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Health index and risk assessment models for Gas Insulated Switchgear (GIS) operating under tropical conditions

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ABSTRACT

This article contains the development of the Health Index (HI) and the Risk Assessment (RA) models for Gas Insulated Switchgear (GIS) operating under tropical conditions. A case study of 631 bays of GIS in tropics with service time from 1 up to 30 years is used during the development of the models.

The basis for the HI model is the condition assessment of subsystems in GIS. This assessment translates the measured parameters from GIS subsystems into condition status based on a set of norms and rules. The condition status is presented in a score, where the non-linear scaling is chosen as it allows the poor parameters to really stand out.

On the other hand, the RA model calculates the risk of a GIS major failure. The Total Failure Probability (TPF) unifies six risk indicators of GIS failures under tropical conditions. The risk may fall into one of the four categories, namely: Low, Medium, High, and Very High.

1. Introduction

Following the deregulation in the energy sector during the 1990′s, also, as triggered by the aging of infrastructure and the increasing demands from regulator and customers, many network utilities adopt the asset management with the hope to gain more earnings, better credit ratings, and stock price [1]. In line with this fact, the emerge of asset management international standard, like the ISO 55000 series in 2014, gains rapid acceptance among network utilities around the globe.

The asset management has its core in the asset decision-making processes. This activity lies simultaneously at the strategic, tactical, and operational level of asset management system, over the lifecycle of the asset.

At the operational level, the asset managers deal with sustaining the asset performance within a short-time horizon, i.e., usually from daily up to one fiscal year [2]. Meanwhile, at the tactical level, the asset managers translate the organizational strategic plan into multi-years asset plans.

This article exemplifies the development of decision-making tools at both operational and tactical levels with a case study of the Gas Insulating Switchgear (GIS) operating under the tropical conditions. The GIS is chosen because of the following reasons: 1. It is a critical asset in the transmission network; 2. There are fewer references on decision-making tools for GIS, in comparison with, for example, the power transformer; 3. Under tropical conditions, we observed failure rate of GIS over twice the value reported by the 3rd CIGRE survey of 2007 [3].

The decision-making tools consist of two, i.e., 1. The Health Index (HI) model; and 2. The Risk Assessment (RA) model. The HI model provides the condition status of GIS in a score. This is helpful since an asset manager is usually responsible for about tens to hundreds of bays of GIS in his network.

At the tactical level, the asset manager needs to identify which GIS is more critical than the others to prioritize the mitigating actions. The decision should be risk-based [4]; therefore, the RA model is proposed in this paper. The model is limited to the risk of having a GIS major failure in the network. Here, the HI-score is incorporated into the calculation of the probability of GIS failure.

The model highlighted the need to only involve condition indicators in the Health Index. These condition indicators should be based on evidence, like from visual inspection or diagnostic and test measurements. On the other hand, the non-condition indicators that might accelerate the appearance of a failure mode have been grouped into the risk indicators (which is also called as susceptibility indicators).

Section 2 reports the field investigation in our case study of 631 bays of GIS operating under tropical conditions. The aim of this section is to present the critical parameters that can lead to GIS failure and summarize the possible methodologies to capture these parameters.

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This step utilizes the Failure Mode Effect Analysis (FMEA) approach.

Section 3 provides the health index model. The basis of the model is the condition assessment that translates the measured parameters into the condition status (and later into the score), based on a set of norms and rules. Section 4 presents the Risk Assessment model, and Section 5 provides the verification of the models on a 150 kV GIS from the case study.

2. Field investigation

2.1. The case study

The case study consists of 631 bays of 500 kV and 150 kV GIS settled under tropical conditions. The historical data used in this study comes from the company records from 2005 up to 2014, including installations since 1984. The service time started from 1 up to 30 years, with an average of 16 years, which represents 9550 CB-bay-years for 150 kV GIS and 1552 CB-bay-years for 500 kV GIS.

The population is heterogeneous as the GIS can be distinguished by different parameters, i.e., grounding type, installation design, phase configuration, driving mechanism and termination type. There are 12 different GIS manufacturers included in this case study.

