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Condition Assessment of Gas Insulated Switchgear Using Health Index and Conditional Factor Method

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Abstract: This paper proposes a comprehensive procedure to assess the condition of gas insulated switchgear (GIS) equipment by using the conventional weight and score method and introducing a conditional factor to improve the accuracy of the health index evaluation. Generally, the inspection and testing of GIS components are conducted according to manufacturer recommendations and guidelines in the international standards. However, this raw data has not been simplified and systematically processed for condition assessment. The score and weight technique are applied to transform the physical condition according to visible and measurable aging to numerical values in terms of component and bay health index values. The accuracy of the obtained health index has been improved by a conditional factor, which considers invisible aging factors, such as age, number of switching operations, degree of satisfactory operation, obsolescence, and adequacy of the interrupting rating. Here, a condition evaluation procedure has been developed and compared with the fuzzy logic method and the health index dominant score technique with satisfactory results. Subsequently, the proposed procedure has been developed as web application software to evaluate 175 bays of GIS in both 115 and 230 kV networks of an independent power producer supplying electricity of 3094 MW to a large industrial estate in Thailand. Eight GIS bays showed moderate or poor condition and the proper actions were assigned to prevent their failure. The software is in use in practice as a decision support tool to effectively manage the maintenance tasks and to improve supply reliability.

Keywords: condition assessment; conditional factor; gas insulated switchgear; health index; maintenance strategies

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1. Introduction

Nowadays, gas insulated switchgear (GIS) technology is widely utilized to improve supply reliability with space limitation. Although it is designed to be maintenance-free, GISs do deteriorate and can be damaged because of the ambient temperature, surrounding environment, electrical or mechanical stresses, or by abnormal operating conditions as mentioned in [1,2]. Failure of the GIS can occur while it is in-service before the scheduled maintenance. Moreover, the replacement of an old model GIS is complicated and requires significant cost and effort. Hence, of prime concern are the condition assessment and lifetime estimation of GIS and other high voltage assets in the transmission and distribution grid [3,4], especially so as to guarantee the quality of electricity supply [5]. Traditionally, maintenance of GIS is conducted according to the pre-determined interval recommended by the manufacturer and by guidelines in international standards known as preventive maintenance. However, this practice is not optimal due to over-maintenance or late-maintenance for some GIS bays, which could lead to high maintenance and outage costs. Therefore, it has shifted to condition-based maintenance with the aim of determining the actual condition of a GIS and its components so as to properly plan the maintenance task. To know the actual condition of GIS components, condition monitoring and diagnostic techniques have been applied to detect abnormal conditions from various measurable parameters [6–10] and the appropriate test methods should be clearly specified [11–14].

The simplified structure of GIS is shown in Figure 1 as a double busbar arrangement. In practice, the major components are clearly categorized from the GIS single line diagram and bus structure plan. Primary components include circuit breaker (CB), earthing switch (ES), disconnecting switch (DS), high-speed earthing switch (HS), current transformer (CT) and voltage transformer (VT). The secondary components are grouped into local control cabinet (LCC), gas compartment (COMPT) and body housing.

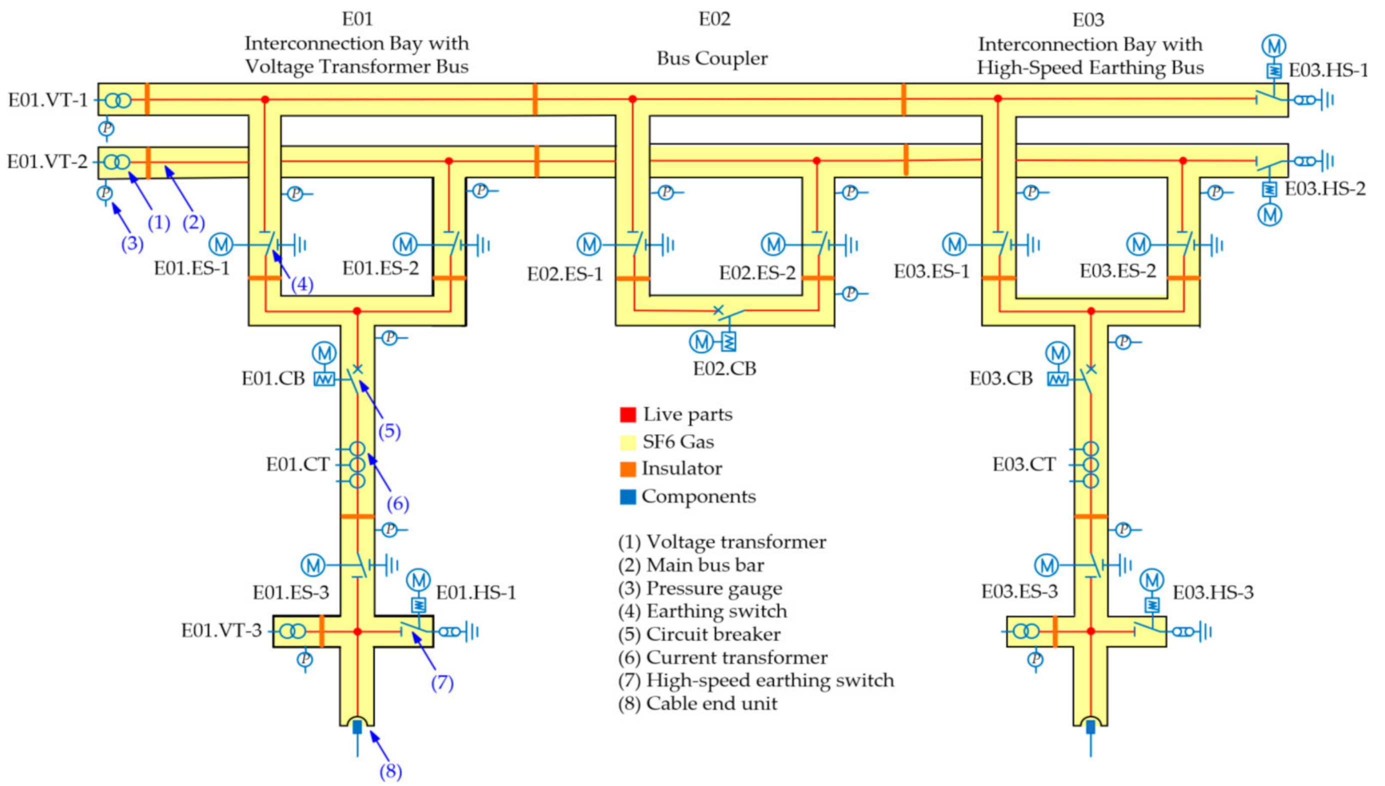


Figure 1. GIS in double busbar arrangement diagram.

In Table 1, the practice test methods and inspection items—of both real-time online inspection with routine visual inspection (RVI) and offline test conducted during shutdown maintenance—are presented for seven major GIS compartments (CB, DS, ES, CT and VT, and local control cabinet and gas compartment) as follows.

Table 1. Field diagnostic and testing information.

Components	Type of Test Methods
CB	routine visual inspection, mechanic/electric control driving mechanism, function test of auxiliary relay, contact resistance, insulation resistance, operating timing
LCC	special test/routine visual inspection, position indicator inspection, indicating meter, annunciator and alarm circuit
COMPT	routine visual inspection, SF6 gas leakage, SF6 gas quality, gas monitoring/density switch
DS/ES/HS	special test/routine visual inspection, operating mechanism inspection, driving mechanism inspection
CT	special test/routine visual inspection, winding insulation resistance, CT ratio and polarity, CT magnetizing curve
VT	special test/routine visual inspection, winding insulation resistance, VT ratio and polarity

In condition evaluation, the maintenance data obtained from RVI as well as from online and offline tests are considered. This maintenance and testing data together with the GIS technical data should be verified and systematically recorded in electronic form. The availability of the required data and data migration from hard copy to centralized database are significant for the existing GIS with long time in service. Generally, the norms and rules for condition interpretation suggest several approaches such as comparison with the recommendation from manufacturer or international standard, trending analysis, and comparison with similar component model [1,4,8–10,15–18]. However, those evaluation techniques require expert judgment as mentioned in [7–9]. In addition, some researchers have introduced a systematic condition evaluation procedure by applying the score and weight method to determine the health index of the high voltage equipment, especially the power transformer [8,19], but only a few studies have been performed with GIS [9]. One paper proposed the health index and risk assessment model of GIS used in a tropical area based on norms and weighting factors. Several papers applied a fuzzy logic method to determine the health index of a power transformer in a transmission network [20–22].

