Assessing Circuit Breaker Life Cycle using Condition-based Data

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***Abstract*—How to make decisions to optimally allocate the resources by deciding when to perform maintenance on power apparatus is a critical issue, especially with present economic scenario in power industry. This paper proposes a new approach to assess the circuit breaker's life cycle or deterioration stages using its control circuit data. In this approach, the "classical" healthy, minor and major deterioration stages have been mathematically defined by setting up the limits of various performance indices. The model can be automatically updated as the new real-time condition-based data become available to assess the CB's operation performance using probability distributions. The methodology may also be used to quantify the effect of maintenance making use of the defined performance indices, which further helps in developing system-wide risk-based decision approaches for maintenance optimization. Case studies using field data recorded at different times during operations of circuit breaker are presented at the end.**

***Index Terms*— Circuit breaker, condition-based data, life cycle, reliability, maintenance, risk.**

I. Introduction

Maintenance of power apparatus plays an important role in asset management and reliability of power system. It is vital to optimally allocate maintenance resources and to decide when to perform maintenance on power equipment. Power industry is gradually changing from scheduled maintenance to "as needed" or "just-in-time" maintenance, which means that it is important not to "over maintain" the equipment. Also, if too little maintenance is done on the equipment, it may fail due to wear and deterioration. Even when maintenance is performed, the inadequate type of maintenance will not improve the condition of the equipment. The attention must be put on the troubled area. Otherwise unnecessary maintenance action is simply a waste of time, effort and money [1].

An effective maintenance that can reduce the frequency of service interruptions and the many undesirable consequences of such interruptions is in great need. Commonly used maintenance strategies are reviewed and reported in [2]. These approaches range from scheduled maintenance to reliability-centered maintenance (RCM) and condition based maintenance (CBM) [3]-[7]. RCM allows modeling the component deterioration process and linking it to the condition of the device [8][9]. These models are further developed for circuit breakers and transformers with objective being determination of the Mean Time to First Failure (MTTFF), estimation of the failure probability and prediction of cost reduction [10]-[12].

In failure models, the deterioration process is represented by a sequence of stages of increasing wear, finally leading to equipment failure. Deterioration is of course a continuous process in time and only for the purposes of easier modeling is it considered in discrete steps. The common way to define deterioration stage is by duration, e.g. the second stage is reached, on average, in three years, the third in six, and so on. The problem with this approach is that the mean time is usually obtained from a large amount of historical data from many circuit breakers that are working under different operation environment, such as temperature, humidity, open/close frequency, different level of rated voltages and current, etc. The deviation among CBs may impede an attempt to determine the stage of deterioration. Since the mean times between the stages are usually uneven, they are selected from performance data or by judgment based on experience.

Under a predictive maintenance model, maintenance is carried out as needed. The need for maintenance is established through condition monitoring which is the on-going inspection and surveillance of the operation of equipment to ensure proper performance and to detect abnormalities indicative of approaching failure. Reverences [13][14] have proposed a methodology utilizing the control circuit data of CB to define several performance indices. Time instants in the waveforms captured from the control circuit when CB operates (either open or close operation) to reflect the health/condition of various assemblies such as trip coil, close coil, auxiliary contacts etc. are used. The disadvantage of the previous method is that it uses only two maintenance state: healthy and failure. This ignores the possibility that different types of maintenance can be done to correct specific problems. With the inclusion of more than one maintenance state, a maintenance model can be more sufficiently applied to practical situations.

To overcome the deficiency, this paper proposes methodology suitable for practical applications and it can be applied in real time using field measured condition-based data. Section II deals with details of formation the proposed methodology, next section with the model development and test case are given at the end.

