Priority Assessment of Online Monitoring Investment for Power System Circuit Breakers—Part I: Qualitative-Quantitative Approach

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***Abstract*—Recognition of the circuit-breaker's (CB) vital role in reliable operation and protection of power systems (i.e., during energization, disconnecting loads, and clearing faults), helps to understand the requirement and importance of its maintenance management as well as maintenance scheduling. Condition-based maintenance (CBM), employing online monitoring (OLM) of CBs, has been long reported as the most practical maintenance policy on the power system CBs. There are a large number of CBs in a power system to be monitored; however, to address the financial limitations for OLM implementation (in utilities), a method will be proposed to find the most critical breakers for enforcing effectively the CBs CBM planning in this power system. This paper employs some qualitative and quantitative criteria to develop this method. While, the former criterion is deals with through assessing the condition of CBs through fuzzy sets theory. And the latter criterion is dealt with through the evaluation of CBs' influence on the overall system reliability (through introduced indices). This method is applied on a sample transmission substation with a *breaker*-and-a-*half* configuration. Numerical analysis of this simulation results demonstrates how this method can be employed to prioritize the CBs for OLM.**

***Index Terms*—Circuit breaker (CB), condition-based maintenance (CBM), fuzzy sets theory, online monitoring (OLM), prioritization, reliability.**

Nomenclature

DM	Decision-making.
AHP	Analytical heretical process.
FAHP	Fuzzy analytical heretical process.
OLM	Online monitoring.
CRI.	Criterion.
$W_{\mathrm{Qul,CB}}$	Final qualitative weight of CB.
$W_{\mathrm{Qun,CB}}$	Final quantitative weight of CB.
I^F	Failure frequency index.
I^{EC}	Expected cost index.

I. Introduction

Maintenance management of power system components has been always one of the main challenges among power system operation concerns. Experiencing the fast development of power industry and networks rapid expansions (as a consequence of power system components growth), utilities have limitations on the annual investment and operational costs. Consequently, more cost-effective maintenance planning is sought. These days, various types of maintenance have been implemented in power systems all over the world. Among them, reliability-centered maintenance (RCM), time-based maintenance (TBM), and condition-based maintenance (CBM) can be addressed. It is worth mentioning that these various approaches have different impacts on power system components [1], [2].

Circuit breakers (CBs) from long ago are recognized as one of the most critical components in a power system since their failures or imperfect operations would severely affect the performance of power system operation and control. In response, an accurate and regular maintenance schedule should be developed for CBs. Among the popular maintenance patterns, CBM has been reported as the most efficient one for power system CBs (due to its imminent economic achievements and capability of being managed in the future smart environments). The online monitoring system is the main requirement for establishment of CBM on CBs [1]–[7].

The other important issue is the fact that due to the large number of CBs in a power system (while in course of maintenance budget allocation and CBM implementation, the financial constraints of the utilities are present), the online monitoring of all CBs in a power system is neither technically feasible nor economically reasonable. Hence, power system operators have to seek the most critical CBs in a power system to be equipped with OLM.

Considerable efforts can be traced in the literature in seeking the most critical components in a power system. This will pinpoint the importance of the topic under scrutiny. Reference [7]

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adopts an RCM model on the medium-voltage (MV) CBs. It conducted its reliability analysis, employing some indices based on the energy not supplied (ENS). The paper has not delved into the details of modeling and, as a result, does not address the problem satisfactorily. In [8], a conceptual risk index is employed to find the critical components in gas-insulated substations (GIS). It prioritizes the components with respect to the qualitatively calculated risk index. Its main shortcoming is the weak analysis of the qualitative parameters. It also did not delve into the maintenance effects on system reliability. A fuzzy approach is proposed in [9] and [10] wherein the components prioritization is done considering two criteria: components criticality and their failure consequences. The former is estimated by the component failure rate, while the latter is associated with the number and order of the identified minimal cutsets. The work seems incomplete due to the fact that it neglects some main factors of considerable importance in CBs criticality assessment. Reference [11] has employed new indices based on the mean outage duration, nevertheless, ignoring the failure-rate variations. Reference [12] tackled the problem in distribution networks from a reliability perspective and prioritizes the critical components in power distribution systems. It, however, employed some indices which are of the same originality and, hence, cannot lead to an efficient solution. Severity, probability of occurrence, and likelihood of detection are the three parameters employed in [13] and [14] in ranking the failure modes and the components as well.

These deficiencies demonstrate that development of new sophisticated algorithms for this purpose is still required. Moreover, some previous techniques in past papers are hardly appropriate to be adopted in the case of CBs OLM. The reason lies in the fact that not only does OLM affect the failure rate of the CB, but it also has considerable influence on its outage duration. CB's different mechanisms and insulation types in addition lead to the previously introduced indices on the components importance measures, which are: imperfect, inapplicable, or infeasible.

II. Formulation of the Priority Assessment Algorithm

In order to find power system most critical CBs and accordingly to allocate the maintenance resources to them, a decision-making (DM) problem is defined and solved in this paper. Technically approached, the critical CBs, which have the most influential impacts on reliability of the whole system, have to be identified for OLM. In response to the past shortcomings, this paper contributes to propose a prioritization methodology for CBs OLM on the basis of qualitative and quantitative concepts in which almost all of the constraints experienced on real-world and practical concerns are overcome. The impact of CBs on power system reliability depends on their condition and location in the power network. The former dealt with the qualitative approach (i.e., considering CBs drive mechanism, quenching medium, etc., which cannot be mathematically modeled). And the latter is determined through quantitative evaluations (i.e., the system reliability perspective).

This paper presents a practical prioritization scheme on the basis of qualitative-quantitative approach. All of the qualitative criteria interrelated with the problem dealt with fuzzy analytical hierarchical process (FAHP), as a multiple criteria decision-making tool. The quantitative aspects and criteria are treated via some proposed reliability-oriented indices. The proposed indices are on the basis of failure frequency, load interruption costs, and different loads importance.