2.2. Tropical parameters

The tropical conditions consist of two parameters, namely: climate and pollutants. The tropical climate has humid ambient, constant warm-temperature, high rain precipitation and frequent lightning incidence. Meanwhile, the pollutants can be either natural or man's made pollutants. Natural pollutants like salty aerosol or salty film are found in areas close to the sea, while man's made pollutants from the industries or cars, such CO, or SO_2, are located in big cities. Tables 1 and 2 give comparisons of these parameters to the subtropics condition. The man's made pollutants level may vary among countries.

From the parameters in the tables, the corrosion is faster under tropical conditions because of some reasons: 1. Constantly warm temperature with high rain precipitation and long periods of condensation during the night will provide a thin film layer of electrolyte on a metallic surface as a basis for corrosion; 2. The presence of pollutants accelerates the corrosion. The exposed parts in GIS are susceptible to corrosions, especially when the coating was using the incorrect material. Corrosion in between enclosures introduces leakages that in turn reduces the insulation performance.

Also, as seen in Table 2, the amplitude and density of the lightning are higher in the tropics. This increases the susceptibility to insulation breakdown if the surge arrester protection fails.

2.3. Statistical failure analysis on GIS in case study

International Standard in [5] defines failure as the termination of the ability of an item to perform a required function. The definition is extended based on [6] to differentiate between major and minor failures.

The statistical failure analysis has been performed on 35 major failures collected from the case study. 25 failures occurred in 150 kV GIS, while the rest in 500 kV GIS. The failure rates are presented in Table 3, together with the result of the 3rd CIGRE's survey in 2007. The year shown in the table is the construction year.

According to the table, in total, the failure rates in the case study are about twice the value of CIGRE's survey. Also, the GIS from older generation contributed to the higher failure rate. The reason is still unclear, but apart from aging [7], it could be related to 1. Delayed of the overhaul project; and 2. Design improvement of new GIS.

Further statistical analysis has been performed to find the most failed components and the distribution of failure modes in the case study as given in Tables 4 and 5. CIGRE only provides the failure modes of GIS from all voltage classes.

Table 4 shows that surveys from both CIGRE and the case study have similar percentage distributions of failed components for class-5 GIS. In class-2 GIS, the result from the case study demonstrates the

Table 1
Comparison of climate parameters between Tropics (Jakarta, Indonesia) and Subtropics (Amsterdam, the Netherlands) [16–20].

Parameter	Jakarta	Amsterdam
Avg. Annual Relative Humidity (%)	**80**	**83**
Avg. Annual Temperature (°C)	**27**	May–Oct: **14** Nov–Apr: **4**
Avg. Annual Rain Precipitation (mm)	Oct-Mar: **210** Apr-Sep: **90**	**60**
Lightning flash density (strikes/km^2/year)	**15**	**1**
Avg. lightning peak current (kA)	Negative:**71** Positive: **75**	Negative:**19** Positive: **23**
LI_{50} Positive/Negative polarity (kA)*	**28/17**	N/A

* 92% of population is the negative lightning impulse. The number covers the west part of Java.

Table 2
Comparison of pollutants level between Jakarta and Amsterdam [21,22].

Parameter	Jakarta, INA	Amsterdam, NL
Avg. PM_{10} (μg/m^3)	59	27
Avg. SO_2 (μg/m^3)	32	0.8
Avg. CO (μg/m^3)	2947	406
Avg. NO_2 (μg/m^3)	17	39

Table 3
GIS failure rates from the case study and the 3rd CIGRE's survey of 2007. The number is given in per 100 CB-bay-years.

kV	1980s	1990s	2000s	All	CIGRE 3rd Survey
150	1.09	0.51	0.1	0.48	0.24
500	1.54	1.38	0	1.37	0.5

Table 4
Statistics of major components failures in GIS in case study and from the CIGRE's survey of 2007.

