Model for Quantifying the Effect of Circuit Breaker Maintenance Using Condition-Based Data

Satish Natti, *Student Member, IEEE*, and Mladen Kezunovic, *Fellow, IEEE*

***Abstract*—Recent trend in maintenance is to optimize the frequency of inspection and repair according to the condition of the equipment being maintained. Condition-based maintenance introduces additional investment in monitoring equipment and analyzing systems. This approach is acceptable only if the benefits are greater than the existing cost of maintenance and additional equipment/software. Low cost "circuit breaker monitors" along with signal processing modules and expert system modules are available to monitor the circuit breaker control circuit signals.**

This paper presents a model for quantifying the effect of circuit breaker maintenance using the on-line condition data. This model can be used in developing system level maintenance strategies.

***Index Terms*— Circuit breaker, condition data, maintenance, optimization, probabilistic model, reliability**

I. Introduction

POWER industry is slowly moving from scheduled maintenance to 'maintenance as needed'. Circuit breaker is one of the most important equipment in a power system and its failure may result in substantial cost of replacement. Technology developments offer various condition monitoring techniques which directly (or indirectly) affects the existing maintenance policies [1]-[7]. Data acquisition systems, signal processing techniques and expert systems made the condition monitoring techniques much more refined and automated as well [8]-[9]. It is necessary to develop models to convert the condition data into failure rates which helps to relate the effect of maintenance to component reliability.

Probabilistic maintenance models are developed for power transformers and circuit breakers in [10]-[13] to understand the component reliability. It is understood that enhancement in individual component reliability may or may not result in improving system reliability. System level maintenance strategies need to be developed making use of condition monitoring data. An overview of existing maintenance approaches is reported in [14]. Reliability Centered Maintenance (RCM) approaches are more attractive but they fail to connect the effect of maintenance to the reliability quantitatively. An effort was made to link the maintenance to reliability quantitatively in [15]. A program called Asset Management Planner (AMP) has been developed based on probabilistic maintenance model [16]. A risk-based resource optimization for transmission system maintenance has been described in [17]-[19] with objective being total cumulative risk reduction. An attempt was made to compare the effect of different preventive maintenance strategies on system reliability and cost in [20]. This approach, called Reliability-Centered Asset Management (RCAM) is based on RCM principles trying to relate more closely the effect of maintenance on system reliability and cost. This paper presents a model to quantify the effect of maintenance and its usage in developing system level maintenance strategies for circuit breakers.

The paper is organized as follows. Section II gives an overview of condition monitoring data of circuit breaker. Section III describes the proposed model and a case study is presented in section IV. A brief discussion is presented in section V, followed by conclusions.

II. Condition Monitoring Data of CB

CIGRE working group A3.12 conducted a failure survey focusing on reliability of circuit breaker control systems [21]. The failure percentage of the control circuit is rated second to the operating mechanism among all the circuit breaker assemblies. The condition monitoring techniques are relatively easy to develop since the secondary circuit is readily accessible for on-line monitoring. A shunt can be mounted at the control circuit in the breaker cabinet, and electrical parameters of current or voltage are recorded representing both analog and contact signals. These collected parameters represent a "signature" of the circuit breaker. Fig. 1 shows the electrical representation of CB control circuit. A full list of recorded signals is provided in Table I.

There are portable testing devices available on the market to collect and display the control circuit signatures [7]. A low cost circuit breaker monitor (CBM) is developed which utilizes the data acquisition and analysis system to achieve

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automated analysis [8]-[9]. A representative set of control circuit signals captured during the close operation of the breaker is shown in Fig. 2.

