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Condition Assessment of Medium Voltage Gas Insulated Ring Main Unit Using Health Index

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Abstract

This paper presents a study on the formulation of a Health Index (HI) to assess the condition of gas-insulated Ring Main Units (RMUs). A total of 250 condition monitoring records for 11 kV distribution Ring Main Units (RMUs), aged between 1 and 27 years, were obtained from a Malaysian utility operator, with the sample randomly selected from a central region state that has the highest concentration of RMU assets in the country. The development of the HI algorithm was based on scoring, weighting, and ranking techniques. In addition to the HI, a risk factor was introduced to enhance the accuracy of the final HI estimation. Condition monitoring (CM) data were gathered using condition-based monitoring (CBM) techniques such as thermal scanning, ultrasonic testing, transient earth voltage measurement, SF_6 gas level monitoring, and visual inspection. The ranking, weighting, and scoring for each parameter were determined based on expert assessments, utility practices, and relevant standards. The risk factor was established by considering environmental conditions, Original Equipment Manufacturer (OEM) data, and the risk of ageing mechanisms. Subsequently, the final HI for each CM data set was calculated. The findings showed that the HI approach can effectively be used to assess the condition of RMUs based on CM data. A statistical analysis of the 250 RMU records revealed that 44% of RMUs have a high HI, 51% have a medium HI, and 6% have a low HI. This indicates that the maintenance cycle for 44% of the RMUs can potentially be extended. The results are expected to support the development of optimized maintenance planning and cost management strategies.

Keywords

Health Index, Gas-Insulated Ring Main Unit, Condition Monitoring, Risk

Factor, Condition Assessment

1. Introduction

Switchgear is essential to the distribution of electricity to consumers as it protects, controls, and isolates power systems based on voltage levels. Most medium voltage switchgear, or Ring Main Units (RMUs), are widely deployed, and their performance has a significant impact on the quality of electricity supply to customers [1]. As of 2022, an estimated 87,947 distribution substations with various types of switchgear for 11 kV to 33 kV distribution networks were installed and operational in Malaysia [2]. Failures in switchgear, particularly in the operating mechanism or insulation, are common issues [3]. These failures lead to increased costs related to the replacement of switchgear, substation renovation, disassembly, testing, recommissioning, and other associated tasks. Condition-Based Monitoring (CBM), which monitors parameters such as thermal activity and partial discharge, has become a common practice among utilities for early detection of failure onset, helping to minimize the risk of flashover [4]. Switchgear failures generally fall into two main categories: insulation failure and operating mechanism failure [5]. Consequently, based on Malaysian utility practices, CBM is routinely conducted. However, the CBM data for each switchgear unit is currently analyzed conventionally by Malaysian utilities. As the number of switchgear units continues to grow, maintenance engineers face increasing challenges in analyzing reports and prioritizing urgent maintenance actions. To assess the condition of RMUs, Health Index (HI) methodologies previously applied to other critical electrical assets such as transformers are now being considered. This research focuses on distribution medium voltage switchgear by leveraging the CBM data currently available from the Malaysian power utility.

2. The Ring Main Unit (RMU)

A common box, mechanical key interlocking, internal arc pressure release, cable voltage test interface, outdoor box size, and regional variations are among the criteria for an IEC standard ring network cabinet [6]. Although RMUs are designed to be maintenance-free, as stated in [7] [8], they can deteriorate over time due to operations, environmental conditions, temperature fluctuations, and other factors. The largest configuration of a simplified RMU structure consists of two fuse switch (S) ways and three ring feeder (F) ways (3S + 2F). **Table 1** summarizes the design types of RMUs installed in 11 kV systems. These include several panel configurations within a single unit, such as 2S + 1F, 2S + 2F, 3S, 3S + 1F, and 3S + 2F. Each panel typically consists of four main compartments: a cable compartment for cable termination, an SF_6 gas tank for the busbar compartment, an operating mechanism and indicator section, and a fuse compartment for the transformer feeder.

Table 1. RMU design and numbers of panel.