Components	Class-2			
	CIGRE		Case Study	
	Abs.	%	Abs.	%
Circuit Breaker (CB)	17	27%	4	16%
Disconnector/Earthing Switches	27	42%	6	24%
Busbar & Busduct	6	9%	5	20%
Terminations	4	6%	6	24%
Surge Arrester	0	0%	0	0%
Instrument Transformer	3	5%	2	8%
Other	7	11%	2	8%
Components	**Class-5**			
	CIGRE		Case Study	
	Abs.	%	Abs.	%
Circuit Breaker (CB)	8	50%	4	40%
Disconnector/Earthing Switches	8	50%	4	40%
Busbar & Busduct	0	0%	0	0%
Terminations	0	0%	1	10%
Surge Arrester	0	0%	1	10%
Instrument Transformer	0	0%	0	0%
Other	0	0%	0	0%

Table 5
Statistics of failure modes in GIS in case study and from the CIGRE's survey of 2007.

Failure Mode	CIGRE (All Class)		Case Study (Class-2)		Case Study (Class-5)	
	Abs.	%	Abs.	%	Abs.	%
Failing to perform requested operation	227	63%	4	16%	4	40%
Loss of electrical connections integrity in primary (e.g. fails to carry current)	1	0.3%	4	16%	0	0%
Loss of electrical connections integrity in secondary	2	0.7%	0	0%	0	0%
Dielectric breakdown in normal service (without switching operation)	67	18%	8	32%	2	20%
Dielectric breakdown in connection with switching operation	14	4%	4	16%	0	0%
Loss of mechanical integrity (mechanical damages of different parts, big SF_6 leakage)	16	5%	3	12%	2	20%
Other (including unknown)	31	9%	2	8%	2	20%

failed components are distributed among the switching components (circuit breaker and switches), terminations, and busbars; while in the CIGRE survey, the disconnector switches are more dominant. In class-5 GIS, both polls agree that Circuit Breaker (CB) and switches are the most frequent failed components.

The CIGRE survey in Table 5 shows that for all voltage classes, the failure mode is dominated by the "failing to perform the requested operation". This result is similar to in class-5 GIS of case study. On the other hand, the "dielectric breakdown" is also significant as this mode is dominant in class-2 GIS of case study, and it covers 22% of failures in the CIGRE's survey. "Loss of electrical integrity" seems to be characteristic for class-2 GIS in the case study, while the percentage distribution of "loss of mechanical integrity" is more significant for GIS in the case study for both classes than the CIGRE's.

A life-data analysis of failures that committed to the unit loss has been conducted. In the case study, 26 out of 35 major failures resulted in the replacement of major parts or even a complete bay of GIS. 25 failures were due to the following failure modes: 1. The insulation breakdown; 2. The primary conductor-joint failure; and 3. The driving mechanism failure.

To obtain a good result, the number of failures in the analysis should not less than five [8]. The available data made possible to generate the hazard rate curves based on the subpopulations of outdoor-150 kV GIS, indoor-150 kV GIS, and outdoor-500 kV GIS. The hazard rate is obtained by dividing the probability density function with the reliability function. It determines the frequency of failures of GIS per CB-bay/year. There is no reported failure for the indoor-500 kV GIS. Fig. 1 shows these curves with 90% confidence bounds.

As seen in Fig. 1, the outdoor GIS has steeper hazard rate, especially in 150 kV GIS. This is probably because the outdoor GIS is exposed to higher environmental stress. The B-lives and the mean-life of each group are given in Table 6.

2.4. Forensic investigation

A forensic investigation through detailed inspections of failed parts and components, and by identifying the cause thoroughly from a comprehensive power failure reports have been conducted on 11 major failures from the case study. Seven cases occurred during normal operation, two incidents occurred in parallel with switching operation, and another two cases were triggered by external voltage transients, including lightning and fault at the connected cable line. Some figures of failed parts from the case study are shown in Fig. 2.

