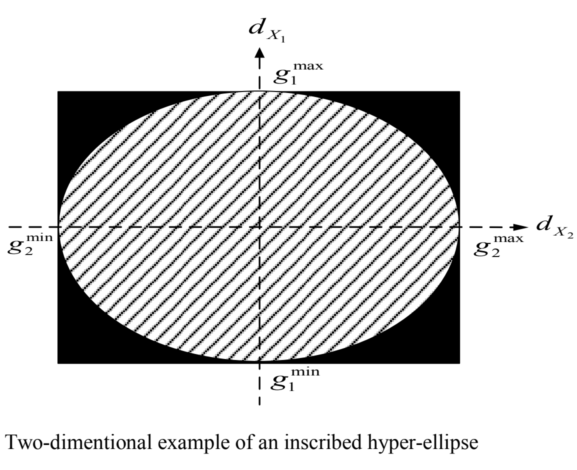

Fig. 3. Two-dimentional example of an inscribed hyper-ellipse

$$d_{x_m}^{\min} = 0 \qquad if \;\; x_m > A_m^{\min} \quad \forall m = 1,2,...,k \tag{6}$$

However, the limit violation vector d_{X_m} lies inside the hyper-box when x_m exceeds the alarm limit but does not exceed the trouble limit, and its value is zero when any of the components of x_m lie within its desired alarm limits.

The effects of these k-dimensional limit violations can be transformed to a scalar value by approximating the hyper-box by the inscribed hyper-ellipse, as illustrated in Fig. 3, for two-dimensional case. The hyper-ellipse is given by the expression below:

$$\sum_m \left(d_{x_m} / g_m \right)^{2n} = C^{2n} \tag{7}$$

The trouble condition indicated with d_{X_m} lies outside the hyper-ellipse is given as follows:

$$\sum_m \left(d_{x_m} / g_m \right)^{2n} \geq C^{2n} \tag{8}$$

The next subsection demonstrates how this concept can be employed in the case of a CB health and reliability assessment using the condition monitoring data.

B. Application to CB Health Assessment

For any parameter of interest for a breaker, e.g., different operation timings, pressure, temperature, etc. one can assign the hyper-ellipse introduced above having the alarm and trouble limits available. For instance, for monitoring the breaker temperature over time, it is assumed that the desired temperature level for the breaker i is known and is represented as T_i^d. The upper and lower alarm limits and trouble limits of temperature for this breaker are represented as $A_{T_i}^{\max}$, $A_{T_i}^{\min}$, $T_{T_i}^{\max}$, $T_{T_i}^{\min}$, respectively. The normalized upper and lower temperature limit violations beyond the alarm limits are defined as follows:

$$d_{T_i}^{\max} = \left[T_i - A_{T_i}^{\max} \right] / T_i^d \qquad if \;\; T_i > A_{T_i}^{\max} \tag{9}$$

$$d_{T_i}^{\min} = \left[A_{T_i}^{\min} - T_i \right] / T_i^d \qquad if \;\; T_i < A_{T_i}^{\min} \tag{10}$$

$$d_{T_i} = 0 \qquad if \;\; A_{T_i}^{\min} \leq T_i \leq A_{T_i}^{\max} \tag{11}$$

With each single operation of the breaker or arrival of new monitoring data, the temperature would be captured and as time goes on with N operation of the breaker, the temperature limit violations represent an N-dimensional vector space. In order to define the temperature health index for the breaker, it is necessary to transform the vector-valued limit violations to a scalar value. For an N-dimensional vector space, a hyper-box is formed by the alarm and troubled limits as introduced earlier in this paper, and by approximating the hyper-box with a hyper-ellipse inscribed within, a scalar-valued health index can be formed for the breaker from the monitored temperature viewpoint. For each upper and lower limit of the temperature, the normalization factor g_{T_i}, which is taken as the difference between the trouble limit and the alarm limit, is defined as:

$$g_{T_i}^{\max} = \left[T_i^{\max} - A_{T_i}^{\max}\right] / T_i^d \tag{12.a}$$

$$g_{T_i}^{\min} = \left[A_{T_i}^{\min} - T_i^{\min}\right] / T_i^d \tag{12.b}$$

By substituting d_{T_i} and g_{T_i} in the hyper-ellipse equation, and by setting the value of constant C to 1.0, the breaker temperature health index is obtained as

$$HI_{T_i}^j = 1 - \left[\left(d_{T_i}^{\max} / g_{T_i}^{\max}\right)^{2n} + \left(d_{T_i}^{\min} / g_{T_i}^{\min}\right)^{2n}\right]^{1/(2n)} \tag{13}$$