Configuration	Numbers of RMU panel
	Number
2S + 1F	3 (2 ring + 1 transformer feeder)
2S + 2F	4 (2 ring + 2 transformer feeder)
3S	3 (3 ring FEEDER)
3S + 1F	4 (3 ring + 1 transformer feeder)
3S + 2F	5 (3 ring + 2 transformer feeder)

The condition assessment of electrical assets involves evaluating manufacturer recommendations, international standards, trend analysis, and similar component models, often relying on expert judgment and long-term data analysis [9]. Researchers have developed systematic procedures for assessing the condition of major switchgear and transformers by employing structured condition-based maintenance and Asset-Based Risk Management to guide maintenance decisions [10]. For example, a study in [11] proposed using weighting and scoring methodologies to evaluate the condition of Gas-Insulated Substation (GIS) equipment for 115 kV systems. In 2022, researchers introduced the Fuzzy Analytic Hierarchy Process (FAHP) to assess the health status of Gas-Insulated Switchgear (GIS), incorporating Failure Mode and Effects Analysis (FMEA) for component-level health evaluation [12]. For medium voltage switchgear, a method utilizing Dempster-Shafer multi-evidence fusion for health assessment was proposed, integrating subsystem indicators into a single HI, and tested on 12 kV and 35 kV switchgears [13].

Additionally, a dynamic condition assessment system for substation equipment using an Asset Performance Management System (APMS) has been introduced [14]. This system includes equipment sensors, a data pipeline, intelligent models, and a human-machine interface. In 2022, researchers also proposed a weighting and scoring method to enhance the accuracy of HI assessments in GIS, which was tested on 175 GIS bays in Thailand using a web-based software tool [15]. Traditionally, Time-Based Maintenance has been used for RMU maintenance and repair [16], but advancements in CBM now offer more effective solutions for switchgear asset management. However, manual analysis and prioritization of CBM data using key condition parameters such as thermography, ultrasound, and internal partial discharge have proven to be ineffective for managing the large volume of RMU monitoring data [17]-[19].

This study aims to develop a condition assessment framework for 11 kV RMUs in Malaysia using a scoring and weighting methodology. The framework encompasses field condition monitoring, scoring, weight determination, HI calculation, and maintenance decision-making. Common CBM techniques employed by the utility include ultrasound, internal partial discharge (TEV), thermal scanning, visual inspection, and SF_6 gas level monitoring [20]-[22]. CBM data from the Malaysian power company will be analyzed to identify early failure indicators and develop mitigation strategies.

The study will also develop an HI algorithm, integrating regular visual inspections and CBM into the condition assessment process [23]. Annual visual examinations and condition-based monitoring help ensure the RMU's operational reliability, with data migrating from hardcopy records to a centralized database to support long-term operational planning [24].

3. Condition Assessment and Maintenance of RMU

Electrical utilities commonly employ three maintenance strategies: Time-Based Maintenance (TBM), Condition-Based Maintenance (CBM), and Predictive Maintenance (PM). TBM involves performing scheduled preventive tasks at fixed intervals, regardless of equipment condition. In contrast, CBM monitors the operational state of assets and provides alerts when deviations from normal conditions are detected. PM further enhances this approach by utilizing sensor data and analytical tools to evaluate asset performance, enabling dynamic thresholding and early fault prediction [25]. This study emphasizes the implementation of CBM in switchgear maintenance, with a particular focus on the standard practices and acceptance criteria adopted by the Malaysian power utility. Notably, no standardized methodology currently exists for this complex assessment process, highlighting the need for a structured and data-driven approach.

3.1. Thermal Monitoring

Power connections in medium voltage equipment, particularly within substations, are critical to ensuring reliable system operation. However, assessing the quality of on-site joints remains challenging due to limited testing equipment and restricted visibility of contact points. Defective connections may lead to elevated temperatures, increasing the risk of insulation degradation and equipment failure. Thermal monitoring is a vital diagnostic tool for identifying faulty joints, and recent technological advancements now enable real-time monitoring of all critical contacts in medium voltage switchgear [26]. In the Malaysian power utility context, thermal monitoring acceptance thresholds are customized to suit the country's tropical climate. **Table 2** presents the acceptance criteria for thermal monitoring currently adopted by the Malaysian power utility.

Table 2. Thermal monitoring acceptance criteria.

Features	Thermal scanning activity Acceptance Criteria	
Function	To check if there is any thermal activity due to loose contact or any high resistance surface between any electrical contact	
Interval	12 months	
Acceptance criteria	**ΔT**	**Condition**
	0	Good
	1˚C - 5˚C	Fair
	>5˚C	Poor

Thermal monitoring of switchgear is typically conducted on an annual basis (every 12 months), using three-tiered acceptance criteria: a temperature rise of 0˚C indicates a good condition, 1˚C - 5˚C signifies a fair condition, and a rise exceeding 5˚C is classified as poor. Maintenance decisions are guided by these annual records, with equipment in poor condition requiring immediate corrective action.