The Failure Mode Effect Analysis (FMEA) determines the potential failure modes from case study. This analysis breaks the GIS into subsystems, and analyses how failures may occur in each (sub) function of subsystems. The results are as follows:

1. The non-dielectric failures may trigger the insulation breakdown, for instance, the primary-joint failure (e.g., due to loosening contacts) and the loss of mechanical integrity in the driving mechanism (e.g. insufficient distance at open positions of contacts).
2. The partial discharges (PD) have been suspected to occur before a complete insulation breakdown. The origins of PD can be due to: poor contacts at the energized parts, free moving particles, microcrack inside the epoxy cable-termination due to, for example, the improper installation procedure, and the insufficient distance between contacts due to loss of integrity at mechanical coupling in driving mechanism.
3. High humidity has been observed in many non-CB enclosures of 150 kV GIS, especially the ones without desiccants. PD and humidity may react to produce by-products which are corrosive. Solid by-products may be accumulated at the spacer surface that significantly reduces the breakdown strength.
4. High humidity also increases the possibility of condensation on the surface of the spacer. Once it occurs, the breakdown strength will be reduced.
5. In a degraded insulation system, the breakdown is more likely to occur under voltage transients. It is even worse if the surge arrester fails to protect.

2.5. Condition parameters for GIS in tropics

Before summarizing the critical parameters, the hierarchical layers in GIS should be understood. Physically, a GIS consists of enclosures with major components (e.g., CB, switches, busbars, termination) contained inside them. Generally, there are five subsystems in each major component, namely: 1. The primary (conductors, joints, main contacts); 2. The secondary (relays and indicators); 3. The dielectrics (solid spacer and SF_6 gas); 4. The driving mechanism (including mechanical coupling and energy storage); and 5. The construction and support (enclosure, foundation, and the monitoring gauges).

Our investigations confirmed that the dielectric is the most critical subsystem in GIS, followed by the primary and the driving mechanism subsystems. These subsystems are grouped as the "dominant subsystems", while the rest as the "non-dominant subsystems". Table 7 summarizes the condition parameters for all subsystems in GIS and the methodologies to capture them. The model only uses the parameters that can be obtained through routine visual inspection (RVI), and diagnostic test and measurement (DM), live or offline, without opening the GIS enclosures. The sensitivity in the table means how sensitive the parameter is in indicating deterioration that leads to failure on related subsystem in GIS, based on the experiences in the case study and presented works in literature.

3. GIS health index model

3.1. Methodology

The core of the HI model is the condition assessment of parameters of subsystems in GIS. The condition parameters have a different relative degree of importance to the HI score. Therefore, the condition parameters have been classified into "dominant" and "non-dominant" parameters.