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II. PROPOSED METHODOLOGY

A. Condition-based Data

According to the failure survey conducted by CIGRE Working Group A3.12, majority of CB failures are due to malfunction of operating mechanism and control circuit in that order compared to other CB assemblies [15]. The condition monitoring techniques are relatively easy to develop since the secondary circuit is readily accessible for on-line monitoring. There are portable test devices available on the market to collect and display the control circuit signals which are analog and/or digital waveforms [16]. A low cost circuit breaker monitor (CBM) developed for recording and automated analysis of condition-based data both offline and online is reported in [17]. Signal processing and expert system modules for extracting the exact timings of the signal parameters for both open and close operations are implemented in [18]. The list of events, corresponding definitions and timing parameters are presented in Table I [18]. Based on the preliminary research done in [13], only timing parameters t_2-t_6 are considered in this paper.

TABLE I. LIST OF EVENTS AND SIGNAL PARAMETERS

Event	Event Description	Signal Parameter
1	Trip of 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

B. Probability distribution

A normal distribution is assumed for all signal parameters for the purpose of illustration. The probability distribution of signal parameter t_2 is shown in Fig.1. To proceed with the methodology, three bands for each timing parameter are defined: healthy, minor deterioration and major deterioration. If one new value of t_i falls in the "healthy" range, then it indicates that those parts of the breaker which cause the occurrence of time instant t_i operate properly. One new value of t_i falls in the second band means that the associated parts respond with some delays and may be in the minor deterioration. If one new value of t_i falls in the third range that suggests that the associated parts can't respond in time and may be in the major deterioration stage. To be more specific, for instance, if t_2 falls out all of three ranges, it means that there is some problem associated with the close coil. These limits are specific to each circuit breaker and can be determined once and for all.

In general, probability that breaker operates correctly with respect to t_i is defined as $p(t_i^1) = \Pr(l_i \le t_i \le u_i^1)$, $p(t_i^2) = \Pr(u_i^1 \le t_i \le u_i^2)$, $p(t_i^3) = \Pr(u_i^2 \le t_i \le u_i^3)$, where l_i is the lower limit and u_i is the upper limit, superscript 1,2,3 denotes the three stages: healthy condition, minor deterioration and major deterioration respectively. Those probabilities are used to define performance indices for various part assemblies of circuit breaker.

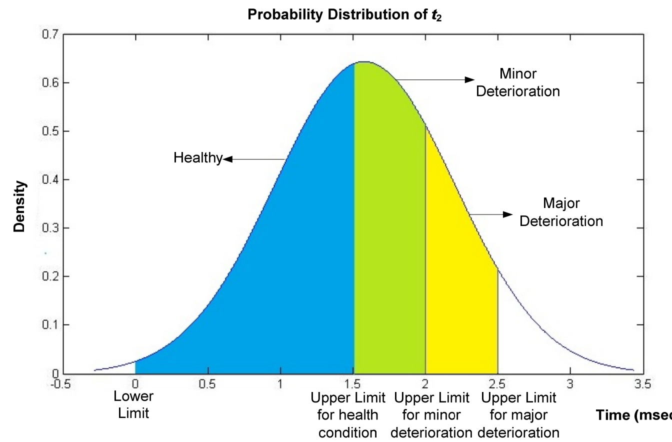

Fig. 1. Probability distribution of parameter t_2

C. Condition assessment

Reference [13] has listed five part assemblies. Due to page limit, only performance indices related to the open operation will be considered in this paper.

- *Performance of trip and close coils*

A sample representation of trip coil current is shown in Fig.2. After 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' corresponds the time at which the operating mechanism starts moving with the help of trip coil energy. The coil current starts dropping down to zero at time 't_4'. The trip coil current signals should be fairly smooth except for the dips at the beginning and end of the waveform.

Possible abnormalities associated with trip coil include: pick up delayed, dip delayed, drop-off delayed, etc. In worst case, these abnormalities may result in breaker not opening when it is supposed to. These abnormalities can be addressed by probabilities $p(t_2)$, $p(t_3)$ and $p(t_4)$ corresponding to the timing parameter t_2, t_3 and t_4. These time instants should occur within the tolerance limits to assure proper operation of trip coils. The performance index related to trip coil is defined as the probability that trip coil fails to operate properly,

