

Article

D-Distance Technique to Determine Failure Probability of Power Circuit Breaker

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Abstract: In this paper, a new D-distance factor is proposed to determine the failure probability and to prioritize maintenance actions of power circuit breakers in high-voltage substations. The D-distance factor is calculated by using the condition index and renovation index of a high-voltage circuit breaker (HVCB). To facilitate effective decision-making on maintenance with a simple method and less computational effort, the proposed model incorporates the weighting–scoring method (WSM) and analytical hierarchy process (AHP) with the various diagnostic methods for condition index assessments as well as the operation requirements of HVCBs for renovation index assessments. Many significant parameters from circuit breaker testing, such as insulation resistance, contact resistance, contact timing, SF₆ gas measurements, gas leakage rate, visual inspection, etc., have been considered for condition index determination. In addition to these, other significant parameters, such as age of the circuit breaker, age of the interrupter and mechanism, number of fault current interruptions, actual load current to rated current ratio, actual short circuit current to rated interrupting current ratio, maintenance ability, spare parts availability, maintenance expertise level, etc., are also considered for renovation index determination. To validate the proposed model, the practical test data of twenty 115 kV HVCBs in various substations of a distribution utility in Thailand were utilized and tested. By analyzing the actual condition and operation requirement of the circuit breaker, the output, as the condition index and renovation index using the proposed method, is discussed with HVCB experts in the utility to adjust the scores and weights of all criteria to obtain the most accurate and reliable model. The results show that the D-distance technique measured from the risk matrix, which is defined as the failure probability, can be used to rank the maintenance schedule from urgent to normal maintenance tasks. In addition, various failure probabilities in the risk matrix of the circuit breaker can be used to determine the appropriate maintenance strategies for the power circuit breaker in each group. Finally, the proposed method could help the utility managers and maintenance engineers manage the maintenance planning effectively and easily for thousands of HVCBs in the grid, and it can be further applied with other high-voltage equipment in both transmission and distribution systems to facilitate the maintenance activities according to available costs and human resources.

Keywords: D-distance; power circuit breaker; condition index; renovation index; risk assessment; risk factor; weighting–scoring method



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1. Introduction

A power circuit breaker, a mechanical switching device, is one of the key elements in an electrical power system. Its function is to make, carry, and interrupt currents occurring in the circuit under normal conditions, and to carry for a specified time, to make, and to interrupt currents arising in the circuit under defined abnormal conditions, e.g., a short circuit. A power circuit breaker consists of an interrupting unit, supporting porcelain

column, operating mechanism, metallic frame and structure, and control unit. In general, it works together with an instrument transformer as a sensing device and protective relay, as a brain that decides the electrical system condition. Once power circuit breakers in a high-voltage substation have been installed and put into service, cumulative stresses, such as thermal, electrical, and mechanical stresses during normal operation as well as abnormal operating conditions, such as a fault, are imposed on the equipment for a period of time [1–4]. These stresses and faults significantly accelerate degradation, adversely affect the condition, and reduce the performance of the equipment. Consequently, the high-voltage circuit breaker (HVCB) is gradually degraded, and its lifetime is shortened. Finally, the failure of a HVCB could occur, leading to power interruption, and the system reliability could be reduced. The guide to investigate, analyze, and report HVCB failures and causes were introduced [5].

Various diagnostic methods to investigate the causes of failure in HVCBs were developed and implemented, such as an active breaker incidence (ABI) matrix to capture the active failure of breakers leading to load-point failures [6], the relationship of subjective historical data and failure rate [7,8], the dynamic resistance measurement [9], coil current measurement [10], radiometric monitoring [11], contact erosion [12], and full mechanical and electrical test methods [13]. Many of these were practically applied to prevent unpredictable failure and extend the end of life of HVCBs. Both on-line and off-line condition monitoring and various diagnostic testing methods were introduced, such as a hybrid model that determines reliability and uncertainty based on the prognostics of HVCBs [14], reliability assessment model using an aging failure model [15], condition monitoring model [16,17], and condition assessment of gas-insulated switchgear using health index and conditional factor methods to improve the calculation accuracy [18]. Some circuit breaker failure prognosis methods and models were also mentioned to maintain system reliability [19,20]. These effective monitoring and diagnostic methods have been continually developed for condition and performance assessment in forms, i.e., health index, condition index, risk index, and failure probability, for the most effective operation and maintenance management [21–24]. Subsequently, the maintenance tasks could be prioritized while their relevant costs could be minimized for better technical and economic aspects [25–27]. Some asset management strategies, such as the weighting–scoring method; Weibull estimation technique, based on actual historical testing results; and the technical information of equipment and systems, were implemented to predict the lifetime and the end of life of the HVCB [28,29].

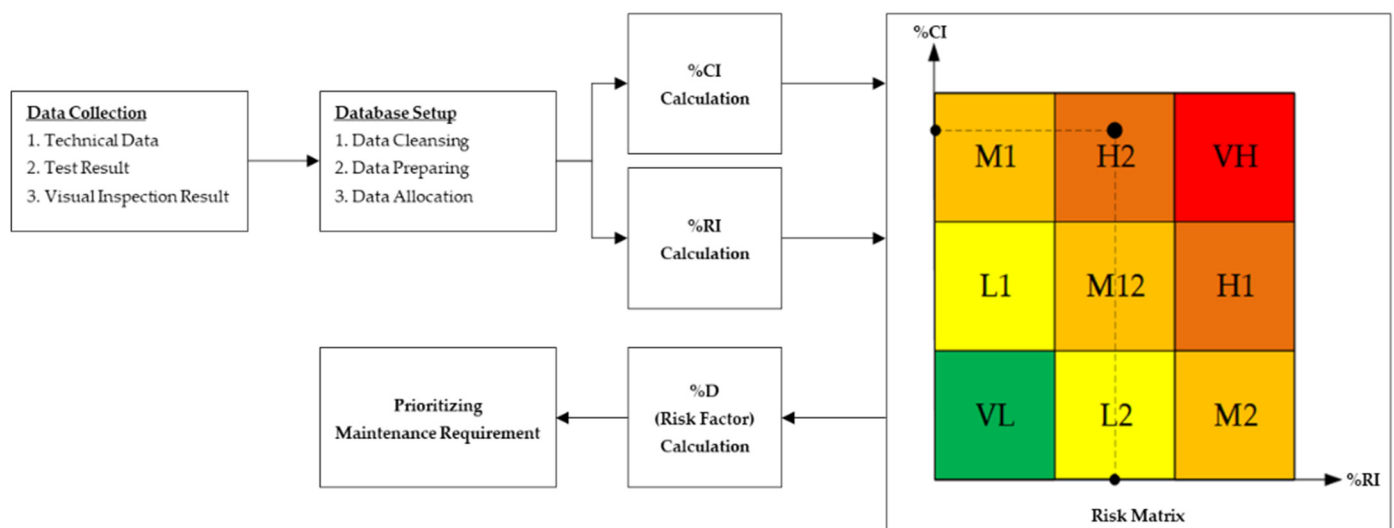
The failure rate is the frequency in which a component failed, which is expressed in failures per period. It is a significant indicator for maintenance engineers to evaluate their maintenance strategy, planning, and management. A lower failure rate refers to better performance of a maintenance management program. In a distribution system, the practical failure rate and consequences of HVCB failure are higher than other switching devices and metering instruments, such as a disconnecting and ground switch, current transformer, and voltage transformer [30]. Their failure causes are recorded and illustrated in Table 1. Therefore, the maintenance strategy for HVCBs should be intensively focused.