The score and weight method has been adopted for condition evaluation in this paper because it is a simple and straightforward method. However, the score and weight technique had been applied to transform the physical condition according to visible and measurable aging into numerical values in term of a component and bay health index [8,9,19] without considering other relevant aspects. Moreover, this paper aims to describe a comprehensive evaluation procedure for GIS condition evaluation; and to improve the accuracy of the obtained health index by multiplying it with the conditional factor—which considers invisible aging factors such as age, number of switching operations, degree to which its operation is satisfactory, obsolescence, and adequacy of the interrupting rating. To validate the accuracy of the proposed model, our condition evaluation procedure is developed and compared with the fuzzy logic method and other health index evaluation techniques. Finally, we test the proposed procedure by developing it as a web application software tool to evaluate 175 bays of GIS in both 115 and 230 kV networks of an independent power producer supplying electricity to a large industrial estate in Thailand.

This paper is organized as follows. Section 2 describes the field diagnostic testing and information requirement to evaluate and implement in the web application software. Section 3 describes the web application architecture for a database management system and graphic user interface. Section 4 provides the condition assessment methodology. The health index and conditional factor are described for the calculation process based on the weight obtained by AHP application. Section 5 provides the condition assessment results and discussion. This section also describes the verification of the condition assessment procedure with other methods and web application graphic user interface. Finally, Section 6 presents the conclusions drawn from the research.

2. Field Diagnostics Testing and Information Requirements

Nowadays, manufacturers and both non-governmental international organizations IEEE and CIGRE recommend that major maintenance—which must open the gas compartment—is not required before 25 years in operation [23]. Exceptions include, for example, short circuit current and fault interruptions exceeding the pre-determined number provided by the manufacturer. Therefore, in general only routine maintenance is carried out and aims to ensure the satisfactory operation of GIS. Moreover, the function tests of both electrical and mechanical parts should be regularly performed according to the scheduled maintenance recommended by the GIS manufacturer. The sources of testing methods and recommendations, as well as data on practical on-site testing by skilled persons, were gathered and applied to evaluate the condition of the asset, as follows.

2.1. Technical Data

To collect the essential data for condition assessment, the information in terms of the design and engineering of equipment are systematically gathered from the technical information provided. General information about a GIS substation consists of the equipment name, engineering tag number, serial number, installation site, installation date, model, manufacturer, manufacture date, feeder name, GIS bay description, bay function, system rated voltage, equipment rated voltage, rated current, rated short circuit breaking current, short circuit duration, structure of compartment, rated operating pressure of each compartment, basic lightning impulse insulation level (BIL), cable housing type and detail, etc. Since there are various models of GIS from a variety of manufacturers installed in our electrical network, some evaluation criteria must be defined according to the model-specific criteria to authenticate the actual condition of the asset: for example, operating current of motor driving mechanism, CB close–open time, and operating pressure of gas compartment. Therefore, some significant data from the instruction manual or from the manufacturer of each GIS model must be systematically recorded in this section for later retrieval in the condition evaluation process.

2.2. Maintenance Data and Judgement

The previous field-testing methods and inspection data were analyzed to design a user-friendly data collection system, using test forms to record inspection test results with an additional print-out function for further use in the inspection report. In addition, the complete maintenance data recommended by the manufacturer, operational experience of a utility, as well as international standard recommendations were inputted into the web application software. To collect the maintenance data, RVI was performed every 3 months and during major maintenance every 3–5 years, an interval pre-set according to the time-based maintenance schedule. Examples of test methods and test items are shown in Tables 2–7. The evaluation criteria of major components consist of LCC, SF6 COMPT, CB, DS/ES/HS, CT and VT. The score and evaluation criteria of major components are referred to for a GIS model, as well as their practical implementation.

Table 2. LCC testing methods and visual inspection.

Type of Test Methods	Test Items	Condition and Score		
		Normal (5)	Satisfactory (3)	Poor (0)
visual inspection	unit physical damage, MCBs and auxiliary, wiring and terminals, heating circuit function, cleanness, position indicator, heater and temperature control circuit, annunciator, indicating lamps, volt-amp meters, semaphore position, key and selector switch, push button and control switches, MCB, fuse and auxiliary relays, control cable	normal	satisfactory	poor
indicating meter	body and seal check, zero adjustment check, wiring, cabling, terminals	normal	satisfactory	poor
	turn ratio percentage error (%)	pass	-	fail
annunciator and alarm circuit	annunciator and alarm circuit	normal	satisfactory	poor

Table 3. CB testing methods and visual inspection.

Type of Test Methods	Test Items	Condition and Score		
		Normal (5)	Satisfactory (3)	Poor (0)
visual inspection	damage to physical units, cleanness, foundation, grounding, tightness of pipes and union coupling, local control panel, wiring and terminals, body and housing, tightness of all parts, alarm and lockout of pressure monitor, hydraulic oil system, storage spring, terminal and auxiliary relay, SF6 gas pressure, control cable	normal	satisfactory	poor
	number of CB operation counter	<5000	-	≥5000
	hydraulic pump counter	<5000	-	≥5000
hydraulic drive mechanism	hydraulic oil level and oil leakage, hydraulic oil color, physical units	normal	satisfactory	poor
	resistance of closing/tripping circuit (ohm)	<100	100–120	>120
	carbon brush height (mm)	>15	10–15	<10
	CB operation and hydraulic pump counter	<5000	-	≥5000
	motor running time	<30	30–40	>40
	motor running current	<7	7–10	>10
	spring charging time	<30	30–40	>40
function test of auxiliary relay	auxiliary relay/timer function, stored operating sequence, position indicator, heating circuit	normal	satisfactory	poor
contact resistance measurement (uΩ)	contact resistance phase	<200	200–220	>220
	contact resistance phase-difference	<5	5–20	>20
insulation resistance (GΩ)	phase to ground, phase to phase, primary and secondary	>20	10–20	<10
operating timing measurement (ms)	closing time phase	<60	-	≥60
	closing/opening time differential	<5	-	≥5
	opening time phase	<40	-	≥40
	closing-opening time phase	<120	-	≥120

Table 4. DS/ES/HS testing methods and visual inspection.

Type of Test Methods	Test Items	Condition and Score		
		Normal (5)	Satisfactory (3)	Poor (0)
visual Inspection	physical units, operating mechanism elements, purification and lubrication of operating mechanism elements, limit switches, crank locking switches and position indicator, solenoids, auxiliary switch, wiring and cabling, grounding terminals, tightness of electrical connector, cleanness, SF6 gas pressure, control cable connect, cover mechanism box, shaft mechanism drive	normal	satisfactory	poor
operating mechanism inspection	manual operation, movement of operating linkage, interlocking, heating circuit function	normal	satisfactory	poor
	closing/opening motor current (A)	<7	7–10	>10
	closing/opening time (sec)	<30	30–40	>40
routine visual inspection	SF6 gas pressure, control cable connects, cover mechanism box, shaft mechanism drive	normal	satisfactory	poor

Table 5. CT testing methods and visual inspection.