3.2. Surface Partial Discharge Monitoring

Partial discharge (PD) in medium voltage (MV) switchgear arises from dielectric breakdown, where electrical stress becomes concentrated within the insulating medium. Early detection and accurate localization are critical to preventing insulation failure. PD can generally be categorized into three types: tracking, arcing, and corona discharge. Ultrasonic waves generated by PD can propagate through air vents and panel openings, enabling external detection and analysis for timely intervention [27]. **Table 3** presents the surface partial discharge acceptance criteria adopted by the Malaysian power utility.

Table 3. Surface partial discharge acceptance criteria.

Features	Surface partial discharge scanning activity	
	Acceptance criteria	
Function	To check if there is any external/surface—partial discharge	
Interval	12 months	
Acceptance criteria	**dB**	**Condition**
	<0 dB—no sound	Good
	≥1 dB—arcing, tracking	Fair
	≥4 dB—corona	Poor

The monitoring interval for surface partial discharge is set at 12 months. The condition is classified based on sound intensity: values below 0 dB indicate no detectable discharge (good condition), values of 1 dB or more suggest arcing or tracking (fair condition), and readings of 4 dB or higher indicate corona discharge (poor condition). Equipment identified in poor condition requires immediate maintenance action.

3.3. Internal Partial Discharge (TEV)

Transient Earth Voltage (TEV) is induced on earthed metal cladding during partial discharge events, radiating outward and manifesting on the external surfaces of switchgear. The amplitude of TeV typically ranges from millivolts to several volts [28]-[30]. TEV pulses, which result from current spikes caused by partial discharges between conductors and earthed metal components, can be easily detected without the need to remove panels or make direct electrical connections. These measurements provide a valuable indication of potential insulation failure.

The Malaysian power utility categorizes TEV levels based on standardized acceptance criteria, as shown in **Table 4**.

Table 4. TEV category and acceptance criteria.

Features	TEV scanning activity Acceptance criteria	
Function	To check if there is any internal partial discharge	
Interval	12 months	
Acceptance criteria	**dB**	**Condition**
	<20 dB	Normal
	20 ≤ dB ≤ 28	Moderate
	≥29 dB	Caution

Under current utility practices in Malaysia, TEV monitoring is conducted annually. Readings below 20 dB are considered normal, while values ranging from 20 dB to 28 dB indicate moderate condition and require increased monitoring at three-month intervals. TEV levels exceeding 29 dB are classified as cautionary and warrant immediate investigation to prevent potential equipment failure.

3.4. Visual Inspection

Visual inspection is a routine technique used for data acquisition, condition analysis, and quality control in facility maintenance. It is typically conducted alongside other CBM activities. This method involves a general examination of the switchgear to identify any visible signs of damage or abnormality. The visual inspection process employed by the Malaysian power utility is summarized in **Table 5**.

Table 5. Summary of visual inspection activities.

Features	Visual inspection activity Acceptance criteria
Function	Check any defected of the switchgear
Interval	12 months
Acceptance criteria	• Audit of the substation • Verification of switchgear external condition • DC power supply • Safety equipment and signage • Switchgear accessories

4. Development Health Index (HI) for RMU

The condition of RMUs is assessed using a scoring and weighting system. Each weight reflects the relative importance of a component that contributes to potential failure, while the score represents the performance level of each defined attribute. The result is a single weighted score that quantifies the overall condition of each component or compartment.

4.1. Visual Inspection

To develop a systematic approach for data collection and analysis, results from available CBM techniques were reviewed. A spreadsheet was created to consolidate key information from CBM data for each substation, supporting further analysis and maintenance decision-making. CBM data, previously recorded in hardcopy reports for each critical RMU compartment, were transferred to the spreadsheet for integration. The condition evaluation methods are categorized into five groups, as summarized in **Table 6**.

Table 6. Test method and assessment group.

Group	Compartment and test method	
	Compartment	Test method
1	Mechanisme compartment	Aged of the RMU, thermography, airborne ultrasonic, TEV
2	Fuse compartment	Thermography, airborne ultrasonic, TEV, cable type
3	Cable compartment	Thermography, airborne ultrasonic, TEV, cable type
4	Tank/Busbar compartment	Thermography, airborne ultrasonic, TEV, gas level
5	General visual inspection	Overall condition of RMU (good, moderate, poor)

4.2. Scoring and Weightage Determination for Testing and CBM Parameters

The second phase of the assessment involves assigning scores to each CBM parameter for each compartment, using a scoring system based on methodologies previously applied to the evaluation of electrical assets such as power transformers [31]. The criteria are aligned with the acceptance limits defined in the utility's CBM manual and are categorized into three tiers: 5 points for excellent condition (exceeding acceptance standards), 3 points for acceptable condition (within the acceptable range), and 0 points for poor condition (below acceptance criteria). These scoring categories are consistent with those used in previous studies [9] [15] [32]. **Table 7** summarizes the scoring methodology.