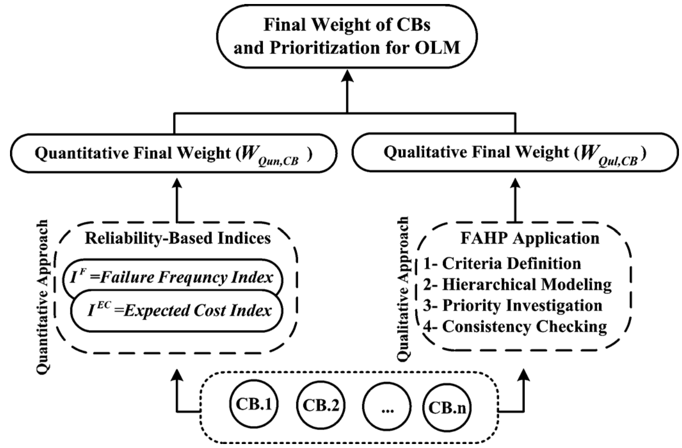

Fig. 1. Overview of the proposed scheme for CBs prioritization for OLM.

An outline of the proposed scheme is presented in Fig. 1. The main features associated with the proposed scheme are summarized as follows.

a) It can effectively evaluate the OLM effects on the CBs failure rates and repair times.
b) It can simultaneously evaluate the benefits and losses due to the adaptation (or not adapting) of OLM on CBs.
c) It removes all of the ambiguities of the decision-making about the CBs OLM.
d) It is constructed on the basis of the available data and information and can effectively get the most of them.
e) It recognizes a different level of importance for various load types.
f) It can be easily jointed to the optimization techniques and solved via different optimization approaches.

As demonstrated in Fig. 1, CBs are prioritized based on the weights obtained from aforementioned approaches (i.e., qualitative approach used for assessing the condition of CBs through FAHP and the quantitative approach employed for the determination of CBs influence on the overall system reliability using the proposed indices). To determine the cumulative weight of CBs, two qualitative and quantitative weighting coefficients are combined to develop an optimal and practical solution as follows:

$$W_{\mathrm{CB,i}} = \boldsymbol{w}_{\mathrm{Qun}} W_{\mathrm{Qun,CB,i}} + \boldsymbol{w}_{\mathrm{Qul}} W_{\mathrm{Qul,CB,i}} \tag{1}$$

where

$W_{\mathrm{Qun,CB,i}}$	quantitative weight of the ith CB through the reliability indices;
$\boldsymbol{w}_{\mathrm{Qun}}$	normalization coefficient specified for the quantitative weight;
$W_{\mathrm{Qul,CB,i}}$	qualitative weight of the ith CB using FAHP;
$\boldsymbol{w}_{\mathrm{Qul}}$	normalized coefficient specified for qualitative weight $(\boldsymbol{w}_{Qul} + \boldsymbol{w}_{Qun} = 1)$.

The proposed qualitative-quantitative approach is presented in Sections III–VII. The proposed method is applied on a sample transmission substation with a *breaker*-and-a-*half* configuration.

III. Overview on Qualitative Decision Making (DM) via AHP and FAHP

Decision making in complex environments, consisting of multiple alternatives and criteria, is one of the most important modern management problems [15]–[21]. AHP has been regarded as one of the most practical techniques in multicriteria DMs in almost all fields of engineering. Its ability to make people's thinking process hierarchical and to consider almost all of the qualitative criteria interrelated with the problem is among the reasons of its popularity [15]. As a consequence, this approach is pursued in this paper to deal with the at hand prioritization problem.

AHP is founded based on the relative pair-wise comparisons of the criteria. The method makes the decision maker capable of concentrating on just two parameters through each comparison, and this leads to a more efficient and appropriate outcome. In some cases, a DM cannot be done in crisp. It happens when the experts cannot compare the criteria in a certain manner or there are some imprecision. The subjective judgments of the experts can be another reason in some cases which will lead to a not appropriate solution [16]–[18]. This shortcoming, attributed to the conventional AHP, can be dealt with FAHP in which the comparisons can be done through fuzzy numbers [19], [21].

The AHP/FAHP method is generally comprised of three main stages as summarized in the following. Further information can be available in [15].

1) Step. I: Hierarchical Modeling of the Problem: In the first stage, decision maker has to decouple the whole problem into some simple parts in such a way that all the decision problem features could be covered through a hierarchical structure as shown in Section IV.

2) Step. II: Pair-Wise Comparison and Priority Investigation: In the second stage, decision maker has to compare those based on his/her information and expertise. Some questionnaires are prepared and distributed among a total number of n experts and engineers involved in the DM process. The fuzzy linguistic variables are employed to complete the comparison matrices [21].

Each fuzzy number which are here assumed to be triangular due to simplicity and common applicability, can be defined by a triplex (l, m, u) in which m, l, and u are respectively representatives of the mean, lower, and upper bounds of the membership function. The membership function associated with each fuzzy number is assigned as follows [21]:

$$\mu(x) = \begin{cases} \frac{x-l}{m-l} & l < x < m \\ \frac{u-x}{u-m} & m < x < u \\ 0, & \text{otherwise.} \end{cases} \tag{2}$$

As a result, the linguistic variables in conventional AHP change into the fuzzy linguistic variables whose definitions is provided in Table I. In this way, the decision makers' subjective judgments, uncertainty and imprecision of the specialists can be easily dealt with by then, leads to more reliable and accurate final results.

TABLE I
Fuzzy Linguistic Variables for Pair-Wise Comparison [21]

Scale	Definition	Membership Function
$\tilde{1}$	Equally important	(1,1,2)
$\tilde{3}$	Moderately more important	(2,3,4)
$\tilde{5}$	Strongly more important	(4,5,6)
$\tilde{7}$	Very strongly more important	(6,7,8)
$\tilde{9}$	Exceedingly more important	(8,9,9)

When finding the final weight of each criterion through fuzzy weighting, the results obtained from n number of experts collaborating in the DM process would be involved as shown in the following (3.1)–(3.4). In the equations, the subscripts denote the ith and jth criterion, and kth expert; n is also representative of the number of experts involved in DM problem

$$\tilde{a}_{ij} = (l_{ij}, m_{ij}, u_{ij}) = [l_{ij}, u_{ij}] \tag{3.1}$$

$$l_{ij} = (\prod_{k=1}^{n} l_{ijk})^{1/n} \tag{3.2}$$

$$m_{ij} = (\prod_{k=1}^{n} m_{ijk})^{1/n} \tag{3.3}$$

$$u_{ij} = (\prod_{k=1}^{n} u_{ijk})^{1/n}. \tag{3.4}$$

3) Step. III: Consistency Checking: One of the most important issues in a DM process in all fields of engineering is the consistency of the comparisons made by different experts. Since the world of experience is vast and we deal with it in pieces (according to our concern at a specific time) our judgments can never be perfect.