Type of Test Methods	Test Items	Condition and Score		
		Normal (5)	**Satisfactory (3)**	**Poor (0)**
visual inspection	physical units, earthing connection, wiring and terminals, heating circuit function, cleanness, SF6 gas pressure, control cable connection	normal	satisfactory	poor
insulation resistance (IR)	secondary winding IR (MΩ) primary winding IR (MΩ)	>100 >1000	50–100 500–1000	<50 <500
ratio and polarity	CT ratio error percentage CT polarity	pass normal	- -	fail poor
CT magnetizing curve test	saturation ratio (Isat/Isec) refer to safety factor or accuracy limit factor, accuracy power (VA) and knee point voltage (V)	pass	-	fail

Table 6. VT testing methods and visual inspection.

Type of Test Methods	Test Items	Condition and Score		
		Normal (5)	**Satisfactory (3)**	**Poor (0)**
visual inspection	physical units, grounding, wiring and terminals, heating circuit function, cleanness, SF6 gas pressure, control cable connection	normal	satisfactory	poor
insulation resistance (IR)	secondary winding IR (MΩ) primary winding IR (MΩ)	>100 >1000	50–100 500–1000	<50 <500
ratio and polarity	VT ratio error percentage (%) VT polarity	pass normal	- -	fail poor

Table 7. SF6 gas compartment testing methods and visual inspection.

Type of Test Methods	Test Items	Condition and Score		
		Normal (5)	**Satisfactory (3)**	**Poor (0)**
visual inspection	ground structures connection, steel structure, bolt and nut, presence of rust, painting condition	normal	satisfactory	poor
SF6 gas leakage	SF6 gas leakage	no leakage	-	leakage
moisture content	dew point (C) moisture (ppmV) SF6 volume percentage (%) SO2 content (ppm)	<−5 <200 >97 <2000	- - - -	>−5 >200 <97 >2000
density switch test	function test	normal	-	malfunction
gas pressure check	gas pressure in all compartments	normal	-	malfunction

For an example of a testing information analysis, in Table 7, the information relating to testing and inspection consists of 4 categories, including SF6 gas leakage, gas quality measurement, gas monitoring system and routine visual inspection. To evaluate the condition of the gas compartment, the gas quality was essentially analyzed by the SF6 decomposition products, which is used to identify the localization of defects and estimate the condition of the equipment [24,25]. In the investigation process, the gas decomposition products from switching devices and static components have different characteristics. How normal the switching activity of a CB is can be verified not only by the decomposition product but also by abnormal arcing or sparking [24]. Although several diagnostic methods have been performed on GIS, failures still sometimes occur before a major maintenance or diagnostic schedules [2,26]. The failure characteristics and consequences need to be further studied to verify the failure mechanisms and failure causes such as manufacturer defect, poor installation practice and incorrect operation procedure, or aging, as mentioned in [27–29]. Therefore, the above evaluation criteria for the testing of items are investigated and arranged with the aim of determining the condition of a GIS bay and its major components. To assess the actual condition of major components, the field testing and inspection should be performed with all 175 GIS bays to identify their actual condition, and subsequently to maintain asset performance and prevent failure that could occur in service.

3. Database Management System and Graphic User Interface

The web-based asset management system plays an importance role in maintenance management systems (CMMS). It is used as a data-based centralization to manage an enterprise's asset. In this paper, a web-based CMMS is developed for condition monitoring and asset management of an independent power producer. In the web application design stage, the operational aspects consist of graphic user interface (GUI), usability, content information and graphic design. Data processing, calculation, and test result interpretation features in web application software are modeled as shown in Figure 2. The web application architecture consists of GUI, operational programming language, analytical programming, database management system (DBMS) and user levels, as follow:

(1) GUI: The information is requested from the DBMS web server, which illustrates the technical information, test inspection record/results and condition evaluation using PHP and JavaScript as programming languages. In outcome information, the test inspection reports are designed to present the technical information, inspection field testing and condition evaluation report.

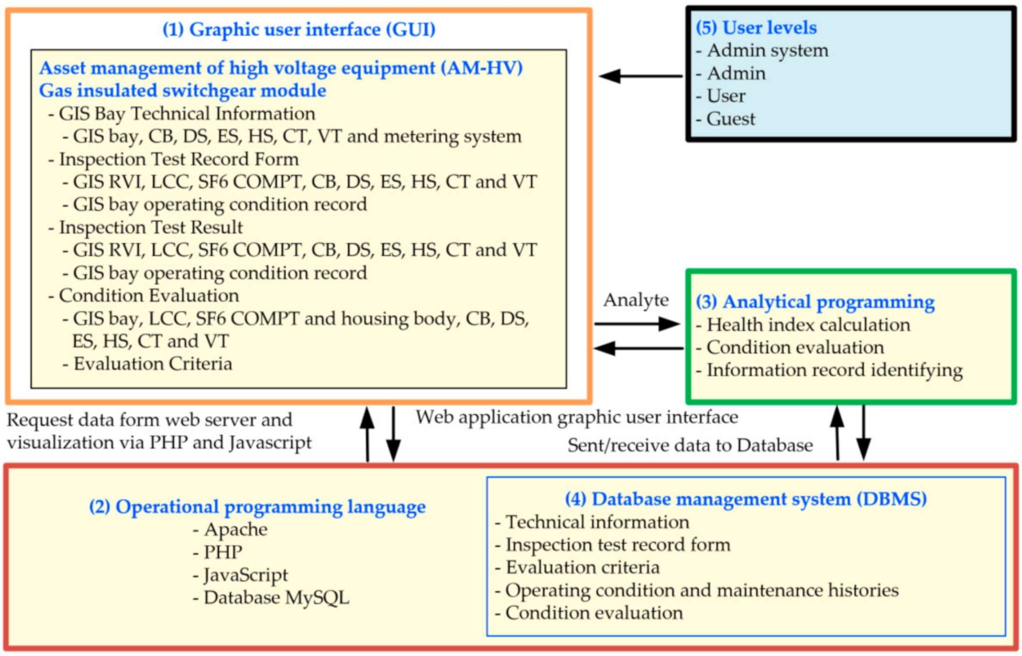


Figure 2. Web application architecture and database management system.

(2) Operational programming language: The web application visualization is developed using PHP with Apache, MySQL, and JavaScript. It is also compatible to work on mobile phone, tablet, and laptop with security service via a reliable virtual private network (VPN).

(3) Analytical programming: To develop the web application repositions, the PHP language and JavaScript are used for data processing, calculation, and test result interpretation. The main feature of web application repositions are designed for health index

(HI) calculation, condition evaluation (for example, condition illustration for normal in green and satisfactory in orange color) and the search function of the recorded data.

(4) DBMS: The information includes engineering equipment tag design, technical information, evaluation criteria, inspection test results, and operating condition and maintenance histories. The DBMS is connected to the web allocation GUI by using Apache, PHP and JavaScript to record the data into MySQL server.

(5) User levels: The permission of the web application software is designed according to responsible tasks and priority in the organization to prevent incorrect/faulty recording of information, and consists of an admin system, admin, user, and guest. First, the admin system operates for the full functions of the web application software including user registration system, user management system, information record/result for all modules and edit/delete data in the DBMS. Secondly, the permission of admin is removed for the user registration system. Thirdly, the user is permitted to operate in information record/result for all module and edit/delete data in the DBMS information. Lastly, a guest user can operate the web application as viewer only.

4. Condition Assessment Methodology

The development of a condition assessment procedure is an essential part to process the required data and to deliver the valuable output to optimize the maintenance task in the organization, and to define the proper maintenance strategy [26,30–32]. The objective of this work is to develop a decision support tool to use in a power producer grid in an industrial estate. The condition assessment procedure illustrates the actual condition of all major components in a GIS bay via the visible aging obtained from the field testing and inspection along with the actual operating data, and incorporates the invisible aging obtained from the CF.