In the distribution system of a utility in Thailand, there are 317 substations and more than one thousand and five hundred units of active HV circuit breakers. With the limitation of manpower, material (spare parts), and annual budget (money), the maintenance action plan needs to be designed appropriately to manage the limited resource effectively. The failure probability determined from the risk matrix is an effective tool to facilitate the effective allocation of limited resources directly to the most urgent HV circuit breaker. Twenty pilot units of HV circuit breakers with diverse ages and conditions are selected from various substations and applied with the proposed failure probability model using the D-distance assessment of HVCBs from the risk matrix.

Table 1. Power circuit breaker failure detail.

Major Components	Minor Components	Failure Modes	Environments	Situations	Root Causes
interrupting unit	fix contact/moving contact, terminal plate, arc quenching system	leakage, broken, stiff, loose, rusty, dirty,	rain acid, corrosion from salt water, pollution as smoke from agriculture, animals, lightning	fails during installation, energization, re-energization, operation, maintenance, testing, after service	mistakes during design, construction installation, and operation, careless, lack of maintenance, overloading, deterioration, end of life, animal, surrounding, human error
operating mechanism	energy storage, latching linkage, motor, dashpot	short circuit, flashover, hot spot, damaged, non-operating, malfunction, properties changed, failed test			
SF ₆ gas system	gas density gauge, pressure switch, gas quality, gas tightness				
external insulation	cleanliness of surface				
control and auxiliary circuit	closing/tripping circuit, electrical supply/wiring, auxiliary switch, magnetic contactor, heater circuit, counter				

The whole conceptual process of the proposed method is shown in Figure 1. The data of the HVCBs, including technical data, test results, and visual inspection results, are collected annually by the utility engineer and technician. Then, the collected data are cleaned to avoid human error, and primarily prepared and allocated to databases before being further applied to calculate the %CI and %RI. Both the %CI and %RI are plotted on the risk matrix to determine the %D, which is used to prioritize the maintenance requirement.

**Figure 1.** The overview diagram of the proposed method.

The D-distance factor is calculated by using the percentage of the condition index (%CI) and the percentage of the renovation index (%RI). To obtain the %CI and %RI, actual data, including technical data, routine and special test results, and visual inspections, are applied in the assessment model as shown in Figure 2. The weighting–scoring method or WSM is a numerical technique used to calculate the condition and renovation indexes from various evaluation criteria. A scoring technique is used to transform the raw inspection and testing results from each test method to a quantitative value known as a score, while

a weighting technique is used to assign the numerical value representing the importance of each test method as well as the significance of each component in a HVCB unit, known as the weighting value [31]. The importance of the weight setting is arranged regarding the importance and effectiveness of each concerned item. Hence, criteria or sub-criteria weights need to be determined appropriately and logically. The score is classified based on international standards and expert experiences. The opinions of the experts are brainstormed along with the application of the analytical hierarchy process (AHP), which is a mathematical tool using pairwise-comparing opinion and expertise from experts to each criterion to obtain the numerical weight. The large number of weights implies the significance of that criterion and its effect on the overall index variation. Subsequently, the final weighting and scoring values can be assigned to each criterion.

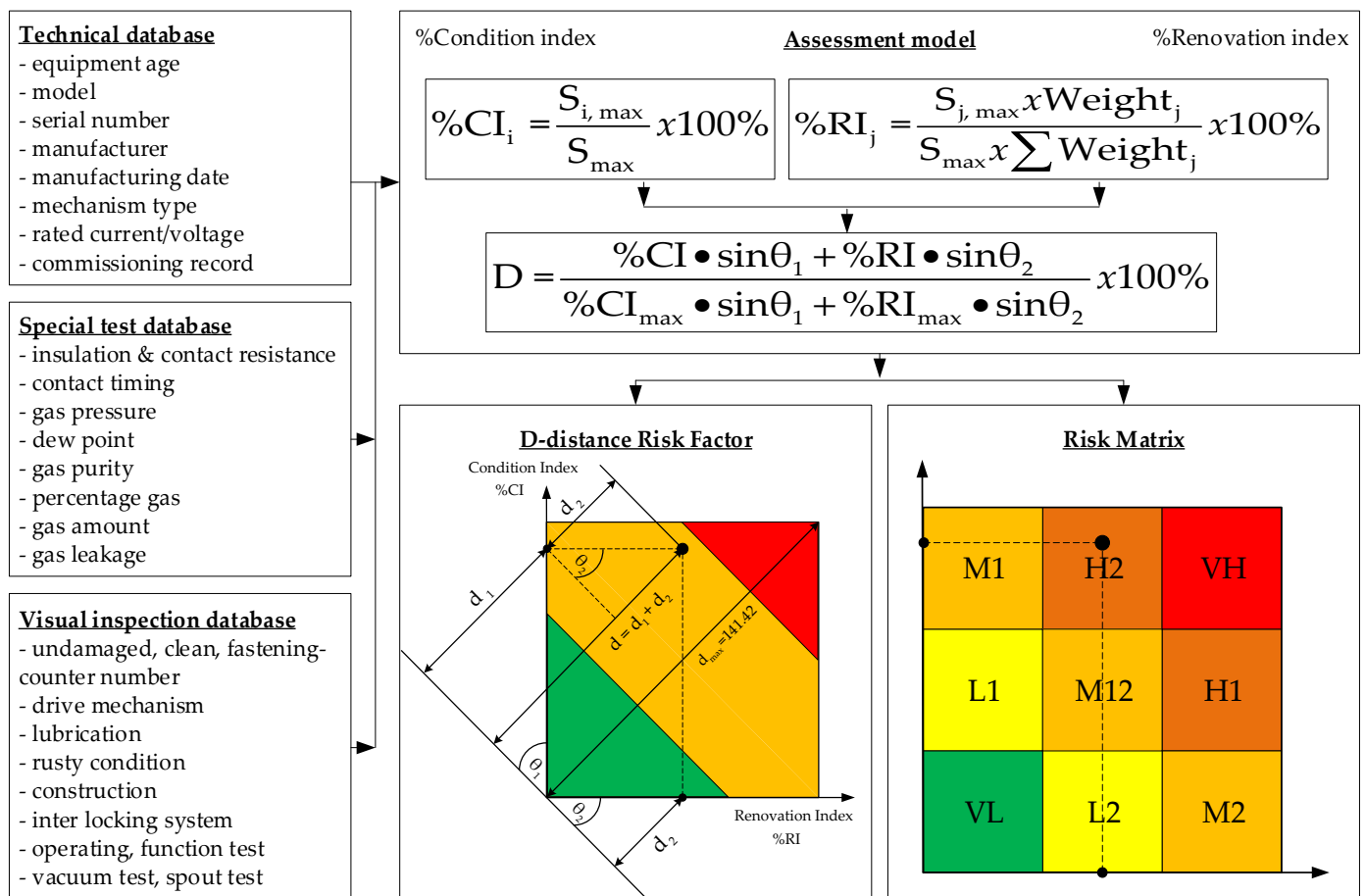


Figure 2. The overall procedure of the assessment model.