Completing the framed weighting tables or matrices, the consistency of the qualitative weighting and comparison has to be verified. This consistency verification in FAHP is done through a consistency index (CI), introduced by (4) [15]

$$CI = \frac{\lambda_{\max} - n}{n-1} \tag{4}$$

where $\lambda_{\max}$ and n, respectively, denote the maximum eigenvalue and the order of comparison matrices. The consistency ratio (CR) can be obtained via (5) [15]

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \tag{5}$$

where the random consistency index (RI) can be obtained through [15]. Once the CR becomes lower than 0.1, the consistency of the experts knowledge would be confirmed. Otherwise, the source(s) of inconsistency must be identified, and resolved. Then, rerun the analysis [15]–[20].

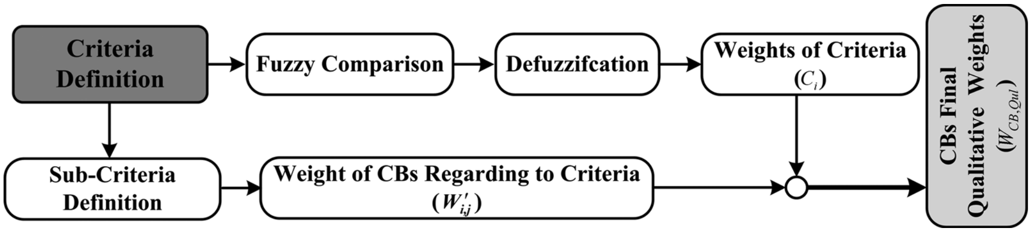

Fig. 2. Outline of the procedure for determination of CBs qualitative weights.

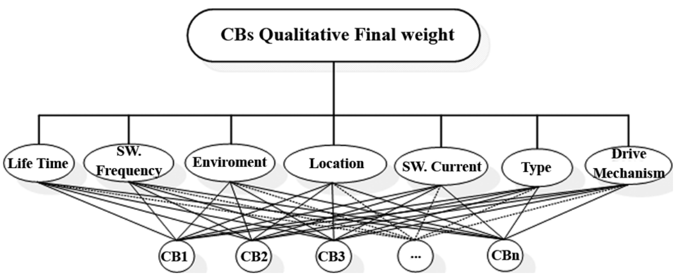

Fig. 3. Hierarchical structure of the CBs prioritization problem, realizing the qualitative approach.

TABLE II
DEFINED QUALITATIVE CRITERIA FOR CBs PRIORITIZATION PROBLEM TO BE MONITORED ONLINE

CRI. 1	Location
CRI. 2	Switching Current
CRI. 3	Quenching Medium (Type)
CRI. 4	Drive Mechanism
CRI. 5	Life Time
CRI. 6	Switching Frequency
CRI. 7	Environmental Conditions and Accessibility

IV. FHAP IMPLEMENTATION TO THE CBs PRIORITIZATION

The method is applied (step by step) to the prioritization problem of concern for the CBs to be monitored online from qualitative approach point of view. An overview of implementation procedure is depicted in Fig. 2.

A. Criteria Definition and Problem Hierarchical Modeling

The first step toward the hierarchically modeling of the problem is to find the most important criteria (CRI.) which make the basis of AHP/FAHP DM process. There are some qualitative important parameters, which are of considerable importance on criticality of CBs condition. Those are discussed in the following and provided in Table II. The hierarchical structure of the problem including the goal and criteria can be framed as depicted in Fig. 3.

1) Location: CBs can be located outdoor, indoor, and/or can be of an encapsulated type (isolation medium N_2, air, or SF_6). The CBs located indoors have a much lower vulnerability to the weather conditions or environmental pollutions in comparison with those of outdoors. In the cases where CBs are totally encapsulated, the environmental effects can be disregarded.

2) Switching Current: One of the most important parameters affecting a CB's condition is the switching current type and its effective value. The switching current is directly related to the place of CB in a system. For instance, medium voltage CBs associated with the feeders of both lines and transformers usually operate under a short circuit current. On the other hand, the short circuit current of the transformer feeder is much higher than that of the line feeder. Moreover, the CBs of the bus-couplers usually operate under their rated currents [3]–[8], [22].

Noteworthy is that the transient phenomena have considerable effects on the switching process of a circuit breaker involved in switching of a reactor, a capacitor bank or a short-line fault. As a result, different importance has to be attributed to them.

3) Quenching Medium (CB Type): The studies demonstrate that the SF_6 and minimum oil CBs have more operation problems as compared with vacuum CB [22]. As a result, this important criterion has to be considered in the CBs prioritization for OLM.

4) Drive Mechanisms: Power system CBs are of various drive mechanisms (e.g., hydraulic, pressure, spring, and so on), each of which have different imperfect operation probability. Hence, another factor which affects the CBs criticality is found to be their drive mechanisms.

5) Lifetime: CBs in power systems are commonly operate almost normally within a 20-year to 30-year period. Then after, due to their wear-out feature, they tend to be replaced or put under earlier maintenance plans. This necessity would be sensed more frequently as time elapses.

6) Switching Frequency: CBs can have a different number of switching operations depending on their applications. This feature has to be considered once aiming to prioritize them.

7) Environmental Conditions and Accessibility: Power system CBs can be located somewhere whose accessibility is hard which implies an increase in the costs associated with the periodical inspections. In such cases, the CBs have to be assigned more criticality to be monitored.

B. Subcriteria Definition and Normalized Weights

To have a higher accuracy in the weighting process of the defined criteria, some subcriteria associated with each criterion are defined as presented in Fig. 4.

The weighting for the defined subcriteria are done via simply assigning one of the numbers 1 to 10, to each of them. The nearer the number to 10, the more important it is and, finally, the weights are normalized.

Table III presents the obtained weights of subcriteria based on a combination of experts' consultation and values presented in some literature [3]–[7], [22]. Consequently, the qualitative weight of each CB regarding these weights of subcriteria is determined. For example, referring to Table III for an outdoor SF_6

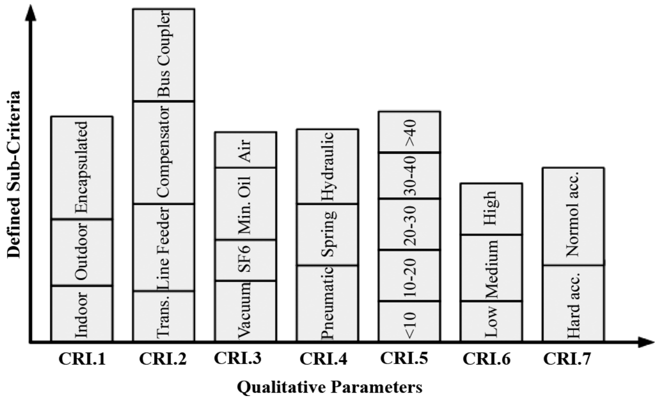

Fig. 4. Contribution of each criterion base on its subcriteria.