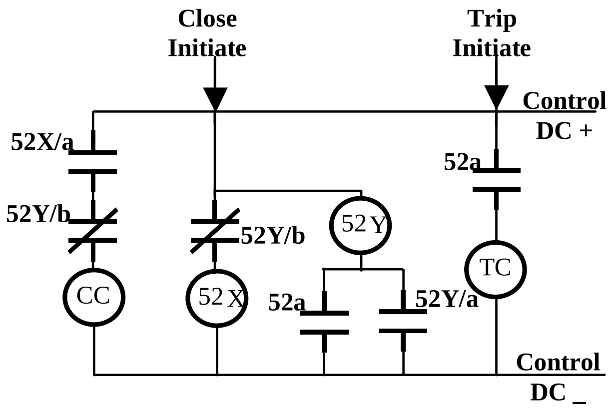

Fig. 1. Electrical representation of circuit breaker control circuit [8]

TABLE I
WAVEFORM ABNORMALITIES AND SIGNAL PARAMETERS [22]

Event	Event Description	Signal
1	Trip or close operation is initiated (Trip or close initiate signal changes from LOW to HIGH)	T1
2	Coil current picks up	T2
3	Coil current dips after saturation	T3
4	Coil current drops off	T4
5	B contact breaks or makes (a change of status from LOW to HIGH or vice versa)	T5
6	A contact breaks or makes	T6
7	Phase currents breaks or makes	T7
8	X coil current picks up	T8
9	X coil current drops off	T9
10	Y coil current picks up	T10

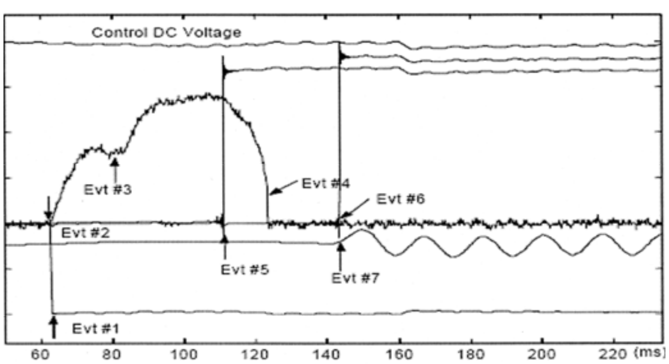

Fig. 2. Control circuit signal during close operation of circuit breaker [22]

III. FAILURE RATE ESTIMATION MODEL OF CB

A failure rate estimation model is proposed utilizing the breaker control circuit data [23]. The model quantifies the effect of maintenance in terms of reduction in failure probability and/or extended life time which may be utilized instantly in on-line reliability and risk analyses. The proposed model is shown in Fig. 3. Following steps are involved in the proposed failure rate estimation process:

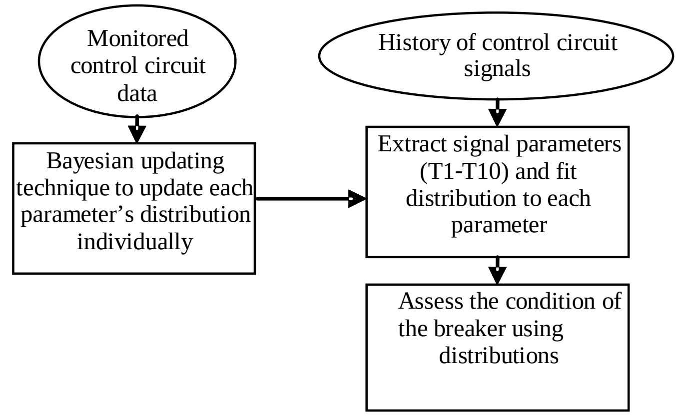

Fig. 3. Failure rate estimation model of circuit breaker

Step 1: Develop a history of CB control circuit signals
Step 2: Extract signal parameters and fit distribution to each parameter
Step 3: Update these distributions as the new condition data is coming using Bayesian updating approach.
Step 4: Relate the control circuit data to the health of the breaker in terms of different condition levels.
Step 5: Develop a Markov model to estimate the failure rate of the breaker having the proposed condition levels and a history of data as inputs.

IV. CASE STUDY

A. History of CB Control Circuit Signals

To illustrate the proposed method, a history of each signal parameter is developed using the waveforms taken from control circuit of similar circuit breakers over a period of time. The type of manufacturer and table of signal timings are listed in appendix. Only a few signal parameters are considered (T2-T6) because of their relative importance and for the ease of analysis.