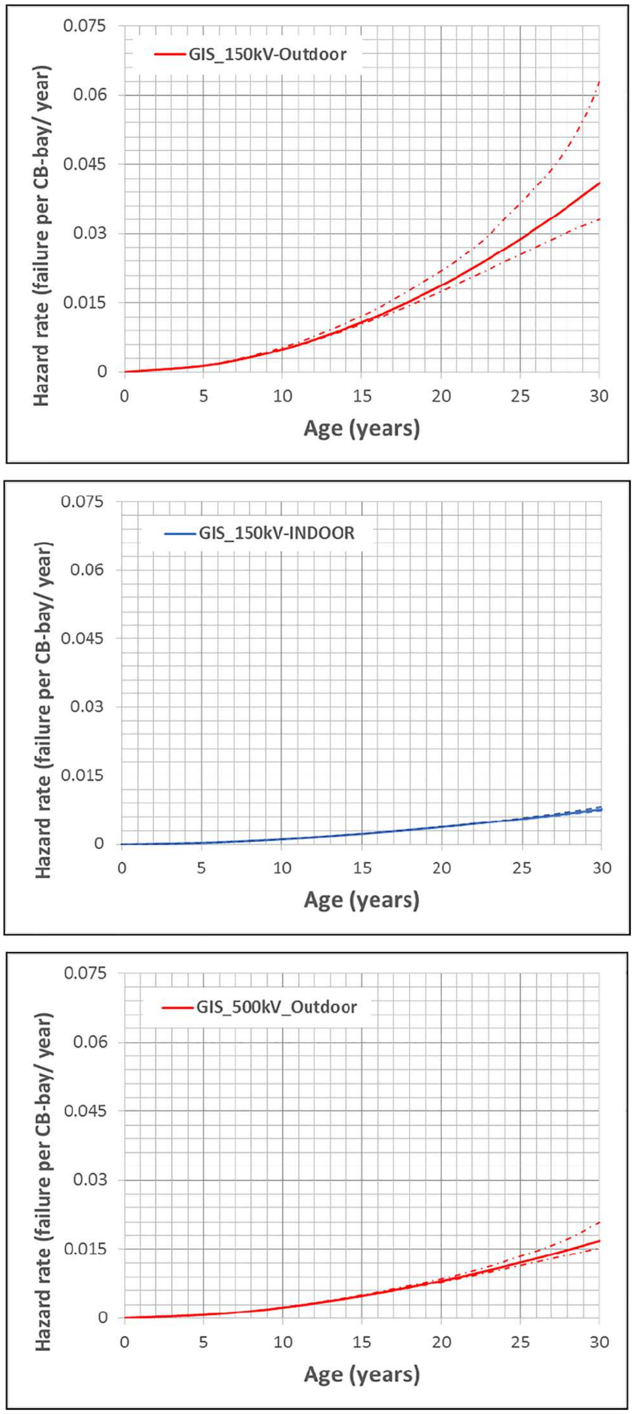

Fig. 1. The hazard rate of GIS (number of failure per CB-bay/year) from different voltage levels in the case study. Respectively from top to bottom: 150 kV-outdoor GIS, 150 kV-indoor GIS, and outdoor-500 kV GIS. (Dashed lines indicate the upper and lower of 90% confidence bounds of hazard rate).

In the condition assessment, the parameters obtained from RVI and DM activities are translated into health status stated in a non-linear score of 1, 10, 30, and 100, based on a set of norms and rules. Table 8 gives the general interpretation of these scores. The approaches to generate norms and rules are provided in the next subsection.

The HI calculation started from the subsystems of GIS components. The summation of subsystem scores defines the component score. Following that, the worst component score defines the score of the bay. Finally, the worst bay score defines the substation score (see Appendix A). In GIS, one or more components may share the same dielectric subsystems in one enclosure. Therefore, at the component level, HI scoring is also possible with the enclosure approach.

Table 6
B-lives and mean life resulting from the statistical analysis of the outdoor-150 kV, indoor-150 kV, and outdoor 500 kV GIS in the case study. The upper and lower values within 90% confidence bounds are given in parenthesis. The value is in years.

Parameter	150 kV Outdoor	150 kV Indoor	500 kV Outdoor
B1 life	8 (4–17)	14 (12–18)	11 (6–18)
B5 life	15 (10–22)	25 (21–30)	19 (15–25)
B10 life	19 (14–26)	33 (26–41)	25 (19–32)
Mean life	36 (27–48)	65 (41–104)	49 (29–80)

Fig. 2. Failed parts of GIS from the case study. *Top*: male and female contacts of failed primary joint-conductors. *Bottom*: insulation breakdown that manifested in flashover of GIS spacer.

3.2. Norms and rules generation

There are several approaches to the norms and rules generation in the HI model, i.e., 1. By setting the boundary from the statistical data; 2. By comparison with the recommendation from standards or guides; 3. By a trending analysis; 4. By comparison with the other results from the sister component(s); 5. By deterministic approach supported by the laboratory experiments; 6. From the expert judgment (for example through a Delphi method); and 7. By the combination of the methods above.

An example of the norm generation for the humidity limit in GIS by using statistical data from the case study is given in the next paragraphs. The other norms and rules generation for GIS can be found in [7,9–11].

The statistical analysis through the distribution fitting method can be used for the definition of the boundary values [12]. An estimated probability density function (PDF) is firstly defined, then the common boundary of “Good”, “Deteriorate”, and “Bad”, is calculated from the 1-σ (68.3%) and 2-σ (95.4%) values. Therefore, if the humidity content in the enclosure is higher than 68.3% of the estimated PDF, the condition status will be “Deteriorated”. While, if the value is above 95.4%, the status is “Bad”. Confidence bounds of 95% are typically added at the boundary of 95.4% [12]. In this model, the boundary is used to further classify “Bad” and “Very Bad” conditions.