TABLE III
DEFINED SUB-CRITERIA AND THEIR NORMALIZED WEIGHT

CRI*.1	Indoor	Outdoor	Encapsulated		
NW*	0.286	0.571	0.143		
CRI.2	Transformers	Line feeder	Bus coupler	Compensator	
NW	0.5	0.322	0.167	0.011	
CRI.3	Vacuum	SF6	Minimum oil	Air	
NW	0.083	0.333	0.294	0.411	
CRI.4	Pneumatic	Spring	Hydraulic		
NW	0.333	0.167	0.5		
CRI.5	<10	10-20	20-30	30-40	>40
NW	0.12	0.145	0.167	0.203	0.355
CRI.6	Low	Medium	High		
NW	0.143	0.286	0.571		
CRI.7	Hard accessibility	Normal accessibility			
NW	0.727	0.273			

*NW: Normalized Weight, CRI.i: ith Defined Criterion in Table II

CB, which is equipped with a spring-drive mechanism, the following weights are obtained: 0.571, 0.333 and 0.167; for CRI.1 (location), CRI.3 (type) and CRI.4 (drive mechanism), respectively.

C. Comparison and Criteria Weighting

Having obtained the CBs weights associated with the criteria, this step deals with finding the final weight of each criterion

$$\tilde{C} = \begin{pmatrix} \tilde{c}_{11} & \tilde{c}_{12} & \tilde{c}_{13} & \tilde{c}_{14} & \tilde{c}_{15} & \tilde{c}_{16} & \tilde{c}_{17} \\ \tilde{c}_{21} & \tilde{c}_{22} & \tilde{c}_{23} & \tilde{c}_{24} & \tilde{c}_{25} & \tilde{c}_{26} & \tilde{c}_{27} \\ \tilde{c}_{31} & \tilde{c}_{32} & \tilde{c}_{33} & \tilde{c}_{34} & \tilde{c}_{35} & \tilde{c}_{36} & \tilde{c}_{37} \\ \tilde{c}_{41} & \tilde{c}_{42} & \tilde{c}_{43} & \tilde{c}_{44} & \tilde{c}_{45} & \tilde{c}_{46} & \tilde{c}_{47} \\ \tilde{c}_{51} & \tilde{c}_{52} & \tilde{c}_{53} & \tilde{c}_{54} & \tilde{c}_{55} & \tilde{c}_{56} & \tilde{c}_{57} \\ \tilde{c}_{61} & \tilde{c}_{62} & \tilde{c}_{63} & \tilde{c}_{64} & \tilde{c}_{65} & \tilde{c}_{66} & \tilde{c}_{67} \\ \tilde{c}_{71} & \tilde{c}_{72} & \tilde{c}_{73} & \tilde{c}_{74} & \tilde{c}_{75} & \tilde{c}_{76} & \tilde{c}_{77} \end{pmatrix} = \begin{pmatrix} \tilde{\boldsymbol{C}}_{\mathbf{1}} \\ \tilde{\boldsymbol{C}}_{\mathbf{2}} \\ \tilde{\boldsymbol{C}}_{\mathbf{3}} \\ \tilde{\boldsymbol{C}}_{\mathbf{4}} \\ \tilde{\boldsymbol{C}}_{\mathbf{5}} \\ \tilde{\boldsymbol{C}}_{\mathbf{6}} \\ \tilde{\boldsymbol{C}}_{\mathbf{7}} \end{pmatrix}. \tag{6}$$

Hence, FAHP matrices are employed $(\tilde{c}_{ii} = \tilde{1})$ based on step II (described in the previous section). The procedure is on the basis of pair-wise comparison which is done as shown in the matrix (6). Note that due to the reciprocal condition of pair-wise comparisons in FAHP method (if the priority of ith criterion compared to jth criterion is $\tilde{c}_{ij}$, the priority of jth criterion in comparison with ith criterion will be $\tilde{c}_{ij}^{-1}$), it is not necessary to complete the whole comparison matrix but to complete a half. The numbers employed in the comparison process are fuzzy linguistic numbers which are explained before in Table I. Eventually, final weight of each criterion $(\tilde{\mathbf{C}}_{\mathbf{i}})$ would be calculated via the geometric mean value of each row or column through.

$$\tilde{\boldsymbol{C}}_i = \sqrt[7]{\prod_{j=1}^{7} \tilde{c}_{ij}} \tag{7}$$

where $\tilde{\mathbf{C}}_{\mathbf{i}}$ is the final fuzzy weight of ith criterion and $\tilde{c}_{ij}$ is the relative fuzzy weight of the ith criterion with respect to the jth criterion. The final crisp weight of each criterion (C_j) would be then computed through a mean operation on the fuzzy final weight of that criterion reflected via a triplex number.

D. CBs Final Weights Evaluation With Respect to the Qualitative Criteria

Having performned the weighting process of the defined subcriteria and criteria, a final table would be reached. This leads to the final weights of each CB with respect to the qualitative approach and is shown in Table IV. The final weight of each CB would be finally found through.

TABLE IV
WEIGHT OF CBs WITH RESPECT TO THE QUALITATIVE CRITERIA

	CRI1*	CRI2	CRI3	CRI4	CRI5	CRI6	CRI7
C_j*	C_1	C_2	C_3	C_4	C_5	C_6	C_7
CB1	$W'_{1,1}$	$W'_{1,2}$	$W'_{1,3}$	$W'_{1,4}$	$W'_{1,5}$	$W'_{1,6}$	$W'_{1,7}$
CB2	$W'_{2,1}$	$W'_{2,2}$	$W'_{2,3}$	$W'_{2,4}$	$W'_{2,5}$	$W'_{2,6}$	$W'_{2,7}$
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
CBn	$W'_{n,1}$	$W'_{n,2}$	$W'_{n,3}$	$W'_{n,4}$	$W'_{n,5}$	$W'_{n,6}$	$W'_{n,7}$

* CRI.i: ith Defined Criterion in Table II, C_j: Weight of jth Criterion

$$W_{\mathrm{Qul,CB,i}} = \sum_{j=1}^{7} \boldsymbol{W'}_{ij} \times C_j \quad \forall\, i = 1, \ldots, n \tag{8}$$

where $W_{\mathrm{Qul,CB,i}}$ is the final weight of ith CB with respect to the qualitative criteria and $\boldsymbol{W'_{\mathbf{ij}}}$ is its weight with respect to the subcriteria of the jth criterion.