After successful validation of the proposed D-distance risk factor with the pilot HVCBs of the 20 units, this method can be further applied with the rest of the HVCBs in the transmission and distribution substations in the grid. The proposed method can also be adapted to implement with other high-voltage equipment or HVCBs in other voltage ratings, such as a medium-voltage switchgear, a power transformer, an instrument transformer, a disconnecting switch, and a lightning arrester, by adjusting some evaluation criteria and scoring details according to the physical behavior and operating principle of those devices. With this proposed method, the huge amount of maintenance tasks regarding HVCBs and other high-voltage equipment in an electrical system can be logically prioritized according to the known failure probability of those devices. For HVCBs with a high %CI, the servicing, repairing of defected components, or replacement of the defective components by a new one should be executed to lower the %CI, while for HVCBs with a high %RI, the planned replacement or relocation should be appropriate. Therefore, with the known %CI, %RI, and

failure probability, the appropriate maintenance strategy can be effectively planned and managed based on limited resources according to the criticality level of HVCBs in these three aspects. With a clear strategic action plan, high performance of maintenance actions as well as a better asset management strategy could be achieved, and the failure rate of HVCBs could be reduced, resulting in better reliability of the electrical transmission and distribution system.

2. Failure Probability Assessment and Maintenance Strategy

In this paper, a failure probability assessment of HVCBs is presented. The failure probability is identified in terms of the D-distance factor, which is calculated by using the percentage of the condition index (%CI) and the percentage of the renovation index (%RI). To obtain the %CI and %RI, actual data, including technical data, routine and special test results, and visual inspections, are applied in the assessment model. Then, twenty HVCBs in various substations are applied with the assessment program, and the results are satisfied. The technical data sets, including age, serial number, manufacturer, model, mechanism type, rated current, rated voltage, and related international standards and recommendations, as well as the commissioning test record, are segregated into the individual data of the equipment, while some common data, which is similar for a particular model, are also set up as model data, such as spare part availability, maintenance effort, time consumed, etc. In the condition index evaluation, both individual and model data are simultaneously retrieved from the database and further calculated according to the above procedure.

2.1. Condition Index Calculation

The Condition Index (%CI) represents the equipment's condition in numeric form, which is determined by using the WSM technique. First, the score (S_i) of various routine and special tests as well as a visual inspection of the circuit breaker must be determined to transform the physical condition to a numerical value. To achieve that, the test results are compared and justified based on the recommendation in the international standards, commissioning record, and instruction manual from the manufacturer, as well as the knowledge in engineering, operation, and maintenance. The special tests include the contact timing test together with SF₆ pressure, dew point, percentage and purity, amount of SO₂, gas leakage rate measurement, as well as counter and operating checks. In addition, the routine tests consist of tests on insulation and contact resistance, undamaged, clean, fastening terminal, and function checks. Visual inspection records have been designed with sufficient guidelines to observe and to consistently gather the general condition of HVCB components, such as undamaged parts, cleanness, fastening, operating, counter, drive mechanism condition, lubrication, rusty, construction condition, interlocking system operation, vacuum test, and spout test. The criteria and scores of all tests are detailed in Table 2.

Table 2. Weighting–scoring method for the condition assessment of HVCB.

Test Method	Score (S_i)			Weight (W_i)
	0	3	5	
insulation resistance (GΩ)	≥ 10	-	< 10	10%
contact resistance (μΩ)	≤ 40	-	> 40	10%
contact timing (%deviation)	≤ 10	-	> 10	10%
SF ₆ pressure (bar)	> 6	6–5.5	< 5.5	10%
SF ₆ dew point (°C)	≤ -10		> -10	10%
SF ₆ percentage (%)	≥ 80	-	< 80	10%
SF ₆ purity (%)	≥ 99	-	< 99	10%
amount of SO ₂ (ppm)	≤ 10	-	> 10	10%

Table 2. Cont.

Test Method	Score (S_i)			Weight (W_i)
	0	3	5	
gas leakage rate (frequency per year)	≤ 5	-	> 5	10%
undamaged, clean, fastening, counter, operating, thermos-scan, function, drive mechanism lubrication, rusty, construction, annunciator operation, interlocking system, hi-pot test, vacuum test, spout test check	normal	-	abnormal	10%

The %CI is calculated by using Equation (1) according to the WSM technique. However, the worst score ($S_{i, worst}$) from all tests in each major criteria is applied in the %CI calculation to make the model sensitive in early warning whether to repair or to replace any equipment.

$$\%CI = \frac{S_{i, worst} \times W_i}{S_{i, max}} \times 100\% \quad (1)$$

where %CI is the percentage condition index of any circuit breaker, $S_{i, worst}$ is the worst score of all tests in each criteria, and $S_{i, max}$ is the maximum score of all criteria. A higher %CI implies a poorer condition of the equipment, which means a large deviation from the instruction manual or international standard recommendation and commissioning record, whereas a smaller %CI represents a better condition.

The judgement of condition index is presented in Table 3. The evaluated result is displayed as a traffic light color of green, orange, or red for good (%CI is lower than 40), moderate (%CI is between 40 to 80), and poor condition (%CI is greater than 80), respectively. The numerical boundary of %CI is determined from sensitivity analysis by first simulating the possible defective parts found and recorded in the utility's failure record forms according to the test methods described in Table 2 and observing the obtained %CI, then fine tuning the weighting value by combining more defective parts as much as possible and observing their impacts on the %CI. Once the rough boundary values are determined by simulated test cases, it is further tested with the actual data by comparing the actual condition of the equipment, historical failure rate, maintenance record, as well as the historical test results with the calculated results of the proposed method. This sensitivity analysis is performed by the brainstorming of utility experts with their expertise in engineering, operation, and maintenance of HVCBs from various departments to share their opinions on the %CI values obtained from various simulated and actual cases together with statistical methods and variance of distribution from evaluated populations. By this means, the boundary values between good to acceptable and acceptable to poor conditions can be determined, but it needs to be reconsidered for adjustment to improve the accuracy of this evaluation procedure when a greater number of HVCB populations have been evaluated.