The equation indicates that the breaker is healthy from the monitored temperature viewpoint if $HI_{T_i} = 1$ and has some problems if $HI_{T_i} < 0$. For the values between these limits of 0 and 1, the breaker temperature is identified as being in the alarm state. The same process as introduced through (9)-(13) would be followed for other desired monitored parameters of the breaker under study (e.g., travel times, contact velocity, interrupter wear, SF6 gas pressure, etc.) and the health index corresponding to each monitored parameter would then be captured. The application process is the same, while the only difference is the use of different threshold levels for different parameters and so do different hyper-ellipses assigned. With several operations of the breakers (say *n* operation practices either opening or closing), *n* number of health indices corresponding to each parameter would be obtained during time whose trend would show how healthy the breaker is working with regard to that specific parameter and would help to decide whether the breaker is in need of some specifically related maintenance considerations.

In order to evaluate the overall health index for the breaker, it would be helpful if combining the above introduced health indices corresponding to various monitoring signals. The breaker composite health index would be essentially indicative of the breaker overall health and reliability and would be useful for the operator in further investment, maintenance, or even operational decision making, such as power system topology control and line switching implementations. The breaker composite health index would be evaluated via (14) as

$$CHI_i = \frac{\sum_{j=1}^{m}\left(1 - \left(\left(d_{J_i}^{\max} / g_{J_i}^{\max}\right)^{2n} + \left(d_{J_i}^{\min} / g_{J_i}^{\min}\right)^{2n}\right)^{1/(2n)}\right)}{m} \tag{14}$$

where, CHI_i is the composite health index of breaker *i*; *j* is the indicator for the number of the monitored parameters to be included in the analysis, and $d_{J_i}^{\max}$, $d_{J_i}^{\min}$, $g_{J_i}^{\max}$, and $g_{J_i}^{\min}$ are introduced earlier in this paper. The defined CHI_i is updated as time goes on with the arrival CB condition data. The trend of the index is expected to be a reliable indicator of the breaker health condition. If the index is on the rise, it demonstrates that the breaker is not reliable and/or in a need for maintenance. Otherwise, the breaker is considered healthy.

IV. Performance Evaluation

A. Monitoring Technology Being Used

The technology being used is the Circuit Breaker Sentinel (CBS) monitoring system for SF6 single pressure power circuit breakers rated 38 – 800 kV. The readers are referred to [30] for more detailed information on the technology. Six breakers operated in the selected substation under the territory of the Tennessee Valley Authority (TVA) in the U.S. were selected to be in the focus of this study. Detailed characteristics of the breakers are provided in Table II.

TABLE II
GENERAL CHARACTERISTICS OF THE STUDIED BREAKERS

Features		CB1	CB2	CB3	CB4	CB5	CB6
CB Type	242PMG63	■	■	■		■	
	550PM50				■		■
CB Mechanism	AHMA-11	■					
	HMB-8		■	■	■	■	■
CB Tap Ratio	600				■		■
	1000	■	■	■		■	
Aux. CT Rating	2	■	■	■	■	■	■

B. Monitored Signals and Employed Data

The monitoring equipment supports all the different types of breaker monitoring signals introduced in Table I. For example, the CB#1 monitored operation and travel waveforms in 20 operation experiences in both opening and closing are demonstrated in Fig. 4. They range from the trip/close coils and A/B contact statuses in digital format and phase currents and traveling movement in analogue. The monitored tank and mechanism temperature as well as the gas and temperature-compensated pressure over time are demonstrated in Fig. 5 and Fig. 6, respectively.