E. Weighting Consistency Checking

As explained earlier, the weighting consistency is checked through (5).

V. INVESTIGATING THE QUANTITATIVE CRITERIA ON THE CBs PRIORITIZATION THROUGH RELIABILITY ANALYSIS

Among all the system CBs, those which are not in an appropriate condition with respect to the qualitative criteria and have a considerable influence on the overall system reliability are assigned the most criticalities. (See Fig. 1.) All of the qualitative criteria that have been dealt with through FAHP are presented in the previous section. Here, the DM problem is quantitatively discussed through some critical reliability analysis. Basically, due to their various failure rates and various locations in the system, CBs could be of different effects on the system reliability. As a consequence (to the outlined shortcomings associated with the past indices employed for components criticality assessment, and their inability to be used for CBs prioritization to be put under OLM), the following indices are proposed based on the two most important factors associated with a CB (i.e., failure frequency and costs). The reason to propose the indices on the basis of these factors lies in the fact that OLM could be of considerable impact on both CB failure rates and repair times. Also, these factors are among the major concerns for power system operators, planners, and decision-makers.

A. Failure Frequency Index $\left(\boldsymbol{I}_i^F\right)$

Due to the fact that CBs failure rates are of critical roles on the system reliability analysis and also could be affected through OLM, failure frequency index is proposed as in (9). In the proposed equation, the load point importance is also incorporated since in practice, a different level of importance should be assigned to different load points; due to different criticality associated with various operational conditions, customer categories, and so on. This consideration makes the developed scheme more practical.

$$F_i(U_i) = \sum_{j=1}^{n_L} \omega_j f_j^{U_i} \tag{9}$$

where the following nomenclature can be applied:

- F_i total failure frequency when ith CB has a mean outage duration equal to U_i;
- ω_j importance factor of the jth load point $(0 \leq \omega_j \leq 1)$;
- $f_j^{U_i}$ failure frequency of the jth load point when ith CB has a mean outage duration equal to U_i;
- n_L total number of load points.

In order to assess the OLM impacts on the interrupted power, three conditions are considered for a CB, that is, current state (U_0), two future states: OLM-adapted state (U_l), and non-OLM-adapted state (U_u), by which OLM effects can be evaluated on the CBs failure rates. They are defined as follows.

- U_o mean outage time of CB once considered in its operational state;
- U_ℓ minimum possible outage duration of CB;
- Uu maximum possible outage duration of CB.

Different expert's viewpoints on power system CBs OLM process might exist. A CB may be determined critical to be monitored online once its OLM leads to the maximum benefit of a power system or lack of an OLM system for CB causes a maximum loss in a power system. Therefore, this index is decomposed into two parts (i.e., normalized failure frequency benefit (I_i^{FB}) and normalized failure frequency tort (I_i^{FT})). The former is related to the investigation of minimum system failure rate with respect to the OLM adapted state on ith CB, while the latter is associated with the maximum system failure rate with respect to the non-OLM adapted state to ith CB, as provided in following equations:

$$I_i^{\mathrm{FB}} = \frac{F_i(U_i = U_0) - F_i(U_i = U_\ell)}{\sum\limits_{j=1}^{n_C} I_j^{\mathrm{FB}}} \tag{10}$$

$$I_i^{\mathrm{FT}} = \frac{F_i(U_i = U_u) - F_i(U_i = U_0)}{\sum\limits_{j=1}^{n_C} I_j^{\mathrm{FT}}} \tag{11}$$

where

- $F_i(U_i = U_0)$ total failure frequency when ith CB once considered in its operational state;
- $F_i(U_i = U_l)$ total failure frequency when ith CB is equipped with the OLM system;
- $F_i(U_i = U_u)$ total failure frequency when ith CB is under the maximum possible outage duration;
- n_c total number of CBs.

B. Expected Cost Index $(\boldsymbol{I}_i^{EC})$

One of the most crucial factors in decision makings is the cost-oriented criteria. In the at-hand DM problem, the costs could be changed due to the load categories, interruption duration, and the load points different failure-rate indices. Equations (12) and (13) are proposed to evaluate the costs of a failure occurring in each supplying path

$$\mathrm{EC}_i(U_i) = \sum_{j=1}^{n_L} (L_{Kj} f_j^{U_i} c_{j0} + L_{Kj} f_j^{U_i} r_j^{U_i} c_{Lj}) \tag{12}$$

where

- $\mathrm{EC}_i(U_i)$ expected cost once the outage duration of ith CB is U_i;
- c_j^0 constant initial interruption cost of jth load point ($\$/\mathrm{kW}$);
- L_{kj} interrupted load amount of the jth load point (kW);
- $f_j^{U_i}$ outage frequency of the jth load point once ith CB has the mean outage duration equal to U_i;
- $r_j^{U_i}$ repair time/switching time (depends on the switching arrangements) of jth load point once ith CB has the mean outage duration equal to U_i (h/f);
- c_{Lj} interruption cost growth rate of the jth load point ($\$/\mathrm{kWh}$).

Note that when facing the common shortage of data and information needed, the following equation can be employed where the relative importance of load points are reflected:

$$\mathrm{EC}_i(U_i) = \sum_{j=1}^{n_L} (L_{Kj} f_j^{U_i} r_j^{U_i} \omega_j(t))$$
$$\omega_j(t) = \omega_{j0} + \omega_{jL}^*(t) \tag{13}$$

where

$\omega_j(t)$ importance factor assigned to the jth load point;

ω_{j0} constant importance factor assigned to the jth load point;

$\omega^*_{jL}(t)$ relative weighting function of the load growth rate of jth load point.

