Cost/Benefit Analysis for Circuit Breaker Maintenance Planning and Scheduling

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***Abstract*— Maintenance planning and scheduling of circuit breakers (CBs) always involves the cost and benefit analysis. This paper introduces a new framework for cost/benefit assessments using condition-based monitoring data. The signals monitored at the CB control circuit are first utilized to determine the CB deterioration status. This information is used to decide which type of maintenance, e.g., minor, major, or replacement, needs to be practiced for different CBs. System wide analysis is then performed to assess the cost benefits of the maintenance by calculating the costs imposed to the system in the case of CB mal-operation. A new benefit to cost ratio (BCR) index is introduced to deal with the CB maintenance prioritization process. The proposed approach is implemented on a breaker-and-a-half substation configuration and the results demonstrate the applicability of the presented framework in real world scenarios.**

I. INTRODUCTION

Improved power system planning and operation policy is one of the main goals in the present economic scenario of power industry [1]. Among the main expenditures in power system exploitation, maintenance is recognized as a major cost factor due to large number of power system components [1]. The power system equipment has been around for a while, hence maintenance tasks need to be adapted to different equipment ages and various aging mechanisms. Power industry has been considering gradually changing from scheduled maintenance or planned maintenance to maintenance as needed or condition-based maintenance. It is widely recognized that it would be ideal for maintenance to be conducted on the components needing it the most, otherwise unnecessary maintenance action is simply a waste of time, effort, and money [2]. This requires the power system components to be differentiated based on their deterioration status on one hand and their role and impact on power system operation on the other. The components which have high probability of failure and those whose failure will deteriorate power system performance the most need more focused and more frequent maintenance practices [3], [4].

Circuit breakers (CBs) are the components that are used in power systems in large numbers. They are assigned two major roles: to react to protective relay trip decisions by disconnecting faulted power apparatus and to facilitate the operator role in performing topology switching needed to reroute power flows or isolate components for maintenance. Hence, special attention needs to be paid to ensure that CBs are reliable and available to operate when necessary [5].

Most of the research efforts on the condition monitoring of CBs have been focused on real time automated monitoring applications [6]-[9]. Other research direction was more concerned with the evaluation of CB impacts on the system overall performance in the context of risk analysis and tried to prioritize the maintenance schedule and resource allocations from the system reliability [10] and security [11] perspectives. The focus was also put on the deterioration modeling of the component based on its conditions [12]-[14], where the use of state diagrams in deterioration, inspection, and maintenance modeling has been explored either through the Markov approaches or Monte Carlo Simulations. Economic analysis of CB maintenance planning and scheduling, however, has not been widely researched yet, except for recognizing some general and valuable guidelines as given in the IEEE standard C37.10.1-2000 [15] where the selection of monitoring techniques for CBs has been approached through the failure mode and effect analysis and the economics associated with each type of CB failure have been quantified.

This paper is focused on proposing a framework for CB cost/benefit analysis to be used in the maintenance planning and scheduling. The paper is structured as follows. Section II presents a background on the CB control circuit monitoring signals and how they can be related to the CB reliability. Section III is devoted to the proposed methodology for the cost/benefit analysis. Numerical analysis is conducted in Section IV, and the conclusions are offered at the end.

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II. BACKGROUND

The approach proposed in [16] has been utilized in this paper to find the CB's reliability index. The control circuit monitoring data (timing signals and waveforms) for certain time duration is first extracted via the locally installed monitors. Then, using the signal processing techniques together with the expert systems, one can extract various features of the waveforms [18]. An appropriate probability distribution can be fitted to each of the extracted timing signals using the current and historical signal records. As new monitoring data comes in, this distribution assigned to the considered signal is updated. The upper and lower limits (permitted values) of each timing signal are then defined. The timing value can be considered normal if it falls within this span otherwise, it is concluded that this timing value indicates some problems needing maintenance since some CB parts associated with the timing signal did not operate properly within a certain probability [16]. The CB reliability associated with a timing signal can be obtained by the shaded area in Fig.1, using (1).

$$R_k^t(B_i) = \int_{t=\sigma_k^{\min}}^{t=\sigma_k^{\max}} f_k^t(B_i, t)\,dt \qquad (1)$$

where, $R_k^t(B_i)$ and $f_k^t(B_i,t)$ are, respectively, the reliability index and density function of the k^{th} monitored timing signal associated with the i^{th} CB in a substation at time t, and $[\sigma_k^{\min}, \sigma_k^{\max}]$ is the accepted interval of the k^{th} timing signal.