Table 3. Condition judgement from the %CI assessment result.

Condition Assessment	Good	Acceptable	Poor
%CI	<40	40–80	>80

2.2. Renovation Index Calculation

The Renovation Index (%RI) has been developed to notify the necessity level of renovation tasks to upkeep the reliability of an electrical system. %RI is evaluated by analyzing age, number of interruptions, inadequate rating, technology obsolescence, maintain ability, and symptom level as shown in Table 4. In the %RI evaluation, the equipment symptom and model failure rate are determined by analyzing the historical failure records. The required data sets include defects in major components, defects in minor components, failure mode, environmental effect, failure situation, root cause, down time, up time, outage

duration, and solution. Moreover, the symptom level of the equipment is also determined by considering the defects in major components, minor components, and failure mode. Therefore, a major defect is defined as the equipment has a major failure with an urgent shutdown for repair or replacement and a high cost and high effort to repair. Conversely, a minor defect means that the defect in the equipment does not result in an immediate failure and has a low cost and low effort to repair. The scores and weights of all criteria in Table 4 are applied with the WSM technique to calculate the %RI by using Equation (2). The %RI is classified and displayed as a traffic light color of green, orange, or red for long-term, medium-term, and urgent requirements for renovation or replacement.

$$\%RI = \frac{\sum_{j=1}^n (S_{j,max} \times W_j)}{S_{j,max} \sum_{j=1}^n (W_j)} \times 100\% \quad (2)$$

where %RI is the percentage renovation index, S_j is the score of the sub-criterion j , W_j is the weight of the sub-criterion j , and $S_{j,max}$ is the maximum score in all sub-criteria.

Table 4. Criteria and weighting–scoring method for the %RI evaluation of HVCBs.

Criteria	Sub-Criteria	Scoring (S_j)			Weight (W_j)
		0	3	5	
age and no. of interruptions	overall age (25 years)	<11	11–24	>24	7.675
	age of interrupter (24 years)	<23	23–24	>24	7.675
	age of mechanism after overhaul (12 years)	<11	11–24	>24	7.675
	number of fault current interruptions (times)	<5	5–8	>8	7.675
inadequate rating	ratio of load current to rated current	<60	60–80	>80	10.6
	ratio of short circuit current to rated S/C current	<60	60–80	>80	10.6
technology obsolescence	already replaced by advanced technology	no	-	yes	4.1
	no longer manufactured	no	-	yes	4.1
maintain ability	spare parts availability	easy to find	difficult to find, possible to modify	unable to modify	5.0
	personnel expertise level	good	moderate	poor	5.0
	OEM support/ after sale service quality	good	moderate	poor	5.0
	orphan (amount of installed unit left in system)	≥ 5	-	<5	5.0
symptom	operator level of satisfaction (model's failure rate)	satisfied	-	not satisfied	5.0
	major/ minor failure, cost, and effort to repair	minor defect	-	major defect	20.0

The judgement of the renovation index is presented in Table 5. The evaluated result is displayed as a traffic light of green, orange, or red for long-term (%RI is lower than 24), medium-term (%RI is between 24 to 43), and urgent situation (%RI is greater than 43), respectively. Similar to the %CI boundary determination, the numerical boundary of %RI is determined from sensitivity analysis by first simulating the possible renovation criteria described in Table 4 and observing the obtained %RI, then fine tuning the weighting value by combining more renovation criteria as much as possible and observing their impacts on the %RI. Once the rough boundary values are determined by simulated test cases, it is further tested with the actual data by comparing the actual information of the equipment and historical minor and major refurbishment frequency with the calculated result. This sensitivity analysis is performed by the brainstorming of utility experts with their expertise on HVCBs from various departments to share their opinions on the %RI values obtained from various simulated and actual cases together with statistical methods and variance of distribution from evaluated populations. By this means, the boundary values can be determined, but it also needs to be reconsidered for adjustment to improve the accuracy of this evaluation procedure when a greater number of HVCB populations have been evaluated.

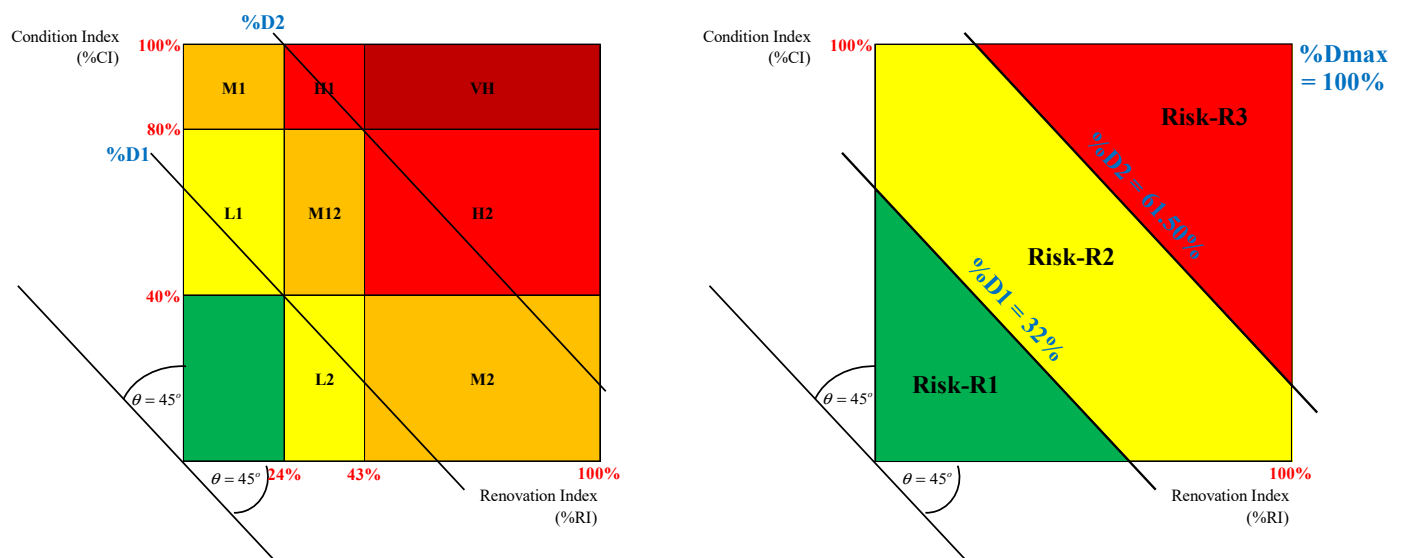
Table 5. Renovation judgement from the %RI assessment result.