Similar to those of the failure frequency index, this index is comprised of the following two parts, that is, expected normalized benefits index $(I^{\mathrm{EC-B}})$ and expected normalized loss index $(I^{\mathrm{EC-T}})$

$$I_i^{\mathrm{EC-B}} = \frac{\mathrm{EC}_i(U_i = U_0) - \mathrm{EC}_i(U_i = U_\ell)}{\sum_{j=1}^{n_C} I_j^{\mathrm{EC-B}}} \quad (14)$$

$$I_i^{\mathrm{EC-T}} = \frac{\mathrm{EC}_i(U_i = U_u) - \mathrm{EC}_i(U_i = U_0)}{\sum_{j=1}^{n_C} I_j^{\mathrm{EC-T}}} \quad (15)$$

where

$\mathrm{EC}_i(U_i = U_o)$ expected cost when ith CB once considered in its operational state;

$\mathrm{EC}_i(U_i = U_l)$ expected cost when ith CB equipped with the OLM system;

$\mathrm{EC}_i(U_i = U_u)$ expected cost when ith CB is under the maximum possible outage duration.

C. Weighted Combination of the Proposed Reliability Indices

Quantitative final weight can now be made on the criticality evaluation of system different CBs based on either failure frequency and expected cost indices with respect to two visualized perspectives, that is, could maximum loss and maximum benefit. The proposed indices are combined via the weighting coefficients to develop the most optimal and practical solution as follows:

$$I_i^{\mathrm{Be}} = \alpha^B I_i^{\mathrm{EC-B}} + \beta^B I_i^{\mathrm{FB}} \quad (16)$$

$$I_i^{\mathrm{Te}} = \alpha^T I_i^{\mathrm{EC-T}} + \beta^T I_i^{\mathrm{FT}}. \quad (17)$$

where

I_i^{Be} final index of the benefits associated with OLM adaptation on the ith CB;

I_i^{Te} final index of losses due to not performing the necessary OLM on the ith CB;

α^B, β^B importance factors of the $I_i^{\mathrm{EC-B}}$ and I_{FB}^i indices $(\alpha^B + \beta^B = 1)$;

α^T, β^T importance factors of the $I_i^{\mathrm{EC-T}}$ and I_i^{FT} indices $(\alpha^T + \beta^T = 1)$.

Technically approached, a CB is quantitatively critical once it leads to the maximum benefits when placed under OLM and maximum imminent losses as well as when it is not under OLM. The concept is depicted in Fig. 5.

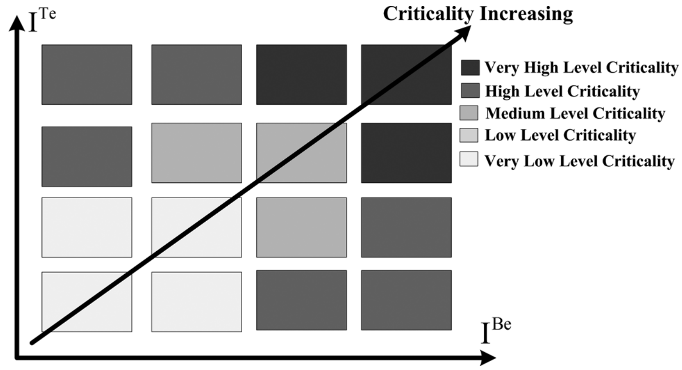

Fig. 5. Criticality variations of CBs with respect to the proposed indices.

Having found the quantitative weights $(W_{\mathrm{Qun,CBi}})$ of the CBs through the mean of defined reliability indices, these weights have to be finally combined with those that were qualitatively obtained through FAHP $(W_{\mathrm{Qul,CBi}})$ via (1). This leads to the final weights of CBs and, as a result, they can be sorted and prioritized for OLM based on their final weights.

VI. Case Study: A Transmission Substation With a *Breaker*-and-a-*Half* Configuration

For the sake of validation, the proposed method is applied to a sample transmission system in three steps as follows:

Step 1) obtaining weights of CBs with respect to the qualitative approach using FAHP;

Step 2) obtaining weights of CBs with respect to the quantitative approach using the proposed indices;

Step 3) prioritization based on the application of combined qualitative and quantitative weights.

Different configurations, such as the switching and the transformation substations, are usually employed in power systems. Among the most common configurations, a-*breaker*-and-a-*half* configuration is employed in this paper.

Fig. 6 illustrates the system under study and presents its structure containing all of the system buses, CBs, and lines associated with the loads and power resources. All CBs are assumed to have medium switching current, located in outdoor, SF_6 type, and with normal accessibility. Drive mechanisms of CB1 and CB3 are from spring type; while, CB2, CB4, and CB5 have a hydraulic drive, and CB6 is equipped with the pneumatic drive. From the viewpoint of a lifetime, CB1, CB5 and CB6 are considered with a lifetime of 30–40 years and the others with a lifetime of more than 40 years.

A. Step I: Calculation of CBs Qualitative Weight $(W_{Qul,CB})$

In this subsection, experts' knowledge on the evaluation of CBs criticality with respect to qualitative criteria defined in Table II is incorporated. On the basis of the qualitative approach steps, introduced in Section IV, two key parameters (i.e., total weight of each criterion $(\mathbf{C_j})$ and weight of CBs in terms of

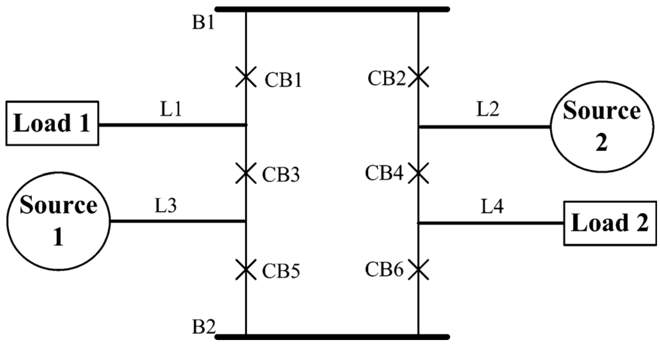

Fig. 6. Breaker and-a-half configuration of a substation.

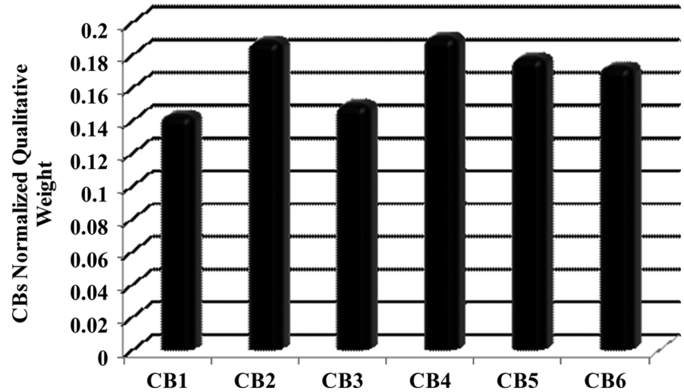

Fig. 7. Final normalized weights of system CBs criticality with respect to the qualitative criteria.