Table 7. Scoring and evaluation criteria for RMU CBM assessment.

Test parameter	Scoring		
	Good (5)	Acceptable (3)	Poor (0)
Thermography	0˚C	1˚C - 5˚C	>5˚C
Airborne ultrasonic	<0 dB	0 - 1 dB	>1 dB
TEV	<20 dB	≤20 ≤ 28 dB	≥29 dB

Continued

Overall visual inspection	Good—no defect	Moderate—minor defect—not affected equipment	Poor—major defect—affected equipment
Cable type	XLPE	-	PILC
SF_6 gas level	Green zone—high level	-	Red zone—low level

To provide a quantitative assessment and better understanding of the HI calculation, the acceptance criteria for condition monitoring parameters were refined, and specific scoring values were assigned based on Malaysia Power Utility CBM practices [32] rather than relying on general acceptance criteria currently in use. Table 8 presents a comparison of the existing approval criteria and the proposed scoring technique for CBM parameters. The acceptance criteria for thermal monitoring, previously classified as Good, Fair, and Poor, were translated into score values of 5, 3, and 0, respectively. The surface partial discharge monitoring method uses a stringent grading system, with ultrasonic values ranging from 0 to 3 dB—poor conditions are assigned a score of 0, while acceptable conditions are assigned a score of 5. For internal partial discharge monitoring, Malaysia Power Utility defines three acceptance levels: typical (less than 20 dB), moderate (20 - 28 dB), and cautionary (29 dB or higher), which are scored accordingly. Visual inspection scoring is based on general inspection standards, categorized into three levels: good (5 points), moderate (3 points), and poor (0 points). Cable type also plays a critical role in RMU performance, as outdated PILC cables can negatively impact reliability. The SF_6 gas level is assessed as well, since low levels may pose operational and safety risks.

Condition monitoring parameters for RMUs are tracked to prevent failures by providing early warnings that support timely corrective actions. CBM monitoring methods can be organized according to each RMU compartment, along with their associated potential failure modes, as outlined in Table 8.

Table 8. CBM activities and parameter captured with possible failure mode.

Test parameter	Failure mode, severity and probability (High = 3, Medium = 2, Low = 1)			
	Possible Failure Mode	Severity, S_i	Probability, P_i	Risk score
Thermography	Flashover due to overheating	High (3)	High (3)	9
Airborne ultrasonic	Flashover due to partial discharge activity	High (3)	High (3)	9
Internal partial discharge (TEV)	Flashover due to internal partial discharge activity	High (3)	Medium (2)	6
Visual inspection	Mechanism failure due to condensation and component ageing.	High (3)	Low (1)	3

The significance of each CBM parameter is determined by its severity and the probability of failure. The weightage assigned to each CBM parameter for every RMU compartment is summarized in Table 9.

Table 9. Summary of weightage determination for CBM parameters for every RMU compartment.

RMU compartment	Weightage for CBM activity	
	CBM activity	Weightage
Cable compartment	Thermography	33%
	Airborne ultrasonic	33%
	TEV	22%
	Cable Type	12%
Tank/Busbar compartment	Thermography	33%
	Airborne ultrasonic	33%
	TEV	22%
	SF_6 gas level	12%
Mechanisme compartment	Thermography	33%
	Airborne ultrasonic	33%
	TEV	22%
	Age	12%
Fuse compartment	Thermography	33%
	Airborne ultrasonic	33%
	TEV	22%
	Cable type	12%

The weightage for each condition-based maintenance (CBM) parameter is derived from an empirical relationship between severity and probability of failure, based on the risk score as defined in Equation (1). The severity and probability values are determined through expert judgment and supported by actual failure records.

$$\text{Risk Score} = \text{Severity}(S_i) \times \text{Probability}(P_i) \tag{1}$$

The weightage for each CBM parameter can be expressed as Equation (2):

$$W_i = \left(\frac{S_i \times P_i}{\sum (S_i \times P_i)} \right) * 100\% \tag{2}$$

where, S_i is severity of the parameter i, P_i is probability of parameter i and the denominator represents the total risk score across all parameters in the compartment.