B. Probability Distribution of Each Parameter

Before proceeding to the formulation, it is necessary to see the interrelation between the parameters. Scatter plot analysis is one good way to see the dependency among the parameters. Fig.4 shows the scatter plots between the signal parameters under consideration. There is no particular relation observed among T2, T3, T4 and T5, and hence they are assumed independent. However, there is a linearly increasing relationship observed between parameters T5 and T6.

For the purpose of illustration, normal distribution is assumed for all parameters. Rename the signal parameters T2-T6 as t_1-t_5, respectively. Let y_{ij} is the j_{th} observation of i_{th} variable and 'n' is the sample size,

$$y_{ij} \sim N(\mu_i, \sigma_i^2),\ \forall j,\ i = 1,2,3,4 \tag{1}$$

where μ_i and σ_i^2 are sample mean and variance.

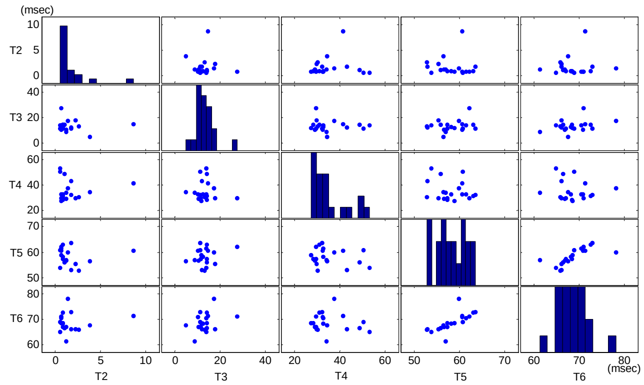

Fig. 4. Scatter plot analysis

Since there is a linear relationship between y_4 and y_5, y_5 is expressed as,

$$y_{5j} = \beta_0 + \beta_1 y_{4j} + \varepsilon_{5j}, \quad \forall j \tag{2}$$

$$y_{5j} \sim N(\beta_0 + \beta_1 y_{4j}, \sigma_5^2), \tag{3}$$

where σ_5^2 is the error variance and, β_0 and β_1 are constants.

C. Bayesian Updating Approach

The parameter set of the problem is given in (4). Assuming non informative prior for all σ_i^2 and uniform prior for all other parameters, the prior, likelihood function and joint posterior distributions are given by (5), (6) and (7) respectively.

$$\Theta = [\mu_1, \mu_2, \mu_3, \mu_4, \sigma_1^2, \sigma_2^2, \sigma_3^2, \sigma_4^2, \sigma_5^2, \beta_0, \beta_1] \tag{4}$$

$$p(\theta) \propto \prod_{i=1}^{5} \frac{1}{\sigma_i^2} \tag{5}$$

$$L(Y|\Theta) = \prod_{j=1}^{n} \left[\prod_{i=1}^{4} \frac{1}{\sqrt{2\pi\sigma_i^2}} e^{-\frac{(y_{ij}-\mu_i)^2}{2\sigma_i^2}} \left(\frac{1}{\sqrt{2\pi\sigma_5^2}} e^{-\frac{(y_{5j}-(\beta_0+\beta_1 y_{4j}))^2}{2\sigma_5^2}} \right) \right] \tag{6}$$

$$p(\theta|_Y) \propto \left(\prod_{i=1}^{5} \frac{1}{\sigma_i^2} \right) \prod_{j=1}^{n} \left[\prod_{i=1}^{4} \frac{1}{\sqrt{2\pi\sigma_i^2}} e^{-\frac{(y_{ij}-\mu_i)^2}{2\sigma_i^2}} \left(\frac{1}{\sqrt{2\pi\sigma_5^2}} e^{-\frac{(y_{5j}-(\beta_0+\beta_1 y_{4j}))^2}{2\sigma_5^2}} \right) \right] \tag{7}$$