$$p_f(TC) = 1 - p(t_2)p(t_3)p(t_4) \quad (1)$$

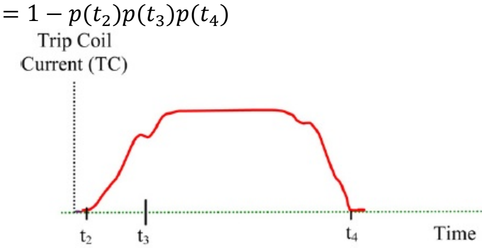

Fig. 2. Trip coil current during openning

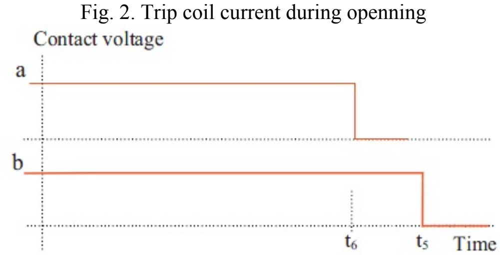

Fig. 3. 'a' and 'b' contacts transition during openning

- *Performance of auxiliary contacts*

As the breaker opens its main contacts, it also changes the status of the auxiliary 'a' and 'b' contacts as shown in Fig. 3. Some possible abnormalities associated with operation of 'a' and 'b' contacts are: delay in transition, premature transition, unstable contacts, noise and contacts bounce. If the timings t_5 and t_6 fall within their tolerance limits, we can say the auxiliary contacts operate normally. The performance index related to auxiliary contacts can be defined as, the probability that auxiliary contacts fails to operate properly,

$$p_f(AB) = 1 - p(t_5)p(t_6) \quad (2)$$

- *Performance of operating mechanism*

The time period between the instant at which the TC rises (t_2) and the instant at which the dip occurs (t_3) is the 'free travel time' that equals to $|t_3 - t_2|$. This free travel time reflects the performance of the trip latch mechanism. The timings t_2 and t_3 need to fall in the tolerance limits for the breaker to have normal free travel time. Any violation reflects an improper operation of trip latch mechanism. The corresponding performance index is defined as the probability that free travel time is abnormal,

$$p_f(FT) = 1 - p(t_2)p(t_3) \quad (3)$$

The coil current also needs to correlate with the event of 'a' or 'b' contact changes. The time period between the dip and the change of 'a' for opening is the mechanism travel time which is equal to $|t_6 - t_3|$ for opening [19]. For normal 'mechanism travel time', the timings t_5 and t_6 need to fall in corresponding tolerance limits. Any violation of these timings can be reported as abnormal operation of breaker. The corresponding performance index is defined as the probability that the mechanism travel time is abnormal,

$$p_f(MT) = 1 - p(t_3)p(t_6) \quad (4)$$

- *Performance of breaker*

In addition to the performance of individual components of breaker, an overall performance of the breaker may be assessed. If none of the timings t_2 to t_6 is violated, we can say that breaker operates properly. If any of these timings falls out the corresponding tolerance limits, we can say that the breaker fails to operate properly. This quantity can be defined as probability that the breaker does not operate properly and is estimated as,

$$p_f(Br) = 1 - \prod_{i=2}^{6} p(t_i) \quad (5)$$

A summary of all performance indices for CB opening is given below in Table II.

TABLE II. LIST OF EVENTS AND SIGNAL PARAMETERS

Operation	Performance index	Performance
open	p_f(TC)	Trip coil
	p_f(AB)	Auxiliary 'a' and 'b' contacts
	p_f(FT)	Trip latch mechanism
	p_f(MT)	Operating mechanism
	p_f(Br)	Breaker as a whole

III. MODEL DEVELOPMENT

A. Assumptions

The proposed model is built based on the following assumptions:

i) Only if all the time instants are within the health condition range, the associated component is considered being in the health stage.

ii) If one or more time instants are within the minor deterioration range, the associated component is considered being in the minor deterioration stage.

iii) If one or more time instants are within the major deterioration range, the associated component is considered being in the major deterioration stage.

iv) If one or more time instants are in the fault range, the associated component is considered being in the failure stage. If one component or the breaker as a whole is in a failure stage, it may respond very slowly or it may get stuck.

v) The component will not recover to the previous stage automatically without proper maintenance.