The GIS condition assessment procedure has been designed to start from all major components up to GIS bay. To evaluate the condition of all major components and GIS bay, it consists of four parts as follows. (1) Technical data creation: The verified technical information is systemically stored in the DBMS to create the database tag information. (2) Data collection of field inspection and operating conditions: The field inspection results and operating conditions are recorded in the DBMS via various testing and inspection forms used at the utility by the maintenance crew. Once the data is complete, it can later be retrieved for the component HI evaluation and in the calculation of the CF score. (3) Evaluation criteria initialization: The weight and score method (WSM) is applied to evaluate the HI and CF score with the aid of the analytical hierarchy process (AHP) to determine the proper weighting value. (4) Graphical user interface to visualize the condition assessment result. The obtained HI results of all major components and GIS bay are presented according to a traffic-light color code and for the dial gauge meter in the web application software in a user-friendly manner.

4.1. Health Index Calculation

The weight and score method (WSM) is a form of multi-attribute or multicriteria analysis. The weight is used to reflect the relative importance of the attribute, while the score reflects the relation to each attribute. In this work, the WSM is applied to calculate the HI from the relationship between weight and score with the aid of AHP techniques [33].

The analytic hierarchy process (AHP) was introduced as a general theory of measurement to reflect the relative strength of qualitative and quantitative aspects. This methodology has been widely applied for multicriteria decision making, especially to determine the weighting value of all field-testing types and of major components, which represents the importance of each field-testing type in health index calculation for a given component, and the importance of each major component in the overall health index calculation. The general process of AHP consists of (1) development of a model for the decision, (2) development of a single pair-wise comparison matrix for the criteria, (3) consistency of the ratio maker's judgment, (4) development of the rating of each decision, and (5) calculation of the weighted average rating for a final decision and normalization for WSM application. To understand the application of the AHP, the hierarchy model is developed as shown in Figure 3.

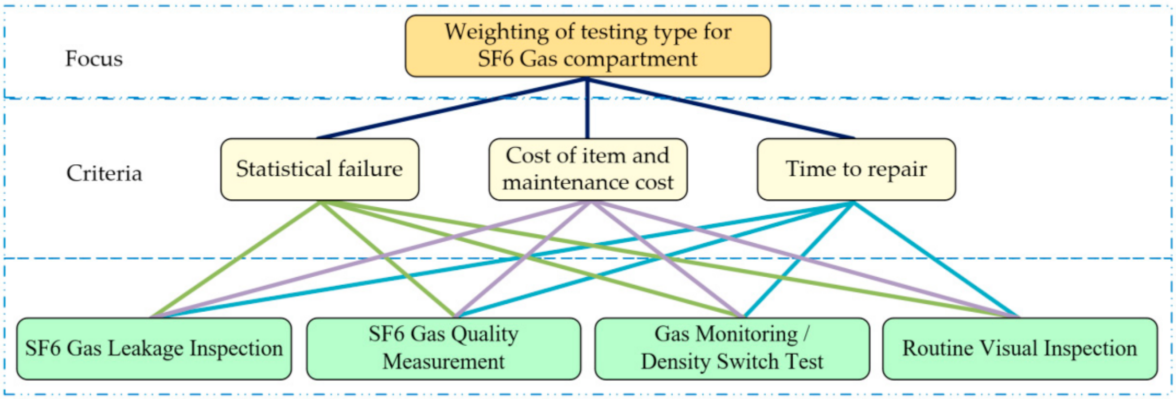


Figure 3. Analytic hierarchy process for weighting determination of field-testing of gas compartment.

To determine the relative strength and pairwise comparisons, the model is separated into three layers consisting of focusing heading, decision criteria, and alternative field-testing types. The process of AHP was applied step by step to brainstorm the opinion of experts working in various departments related to GIS in a utility. The utility experts who have been invited to share their opinions consist of: maintenance engineers with long-time experiences in testing and inspection; engineers in electrical engineering departments who have knowledge in planning, design, and system configuration; and lastly, plant managers who decide on system operation, reliability, and other aspects. The pairwise comparison module has been developed in the Microsoft Excel program and distributed to all invited experts to freely share their opinions. Next, the obtained weighting values are averaged by using the geometric mean method and finally normalized to one hundred percent in total.

To calculate the percentage component health index ($\%HI_c$), the score is defined by the condition of each asset, which is defined as 0 for poor condition, 3 for satisfactory condition, and 5 for normal condition. The $\%HI_c$ is then further used to calculate the percentage bay health index ($\%HI_{BAY}$) by using the obtained $\%HI_c$ and the related weight of those major components. Additionally, the WSM is applied to calculate the conditional factor score of each GIS bay, which is further used to modify the percentage overall health index ($\%OHI$) of the GIS.

Technically, the $\%HI_c$ of each major component in a GIS bay is calculated by using Equation (1):

$$\%HI_{C;j} = \frac{\sum_{i=1}^{M} (S_{TR;i} \times W_{TR;i})}{\sum_{i=1}^{M} (S_{TR;MAX} \times W_{TR;i})} \times 100 \quad (1)$$

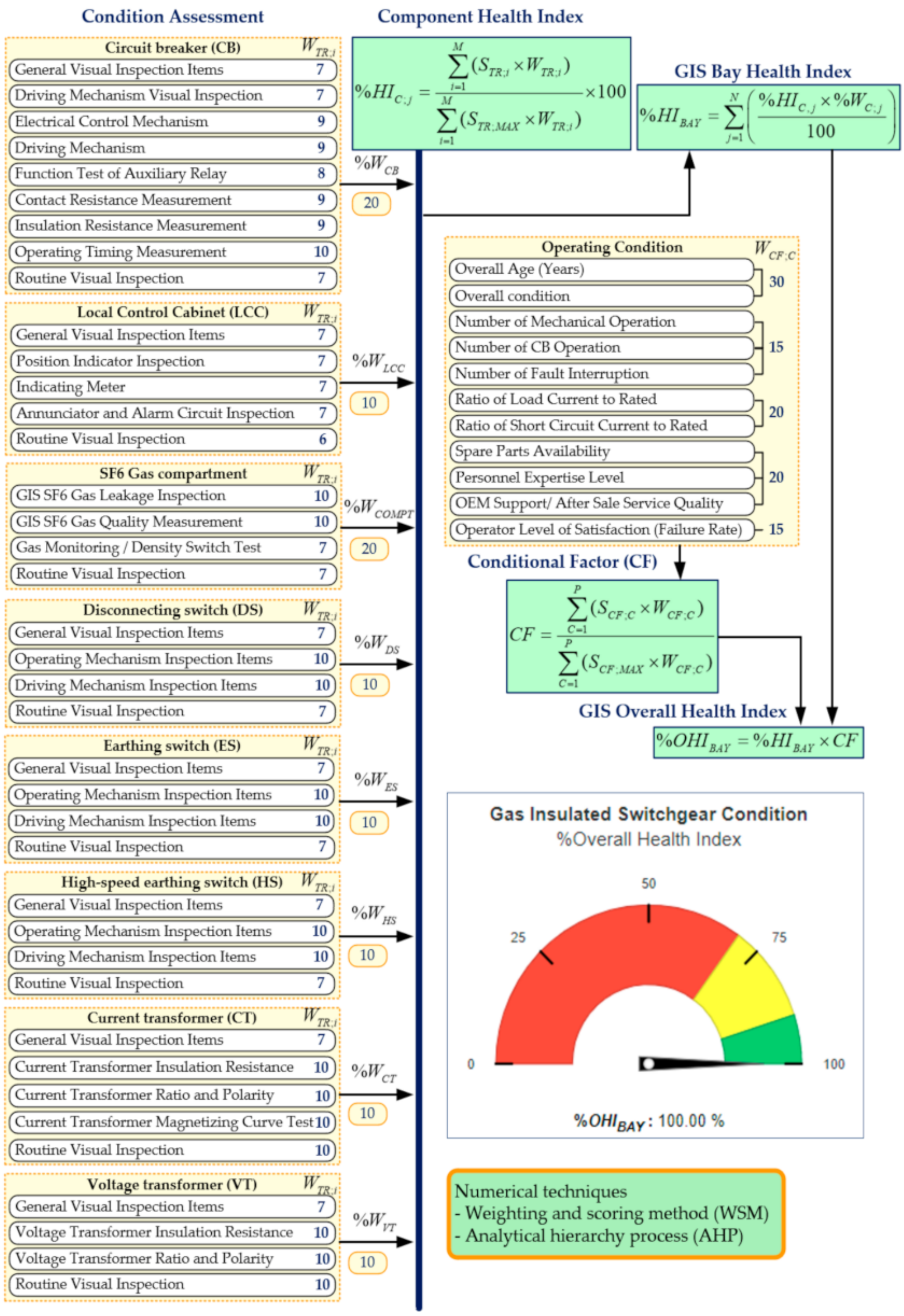
where $\%HI_{C;j}$ is percentage component health index jth; $S_{TR;i}$ is the worst score from the testing results ith; $S_{TR;MAX}$ is maximum score from testing results; $W_{TR;i}$ is weight of testing method ith; and M is number of testing methods.