It has been concluded in [16] that five timing signals, described in Table I, need to be within the specified upper and lower limits for CB to work properly. The reliability status of each CB as a whole can be then evaluated using (2).

$$U^t(B_i) = 1 - \prod_{k=1}^{5} R_k^t(B_i) \qquad (2)$$

in which, $U^t(B_i)$ is the failure probability index of the i^{th} CB in a substation at time t, and $R_k^t(B_i)$ is calculated earlier through (1). Worthy to note is that in this way, the reliability status of each CB in the substation can be calculated at any time using the available monitoring data. In other words, the reliability index for each CB can dynamically be updated using new monitoring data as it arrives. The implementation framework is demonstrated step-by-step in Fig. 2.

TABLE I
LIST OF EVENTS AND SIGNAL PARAMETERS FOR RELIABILITY INDEX EVALUATION OF SUBSTATION CBS

Description of the event	Signal Parameter
Trip coil current picks up	t_1
Trip coil current dips after saturation	t_2
Trip coil current drops off	t_3
B contact breaks or makes (a change of status from low to high or vice versa)	t_4
A contact breaks or makes	t_5

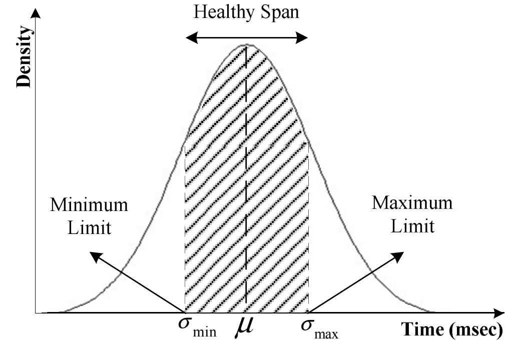

Fig. 1. Probability distribution assigned to a timing signal available from the historical data of CB control circuit monitoring.

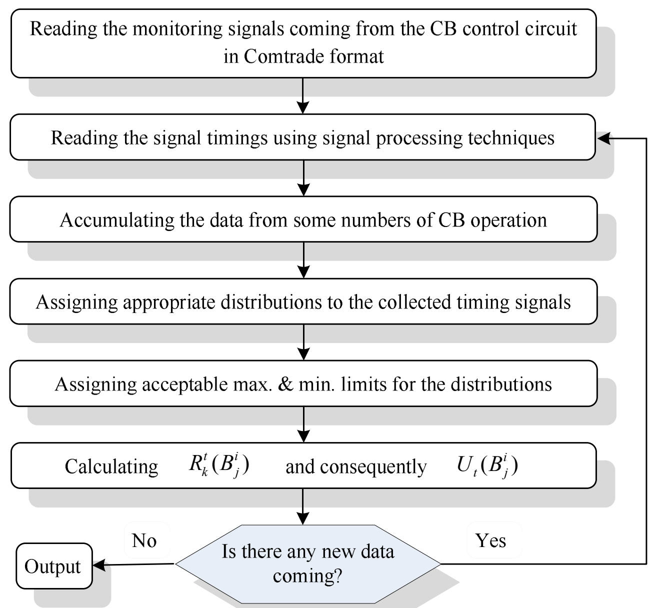

Fig. 2. Step-by-step implementation procedure to assess CB reliability index.

III. PROPOSED METHODOLOGY

A. Concept Development

Since the electric utilities have recently experienced a sharp increase in their operating costs on one hand, and with the recent advent of power system restructuring on the other, the pressure to reduce or control their total costs embracing the investment, operation, and interruption costs has been under much scrutiny so far [3], [4], [17]. Generally speaking, maintenance cost makes a significant contribution to the overall operating costs of a utility. Furthermore, different CBs introduce different maintenance costs, different consequences on the system performance, and different failure costs as well [19].