Therefore, to determine the life cycle stage of specific part assemblies, equations (1)-(5) can be extended as:

Trip coil:

$$p_f(TC^f) = 1 - \sum_{j=1}^{3} p(t_2^j) \cdot \sum_{j=1}^{3} p(t_3^j) \cdot \sum_{j=1}^{3} p(t_4^j) \quad (6.1)$$

$$p_f(TC^3) = \left(1 - p_f(TC^f)\right) - \sum_{j=1}^{2} p(t_2^j) \cdot \sum_{j=1}^{2} p(t_3^j) \cdot \sum_{j=1}^{2} p(t_4^j) \quad (6.2)$$

$$p_f(TC^2) = \left(1 - p_f(TC^f) - p_f(TC^3)\right) - p(t_2^1) \cdot p(t_3^1) \cdot p(t_4^1) \quad (6.3)$$

$$p_f(TC^1) = p(t_2^1) \cdot p(t_3^1) \cdot p(t_4^1) \quad (6.4)$$

Auxiliary contacts:

$$p_f(AB^f) = 1 - \sum_{j=1}^{3} p(t_5^j) \cdot \sum_{j=1}^{3} p(t_6^j) \quad (7.1)$$

$$p_f(AB^3) = (1 - p_f(AB^f)) - \sum_{j=1}^{2} p(t_5^j) \cdot \sum_{j=1}^{2} p(t_6^j) \quad (7.2)$$

$$p_f(AB^2) = \left(1 - p_f(AB^f) - p_f(AB^3)\right) - p(t_5^1) \cdot p(t_6^1) \quad (7.3)$$

$$p_f(AB^1) = p(t_5^1) \cdot p(t_6^1) \quad (7.4)$$

Trip latch mechanism:

$$p_f(FT^f) = 1 - \sum_{j=1}^{3} p(t_2^j) \cdot \sum_{j=1}^{3} p(t_3^j) \quad (8.1)$$

$$p_f(FT^3) = (1 - p_f(FT^f)) - \sum_{j=1}^{2} p(t_2^j) \cdot \sum_{j=1}^{2} p(t_3^j) \quad (8.2)$$

$$p_f(FT^2) = \left(1 - p_f(FT^f) - p_f(FT^3)\right) - p(t_2^1) \cdot p(t_3^1) \quad (8.3)$$

$$p_f(FT^1) = p(t_2^1) \cdot p(t_3^1) \quad (8.4)$$

Operating mechanism:

$$p_f(MT^f) = 1 - \sum_{j=1}^{3} p(t_3^j) \cdot \sum_{j=1}^{3} p(t_6^j) \quad (9.1)$$

$$p_f(MT^3) = (1 - p_f(MT^f)) - \sum_{j=1}^{2} p(t_3^j) \cdot \sum_{j=1}^{2} p(t_6^j) \quad (9.2)$$

$$p_f(MT^2) = \left(1 - p_f(MT^f) - p_f(MT^3)\right) - p(t_3^1) \cdot p(t_6^1) \quad (9.3)$$

$$p_f(MT^1) = p(t_3^1) \cdot p(t_6^1) \quad (9.4)$$

Breaker as a whole:

$$p_f(Br^f) = 1 - \sum_{j=1}^{3} p(t_2^j) \cdot \sum_{j=1}^{3} p(t_3^j) \cdot \sum_{j=1}^{3} p(t_4^j) \cdot \sum_{j=1}^{3} p(t_5^j) \cdot \sum_{j=1}^{3} p(t_6^j) \quad (10.1)$$

$$p_f(Br^3) = \left(1 - p_f(Br^f)\right) - \sum_{j=1}^{2} p(t_2^j) \cdot \sum_{j=1}^{2} p(t_3^j) \cdot \sum_{j=1}^{2} p(t_4^j) \cdot \sum_{j=1}^{3} p(t_5^j) \cdot \sum_{j=1}^{3} p(t_6^j) \quad (10.2)$$