TABLE V
WEIGHT OF CBs WITH RESPECT TO THE QUALITATIVE CRITERIA

	CRI1*	CRI2	CRI3	CRI4	CRI5	CRI6	CRI7
C_i*	*1.58*	*1.13*	*1.69*	*1.64*	*0.42*	*0.62*	*0.75*
CB1	0.571	0.322	0.333	0.167	0.203	0.286	0.273
CB2	0.571	0.322	0.333	0.5	0.355	0.571	0.273
CB3	0.571	0.322	0.333	0.167	0.355	0.286	0.273
CB4	0.571	0.322	0.333	0.5	0.355	0.571	0.273
CB5	0.571	0.322	0.333	0.5	0.203	0.286	0.273
CB6	0.571	0.322	0.333	0.333	0.203	0.571	0.273

* CRI.i: i[th] Defined Criterion in Table II, C_i: Final Weight of i[th] Criterion

each criterion ($\boldsymbol{W}'_{\mathbf{ij}}$)) should be determined to obtain the total qualitative weight of CBs ($W_{\mathrm{Qul,CB}}$).

Based on defined subcriteria (see Table III) and the described condition of CBs of the test system, the weight of CBs for each criterion ($\boldsymbol{W}'_{\mathbf{ij}}$) is obtained. For instance, since CB1 is equipped with a spring-drive mechanism, it is scored by 0.167. In the other words, the weight of CB1 regarding the fourth criterion (drive mechanism in Table II) is equal to 0.167 ($\boldsymbol{W}'_{14}$ in Table V). For each criterion, a similar procedure is applied to all CBs. The results are provided in Table V.

To obtain the total weight of seven defined criteria ($\mathbf{C}_j$ in (8) and Tables IV and V), the fuzzy pair-wise comparison should be accomplished (as explained in Section IV-C). The results are shown in (18) at the bottom of the page. Subsequently, the total fuzzy weights of each criterion are obtained using (7), and the results are presented in (19). This fuzzy matrix is then required to be defuzzified in order to determine the crisp weight values. This is obtained through the mean of the triple fuzzy set. The final crisp weight of criteria (C_j) is provided in the first row of Table V and in the following equation:

$$\tilde{C} = \begin{pmatrix} (1.25, 1.58, 2.46) \\ (0.86, 1.13, 1.57) \\ (1.08, 1.58, 2.23) \\ (0.94, 1.54, 2.1) \\ (0.41, 0.5, 1.32) \\ (0.5, 0.64, 1.01) \\ (0.44, 0.6, 0.98) \end{pmatrix}; \xrightarrow{\text{Defuzzification}} C = \begin{pmatrix} 1.58 \\ 1.13 \\ 1.69 \\ 1.64 \\ 0.42 \\ 0.62 \\ 0.75 \end{pmatrix}. \tag{19}$$

The qualitative weighting consistency is checked through a consistency analysis shown in (4) and (5). As can be seen from the following calculation, the comparisons are concluded to be consistent due to the fact that the consistency ratio (CR) is within the acceptable range of below 0.1

$$\mathrm{CI} = \frac{7.134 - 7}{7 - 1} = 0.023 \rightarrow \mathrm{CR} = \frac{0.023}{1.32} = 0.017. \tag{20}$$

Having found the final weights of the criteria ($\mathbf{C_j}$) and weights of CBs regarding each criterion ($\boldsymbol{W}'_{\mathbf{ij}}$) interrelated with the decision-making problem, the qualitative final weight of CBs ($W_{\mathrm{Qul,CB}}$) is achieved via (8) and the results are illustrated in Fig. 7.

B. Step II: Calculation of CBs Quantitative Weight ($W_{Qun,CB}$)

In order to quantitatively determine the criticality of system CBs, minimal cutset concepts are here employed. Cutsets are the unique combinations of component failures that can cause system failure. Specifically, a cutset is said to be a minimal

$$\tilde{M} = \begin{pmatrix} (1,1,2) & (1,1.33,1.5) & (1,1,2) & (1,1,2) & (3,4,5) & (1.63,2.63,3.1) & (1,2,3) \\ (0.66,0.75,1) & (1,1,2) & (0.5,0.75,1.1) & (0.5,0.75,1.1) & (2,3,4) & (1,1.33,1.5) & (1.1,1.44,1.6) \\ (0.5,1,1) & (0.9,1.33,2) & (1,1,2) & (1,1,2) & (3,4,5) & (1,2,3) & (1.3,2.5,3.1) \\ (0.5,1,1) & (0.9,1.33,2) & (0.5,1,1) & (1,1,2) & (3,4,5) & (1,2,3) & (1,2,3) \\ (0.2,0.25,1.33) & (0.25,0.33,0.5) & (0.2,0.25,1.33) & (0.2,0.25,1.33) & (1,1,2) & (1,1.33,1.5) & (1,1,2) \\ (0.32,0.42,0.61) & (0.66,0.75,1) & (0.33,0.5,1) & (0.33,0.5,1) & (0.32,0.42,0.61) & (1,1,2) & (1,1.33,1.5) \\ (0.33,0.5,1) & (0.62,0.7,0.91) & (0.32,0.4,0.78) & (0.33,0.5,1) & (0.5,1,1) & (0.32,0.42,0.61) & (1,1,2) \end{pmatrix} \tag{18}$$

TABLE VI
TWENTY-EIGHT CUTSETS OF LOAD POINT 1 IN THE SUBSTATION UNDER STUDY

1	L1	8	L3,CB3,Bus1	15	L3,Bus1,CB2	22	L2,CB3,CB1
2	CB3,CB1	9	L3,CB3,CB2	16	L3,CB1,CB1	23	L2,CB3,Bus1
3	CB3,Bus 1	10	L3,CB2,CB1	17	L3,CB1,Bus2	24	L2,CB3,Bus2
4	CB3,CB2	11	L3,CB2,Bus1	18	L3,CB1,CB2	25	L2,CB3,CB4
5	CB3,L2	12	L3,CB2,CB2	19	L3,CB3,CB1	26	L2,CB3,CB6
6	L2,L3	13	L3,Bus1,CB1	20	L3,CB3,CB2	27	L2,CB3,CB5
7	L3,CB3,CB1	14	L3,Bus1,Bus1	21	L3,CB3,Bus1	28	L2,CB3,CB2