For the time being, although employing continuous maintenance strategies on all the system components technically improves the overall power system operation, frequent maintenance across the board does not seem to be neither affordable nor economically justifiable. Considering only technical parameters without any deserving attention to the economic aspects may result in some non-optimal solutions for the maintenance of system components. Hence, selection of the best maintenance strategy for CBs remains to be of keen interest [11]. Consequently, there is a vital need to concentrate on the total imposed cost and total achieved financial benefits due to the maintenance of CBs.

An economic index, called benefit to cost ratio (BCR) is introduced in (1) which is assigned to the i^{th} CB for maintenance prioritization:

$$\text{BCR}_i = \frac{\text{Total Achieved Benefits}}{\text{Total Imposed Costs}} \quad (3)$$

The total imposed cost may include the inspection costs, required manpower costs, material costs, and all the preventive maintenance associated costs applied on the i^{th} CB. It may be different for different CBs in the system based on the deterioration levels and aging mechanisms which calls for different maintenance practices. This cost can be obtained based on the previously introduced approach in Section II to differentiate the CBs on the basis of their component-based reliability performance.

The achieved benefit term reflects what would be the imposed cost if a proper preventive maintenance policy on a certain CB is not applied and it fails. In other words, the proposed approach considers those costs as the benefits of maintaining a particular CB; the costs which are imposed due to the required system re-dispatch, utility lost revenue and customer interruption costs as a result of the CB mal-operation are considered as the benefits of the preventive maintenance.

The first issue which should be considered in the benefits is the cost of corrective maintenance that needs to be performed either in the form of replacement or repair. This cost is entirely associated with the component and its maintenance plan. However, there are some costs related to the system-wide consequence of the CB mal-operation or failure which needs to be quantified.

If a CB fails to operate properly, the adjacent CBs may have to be operated in response and this may lead to some power system components being out as a result. Consequently, a system re-dispatch may be needed to avoid system security violations and bring the system operation back to the normal conditions. The optimal power flow re-dispatch cost may be considered as the system-wide impact from the system security perspective, which constitutes the second monetary term in the analysis. Re-dispatch is commonly done once a contingency brings some threats to the system security. The cost associated with the re-dispatch is here considered to be the most direct consequence of the CB contingency. The re-dispatch is not required once a minor contingency occurs. In such cases, this system benefit may not be included in the proposed analysis [6].

If the mal-operation of a CB leads to a load being interrupted, there will be some other costs imposed from the system reliability perspective. If a CB failure leads to the outage of a customer load, an interruption cost would be consequential. This can be interpreted in two aspects: one is from the utility viewpoint and the other associated more with the customers' perspective. The former reflects the lost revenue the utility could obtain in return for the sold energy and power while in the cases of CB mal-operations, the utility cannot receive the benefits anymore. The later highlights the customer interruption costs which need to be paid to the customer in compensation for the interrupted service. This is yet another monetary cost which will be taken into account in the proposed cost-benefit methodology. Quantifying the BCR index leads to a cost-effective prioritization of CB maintenance plans and scheduling. The CBs with the higher BCR index would be placed in the top of the prioritization list for prompt maintenance considerations. Those CBs placing in the end of the list are not economically attractive for maintenance in substations.

B. Mathematical Formulations

The total imposed costs are essentially considered to be the preventive maintenance expenses incurred while maintaining a CB within a desirable limit of availability. The cost is dependent on the deterioration level of the CB under study and hence could be different for various CBs in the system. Again, it may include the maintenance expenses associated with the maintenance process, required manpower (labor), and necessary materials. All the maintenance costs are reflected in:

$$C_i(U^t(B_i)) = C_i^{PM} = \left(\alpha + \beta . r_\beta\right)_i^{PM} . Wh_i^{PM} \quad (4)$$

where, the following parameters are defined.

C_i	Cost function used in the BCR index for the i^{th} CB.
C_i^m	Total preventive maintenance cost on the i^{th} CB.
α	The CB constant cost per repair and maintenance.
β	The CB variable cost per repair and maintenance.
r_β	Average outage time per CB maintenance trial.
$U^t(B_i)$	The failure probability index assigned to the i^{th} CB.
Wh_i	Working hours required for maintenance on i^{th} CB.