$$p_f(Br^2) = \left(1 - p_f(Br^f) - p_f(Br^3)\right) - p(t_2^1) \cdot p(t_3^1) \cdot p(t_4^1) \cdot p(t_5^1) \cdot p(t_6^1) \quad (10.3)$$

$$p_f(Br^1) = p(t_2^1) \cdot p(t_3^1) \cdot p(t_4^1) \cdot p(t_5^1) \cdot p(t_6^1) \quad (10.4)$$

where the superscript f denotes the failure stage and the other superscripts 1,2,3 denotes the three stages of healthy condition, minor deterioration and major deterioration respectively.

B. *Development steps*

The general model development has the following steps:

i) Capture history of CB control signal changes and extract timings of each signal parameter using signal processing module.

ii) Analyze the relationship between the parameters and fit a probability distribution to each parameter.

iii) Define performance indices using these distributions to assess the conditions (health, minor/major deterioration, failure) of the breaker.

iv) As the new data arrives, update the distribution and performance indices.

In the last step, since the normal distribution is selected to fit all the signal parameters, the distribution is updated by updating the mean and variance of the time instances. We write:

$$X \sim N(\mu, \sigma^2) \quad (11.1)$$

or

$$f(x; \mu, \sigma^2) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{\frac{-(x-\mu)^2}{2\sigma^2}}, \text{ for } x = t_2, t_3, t_4, t_5, t_6 \quad (11.2)$$

The flowchart of the CB assessing model is shown in Fig. 4.

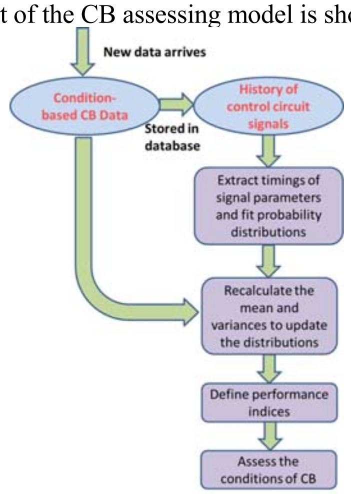

Fig. 4. Model flowchart for assessing the CB conditions

IV. CASE STUDY

To illustrate the proposed methodology, history of each signal parameter is developed using the waveforms taken from control circuit of a GE circuit breaker. Detailed data sets can be found in the Appendix of Ref [13]. The tolerance limits for operation in [18] have been further divided into three bands, as shown in Table III.

TABLE III. LIST OF EVENTS AND SIGNAL PARAMETERS

Event (ms)	Lower limit	Upper limit for health condition	Upper limit for minor deterioration	Upper limit for minor deterioration
t_2	0.00	1.00	1.50	2.00
t_3	13.6	16.1	17.4	18.6
t_4	26.4	30.9	33.2	35.4
t_5	28.7	33.7	36.2	38.7
t_6	22.4	27.4	29.9	32.4

The computed performance indices are shown in the Fig. 5 to Fig. 9.