Renovation Assessment	Long-Term	Medium-Term	Urgent
%RI	<24	24–43	>43

2.3. D-Distance Factor Calculation

In this session, the failure probability of HVCB usage is determined in terms of the D-distance factor (%D), which can be calculated by using Equation (3) and further plotted in the risk matrix as shown in Figure 3. The previously calculated %CI and %RI of each device are further substituted into the calculation. In the risk matrix, the %CI and %RI are considered of equal importance, which is determined by the 45° line at the origin of the risk matrix. Thus, both angles θ_1 and θ_2 are equal to 45°.

$$\%D = \frac{\%CI \sin \theta_1 + \%RI \sin \theta_2}{\%CI_{\max} \sin \theta_1 + \%RI_{\max} \sin \theta_2} \times 100\% \quad (3)$$

**Figure 3.** Measurement of the D-distance factor for the failure probability assessment.

2.4. Risk Matrix with Proper Maintenance Action

After obtaining the %CI, %RI, and %D from the above calculation procedures, those indexes are used to build the risk matrix as shown in Figure 3. From the risk matrix, the green rectangular zone means that the device is in good condition with a long-term renovation requirement resulting in a very low failure probability zone or very low failure probability. On the contrary, the top right red rectangular zone means that the device is in poor condition with an urgent renovation requirement leading to a very high failure probability zone or very high failure probability. Therefore, in Figure 3, there are 5 levels of failure probability in the risk matrix ranging from “very low”, “low”, “moderate”, “high”, and “very high” failure probability represented by the green, light green, yellow, orange, brown, and red color, respectively. Then, different maintenance strategies can be identified as presented in Table 6. Then, with this information, the utility can effectively plan an appropriate maintenance action, such as a short-term repair, planned renovation, or refurbishment. Moreover, an urgent risk can be determined by normalizing as %D and classified into 3 zones as shown in Table 7.

Table 6. Failure probability zone and recommended maintenance action in the risk matrix.

Zone	Definition	Maintenance Strategy
VL	very low	time based maintenance, monthly visual inspection, annually full test
L1	low1	refurbishment on minor defect, eliminate/ restrict root cause
L2	low2	renovation/modifying some sub-components
M1	moderate1	corrective maintenance within 15 days
M2	moderate2	load management, upgrade plan
M12	moderate12	determine the most benefit alternative whether to repair or relocation
H1	high1	de-energizing, corrective maintenance within 7 days
H2	high2	relocation planning
VH	very high	de-energizing, replacement

Table 7. D-Distance factor for failure probability assessment and maintenance actions.

%D Factor	Normal	Moderate	Urgent
%D (%)	<32.00	32.00–61.50	>61.50
maintenance task	normal maintenance	preventive maintenance should be planned	high priority needs executing within 7 days to prevent the failure of equipment

3. Results and Discussions

After the evaluation procedure for the 115 kV HVCB was established, the detailed calculation of the %CI, %RI, and %D was determined and implemented in the developed failure probability assessment program for the HV circuit breaker. It is presently used by a distribution system utility in Thailand to record the technical data of all 115 kV HVCBs installed in the electrical system as well as the testing and visual inspection results. First, the %CI and %RI were evaluated by applying the WSM and AHP technique, and then, the results were further used to calculate the %D. Consequently, the failure probability can be determined, and the proper maintenance tasks can be suggested. All technical and maintenance data as well as maintenance costs are systematically recorded in a central database. Hence, the actual technical and testing data of the HVCB can be quickly retrieved from the database and further used in the analysis. With the developed software program, the evaluation results can be quickly performed and shown in this section. To illustrate the proposed method and evaluation process, pilot 115 HVCB#2 was selected as an example. In Table 8, the condition index of HVCB#2 was determined by starting from the raw data of the visual inspection and test results in the second column.

Table 8. Condition index determination of HVCB#2 by using its actual data and test results.

	Items	Raw Data	S_i	%Wi	$S_i \times \%Wi$	%CI
Group of Test Results						50.00%
1	insulation resistance	5 GΩ	5	10	5×10	
2	contact resistance	34 μΩ	0	10	0×10	
3	contact timing deviation	6.96%	0	10	0×10	
4	SF6 pressure	5.20 barg.	5	10	5×10	
5	SF6 dewpoint	0 C	5	10	5×10	
6	SF6 percentage	100%	0	10	0×10	
7	SF6 purity	100%	0	10	0×10	
8	amount of SO2	20% ppm	5	10	5×10	
9	gas leakage rate	5 time/yr	0	10	0×10	
Visual Inspection						
a	undamaged	Normal	0			
b	cleansing	Normal	0			
c	connector fastening	Normal	0			
d	thermo scan check	Normal	0			
					$S_i, worst \times \%Wi$ $= 5 \times 10$	

Table 8. Cont.

	Items	Raw Data	S_i	$\%W_i$	$S_i \times \%W_i$	$\%CI$
e	counter	Abnormal	5	10		
f	functional operating	Normal	0			
g	mechanism operating	Normal	0			
h	drive mech. lubricant	Normal	0			
i	rusty condition	Normal	0			
j	foundation condition	Normal	0			
k	annunciator operation	Normal	0			
l	interlocking system	Normal	0			
m	hi-pot test	Normal	0			
n	vacuum test	Normal	0			
o	spout test check	Normal	0			

In Table 8, this raw data is transformed to the numerical scoring value by using the criteria determined in Table 2. With the weighting–scoring method, the $\%CI$ of HVCB#2 is 50%, which is an acceptable condition due to the minor problems regarding insulation resistance, SF6 quality, and abnormal operating counter found from the visual inspection. In Table 9, the renovation index of HVCB#2 was determined by starting from the raw data in the third column. Then, this raw data is transformed to the numerical scoring value by using the criteria determined in Table 4. With the weighting–scoring method, the $\%RI$ of HVCB#2 is 30.36%, which is a medium-term renovation requirement due to the increasing problems regarding age, number of fault current interruptions, lack of spare parts, maintenance expertise, and after-sale quality. Finally, the D-distance factor of this HVCB can be determined as 40.18%, which is a moderate-failure probability as shown in Table 10.

Table 9. Renovation index determination of HVCB#2 by using actual data and test results.

	Raw Data		$\%W_i$	$\%S_i$	$\%S_i, Worst$	$\%W_i \times \%S_i, Worst$	$\%RI$
1	overall age	17 yr.		3			
2	age of interrupter	17 yr.	30.6	0	3	18.36%	
3	age of mechanism after overhaul	17 yr.		3			
4	no. of fault interruptions	5 time		3			
5	load to rated current ratio	0%	21.2	0	0	0.00%	
6	Short circuit current to rated current ratio	24.20%		0			
7	already replaced by advanced technology	no	8.2	0	0	0.00%	30.36%
8	no longer manufactured	no		0			
9	spare part availability	difficult to find		3			
10	man, expertise level	moderate	20.0	3	3	12.00%	
11	OEM/after sale quality	moderate		3			
12	orphan (installed unit)	63		0			
13	model's failure rate	satisfied	20.0	0	0	0.00%	

Table 10. D-distance calculation of HVCB#2 by using the evaluated $\%CI$ and $\%RI$.