It is difficult to compute the normalizing constant that makes the above posterior distribution a density. Hence, Markov Chain Monte Carlo (MCMC) technique is used to estimate the posterior distribution of the parameters [24]. MCMC using Gibbs sampler is implemented in MATLAB and the updated distributions are shown Fig. 5. These parameter distributions are further analyzed to assess the condition of the breaker and hence to see the effect of maintenance. Also, combination of selected distributions can be used to assess performance of the individual components of breaker. For

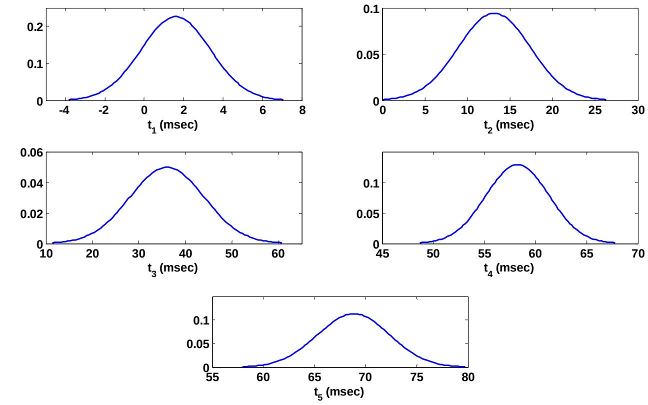

Fig. 5. Updated probability distributions of parameters

example, t_1, t_2 and t_3 are involved in operation of close coil and hence can be combined to asses the close coil performance. Following sections discuss this idea in detail.

D. Assessment of Breaker Condition

An attempt was made to develop certain criterion to assess condition of the breaker. First of all, define upper and lower limits for each parameter such that if new value of 't_i' falls in this range, it is said that those parts of the breaker which causes the occurrence of time instant 't_i', operates properly. For example, if t_2 falls out of the limits, it means that there is some problem associated with close coil. Table II shows the upper and lower limits of the circuit breaker under consideration. These limits are the expert system settings used in developing automated analysis of CB operation earlier [25]. Fig. 6 shows the probability distribution function of timing parameter t_2, result of Bayesian updating approach. The shaded area between the lower and upper limits is the

TABLE II
TOLERANCE LIMITS NORMAL OPERATION [25]

Event	Lower (msec)	Upper (msec)
t_1	0	5.5
t_2	9.8	16.4
t_3	26	43.4
t_4	49.9	67.5
t_5	62	75.8

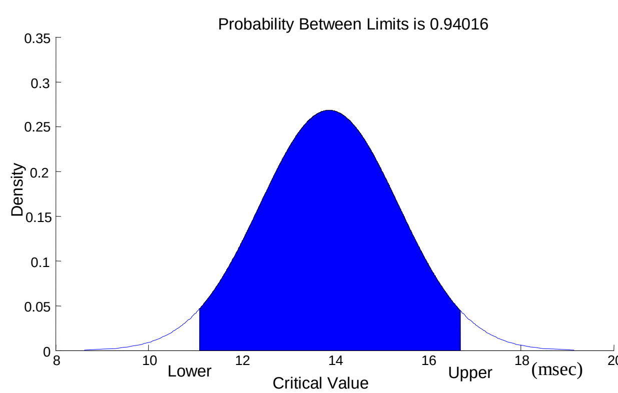

Fig. 6. Updated probability distribution of parameter t_2

probability that the breaker will operate properly.

In general, probability that breaker operates correctly with respect to t_i,

$$p_i = \Pr(l_i \le t_i \le u_i)$$

where, l_i is the lower limit and u_i = upper limit.

The probabilities p_1, p_2, p_3 are associated with close coil operation, where as p_4 and p_5 are associated with auxiliary "a" and "b" contacts of breaker. These probabilities are used to define different indices, and hence to assess the condition of the breaker components. These probabilities depend on individual distributions of signal parameters, which can be effected by the maintenance of the breaker.