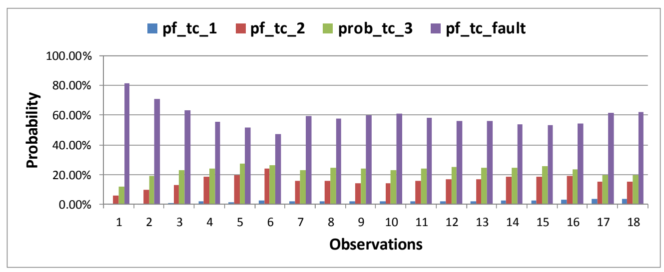

Fig. 5. Performance indices for TC

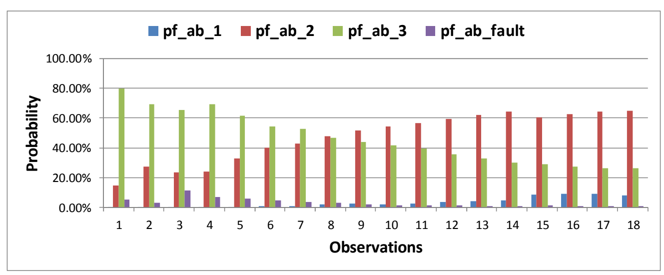

Fig. 6. Performance indices for AB

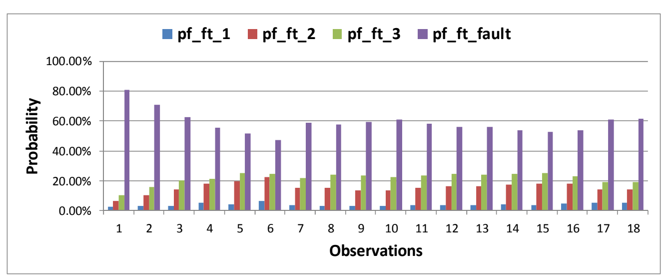

Fig. 7. Performance indices for FT

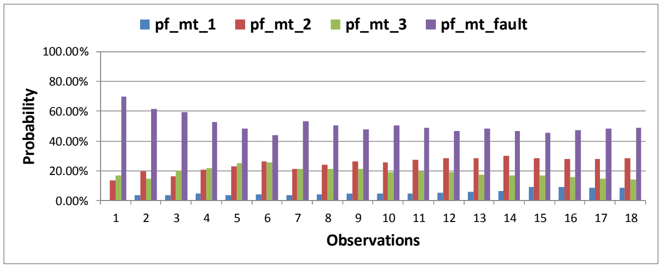

Fig. 8. Performance indices for MT

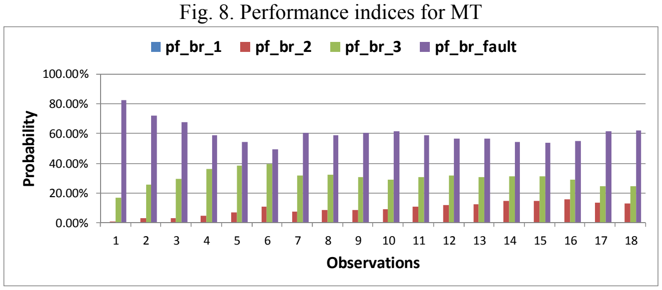

Fig. 9. Performance indices for Br

It is observed that only the auxiliary contacts are functioning well and lie in the minor deterioration stage. The performance index *p*(Br), which depicts the whole breaker is certainly on the edge of failure due to the abnormal operation of trip coil, trip latch and operation mechanism. A major maintenance is in urgent need. Based on these performance probabilities, we get easily apply them to the 'classical' life cycle model, as shown in Fig. 10.

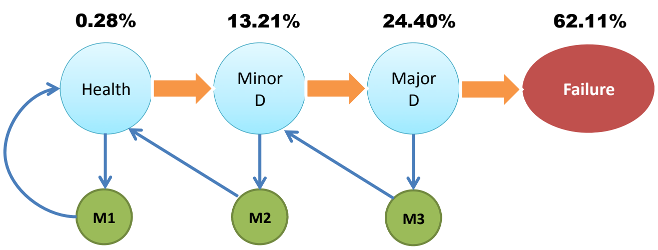

Fig. 10. Assessing life cycle stages

The method proposed in this paper uses real-time condition-based monitoring data and provides a probability to each deterioration stage, which is more reliable than the traditional 'mean time' criteria.

V. Conclusions

A new methodology to assess the circuit breakers' life cycle using condition-based data is proposed in this paper. In addition to confirming that the case study analysis results are in accordance with the test results in Reference [8], this approach also gives a probability of circuit breaker in each deterioration stage in real time. Another advantage of the proposed failure probability index is that it gives insight into which component of the breaker is causing the problem instead of just reporting the failure rate (number of failures per year). Knowing the CB's exact troubled area and its deterioration stage is very important to making appropriate maintenance strategies since difference maintenance policies' may have different cost that varies a lot. A cost–benefit analysis with this proposed methodology will be the research focus in the future.

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