Index	$\%CI$	$\%RI$	$\sin\theta_1$	$\sin\theta_2$	$\%CI_{max}$	$\%RI_{max}$	$\%D$
calculated value	50%	30.36%	0.707	0.707	100%	100%	40.18%

To facilitate such tedious work, the proposed method has been further developed by using the Microsoft Excel program with a Visual Basic Application for automatic data retrieval from the database and evaluation as shown in Figure 4. The criteria for scoring and weighting values can be set in the Excel sheet. To quickly recognize the abnormal results

from testing and inspection results or raw data exceeding the pre-determined criteria, the traffic light color is set as orange or red to provide a pre-warning or alert actuation to the users, respectively. From the developed program, similar results for the %CI and %RI can be obtained as shown in Figure 4.

CONDITION INDEX										
Criteria	Comissioning Value	Standard Recommendation			Test Date DD / MM / YYYY	Test Result	Score	Weight	Condition Index	
		0	3	5					Average	
Insulation Resistance (Resistance, GΩ)		>= 10	-	< 10	30 / 01 / 2015	5.0000		5	10	10.0000
Contact Timing (Comissioning Deviation, %)	Close 30 ms Open 24 ms 23 ms	<= 10	-	> 10	23 / 04 / 2016	0.0870		0	10	0.0000
Contact Resistance (Times)	Contact Resistance 39 GΩ	<= 40	-	> 40	29 / 07 / 2008	33.0000		0	10	0.0000
SF6 Pressure		> 6	6 - 6	< 6	30 / 01 / 2015	5.0000		5	10	10.0000
SF6 Dew Point (Tempepature, °C)		<= -10	-	> -10	30 / 01 / 2015	0.0000		5	10	10.0000
SF6 Percentage (Amount of SF6, %)		>= 80	-	< 80	30 / 01 / 2015	100.0000		0	10	0.0000
SF6 Purity (%)		>= 99	-	< 99	30 / 01 / 2015	100.0000		0	10	0.0000
Amount of SO2 (ppm)		<= 10	-	> 10	30 / 01 / 2015	20.0000		5	10	10.0000
Visual Inspection		Normal	-	Abnormal	30 / 01 / 2015	Abnormal		5	10	10.0000
Gas Leakage Rate (times/year)		<= 5	-	> 5	30 / 01 / 2015	5		0	10	0.0000
Summary								100.0000	50.0000	

RENOVATION INDEX										
Criteria	Comissioning Value	Standard Recommendation			Test Date	Test Result	Score	Weight	Renovation Index	
		0	3	5					Average	
Overall Age (25 Years)	-	< 11	11 - 24	> 24	-	16		3	30.6000	18.3600
Age of Interrupter (24 Years)	-	< 23	23 - 24	> 24	-	16		0		
Age of Mechanism after Overhaul (12 Years)	-	< 11	11 - 24	> 24	-	16		3		
Number of Fault Current Interruption	-	< 5	5 - 8	> 8	-	0		0		
Ratio of Load Current to Rated	-	< 60	60 - 80	> 80	-	0.0000		0	21.2000	0.0000
Ratio of Short Curcuit Current to Rated	-	< 60	60 - 80	> 80	-	24.1975		0		
Already Replaced by Advanced Technology	No	No		Yes	-	No		0	8.2000	0.0000
No Longer Manufactured	No	No		Yes	-	No		0		
Spare Parts Availability	Difficult to find, Possible to modify	Easy to find	Difficult to find, Possible to modify	Unable to modify	-	Difficult to find, Possible to modify		3	20.0000	12.0000
Personnel Expertise Level	Moderate	Good	Moderate	Poor	-	Moderate		3		
OEM Support/ After sale service quality	Moderate	Good	Moderate	Poor	-	Moderate		3		
Orphan (< 5 Units left in system)	-	>= 5	-	< 5	-	63		0		
Operator Level of Satisfaction (Failure Rate)	Satisfied	Satisfied	-	Not satisfied	-	Satisfied		0		
Major/Minor Failure, Cost and Effort to Repair	-	Minor defect	-	Major defect	-	Minor defect		0	20.0000	0.0000
Summary								100.0000	30.3600	

Figure 4. Example of the developed software for evaluating the condition and renovation index with the weighting–scoring technique.

Subsequently, twenty of the existing 115 kV HVCBs installed in several substations in a distribution utility were analyzed with this method using the developed software. The actual HVCB data required for the %CI and %RI assessments are collected and presented in Tables 11 and 12. Similarly, with HVCB#2 in the above example, the actual test data and physical condition of the component's degradation, shown in Tables 11 and 12, are transformed into the numerical scores by using the criteria mentioned in Tables 2 and 4. The raw score and evaluation results of the %CI, %RI, and %D of the twenty 115 kV HV circuit breakers are presented in Table 13.

Table 11. Technical specification, test result, and operation information of twenty 115 kV HV circuit breakers.