1) Performance of Close Coil: Close current (CC) signal that represents the flow of the current through the close coil is shown in Fig. 7. After the close initiate being activated, the CC begins to ramp up towards its maximum value at 't_1'. The waveform should have a smooth and steady shape until it reaches a small dip located towards the top of the waveform at time 't_2'. This dip corresponds to the point at which the coil has released all of its "close" energy. Then, CC may rise slightly or simply remain flat at its maximum value. After the Y coil picks up, CC makes a fairly rapid decent to zero at time 't_3', where its remains until the next breaker close operation.

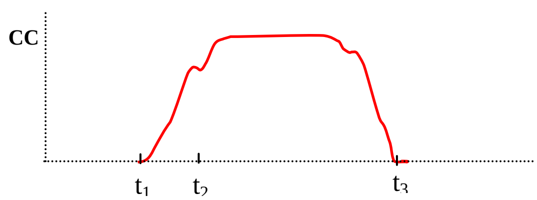

Fig. 7. Close coil current

Possible abnormalities associated with close coil are pick-up premature, pick-up delayed, dip delayed, drop off delayed and distortion. As discussed earlier p_1, p_2 and p_3 are the probabilities that the time instants t_1, t_2 and t_3 occur with in the tolerance limits and hence assuring the proper operation of close coil. The probability that 'the close coil fail to operate correctly' can be computed as

$$Q_{cc} = 1 - (p_1 p_2 p_3)\,.$$

Fig. 8 shows the probability Q_{cc} for the breaker under consideration. These probabilities are computed for each test record sequentially using Bayesian updating approach explained earlier sections. It can be seen that for few records, the probability is as high as 1. This is because at least one of the probabilities (p_1, p_2 or p_3) is zero, which means that corresponding timings (t_1, t_2 or t_3) is violated. In this case, it can be concluded that the close coil failed to operate properly. If Q_{cc} is close to zero, it can be said that the close coil is working properly.

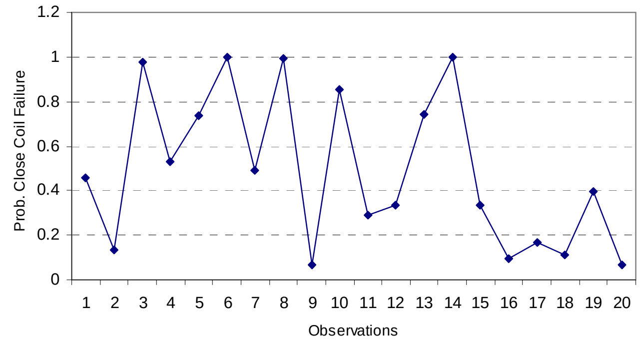

Fig. 8. Probability that the close coil fails to operate normally

The time period between the moment when the current picks up (t_1) and the moment when the dip occurs (t_2) in the coil current is the 'free travel time' equals to $|t_2\text{-}t_1|$ [22]. This 'free travel time' can be used to asses the condition of the close latch mechanism. The timings t_1 and t_2 need to fall in the tolerance limits for the breaker to have normal free travel time. Any violation results in abnormal 'free travel times'. The probability that 'the free travel time is abnormal' can be computed as,

$$Q_{ft} = 1 - (p_1 p_2)\,.$$

Fig. 9 shows how the above quantity changes for the breaker under consideration. It can be seen that four records have higher probabilities, which means that there is some problem associated with close latch mechanism.