4.3. Weightage Determination for RMU Compartment

Data from the CBM reports were analyzed to identify the key and most frequently recorded parameters. The HI development concept is based on a weightage and scoring approach [11] [15] [31], where the criticality of each RMU component is expressed as a percentage in index form. An analysis of RMU failure records from

Malaysia Power Utility over a five-year period (2018-2022), involving 450 RMU units, revealed that most failures (79%) originated from issues within the cable compartment. The tank compartment accounted for the second-highest failure rate (14%), followed by the fuse compartment (4%) and the operating mechanism (3%). This analysis underscores the relative significance of each compartment and serves as the basis for assigning appropriate weightages. A summary of the RMU failure analysis for the 450 units is illustrated in Figure 1.

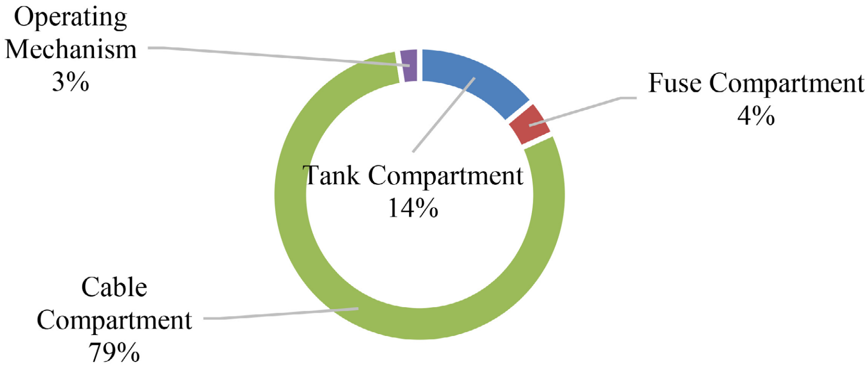

Figure 1. RMU failure analysis for 450-unit.

In addition to analyzing RMU compartment failures, a study was conducted to assess failure severity and to establish a correlation between the frequency of failures and their respective impacts. The reviewed data indicate that the cable compartment significantly contributes to high-impact failures, often resulting in flashovers and requiring the complete replacement of the RMU. A summary of the severity analysis is presented in Table 10.

Table 10. Summary of RMU compartment severity level.

Compartment	RMU compartment severity level	
	Failure mode	Severity level
Cable compartment	Flashover	High—lost of energy supply, total replacement
Tank/Busbar compartment	Flashover	High—lost of energy supply, total replacement
Mechanisme compartment	Mechanical operation	Medium—can be repaired, loss of energy supply
Fuse compartment	Flashover	High—lost of energy supply, total replacement

Based on the analysis, the compartmental weightages used in the HI calculation were established and are summarized in Table 11. These weightages were derived through a combination of statistical analysis of actual failure records, as illustrated in Figure 1, and expert judgment.

Table 11. Weightage for every compartment.

Compartment	Weightage for every compartment
	Weightage (%)
Cable compartment	79
Tank/Busbar compartment	14
Mechanisme compartment	3
Fuse compartment	4

4.4. HI Calculation

The HI calculation in this study utilized the weighted sum method, following techniques adopted in previous research [11] [15]. The approach for computing the RMU HI involves calculating a sub-HI for each sub-compartment within the RMU. Since the RMU consists of multiple compartments, the HI for each compartment group is determined using Equation (3).

$$\mathrm{HI}_{\text{compartment}} = \frac{\sum_{k=1}^{N} S_k \times W_k}{S_{\max,k} \times W_k} \tag{3}$$

where S_k represents the score based on the actual condition of the evaluation parameter for the sub-compartment, $S_{\max,k}$ is the maximum possible score for that respective parameter, W_k denotes the weight assigned to each measured parameter, and N is the total number of parameters measured for each compartment. The overall HI of the RMU is then calculated by summing the weighted HI of all sub-compartments, as shown in Equation (4).

$$\mathrm{HI}_{\text{RMU}} = \sum_{k=1}^{M} \left(\frac{\mathrm{HI}_{\text{compartment},k} \times \%W_k}{100} \right) \tag{4}$$

Here, $\%\mathrm{HI}_{\text{compartment},k}$ is the HI of each previously calculated compartment, $\%W_k$ denotes the weight assigned to each compartment, and M refers to the total number of compartments in the RMU. The number of sub-compartments within the RMU may vary depending on the configuration. For example, an RMU with a 3S + 2F configuration will have three cable compartments and two fuse compartments. In such cases, the lowest HI among the respective cable and fuse compartments is considered for the overall RMU HI calculation, based on the assumption that the lowest HI reflects the most critical condition and requires immediate attention.