No	Details	Unit	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
General Information																						
1	energized date		1/1/14	23/5/04	1/1/09	11/13/97	27/3/94	27/3/94	19/6/98	19/6/98	1/5/87	1/5/87	3/9/97	3/9/97	26/12/01	6/10/94	6/10/94	4/11/05	4/11/98	1/5/97	1/5/97	26/10/93
2	age	yrs.	8	17	13	24	27	27	23	23	34	34	24	24	20	27	27	16	23	24	24	28
3	manufacturing year		2014	2002	2009	1996	1999	1993	2004	2004	1982	1982	1995	1995	1997	2000	1993	2005	1997	1994	1994	1990
4	rated kV	kV	145	145	145	145	123	145	145	145	121	121	145	145	123	145	123	145	145	145	145	145
5	system kV	kV	115	115	115	115	115	115	115	115	115	115	115	115	115	115	115	115	115	115	115	115
6	BIL	kV	650	650	650 + 70	650	550	650	650	650	550	550	650	650	550	650	550	650	650	650	650	650
7	power freq. voltage	kV	275	275	275 + 70	230	230	275	275	275	-	-	275	275	230	275	230	275	275	275	275	275
8	Irated	A	3150	2500	3150	3150	2000	3150	3150	3150	2000	2000	3150	3150	2000	3150	2000	3150	3150	3150	3150	2000
9	kA rated interrupt	kA	40	40	40	31.50	31.50	40	40	40	31.50	31.50	31.50	31.50	40	31.50	40	40	31.50	40	40	31.50
10	S/C withstand duration	s	4	3	1	3	3	3	3	3	3	3	3	3	3	3	1	3	3	3	3	3
11	rated freq.	Hz	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50
12	no. of faults interruption	time	0	5	4	3	0	0	0	0	0	0	3	5	3	6	7	3	5	5	6	5
13	defect level		minor defect																			
Test Results																						
1	insulation resistance	GΩ	5	5	3.84	7.25	5.40	5	6.80	7.80	6.20	6.15	6.98	6.88	4.99	8.80	5.31	5	7.55	7.41	7.66	4.89
2	contact resistance	μΩ	34	32.67	33.22	33.34	23.40	34.15	33.38	33.41	35.40	35.30	33.28	33.50	32.87	33.80	24.10	31.88	33.45	33.53	33.66	34.22
3	contact timing deviation	%	2.33	6.96	3.25	0.00	16.35	6.79	3.16	6.57	1.37	2.21	3.19	3.95	10.38	5.30	1.62	5.41	4.24	8.30	8.89	8.38
4	SF6 pressure	barg.	5.20	5.14	5.50	6.80	6.02	5.25	6.73	6.68	5.67	5.67	6.80	6.75	5.04	6.83	6.47	6.48	6.63	6.80	6.77	5.10
5	SF6 dewpoint	C	0	0	−21.40	−21.40	−18.80	−21.40	−43.90	−48	−16.70	−15.60	−42	−46	−19.20	−47	−20.10	−18.10	−45	−41	−52.20	−18.30
6	SF6 percentage	%	100%	100%	99.10%	99.10%	99%	99%	99.20%	99%	99.20%	99%	99.10%	99.20%	99%	99%	99.10%	99.20%	99.20%	99.10%	99%	99%
7	SF6 purity	%	100%	100%	99.20%	99.10%	99.30%	99%	99.10%	99.10%	99.10%	99.20%	99.20%	99.20%	99.10%	99.10%	99.10%	99%	99%	99%	99.10%	99.10%
8	amount of SO2	ppm	20%	20%	19.50%	19.90%	19.80%	19.80%	19.80%	20.30%	20.10%	20.50%	20.50%	20.70%	19.90%	19.80%	19.90%	20.10%	20%	20%	20.30%	20%
9	gas leakage rate	time/yr	0	5	4	3	0	0	0	0	0	0	3	5	3	6	7	3	5	5	6	5
Operation Information																						
1	overall age	yr.	8	17	13	24	27	27	23	23	34	34	24	24	20	27	27	16	23	24	24	28
2	age of interrupter	yr.	8	17	13	24	27	27	23	23	34	34	24	24	20	27	27	16	23	24	24	28
3	age of mechanism after overhaul	yr.	8	17	13	24	27	27	23	23	34	34	24	24	20	27	27	16	23	24	24	28
4	no. of fault interruption	time	0	5	4	3	0	0	0	0	0	0	3	5	3	6	7	3	5	5	6	5

Table 11. Cont.

No	Details	Unit	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20				
5	load to rated current ratio	%	5.45%	0%	15.35%	0%	27.57%	0%	20.55%	20.55%	37.87%	0%	7.64%	0%	0%	13.07%	0%	44.23%	0%	53.37%	0%	0%				
6	SC to rated current ratio	%	24.20%	24.20%	15.18%	19.27%	93.08%	73.30%	60.42%	60.42%	25.10%	25.10%	13.61%	30.73%	22.18%	91.88%	72.36%	38.51%	48.90%	21.83%	21.83%	23.35%				
7	already replaced by advanced technology		no	no	no	yes	no	no	no	no	yes	yes	yes	yes	yes	no	yes	no	yes	yes	yes	yes				
8	no longer manufactured		no	no	no	yes	no	no	no	no	yes	yes	yes	yes	yes	no	yes	no	yes	yes	yes	yes				
9	spare part availability		difficult to find		easy to find		difficult to find		easy to find		unable to modify		easy to find		unable to modify		easy to find		unable to modify		easy to find					
10	man expertise level		moderate				poor		moderate		good				moderate			good		poor		poor				
11	OEM/after sale quality		moderate								good				moderate				good				moderate			
12	orphan (installed unit)	unit	63	63	12	49	4	5	49	49	3	3	49	49	7	49	20	16	49	49	49	3				
13	model's failure rate		satisfied																							

Table 12. Practical visual inspection results of twenty 115 kV HV circuit breakers.

No.	DetailsVisual Inspection	Unit																			
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
a	undamaged											Normal									
b	cleansing											Normal									
c	connector fastening											Normal									
d	thermo scan check											Normal									
e	counter	Normal		Abnormal						Normal							Abnormal				
f	functional operating											Normal									
g	mechanism operating											Normal									
h	drive mech. lubricant											Normal									
i	rusty condition											Normal									
j	foundation condition											Normal									
k	annunciator operation											Normal									
l	interlocking system											Normal									
m	hi-pot test											Normal									
n	vacuum test											Normal									
o	spout test check											Normal									

Note: Normal, Score = 0; Abnormal, Score = 5.

Table 13. Scores and evaluation results of the %CI, %RI, and D-distance of twenty 115 kV HV circuit breakers.

No.	Detail	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Test Result		Score																			
1	insulation resistance	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
2	contact resistance	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	contact timing	0	0	0	0	5	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0
4	SF6 pressure	5	5	5	0	0	5	0	0	5	5	0	0	5	0	0	0	0	0	0	5
5	SF6 dewpoint	5	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	SF6 percentage	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	SF6 purity	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	amount of SO2	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
9	gas leakage rate	0	0	0	0	0	0	0	0	0	0	0	0	0	5	5	0	0	0	5	0
10	visual inspection	0	5	5	5	0	0	0	0	0	0	5	5	5	5	5	5	5	5	5	5
Condition Index (%CI)		40.00%	50.00%	40.00%	30.00%	30.00%	30.00%	20.00%	20.00%	30.00%	30.00%	30.00%	30.00%	50.00%	40.00%	40.00%	30.00%	30.00%	30.00%	40.00%	40.00%
Operation Information																					
1	overall age	0	3	3	3	5	5	3	3	5	5	3	3	3	5	5	3	3	3	3	5
2	age of interrupter	0	0	0	3	5	5	3	3	5	5	3	3	0	5	5	0	3	3	3	5
3	age of mechanism after overhaul	0	3	3	3	5	5	3	3	5	5	3	3	3	5	5	3	3	3	3	5
4	no. of fault interruption	0	3	0	0	0	0	0	0	0	0	0	3	0	3	3	0	3	3	3	3
5	load to rated current ratio	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	SC to rated current ratio	0	0	0	0	5	5	5	5	0	0	0	3	0	5	5	3	3	0	0	0
7	already replaced by advanced tech.	0	0	0	5	5	0	0	0	5	5	5	5	5	0	5	0	5	5	5	5
8	no longer manufactured	0	0	0	5	5	0	0	0	5	5	5	5	5	0	5	0	5	5	5	5
9	spare part availability	3	3	3	5	5	3	5	5	5	5	5	5	5	5	5	5	5	5	5	5
10	man expertise level	3	3	3	3	5	3	0	0	3	3	3	3	3	0	5	5	3	3	3	3
11	OEM/after sale quality	3	3	3	3	3	3	0	0	3	3	3	3	3	0	3	3	3	3	3	3
12	orphan (installed unit)	0	0	0	0	5	0	0	0	5	5	0	0	0	0	0	0	0	0	0	5
13	model's failure rate	0	0	0	0	5	5	0	0	5	5	0	0	0	5	5	0	0	0	0	5
Renovation Index (%RI)		12.00%	30.36%	30.36%	46.56%	100.00%	83.80%	59.56%	59.56%	78.80%	78.80%	46.56%	59.28%	46.56%	91.80%	100.00%	51.08%	59.28%	46.56%	46.56%	78.80%
%D		26.00	40.18	35.18	38.28	65.00	56.90	39.78	39.78	54.40	54.40	38.28	44.64	48.28	65.90	70.00	40.54	44.64	38.28	43.28	59.40