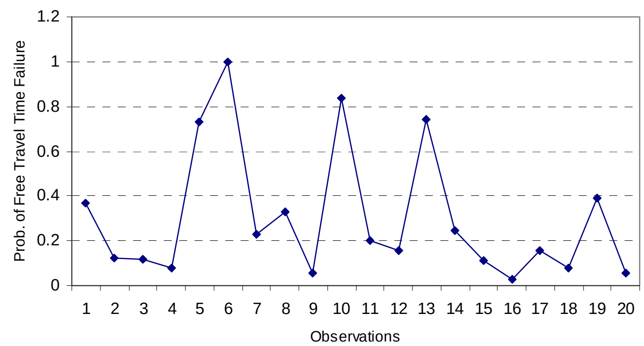

Fig. 9. Probability that "free travel time" is abnormal

2) Performance of Auxiliary Contacts: As the breaker closes its main contacts, the "b" Contact voltage goes to a high value as shown in Fig. 10. The closing operation of the breaker also closes the 52a contacts and forces the "a" Contact voltage to make a transition to a high value. Some possible abnormalities associated with operation of "a" and "b" contacts are delay in transition, premature in transition, unstable contacts, noise and contacts bounce. Probabilities that the time instants t_4 and t_5 occur with in limits are p_4 and p_5. Hence, probability that 'auxiliary "a" and "b" contact fail to operate properly' is,

$$Q_{aux} = 1 - (p_4 p_5)\,.$$

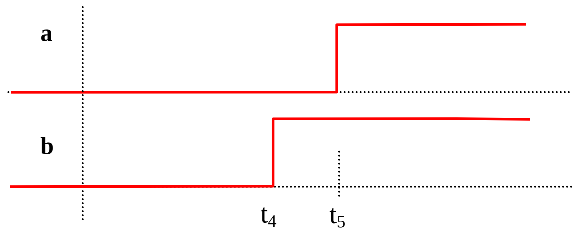

Fig. 10. “a” and “b” contacts transition during close operation

Fig. 11 shows how this probability varies for the breaker consideration. It can be observed that two records are abnormal. Except that, we can conclude that the auxiliary contacts are working properly.

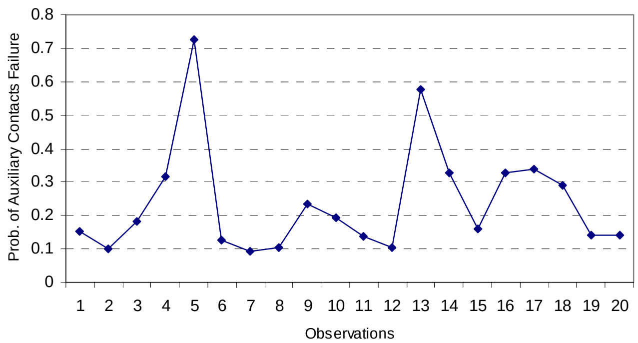

Fig. 11. Probability that the auxiliary contacts fail to operate normally

The coil current also needs to correlate with the event of “a” or “b” contact. The time period between the dip and the operation of “b” for close operation (“a” for open operation) is the mechanism travel time which is equal to $|t_4\text{-}t_2|$ for close ($|t_5\text{-}t_2|$ for open) operation [22]. For normal ‘mechanism travel time’, the timings t_2 and t_4 needs to fall in corresponding tolerance limits. Any violation of these timings can be reported as abnormal operation of breaker. Define, Probability that the ‘mechanism travel time is abnormal’, as

$$Q_{mt} = 1 - (p_2 p_4) .$$

The above quantity is computed for the data set under consideration and is plotted in Fig. 12. Due to the abnormal operation of close coil, the probability p_2 is either zero or close to zero. This is the reason why for few set of records, the Q_{mt} is as high as close to 1.

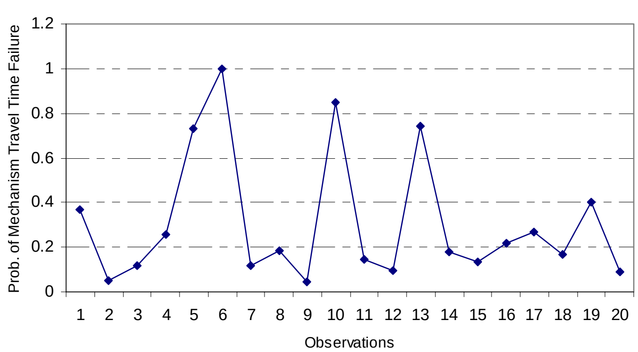

Fig. 12. Probability that the “mechanism travel time” is abnormal

3) Performance of Breaker: In addition to the performance of individual components of breaker, we can also comment on over all performance of the breaker. If none of the timings (t_1-t_5) is violated, we can say that breaker operates properly. In other words, if any of these timings fall out side of 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

$$Q = 1 - (p_1 p_2 p_3 p_4 p_5) .$$

Note that the probability Q is different from the actual failure probability of the breaker, the calculation of which involves consideration of history of data including failures. Fig. 13 shows the corresponding probability Q for the set of records listed in appendix. It is observed that Q is high for few set of records. This is because the close coil is not working properly.