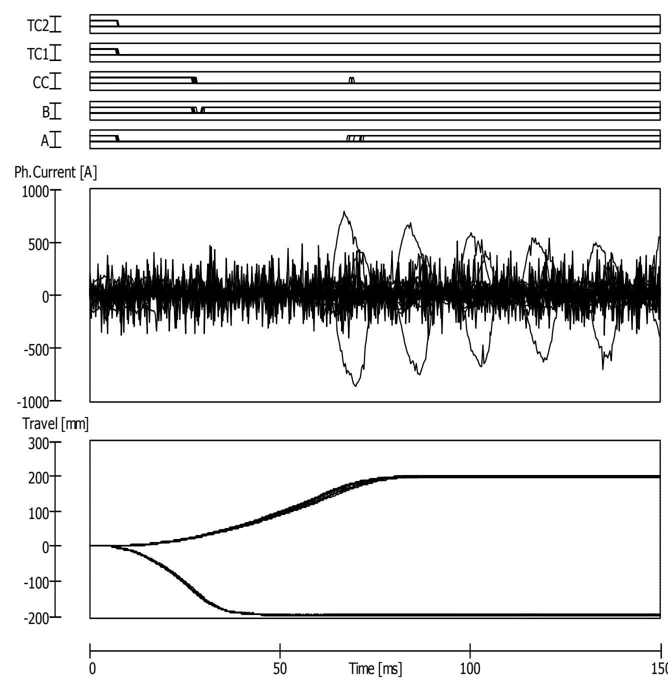

Fig. 4. Several operation waveforms of CB#1 in opening and closing experiences over time.

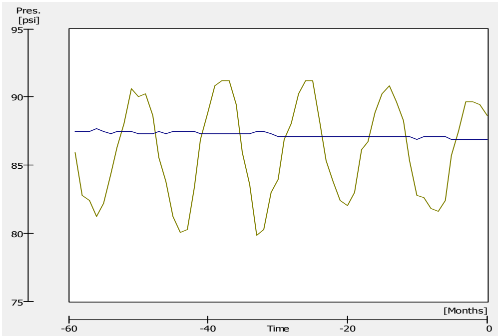

Fig. 5. Waveform of CB#1 Tank and Mech. temprature monitored over time.

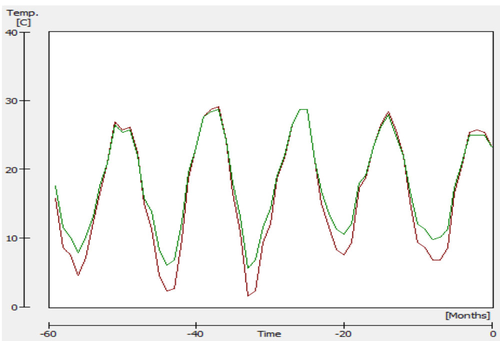

Fig. 6. Waveform of CB#1 pressure and temprature-compensated pressure monitored over time.

The minimum and maximum limits for the alert and troubled states, provided by the monitoring vendor for breaker closing operations, are indicated in Table III for various monitored parameters. Similar data is available for the opening operation of the breakers. The proposed parameters for the CB health assessment ($g_{x_i}^{\min}, g_{x_i}^{\max}$) is calculated in Table IV, using the data provided in Table III.

C. *Numerical Analysis*

The health index, introduced earlier in Section III, is calculated over time and with the arrival of the new monitoring inputs for various parameters, using the information in Tables III and IV. The results for various parameters of CB#4 are illustrated in Fig. 7. The trend for CB overall health index is also demonstrated in Fig. 8 for CB#1, CB#4, and CB#6 in terms of monitoring data arrival over time. The analysis for CB#4 in Fig.7 demonstrates that this CB is performing unhealthy with respect to the temperature signals since the $HI_{T_i}^{CB1}$ stays negative and constantly beyond the expected thresholds over the studied time period, while the monitored pressure signal illustrates a healthy status. One can easily see the decreasing trend in the health index of the last three monitored signals (constantly in the alarm state). This observation, together with the temperature's unhealthy status, would be translated in the CB composite health index to be overall in the alarm mode and the breaker has to be maintained accordingly. This conclusion is confirmed by looking at the CB#4 composite health index in Fig. 8 (health index ≤ 0.5). Fig. 8 also illustrates the health status of the CB#1 as the healthy and reliable, and CB#6 as the one in the alarm state.