5. Risk Factors (*RF*) and The Final Health Index (FHI)

The previous section detailed the calculation of the primary HI for the RMU. However, in real-world scenarios, additional factors must be considered when determining the overall condition of the RMU, including technical, economic, and conditional aspects where the weightage for risk element adopted from previous study [15]. To address this, a risk factor was introduced as a co-joint parameter in the Final HI calculation. This risk factor accounts for parameters such as equipment age, failure history, availability of spare parts, humidity levels, and environmental conditions. These parameters have been shown to significantly influence the RMU's condition, as noted by [33]-[35]. Incorporating these risk factors enhances the accuracy of the Final HI calculation, allowing for a more comprehensive and realistic condition assessment beyond CBM data alone. A similar weighting and scoring method are applied in evaluating the risk factors, with the relevant parameters outlined in **Table 12**.

Table 12. Weightage and scoring for Risk Factor (*RF*).

Risk Element	Weightage and scoring			
	Weightage (%)	Score (0)	Score (3)	Score (5)
Overall age—years of operation	30	≥30	21 - 29	≤20
Numbers of failure rate-based asset retirement record	20	>5%	2% - 5%	<2%
Existence of OEM support and spare part availability	20	No longer available	Difficult to find	Easy to find
Substation humidity level—leads to condensation inside the RMU	15	>60%	60% - 50%	<50%
Substation surrounding area	15	Near to chemical treatment plant	Near to coastal area	Normal environment

Table 13. Example of Risk Factor (*RF*) calculation.

Risk element	Example of *RF* calculation						
	Weightage (%) (A)	Maximum Risk score (B)	Maximum weighted score (A × B)	RMU risk assessment	Risk score (C)	Weighted score (A × C)	*RF* (0 to 1)
Overall age—years of operation	30%	5	1.5	15 years in operation	5	1.5	**0.8 (4/5)**
Numbers of failure rate-based asset retirement record	20%	5	1	3% failure rate	3	0.6	
Existence of OEM support and spare part availability	20%	5	1	OEM support still exists and easy to find	5	1	
Substation humidity level—leads to condensation inside the RMU	15%	5	0.75	55%	3	0.45	
Substation surrounding area	15%	5	0.75	Near to coastal area	3	0.45	
Total			**5**			**4**	

The calculated risk factor value is then used to adjust the initial RMU HI, incorporating the influence of external and unmonitored factors. The Risk Factor (*RF*) is computed using the equation shown in (5).

$$RF = \frac{\sum_{k=1}^{N}\left(S_{RF,k} \times W_{RF,k}\right)}{\sum_{k=1}^{N}\left(S_{RF,\max} \times W_{RF,k}\right)} \tag{5}$$

The *RF* represents the normalized risk score associated with a specific RMU unit. It is calculated based on a set of risk parameters using the following terms: $S_{RF,k}$ is the score for each individual risk parameter, $S_{RF,\max}$ is the maximum possible score for each risk parameter, $W_{RF,k}$ denotes the weightage assigned to each risk parameter, and N is the total number of risk parameters considered. The denominator in the RF calculation is based on the maximum total weighted score for the risk elements. Consequently, the RF value is bounded between 0 and 1, representing the level of deficiency in the HI based on the identified risk elements. An example of RF calculation is illustrated in **Table 13**.

FHI Calculation

The Final RMU Health Index (FHI) is calculated by combining the primary RMU HI with the RF, as shown in Equation (6).

$$\text{FHI}_{\text{RMU}} = \%\text{HI}_{\text{RMU}} \times RF \tag{6}$$

where $\%\text{FHI}_{\text{RMU}}$ represents the percentage-based final health index used for switchgear assessment, RF is the risk factor, and $\%\text{HI}_{\text{RMU}}$ is the percentage of the RMU's primary health index. The calculated $\%\text{FHI}_{\text{RMU}}$ is categorized into three condition groups *Good*, *Moderate*, and *Poor* using a traffic light indicator, as illustrated in **Table 14**. This indicator provides a clear representation of the overall condition of the RMU and enables maintenance engineers to quickly interpret the results and take appropriate action. The final HI serves as a valuable tool for prioritizing maintenance tasks and determining suitable maintenance strategies.

Table 14. Range of FHI classification and suggested action.

Health index	Classification of HI and action		
	Condition of HI	Action	Color
81 - 100	High	Extend maintenance cycle	Green
51 - 80	Medium	Normal maintenance cycle	Yellow
0 - 50	Low	Immediate repair	Red

The computed health indices were analyzed to provide overall insights into the 250 RMU units studied, focusing on the relationship between the impact of risk factors and the correlation between the health index and the age of the RMUs, as adopted from the previous study [36].