The maintenance costs are assumed to be guided by a linear relationship. A constant amount of money is assumed to be spent for any repair or scheduled maintenance on a CB. A variable amount of money is, in addition, assumed to be spent for each hour of outage duration for preventive maintenance. The maintenance cost is assumed to be dependent to the CB failure probability index highlighting the fact that a higher maintenance cost would be required for the CBs with higher failure probability index. In this way, the deterioration status of different CBs can be incorporated into the economic analysis. Maintenance cost is the only cost term considered in the proposed benefit/cost ratio.

In terms of benefits, there would be a corrective maintenance cost imposed as the CB fails which can be formulated as follows.

$$B_i^{CM}(U^t(B_i)) = \left(\alpha + \beta.r_\beta\right)_i^{CM}.Wh_i^{CM} \quad (5)$$

where, B_i^{CM} is the monetary benefit associated with the postponed corrective maintenance cost on the i^{th} CB due to the planned preventive maintenance action. The other parameters are the same as those introduced in (4) but applied to the corrective maintenance schedule.

In order to model the probable re-dispatch cost required to turn the system back into its normal operational condition after a CB mal-operation or failure, the cost function below is taken into account. The objective function is simply a summation of individual polynomial cost functions f_P^j and f_Q^j of real and reactive power injections, respectively for each generator j.

$$B_i^{OPF} = \min_{\theta, V_m, P_g, Q_g}\left(\sum_{j=1}^{n_g}\left(f_P^j(p_g^j) + f_P^j(q_g^j)\right)\right) \quad (6)$$

$$\theta_j^{ref,\min} \le \theta_j \le \theta_j^{ref,\max} \qquad j \in \Gamma_{ref} \quad (7.a)$$

$$V_m^{j,\min} \le V_m^j \le V_m^{j,\max} \qquad j \in 1.....n_b \quad (7.b)$$

$$p_g^{j,\min} \le p_g^j \le p_g^{j,\max} \qquad j \in 1.....n_g \quad (7.c)$$

$$q_g^{j,\min} \le q_g^j \le q_g^{j,\max} \qquad j \in 1.....n_g \quad (7.d)$$

B_i^{OPF} is the objective function commonly approached in an AC OPF model with the constraints introduced in (7). θ, V_m, P_g, Q_g are representing the voltage angle and magnitude, and active and reactive power of the generator j, respectively. Also, n_g and n_b are the number of generators and buses in the system, respectively.

As the third item in the evaluation of a CB maintenance benefit, one must take into account the utility lost revenue which will happen if a particular CB fails and some loads are interrupted as a result, which is quantified as in (8).

$$B_i^{LR} = EENS_i.EP \quad (8)$$

in which, B_i^{LR} is the monetary benefit associated with the utility lost revenue when the i^{th} CB failure leads to a load interruption, $EENS_i$ stands for the expected energy not supplied due to the load interruption, and EP is the electricity price at which the energy is sold by the utility. This benefit for a particular CB is actually the revenue which could be obtained if proper preventive maintenance actions were planned on that CB and the energy could be delivered/ sold.

The last term to be considered as the benefit of a CB maintenance is the interruption costs which can be consequential if a particular CB failure leads to a load interruption due to lack of proper maintenance. This factor, which reflects the CB maintenance criticality from the customers' viewpoint, is quantified as follows [20].

$$B_i^{IC} = EENS_i.VOLL_k \quad (9)$$

in which, B_i^{IC} is the benefit associated with the cost incurred once the system k^{th} load point is interrupted due to the failure or mal-operation of the i^{th} CB in the substation, $EENS_i$ is the same as introduced earlier in (8), and $VOLL_k$ is the value of lost load associated with the k^{th} load point. This is, in fact, the customer discomfort cost and may have to be paid to the customer in compensation for the interruption.