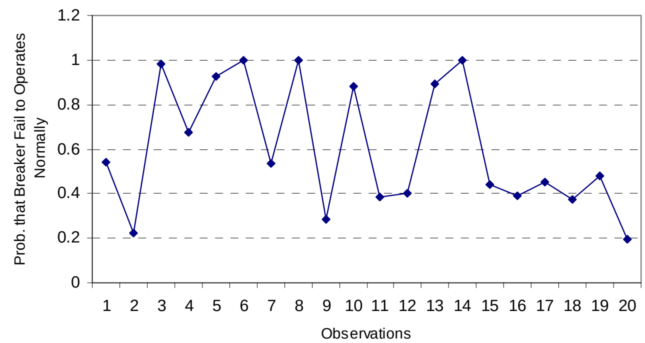

Fig. 13. Probability that the breaker fail to operates normally

V. Discussion

To summarize, various indices are defined and computed to assess the condition of the breaker using individual distributions of signal parameters. It is likely that, these distributions will change after maintenance of the breaker. Hence, it is possible to capture the change in these indices and report as effect of maintenance. The probability Q can be used to define the risk. This extends the use of this model in risk analyses and risk-based maintenance as well. Instead of reporting only the times at which the predefined events happen after the inspection, we can report the calculated indices. This may give some insight into the actual condition of the device and may be useful in taking a better decision about the maintenance activities.

VI. Conclusion

A model to quantify the effect of circuit breaker maintenance using control circuit data is proposed and implemented. The model uses Bayesian approach to update the parameter distributions. Various indices are defined to assess the condition of individual parts of the breaker. The model can also be used in quantifying risk-based maintenance and developing system level maintenance strategies.

APPENDIX

SUMMARY OF TEST RECORDS TAKEN DURING THE CLOSE OPERATION

Manufacturer and Type: GE VIB-15.5-20000-2					
Date	T2 (msec)	T3 (msec)	T4 (msec)	T5 (msec)	T6 (msec)
2/12/2002	1.2150	10.417	28.993	56.597	66.840
2/12/2002	0.8680	12.500	32.639	58.160	68.229
2/13/2002	1.0420	14.236	48.785	55.903	66.493
2/13/2002	1.7360	11.979	43.229	52.951	66.146
2/19/2002	1.3890	17.361	37.500	59.896	78.130
2/21/2002	3.8190	4.8610	34.375	56.424	67.535
2/21/2002	0.6940	11.632	27.257	58.854	68.576
2/21/2002	0.5210	11.285	50.521	60.764	68.924
2/21/2002	0.6940	27.604	29.514	62.153	71.007
3/05/2002	2.2570	17.882	29.687	55.382	66.146
3/05/2002	0.8680	11.458	29.514	57.292	67.014
3/05/2002	0.8680	14.236	28.299	57.292	68.403
3/05/2002	1.2150	8.8540	34.028	56.944	61.285
6/10/2002	0.5210	13.889	53.299	53.819	64.931
6/10/2002	8.6800	14.583	41.493	60.590	71.354
6/10/2002	2.6040	13.194	30.208	52.778	65.799
6/10/2002	1.7360	11.285	32.292	63.542	72.917
6/11/2002	0.8680	14.236	31.076	63.021	72.569
6/11/2002	0.6940	10.243	32.465	60.590	70.833
6/11/2002	0.6940	13.889	32.639	61.458	70.486

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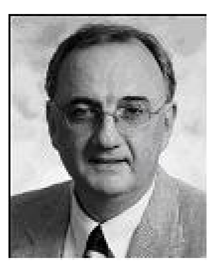

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