To make it better for result understanding and easier to interpret the failure probability assessment result, the risk matrix is employed, and the values of the %CI and %RI are plotted in the risk matrix as shown in Figure 5. Two HVCBs, HVCB#14 and HVCB#15, lie in the high-failure probability zone, while HVCB#1 lies in the low-failure probability zone. The other 17 HVCBs are in the moderate-failure probability zone. Moreover, when considering the %RI, it is found that seventeen HVCBs need urgent renovation action as their ages are approaching the end of life. However, HVCB#16 with 16 years in operation is also in the urgent renovation requirement zone due to a lack of spare parts and maintenance expertise. Two HVCBs need medium-term renovation action with the ages of 13 and 17 years in service, while only HVCB#1 needs long-term renovation action because it is only 8 years in service. Regarding the condition index, eighteen HVCBs are in good condition, but two HVCBs are in moderate condition, HVCB#2 and HVCB#13, because of the problems regarding insulation resistance, SF6 quality, and abnormal items found by the visual inspection. With the above results, the maintenance tasks of thousands of HVCBs in the grid can be easily prioritized with the known causes. This could effectively improve the performance of HVCB maintenance with less cost and effort.

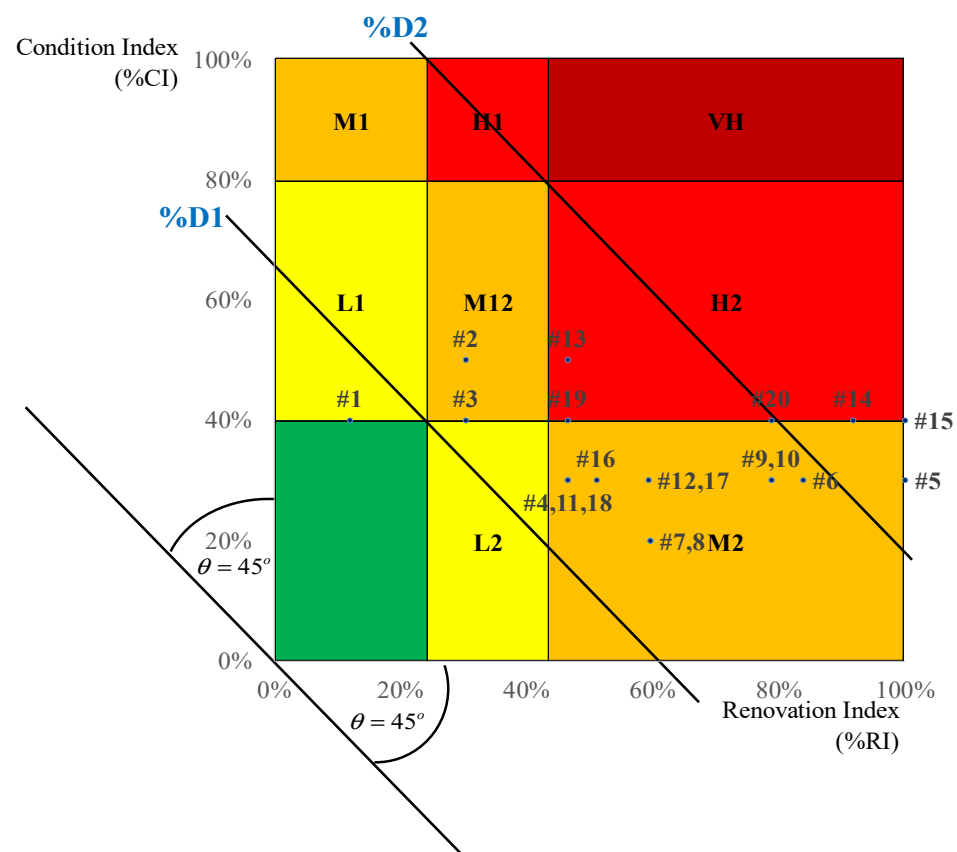


Figure 5. Failure probability evaluation of twenty 115 kV HVCBs using the risk matrix.

4. Conclusions

In the distribution system of a utility in Thailand, there are more than three hundred substations and more than one thousand five hundred units of active HV circuit breakers. With the limitations of manpower, material in terms of spare part availability and testing devices, as well as annual budget, the action maintenance plan needs to be designed appropriately to manage the limited resources effectively. The proposed failure probability determined from the risk matrix is an effective tool to facilitate the effective allocation of limited resources to the most urgent HV circuit breakers. The pilot circuit breakers of twenty units with diverse ages and conditions selected from various substation were applied with

the proposed failure probability model using the percentage condition index and renovation index plotted in the risk matrix. To obtain the condition index and renovation index, the weighting and scoring method as well as the analytical hierarchy process were applied based on both the recommendations in the international standards and practical expertise from operation and maintenance departments. To gain reliable and consistent results, the practical program was developed in the Microsoft Excel program as a database and Visual Basic Application as the programming module. The developed program was used to analyze the condition index, renovation index, and failure probability of twenty high-voltage circuit breakers and, subsequently, to adjust the sensitivity of the assigned score and weight values with the satisfactory result. The result shows eight HVCBs are in moderate condition, while 12 of them are in good condition. Therefore, the condition of the HVCBs is quite satisfactory due to the applied preventive maintenance measures. However, 17 of them have high renovation requirements, which requires careful consideration whether to replace or relocate. According to the obtained failure probability, two HVCBs require the most urgent action because they are in a high-failure probability zone with a high %*RI*, which means that they should be replaced or at least relocated urgently. Therefore, with the known %*CI*, %*RI*, and failure probability, the appropriate maintenance strategy can be effectively planned and managed to achieve better asset management and to improve the reliability of the electrical system.

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