6. Results and Discussion

A total of 250 RMU units were analyzed based on their CBM reports from 2018 to 2022, covering a range of ages, brands, site conditions, and locations. The RMUs studied varied in age from 1 to 27 years in operation. The sample of 250 RMUs was randomly selected from a central region state in Malaysia, which holds the largest concentration of RMU assets compared to other states. The data analyzed spanned a broad range of operational lifespans, providing a comprehensive perspective and generalizability that helped establish the relationship between HI and the age of the RMUs. A summary of the analyzed RMUs is presented in **Figure 2**.

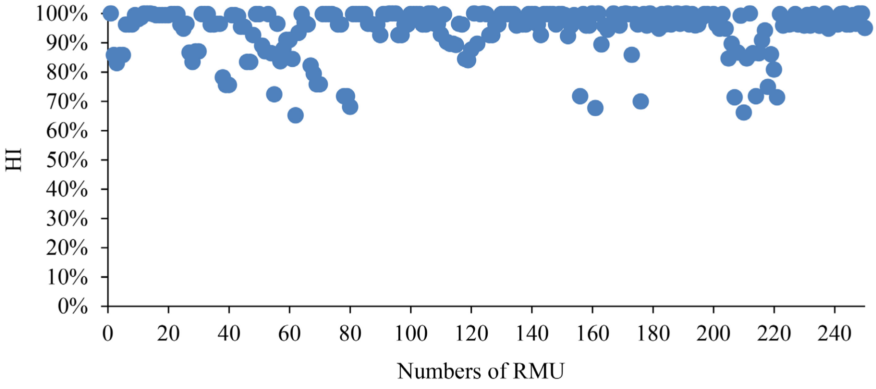

Figure 2. Total number of RMU with HI.

Out of the 250 RMU units analyzed, 231 units (92%) were found to have a high HI level of 80% to 100%, indicating they were in good condition. Meanwhile, 19 units (8%) fell within the medium HI range of 51% to 80%, and no RMUs were identified with an HI below 50%.

Further analysis was conducted to examine the impact of risk factors on RMU condition assessment. **Figure 3** presents a comparison between the initial HI (without risk factors) and the FHI after incorporating *RF*. The analysis reveals a significant influence of risk factors on the FHI, where in some cases, an initially high HI was reduced to a medium level. This provides deeper insights and supports more informed precautionary actions to ensure the development of suitable maintenance strategies for each RMU.

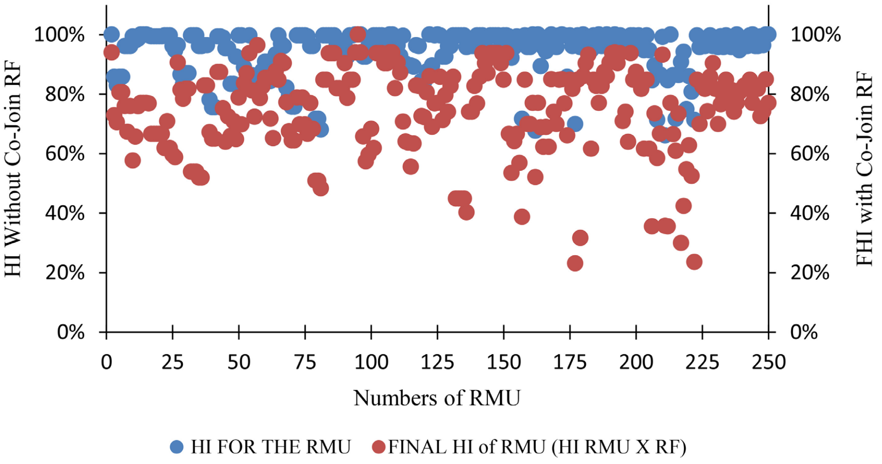

Figure 3. Changes of HI with and without Risk Factor (*RF*).

The FHI analysis shows that only 110 RMU units (44%) remained in the high category after risk factors were considered, compared to 231 units (92%) before. This indicates that 44% of the RMUs can have their maintenance schedules extended. Meanwhile, 125 units (50%) were classified within the medium FHI range of 51% to 80%, reflecting an increase after the inclusion of risk factors. Additionally, 15 RMU units (6%) were identified with a low FHI (below 50%) and require immediate action.