According to Figure 3, the $\%HI_{BAY}$ is calculated by using Equation (2):

$$\%HI_{BAY} = \sum_{j=1}^{N} \left(\frac{\%HI_{C;j} \times \%W_{C;j}}{100} \right) \quad (2)$$

where $\%HI_{BAY}$ is percentage bay health index; $\%HI_{C;j}$ is percentage component health index jth; $W_{C;j}$ is percentage weight of major component jth; and N is the maximum number of major components.

Subsequently, the whole evaluation procedure described above was first developed in a Microsoft Excel file to validate the assigned score and weight values. Several defective cases in different GIS components were simulated to investigate the sensitivity and suitability of the obtained HI value to correlate the actual condition with the quantitative HI. Finally, the consensus weighting value was widely accepted in the organization by all GIS-relevant departments, and can be used to calculate the component health index and bay health index as summarized in Figure 4.



$$\%HI_{C:j} = \frac{\sum_{i=1}^{M}(S_{TR:i} \times W_{TR:i})}{\sum_{i=1}^{M}(S_{TR:MAX} \times W_{TR:i})} \times 100$$

$$\%HI_{BAY} = \sum_{j=1}^{N}\left(\frac{\%HI_{C:j} \times \%W_{C:j}}{100}\right)$$

$$CF = \frac{\sum_{C=1}^{P}(S_{CF:C} \times W_{CF:C})}{\sum_{C=1}^{P}(S_{CF:MAX} \times W_{CF:C})}$$

$$\%OHI_{BAY} = \%HI_{BAY} \times CF$$

Figure 4. Gas insulated switchgear condition assessment procedure.

4.2. Conditional Factor Calculation

The conditional factor (CF) concept was first introduced by [34], and applied to evaluate the condition of the power distribution system. To accurately assess the condition of a high voltage asset, the HI calculation based only on the field testing and inspection or maintenance data is not sufficient, because it considers only the visible aging. The visible aging is the maintenance information, which is measurable via technical assessment with various testing and inspection techniques. To improve the accuracy of the condition assessment procedure, invisible aging—such as age, actual operating condition, operating ambient conditions, satisfactory in operation and historical failure record—is introduced as a CF, which is used to adjust the *%OHI* of the GIS bay.

In Table 8, the criteria for CF calculation and the detail of score-determination are presented. Several aspects have been considered, such as overall age, aging conditions, actual operating conditions, system requirement, satisfactory in operation, and failure statistics.

Table 8. Criteria with score and weight for conditional factor assessment.

Operating Conditions	Weight	Score		
		(0)	(3)	(5)
overall age (years) overall condition	30	>40 fail	31–39 trending	<30 good
number of mechanical operations number of CB operations number of fault interruptions	15	>5000 >2000 >20	4500–5000 1700–2000 15–20	<4500 <1700 <15
ratio of load to rated current ratio of short circuit to rated interrupting current	20	>1.0 >1.0	0.8–1.0 0.8–1.0	<0.8 <0.8
spare parts availability personnel expertise level OEM support/ after sale service quality	20	unable to modify poor poor	difficult to find moderate moderate	easy to find good good
operator level of satisfaction (failure rate)	15	poor	moderate	satisfied

The CF is calculated from the obtained data on all relevant mentioned criteria. The information on each criterion is transformed in to a score for each criterion. The score with its relevant weight for each criterion is used to calculate the CF value, which is subsequently applied to adjust the previously calculated OHI to incorporate the impact of invisible aging. The CF is calculated by using Equation (3):

$$CF = \frac{\sum_{C=1}^{P} (S_{CF;C} \times W_{CF;C})}{\sum_{C=1}^{P} (S_{CF;MAX} \times W_{CF;C})} \quad (3)$$

where *CF* is conditional factor; $S_{CF;C}$ is the score of an individual criterion *c*th; $S_{CF;MAX}$ is the maximum score for each criterion; $W_{CF;C}$ is the weight for an individual criterion *c*th; and *P* is the number of criteria.

4.3. Overall Health Index Calculation

The percentage bay overall health index ($\%OHI_{BAY}$) is calculated by multiplying the obtained $\%HI_{BAY}$ with *CF* as shown in Equation (4):

$$\%OHI_{BAY} = \%HI_{BAY} \times CF \quad (4)$$

where $\%OHI_{BAY}$ is the percentage bay overall health index; *CF* is the conditional factor; and $\%HI_{BAY}$ is the percentage bay health index.

The obtained $\%OHI_{BAY}$ is classified into three zones representing good, moderate, and poor condition of a GIS bay with traffic light indicators as shown in Table 9. The indicator represents the actual overall condition of the GIS bay, which draws immediate attention of the user to quickly interpret the result. This $\%OHI_{BAY}$ is used to manage the maintenance tasks as well as to define the proper maintenance strategy.

Table 9. Range of $\%OHI_{BAY}$ for condition classification and recommended actions.

$\%OHI$	Indicator	Description
90–100%	Good	The system is in good condition and does not need immediate action.
60–89%	Moderate	The system is in moderate condition and needs particular attention.
less than 60%	Poor	The system is approaching its end of life.

5. Results and Discussion

After the development of the DBMS, the condition assessment procedure, a prototype Microsoft Excel file and web application software, the program was applied to evaluate the condition of GIS substations in an industrial estate. The complete actual data consists of 175 bays, which contain 2036 major components. The maintenance data was collected, verified, and systematically recorded in the DBMS since 2019. In Table 10, one of the evaluation cases of a GIS bay-E05 is selected as an example to form a clear understanding of the calculations in detail.

First, the actual testing and inspection data must be transformed in to a score for each test item. Next, the weight of each test is assigned to calculate the component health index. In this example, the problem in the gas leakage and the SF6 gas quality of the gas compartment was found, and its consequence was too severe for electrical discharge due to deterioration of the electrical insulation. Thus, the score of gas leakage and gas quality measurement decreased from 5 to 0 to reflect its poor condition. To calculate the health index of the gas compartment having four inspection items, the WSM is applied by using Equation (1). The calculation detail of the gas compartment health index is shown below.

$$\%HI_{COMPT-E05} = \frac{(0 \times 10) + (0 \times 10) + (5 \times 7) + (5 \times 7)}{(5 \times 10) + (5 \times 10) + (5 \times 7) + (5 \times 7)} \times 100 = 41.18\%$$

As for the above calculation, the $\%HI_c$ of the other GIS components is simultaneously calculated. Most of the major components are three separated-phase components, such as DS, ES and CT; in these cases, the worst health index of the component is selected as a conservatively representative in the condition evaluation.