As the various terms of the benefits associated with the CB maintenance are calculated, the overall monetary benefit can be obtained as follows.

$$B_i = B_i^{CM} + B_i^{OPF} + B_i^{LR} + B_i^{IC} \quad (10)$$

The BCR index can then be calculated for each CB which reflects the economic criticality of the particular maintenance plan and schedule. From an economic point of view, the ultimate goal here is to maximize the BCR index. As a result, the CBs can be prioritized based on the CBR index reflecting the most economically attractive maintenance plans and schedules.

IV. Performance Evaluation

A. Substation under Study

The proposed decision making framework based on the cost-benefit analysis is applied to the IEEE 24-bus test system. A total of 24 substations exist in the test system. The substation 16 has the *breaker-and-a-half* configuration and it is taken as the focus of the study in this paper, as shown in Fig. 3. A generator (G) of 155 MW capacity is located there and, 8 breakers (B1-B8) and 4 transmission lines (L) are used to route power and feed the attached load of 100 MW [21]. All the required system and substation data are borrowed from [21], [22].

B. Data and Assumptions

In order to conduct the cost-benefit analysis, the deterioration stages associated with different CBs in the system have to be identified so that it is possible to know the maintenance costs of each breaker. The common way to identify the deterioration stages for a component (CB in this paper) is by taking the past duration of its operation into account, e.g. the minor deterioration stage is reached, on average, in three years of the CB being installed and operated, the major one in six, and so on. This can be done using the historical inspection data and related monitoring signals. The costs associated with various deterioration stages are assumed to follow the trend introduced in Table II, where PM and CM respectively stand for the preventive and corrective maintenance. The PM costs are borrowed from [14] and the CM costs are assumed to be twice that of PM. The CBs are assumed here to follow the deterioration status in Table III.

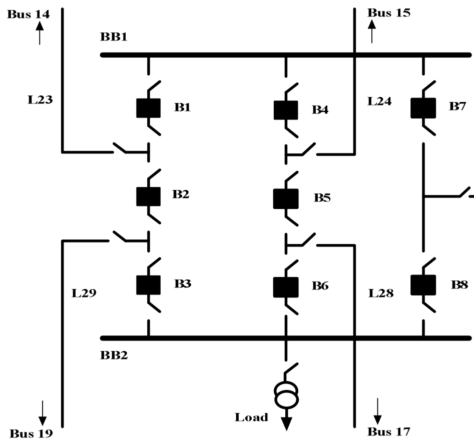

Fig. 3. Substation 16 - breaker-and-a-half configuration.

The electricity price is taken to be 13 cent per kWh [23] and the load is assumed to be an industrial one with the VOLL of 5 $/kWh [24]. A switching time of 1 hour is considered for the consequence evaluation in the case of system re-dispatches [20] and the CB average repair time is considered to be 3 hours.

C. *Numerical Analysis*

Proposed formulations are applied to the substation under study and the associated cost and benefit terms for CBs are calculated as tabulated in Table V. As an example, assume CB3 fails to operate successfully when, either clearing a fault on L29 or a fault on BB2 or maybe as a result of failure due to operator-initiated switching action. In the case of a need to clear the fault, the adjacent CBs, i.e., CB2, CB6, and CB8 need to open and as a result, the L29, BB2, and the load there would be out which would affect the consequence terms in the analysis. Corrective maintenance also has to be conducted on CB3 in form of either a replacement or repair. The costs for the maintenance, the OPF-related cost required for the system re-dispatch to mitigate any security violation, the interruption cost of the load and the utility lost revenue for the interruption will contribute to the benefit of CB3 preventive maintenance policies. The cost of preventive maintenance for CB3 has been also considered to be $2400 according to Table II since its failure probability index is 0.2379, which is within the 0.2 and 0.4 specified span for minor deterioration. The same explanations can be conducted for the other CBs under consideration, too. The BCR index would be finally consequential for each CB, which reflects the cost-effectiveness criticality assigned to each of them, as demonstrated in Table IV. As can be seen, the failure or mal-operation of some CBs has not led to the load to be interrupted (CB1, CB2, CB4, and CB5) at all since the system is strong enough to completely recover itself by a re-dispatch, while in some other cases (CB3, CB6, and CB8), the load has been fully interrupted. The load has been partially interrupted in the case of CB7 failure after a re-dispatch since the generator is out. This may not be the case for other systems. The CBs can then be prioritized based on the BCR indices in an order from the highest to the lowest. The results are shown in Fig. 4. As can be observed, CB6, CB8, and CB3 are the ones with the highest BCR indices compared to the others and, as a result, are the most critical ones for a cost-effective maintenance management in the substation.