TABLE VII
TWENTY-EIGHT CUTSETS OF LOAD POINT 2 IN THE SUBSTATION UNDER STUDY

1	L4	8	L2,CB4,Bus2	15	L2,Bus1,CB5	22	L3,CB4,CB6
2	CB4,CB6	9	L2,CB4,CB5	16	L2,CB1,CB6	23	L3,CB4,Bus2
3	CB4,Bus 2	10	L2,CB2,CB6	17	L2,CB1,Bus2	24	L3,CB4,Bus1
4	CB4,CB5	11	L2,CB2,Bus2	18	L2,CB1,CB5	25	L3,CB4,CB5
5	CB4,L3	12	L2,CB2,CB5	19	L2,CB3,CB5	26	L3,CB4,CB1
6	L2,L3	13	L2,Bus1,CB6	20	L2,CB3,CB6	27	L3,CB4,CB2
7	L2,CB4,CB6	14	L2,Bus1,Bus2	21	L2,CB3,Bus2	28	L3,CB4,CB3

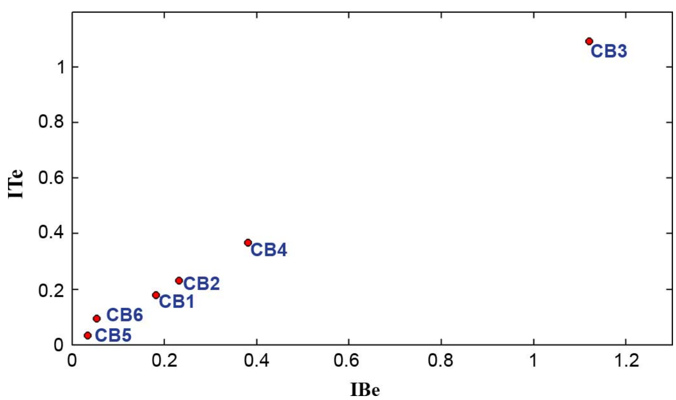

Fig. 8. Normalized indices of the losses not due to OLM with respect to the benefits of performing OLM on system CBs.

cutset if, when any basic event is removed from the set, the remaining events collectively are no longer a cutset [23], [24]. For example, minimal cutset number 5 in Table VI means that from the load point 1 point of view, failures in a combination of CB3 and L2 cause an interruption in load point 1. The cutsets presented in Tables VI and VII can be found, respectively, for load points 1 and 2.

The associated reliability-oriented simulations and modeling procedures are performed in the MATLAB environments. The proposed indices can be calculated using the reliability data and information provided in the Appendix and introduced equations in (9)–(17).

In these studies, α^B, β^B, α^T, and β^T are assumed to be equal. The importance factors associated with different load points are assumed to be equal. The reliability assessments results are demonstrated in Fig. 8.

C. Step III: Final Prioritization Through Combined Qualitative and Quantitative Analysis (W_{CB})

The quantitative weight of each CB is calculated through the mean of I^{Te} and I^{Be} indices that can be seen in Fig. 8. These weights have to be finally combined with those of the qualitative basis, which are obtained through the FAHP. (See Fig. 7.) As a consequence, the final weights of CBs can be found through (1) (it is assumed that two qualitative and quantitative weights have an equal contribution in determining the CBs final weight) and,

TABLE VIII
FINAL CRITICALITY RANKINGS OF CBS IN THE CASE STUDY

Circuit Breakers	Qualitative Weight	Quantitative Weight	Final Weight	Rank
CB1	0.143	0.180	0.323	4
CB2	0.188	0.231	0.419	3
CB3	0.150	1.107	1.257	1
CB4	0.191	0.374	0.565	2
CB5	0.178	0.033	0.211	6
CB6	0.172	0.074	0.246	5

TABLE IX
RELIABILITY DATA OF THE CASE STUDY

Components	$\lambda_i (f\ /\ yr)$	$r_i (h\ /\ f)$
Line 1	18	0.780
Line 2	15	0.930
Line 3	10	0.880
Line 4	12	0.860
Bus 1	2.7	0.200
Bus 2	3.2	0.180
CB 1	150	0.090
CB2	176	0.070
CB3	167	0.076
CB4	168	0.034
CB5	159	0.023
CB6	146	0.056

TABLE X
DIFFERENT RELIABILITY-ORIENTED STATES OF THE CBS UNDER STUDY

CBs	$U_u (h\ /\ yr)$	$U_\ell (h\ /\ yr)$	$U_0 (h\ /\ yr)$
CB 1	40.500	0.562	13.500
CB2	36.960	0.513	12.320
CB3	38.076	0.528	12.700
CB4	17.136	0.238	5.710
CB5	10.971	0.152	3.657
CB6	24.528	0.340	8.176

According to literature [25], [26], the maximum effects of the CBs OLM (OLM-adopted state) on their repair times and failure rates indices are respectively set to be 70% and 87%. In addition, a 300% increase in failure rates is regarded for the worst case (non-OLM-adopted state).

hence, they can be sorted and prioritized for OLM based on their final weights as presented in Table VIII.

VII. CONCLUSION

This paper introduces a novel optimum CBs selection scheme for online monitoring of CBs in a power system. Practically approached, CBs are prioritized on the basis of obtained weights with respect to two points of views (i.e., the qualitative and quantitative approach). From the qualitative point of view, the condition of CBs is assessed through FAHP. In this process, the practical qualitative criteria interrelated with the CBs criticalities are evaluated through the knowledge and expertise of the experts (e.g., on the CBs lifetime, drive mechanisms, and so on). From a quantitative perspective, the influence of CBs on the overall system reliability is investigated using the proposed two novel reliability-oriented indices. These indices are so defined to well evaluate the OLM impacts on the entire power system reliability performance. The main features of the proposed indices are the possibility of considering the CB failure rate and its repair time variations. It also provides a method to study the CBs prioritization process for OLM once faced with multi-input–multioutput systems or where there are several load points. Finally, combining the qualitative and quantitative assessments, system CBs would be prioritized for OLM. The proposed method of this paper is applied to a transmission substation with a *breaker*-and-a-*half* configuration. Its simulation results have demonstrated how the proposed prioritization method can be used for the selection of a set of power system CBs for OLM.

APPENDIX

The reliability data associated with the *breaker*-and-a-*half* configuration are provided in Tables IX and X.

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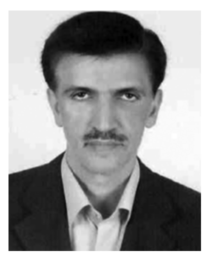

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