TABLE III
ALERT AND TROUBLE LIMITS FOR MONITORED PARAMETERS

Parameter	$A_m^{\min}$	$A_m^{\max}$	$T_m^{\min}$	$T_m^{\max}$
Tank/Gas Temperature (˚C)	-30	100	-40	110
Comp. SF6 Pressure (psig)	76	98	72	102
Travel Close (mm)	195	208	190	213
Closing Speed (m/s)	3.6	5.1	3.1	5.6
Closing Reaction Time (ms)	6	14	1	19
Closing Mechanism Time (ms)	56	71	51	76
Close Coil Time (ms)	23	35	18	40

TABLE IV
ALERT AND TROUBLE LIMITS FOR MONITORED PARAMETERS

Parameter	T_i^d	$g_{x_i}^{\min}$	$g_{x_i}^{\max}$
Tank/Gas Temperature (˚C)	35	10	10
Comp. SF6 Pressure (psig)	88	4	4
Travel Close (mm)	201.5	5	5
Closing Speed (m/s)	4.35	0.5	0.5
Closing Reaction Time (ms)	6.5	5	5
Closing Mechanism Time (ms)	63.5	5	5
Close Coil Time (ms)	29	5	5

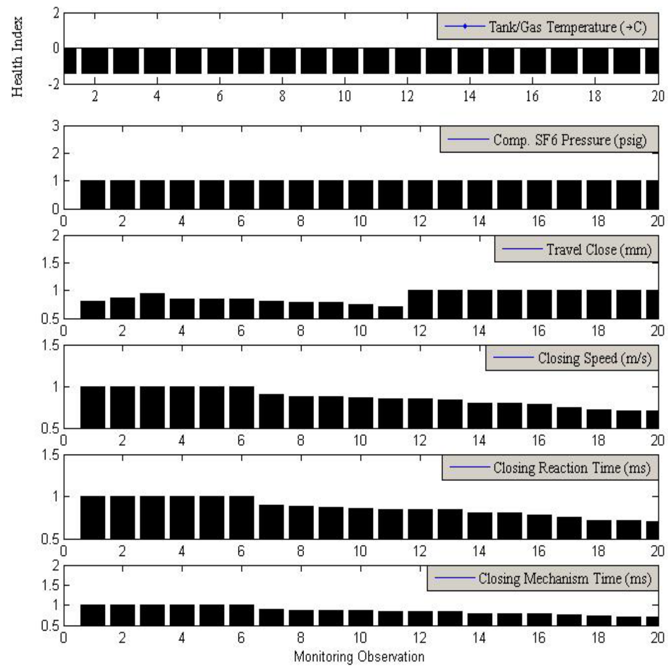

Fig. 7. Health status of monitored paramters for CB#4 closing opertaion.

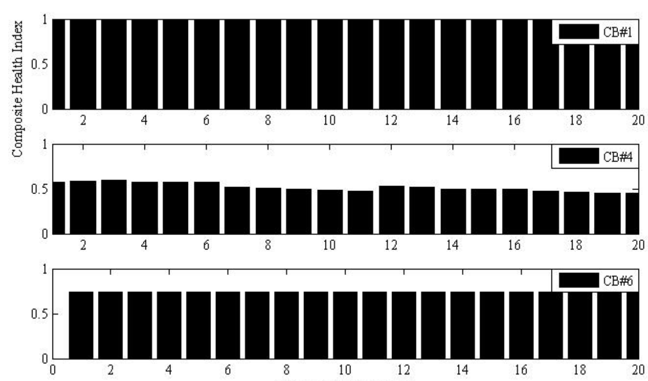

Fig. 8. Trend of the composite health index for several CBs understudy.

CB#6 can be still put in practice for closing operations but its health status is in need of being tracked in the next couple of arrived monitoring data for more reliable decision. The same analysis could be also done for the CB opening operations which will further help in maintenance and other operational decision makings.

V. CONCLUSION

The following summarizes the main contributions of this paper.

- The proposed methodology based on the CB field monitoring data covering various parts of its mechanical/electrical circuitry takes advantage of increasing deployment of smart sensors and monitoring devices.
- The proposed technique provides a quantitative approach to assess the health status of individual CBs and their critical operating parameters in real time.
- The presented approach enables a real-time classification of CBs health assessment (healthy, needs attention, and faulty), which supports a more targeted maintenance activities.
- The possibility of health differentiation of various CBs throughout the system helps improve the scheduling of system-wide maintenance and asset management practices, providing the possibility for considerable long-term economic savings.
- The proposed approach can help identify the transmission lines with reliable CBs that should be switched as a part of the power system topology control approach.

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