In Table 11, the HIs of five GIS bays in a substation are shown and are subsequently used to calculate the $\%HI_{BAY}$ by multiplying the $\%HI_c$ with its weight shown in Table 10. Although most of the $\%HI_c$ values of bay-E05 (including LCC, DS, ES, HS, CT and VT) were 100 %, the $\%HI_{BAY}$ is the worst at 78.90 % due to the problem found in CB and gas compartment in terms of visible aging. This information is useful to acknowledge the problem early on, and the proper operation could be assigned according to the actual condition of GIS components. Simultaneously, the CFs of all GIS bays are calculated and further applied to modify the $\%HI_{BAY}$ into $\%OHI_{BAY}$ as previously explained. The CF evaluation of the five-bay example substation is shown in Table 12.

Using a E05-bay as an example, the above calculation result of bay health index could be modified by the CF to reflect the invisible aging in terms of the overall bay health index. Hence, the bay health index is multiplied with its CF of 0.74. Next, the overall bay health index reduces to 58.38% as shown in Table 12. This reduction in the overall bay health index is caused by problems arising from several fault interruptions and insufficient spare part availability. Therefore, the condition of E05 is changed from a moderate to poor condition with an $\%OHI$ of less than 60%. With these known causes of health index reduction, the proper action can be advised for early remediation of the problem and to prevent subsequent failure.

Table 10. Example of component health index evaluation of GIS substation.

Component	W_c	Type of Test Methods	W_i	Score							
				E01	**E02**	**E03**	**E04**	**E05**	**E06**	**E07**	**E08**
CB	20	general visual inspection items	7	5	5	5	5	5	3	5	5
		driving mechanism Inspection	7	5	5	5	5	5	5	5	5
		electrical control mechanism	9	5	3	5	5	5	5	0	5
		driving mechanism	9	5	5	5	5	0	5	0	5
		function test of auxiliary relay	8	5	0	5	5	5	5	5	5
		contact resistance measurement	9	5	5	5	5	0	5	3	5
		insulation resistance measurement	9	5	5	3	5	5	5	5	5
		operating timing measurement	10	5	5	5	5	0	5	5	5
		routine visual inspection	7	3	5	5	5	0	5	5	5
percentage CB health index (%HI_{CB})				96.27	84.53	95.20	100	53.33	96.26	71.20	100
LCC	10	general visual inspection items	7	5	5	5	3	5	5	5	5
		position indicator visual inspection	7	5	3	5	5	5	5	5	5
		indicating meter	7	5	5	5	5	5	5	5	0
		annunciator and alarm circuit	7	5	5	5	5	5	5	5	0
		routine visual inspection	6	3	3	5	0	5	5	5	5
percentage LCC health index (%HI_{LCC})				92.94	84.71	100	74.12	100	100	100	58.83
SF6 COMPT	20	SF6 gas leakage inspection	10	5	3	5	5	0	5	3	3
		SF6 gas quality measurement	10	5	3	0	5	0	5	5	5
		gas monitoring / density switch test	7	3	5	5	5	5	5	5	5
		routine visual inspection	7	3	3	5	5	5	5	5	5
percentage SF6 gas compartment health index (%HI_{COMPT})				83.53	68.24	70.59	100	41.18	100	88.24	88.24
DS	10	general visual inspection items	7	5	5	5	5	5	5	5	5
		operating mechanism inspection	10	5	0	5	5	5	0	5	5
		driving mechanism inspection	10	5	0	5	5	5	0	5	5
		routine visual inspection	7	3	5	5	5	5	5	5	5
percentage DS health index (%HI_{DS})				91.76	41.17	100	100	100	41.17	100	100
ES	10	general visual inspection items	7	5	5	5	5	5	5	5	5
		operating mechanism inspection	10	5	5	5	5	5	5	5	5
		driving mechanism inspection	10	5	5	3	5	5	5	5	5
		routine visual inspection	7	3	5	5	5	5	3	5	5
percentage ES health index (%HI_{ES})				91.76	100	88.24	100	100	91.76	100	100
HS	10	general visual inspection items	7	5	5	5	5	5	5	5	5
		operating mechanism inspection	10	5	5	5	5	5	5	5	5
		driving mechanism inspection	10	5	5	5	5	5	5	5	5
		routine visual inspection	7	3	5	5	5	5	3	5	5
percentage HS health index (%HI_{HS})				91.76	100	100	100	100	91.76	100	100
CT	10	general visual inspection items	7	5	5	5	5	5	3	5	5
		CT insulation resistance	10	5	5	5	5	5	5	5	5
		CT ratio and polarity	10	5	5	5	5	5	5	5	5
		CT magnetizing curve test	10	5	3	5	5	5	5	5	5
		routine visual inspection	10	3	5	5	5	5	5	5	5
percentage CT health index (%HI_{CT})				91.49	91.49	100	100	100	94.04	100	100
VT	10	general visual inspection items	7	5	5	5	5	5	5	5	5
		VT insulation resistance	10	5	5	5	5	5	5	5	5
		VT ratio and polarity	10	5	5	5	5	5	5	5	5
		routine visual inspection	10	3	5	5	5	5	5	5	3
percentage VT health index (%HI_{VT})				89.19	100	100	100	100	100	100	89.19
percentage GIS bay health index (%HI_{BAY})				90.85	82.29	91.98	97.41	78.90	76.55	86.37	85.05

Table 11. Example of bay health index evaluation of substation.

Component Health Index $\%HI_C$	$\%Wc;j$	**GIS Bay Condition**							
		E01	**E02**	**E03**	**E04**	**E05**	**E06**	**E07**	**E08**
$\%HI_{CB}$	20	96.27	84.53	95.20	100.00	53.33	96.26	71.20	100.00
$\%HI_{LCC}$	10	92.94	84.71	100.00	74.12	100.00	100.00	100.00	58.82
$\%HI_{COMPT}$	20	83.53	68.24	70.59	100.00	41.18	100.00	88.24	88.24
$\%HI_{DS}$	10	91.76	41.17	100.00	100.00	100.00	41.17	100.00	100.00
$\%HI_{ES}$	10	91.76	100.00	88.24	100.00	100.00	91.76	100.00	100.00
$\%HI_{HS}$	10	91.76	100.00	100.00	100.00	100.00	91.76	100.00	100.00
$\%HI_{CT}$	10	91.49	91.49	100.00	100.00	100.00	94.04	100.00	100.00
$\%HI_{VT}$	10	89.19	100.00	100.00	100.00	100.00	100.00	100.00	89.19
$\%HI_{BAY}$		90.85	82.29	91.98	97.41	78.90	91.13	91.89	92.45

Table 12. Conditional factor evaluation and overall bay health index modification.

Operating Condition	W_{CF}	S_{CF}							
		E01	**E02**	**E03**	**E04**	**E05**	**E06**	**E07**	**E08**
overall age (years)	30	5	5	5	5	5	3	5	5
overall condition		5	5	5	5	3	5	5	5
number of mechanical operations	15	5	5	5	5	5	5	5	5
number of CB operations		5	3	5	5	5	5	5	5
number of fault interruptions		5	5	5	5	3	5	3	5
ratio of load to rated current	20	5	5	5	3	5	5	5	5
ratio of short circuit to rated interrupting current		3	5	5	5	5	5	5	5
spare parts availability	20	5	5	3	5	3	5	5	3
personnel expertise level		3	5	5	3	5	0	5	5
OEM support/after sale service quality		5	5	5	5	5	5	5	5
operator level of satisfaction (failure rate)	15	5	5	5	5	5	3	5	5
CF		0.84	0.94	0.92	0.84	0.74	0.62	0.94	0.94
$\%HI_{BAY}$		90.85	82.29	91.98	97.41	78.90	91.13	91.89	92.45
$\%OHI_{BAY}$		76.31	77.35	84.62	81.82	58.38	56.50	86.37	85.05
$\%OHI_{BAY}$ after corrective maintenance as shown in Figure 5		-	81.11	-	-	67.09	-	-	-

In the case of damage causing moderate and poor conditions for overall bay health index of two bays, the multiple failure causes include disconnector switch local control circuit failures in Figure 5a,b for bay-E02, and gas quality measurement due to busbar electrical discharge in Figure 5c,d for bay-E05. After corrective maintenance, the replacement of E02-DS 's auxiliary magnetic relay improves the $\%HI_{DS\text{-}E02}$ from 41.17% to 100% due to problem solving of the operating mechanism and driving mechanism. Subsequently, the $\%OHI_{BAY\text{-}E02}$ increase from 77.35% to 81.11%. Moreover, the problem of bay-05 was corrected by corrective maintenance with electrical busbar replacement in the gas compartment. Consequently, the $\%OHI_{BAY\text{-}E05}$ increased from 58.38% in poor condition to 67.09%, reflecting moderate condition.