The point to emphasize is that CB6, although healthy, is the most economically attractive one for preventive maintenance actions since if it fails, a huge financial consequence would be the outcome. So, it needs to be wisely maintained.

V. Conclusion

The cost-benefit framework for CB maintenance proposed in this paper leads to the following conclusions:

- In the present economic scenario of power industry, both the imposed component maintenance costs and achieved power system operational benefits associated with the CB preventive maintenance practices need special attention.
- The presented approach differentiates various CBs in a substation according to their deterioration status and consequently affects maintenance practices and associated costs.

TABLE II
CB Deterioration Stage Conditions and the Associated PM and CM Maintenance Costs

Deterioration Stage	Failure Probability Index	PM Cost of CB ($)	CM Cost of CB ($)
Health	$U^t(B_i) \le 0.2$	200	400
Minor	$0.2 \le U^t(B_i) \le 0.4$	1200	2400
Major	$0.4 \le U^t(B_i) \le 0.6$	14400	28800
Failure	$U^t(B_i) \ge 0.6$	144000	144000

TABLE III
Deterioration Status of the System CBs in the Analysis

CBs	$U^t(B_i)$	Deterioration Stage
CB1	0.1892	Health
CB2	0.7829	Failure
CB3	0.2379	Minor
CB4	0.1096	Health
CB5	0.5044	Major
CB6	0.1669	Health
CB7	0.3098	Minor
CB8	0.2417	Minor

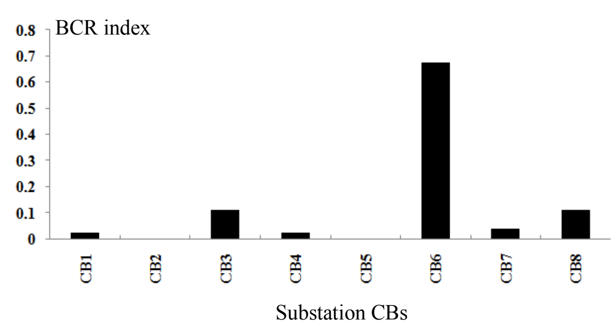

Fig. 4. CB maintenance prioritization based on the cost-benefit analysis.

TABLE IV
COST/BENEFIT ANALYSIS FOR THE COST-EFFECTIVE MAINTENANCE MANAGEMENT OF THE SUBSTATION CBS

System CBs	Maintenance Benefit Indices				Total Benefits	Total Costs	Normalized
	B_i^{CM} (\$)	B_i^{OPF} (\$)	B_i^{LR} (\$)	B_i^{IC} (\$)	B_i (\$)	C_i (\$)	BCR_i
CB1	400	64707.74	0	0	65107.74	200	**0.027547**
CB2	144000	75194.32	0	0	219194.32	144000	**0.000129**
CB3	2400	58945.31	39000	1500000	1600345.31	1200	**0.112852**
CB4	400	63384.16	0	0	63784.16	200	**0.026987**
CB5	28800	74804.35	0	0	103604.35	14400	**0.000609**
CB6	400	59217.81	39000	1500000	1598617.81	200	**0.676379**
CB7	2400	68388.36	18422	510987	600197.36	1200	**0.042324**
CB8	2400	63500.86	39000	1500000	1604900.86	1200	**0.113173**

- The proposed framework recognizes maintenance benefits associated with the impact of the CB failure on overall power system performance including re-dispatch costs, customer interruption costs, utility lost revenue and, the corrective maintenance costs.
- Economic attractiveness of the proposed approach is that the maintenance planning and scheduling can be practiced based on the Benefit-to-Cost index associated with the substation CBs.
- The offered solution gives a choice to the asset manager to decide on the CB maintenance scheduling in an order of cost-effectiveness.
- CBs prioritization on the basis of the proposed approach could also provide considerable long-term savings since the maintenance planning and scheduling is done in an economic manner.

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