Further analysis of the HI results aims to establish a relationship between the HI and the age of the RMUs, to provide an overview and appropriate mitigation strategies for older units. The largest group of RMUs, totaling 125 units (50%), is 10 years old or younger. Additionally, 46 units (20%) are over 20 years old, while 79 units (30%) are between 11 and 19 years old. The analysis reveals that some RMUs older than 20 years are still operational and maintain high HIs. A summary of the RMUs based on their years in operation is presented in **Figure 4**.

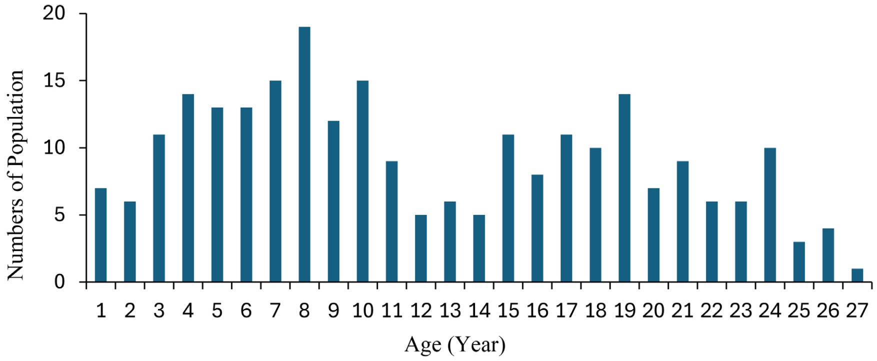

Figure 4. Total numbers of RMU with age analysed.

The FHI calculation indicates that the Final Health Index of RMUs follows a scattered trend, as shown in **Figure 5**, influenced by factors such as loading and climate conditions. This suggests that extra caution is required when managing older RMUs. From the data analyzed, one RMU that has been in operation for 27 years was found to have an FHI of only 26.23%, placing it in the poor category and requiring immediate maintenance. However, 18% of RMUs aged 20 years or more have FHIs ranging from 23% to 87%, demonstrating that FHI can serve as a useful indicator of RMU condition.

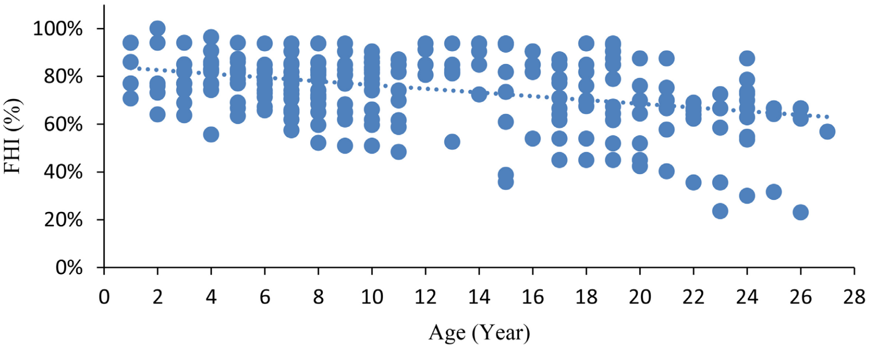

Figure 5. Relationship between FHI and age.

The model of HI has been developed based on CBM data and parameter and the validation of the model will be further assessed and compared to the actual utility practice. The findings will be presented in future publication. The limitation of the HI model developed is purely based on the manual CBM data conducted once a year. The data needs to be integrated into the model for update latest condition. The potential future improvement is to explore the usage of online sensor monitoring for real time health index monitoring.

7. Conclusion

A health status evaluation tool for medium-voltage RMUs has been developed, organizing assessments into key areas, general visual inspection, fuse compartment, cable compartment, mechanism compartment, and tank compartment. The tool integrates a risk component into the HI calculation, providing a comprehensive assessment of RMU condition. Among the 250 RMU units analyzed, 110 units (44%) were found to have a high FHI, indicating they are in good condition and do not require immediate maintenance, allowing for extended maintenance schedules. Additionally, 125 units (50%) fell into the medium FHI category, while 15 units (6%) required immediate repairs due to a low FHI. When the *RF* was considered, an RMU with 27 years of operation showed a poor FHI of 26.23%, requiring urgent maintenance. Meanwhile, 18% of RMUs aged 20 years or more had FHIs ranging from 23% to 87%. By using this single, quantitative health indexing method, maintenance engineers can implement more efficient strategies and make faster, more informed decisions. This HI approach provides a clear overview of RMU conditions for maintenance planning and repair. Besides, it also helps optimize maintenance costs and resource allocation. It introduces an innovative condition assessment method for RMUs in the electrical utility sector.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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