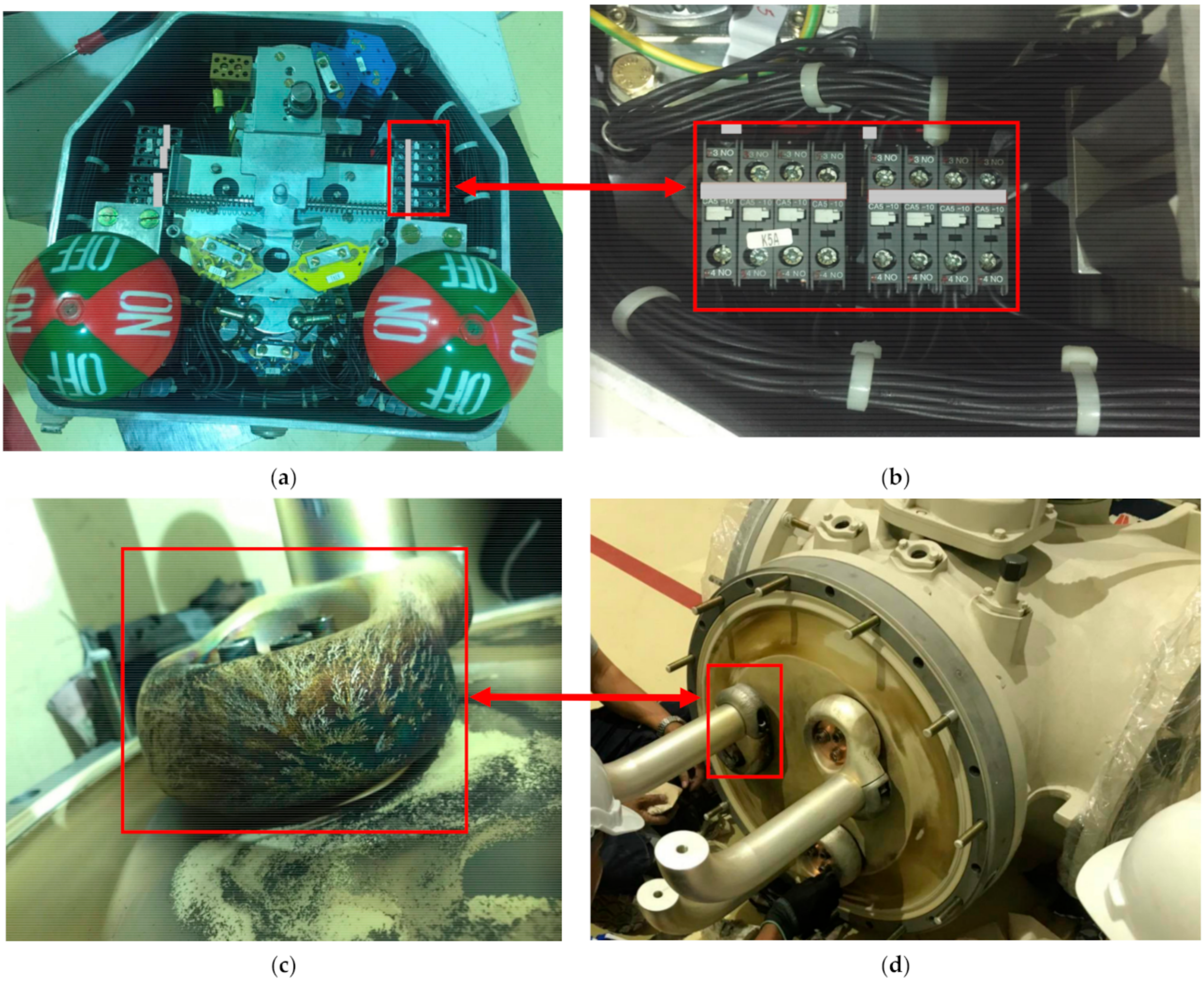


Figure 5. Sample of GIS failure components: (**a**) E02-DS 's auxiliary magnetic relay malfunction; (**b**) E02-new auxiliary magnetic relay; (**c**) E05-busbar electrical discharge; (**d**) E05-new busbar replacement.

To validate the accuracy and suitability of the proposed condition assessment procedure and the results found, experts from the independent power producer—from maintenance and engineering departments as well as plant manager and management team, program developers and software users—provided their opinions during sensitivity checks. This enabled us to correlate the obtained health index value and the actual condition of GIS and their components through various simulated defective cases that used to occur in the system in the past 20 years, as well as considering the actual data from technical and field testing data. To gain more confidence regarding accuracy and reliability of the developed procedure, the proposed procedure and its results were compared and validated with the fuzzy logic method shown in Figure A1 for the developed fuzzy logic model, and with another health index model using dominant score technique developed by other researchers to assess the risk of GIS operating under tropical conditions [9]. Eight GIS bays were selected for comparison because they are in moderate and poor condition while the other bays are in good condition. The comparison results of these three condition assessment models are shown in Table 13. The good agreement between the proposed WSM and fuzzy logic methods can be clearly seen with the error in the range of 0.73% to 4.10%. The error occurs because the fuzzy logic works on the fuzzy rule base system (FRBS) which requires the proper adjustment of various membership functions of each input variable. When comparing the proposed method with the health index dominant score technique, only one GIS bay has a slightly different result because the other method uses a non-linear score of 1, 10, 30, and 100 based on a set of norms and rules, and uses the worst component score to represent the health index score of bays as described in [9]. Since the health index dominant score technique uses the worst score and assigns the scoring criteria to be more sensitive to slight degradation of a GIS component, this makes the probability of failure high and or very high. Hence, when using the health index dominant score technique, the condition of bay E03 is the worst of all the applied models because the criteria for the dielectric subsystem in the afore-mentioned research is designed for high sensitivity with non-linear scoring regarding the problems of gas pressure, gas density, SF6 purity, SO2 content and dew point. Therefore, the problem of E03 bay regarding bad SF6 gas quality leads to a dominant score of 100, and thus a very high probability of failure. However, the proposed method using the weight-average technique results in the E03 bay and gas compartment being assigned a moderate condition.

Table 13. %HI comparison between WSM with aid of AHP, Fuzzy logic model and dominant HI.

Bay	WSM with Aid of AHP		Fuzzy Logic Model Appendix A		HI [9] PLN Research Institute	
	%OHI	Condition	*%OHI*	Condition	Dominant Score	Prob. Fail.
E01	77.70	Moderate	75.91	Moderate	30	HIGH
E02	77.35	Moderate	74.51	Moderate	30	HIGH
E03	84.62	Moderate	83.23	Moderate	100	VERY HIGH
E04	81.82	Moderate	81.23	Moderate	30	HIGH
E05	58.38	Bad	59.32	Bad	100	VERY HIGH
E06	56.65	Bad	58.92	Bad	100	VERY HIGH
E07	86.37	Moderate	84.30	Moderate	30	HIGH
E08	85.05	Moderate	82.86	Moderate	30	HIGH

After the validation of the proposed method, the GIS data in the DBMS was evaluated via the web application software, the result of which is summarized and presented via GUI for 175 bays of nine substations with 11 GIS models: Table 14 presents the summary of the overall bay health index and number of bays categorized by their condition. A majority of overall bay health index values indicates the good condition of 167 bays. Consequently, normal maintenance is suggested to be performed as RVI. In addition, the overall bay health index via GUI illustrates the actual problem of damaged components by the condition evaluation report page. As a result of the moderate condition of the overall bay health index for six bays, it is advised to find the root cause of the problems and solve them. According to the web application report, the problems in those six bays arise from gas quality measurement (SF6 gas low), CT magnetizing curve test, CT and VT secondary circuit having low insulation resistance, respectively. The proportion of good, moderate, and poor overall bay health index values was 95.43%, 3.43%, and 1.14%, respectively. Thus, maintenance strategies can be managed effectively by the prioritization of maintenance tasks on the lowest overall bay health index. In addition, the web application report is used to support the necessary information from the management point of view. The web application display result is shown in Figure 6.

Table 14. Number of bays and their *%OHI* according to their condition.

Range of *%OHI*	Indicator	Bays	*%OHI*
90–100%	Good	167	95.43
60–89%	Moderate	6	3.43
less than 60%	Poor	2	1.14

Figure 6. Bay-E02 web application result display for condition evaluation page.

In the web application, data collection on equipment in terms of technical and management data was completed. The data-based centralization concept was applied to prepare the web application software for further integration with organization management software. From the management point of view, the technical information and inspection test record can be managed by using the web application feature to add, edit, delete and print output of the technical report to support maintenance strategies as CMMS software. To evaluate the condition and health index of an asset, the evaluation criteria need to be completed by reference to the GIS model. Finally, the GIS condition is evaluated and illustrated via the condition evaluation page as shown in Figure 6.

6. Conclusions

In this paper, a procedure for condition assessment of GIS has been proposed using the conventional score and weight method with accuracy improved by using the conventional factor. With the proposed method, the visible aging and invisible aging were considered together to reflect the actual GIS condition. First, the maintenance data from testing and inspection can be systematically stored in the centralized database via the VPN as an online web application form. Next, the actual inspection and testing results are evaluated by using the WSM and the AHP to obtain the $\%HI_C$ and $\%HI_{BAY}$. Since the HI reflects only the visible aging of equipment and its bays, the CF considering invisible aging factors were applied to improve the accuracy of the previously obtained HI to achieve reasonable results for the $\%OHI_{BAY}$. The results have been compared and validated with satisfactory agreement to other methods such as the health index with dominant score techniques and the fuzzy logic method. The proposed procedure has been further developed as web application software, which was used in practice as a decision support tool in an independent power producer business. The 175 bays of GISs in 115 and 230 kV were successfully analyzed by their actual data. Eight of them were in moderate and poor condition and corrective actions were recommended to prevent failure. In addition, the accuracy of the proposed model could be continually improved in the future by regularly reviewing the norms and adjusting the weight according to the defective cases found. Moreover, the failure statistics and available condition monitoring and diagnostic techniques should be considered and integrated in the proposed model, such as dynamic contact resistance and partial discharge measurement to achieve better accuracy.

This software is now in use as a decision support tool in an independent power producer in an important industrial estate in Thailand to facilitate their maintenance plan. The obtained overall bay health index information can be used to prioritize the urgency of maintenance requirement, to effectively plan the available human resource and diagnostic tools and to prevent unplanned outage, as well as to improve system reliability and cost saving.

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Nomenclature

GIS	Gas insulated switchgear
HI	Health index
CF	Conditional factor
AHP	Analytical hierarchy process
IPP	Independent power producer
CB	Circuit breaker
ES	Earthing switch
DS	Disconnecting switch
HS	High-speed earthing switch
CT	Current transformer
VT	Voltage transformer
LCC	Local control cabinet
COMPT	SF6 gas compartment
RVI	Routine visual inspection
IEEE	Institute of electrical and electronics engineers
CIGRE	International council on large electric systems
BIL	Basic lightning impulse insulation level
MCB	Miniature circuit breaker
IR	Insulation resistance
SF6	Sulfur hexafluoride
SO2	Sulfur dioxide
CMMS	Computerized maintenance management system
PHP	Hypertext preprocessor
GUI	Graphic user interface
DBMS	Database management system
WSM	Weight and score method
$\%HIc$	Percentage component health index
$\%HI_{BAY}$	Percentage bay health index
$\%OHI_{BAY}$	Percentage overall health index
OEM	Original design manufacturer
VPN	Virtual private network
FRBS	Fuzzy rule base system

Appendix A

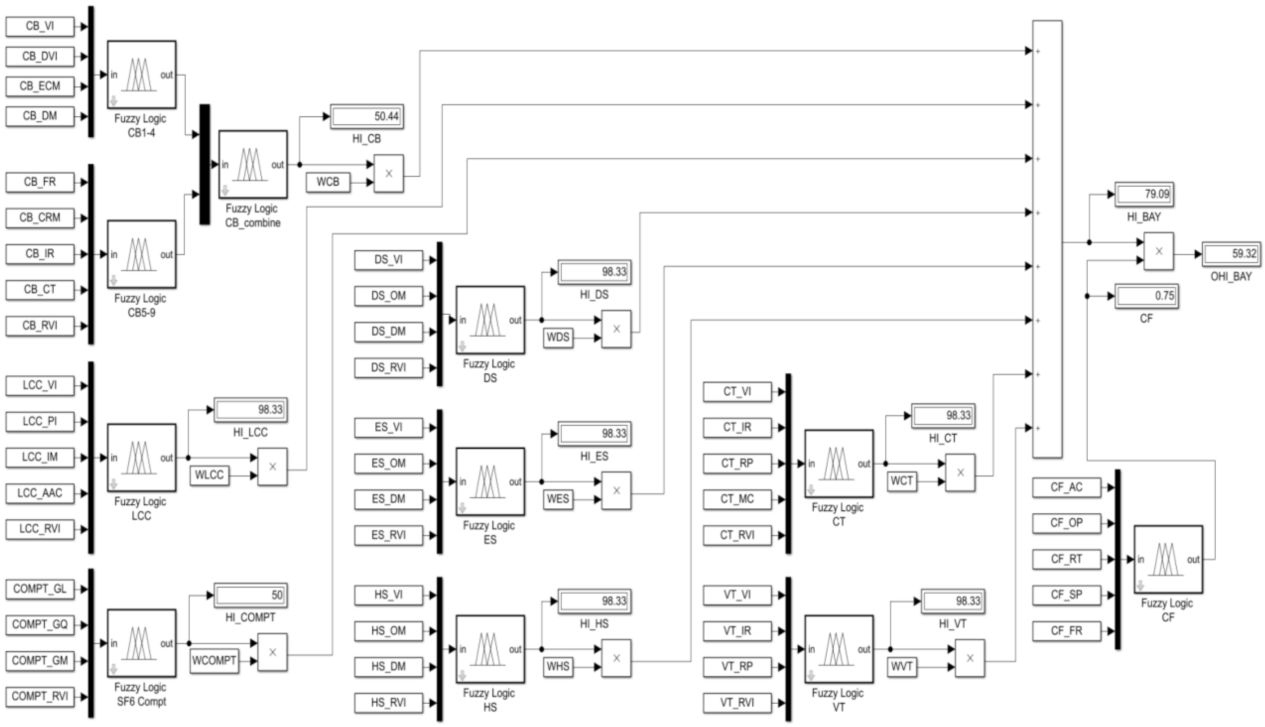

Figure A1. Fuzzy logic model for health index determination of case study E05.

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