Table 7
Condition parameters of subsystems in GIS in tropics and the methodologies to capture the parameters.

Parameter Code	Major Component	What to Check	Method	Condition Parameter	Unit	Sensitivity
Dominant Subsystem-Primary Subsystem						
P1.1	CB		RVI	Cumulative short circuit current	kA^2	+
P1.2	CB		RVI	Number of short circuit interruption	times	+/-
P2.1	CB, Switches		DM	Static contact resistance measurement	μΩ	++
P2.2	All	Contact resistance of primary joint conductor	DM	Hot spot on the enclosure	°C and pattern	+/−
Dominant Subsystem-Dielectric Subsystem						
D1.1	All	Density of SF_6	RVI	Gas Pressure	bar, MPa	+
D1.2			RVI	Gas Density	kg/m^3	++
D2.1		Quality of SF_6	DM	SF_6 Purity	$\%SF_6$	++
D2.2		Partial Discharge Activity	DM	SO_2 content	ppmV	+/−
D2.3			DM	SF_6 by-products other than SO_2	ppmV	+
D2.4			DM	PD Pattern & PD Growth	Multiple	++
D2.5		Possibility to have condensation on the surface of	DM	Humidity content in SF_6	ppmV	++
D2.6		solid insulation	DM	Dew point in SF_6 at gas pressure	C	++
Dominant Subsystem – Driving Mechanism Subsystem						
E1.1	CB DE	Mechanical wear	RVI	Number of mechanical works	times	+
E1.2	Comp. CB	Compressor (energy storage) readiness	RVI	Number of compress. replenish (if any)	times/period	+
E2.1	CB	Mechanical integrity	DM	Contact timing Open & Close	ms	++
E2.2	CB		DM	Contact travel record	Contact position vs. time	++
E2.3	Electric Switches	Electric motor readiness	DM	Motor Current	Ampere	+/−
Non-Dominant Subsystem – Secondary Subsystem						
S1.1	CB, Switches	Any corrosion or dust deposited in wiring	RVI	Corrosion of wiring and aux relays	–	+
S1.2		connections	RVI	Deposited dust in wiring and aux relays	–	+
S2.1			DM	Hot Spot in wiring in LCC	°C and pattern	++
S2.2		Functionality of relays & remote controls	DM	Relay & control function; Indicators check	OK/Not OK	++
Non-Dominant Subsystem – Construction & Support Subsystem						
C1.1	All	Corrosion on enclosures	RVI	Corrosion level	–	+
C1.2			RVI	Deposited Pollutants	–	+
C1.3		Foundation integrity	RVI	Foundation integrity	–	+
C2.1		Accuracy of gauges	DM	Accuracy of gauges	% error	+

Table 8
General interpretation for GIS Health Index score.

Score	Interpretation
1	No found problem, as new, or slight deterioration might occur, and the component can keep working properly
10	Deterioration/aging at normal stage, the asset can survive until the next major inspection.
30	Severe deterioration/aging, additional maintenance may be required.
100	Very severe deterioration/aging (at final stage), additional maintenance or replacement is required, with the possibility of emergency action.

The following demonstration is based on the humidity data from 116 bays of 150 kV GIS from Manufacturer A from 13 locations in the case study. The data was taken from GIS with service time over ten years, and none of them experienced the gas reclamation. The fitted distribution is the Gamma distribution for humidity in CB enclosure, and the Lognormal distribution for humidity in Non-CB enclosure. Fig. 3 shows the PDF and the humidity limit for CB enclosure. The limit of the non-CB enclosure follows the similar approach.

As result, the boundary for humidity limit for 150 kV GIS from Manufacturer A is given in Table 9.

For the other manufacturers, this approach is also applicable as long as the number of data is large enough to have statistical analysis. Otherwise, the maximum limit from the guides, or estimation by using the Magnus formulation can be used [23].

3.3. Health index scoring

In order to gain a comprehensive result, the output of the GIS HI model consists of three different scores, namely: 1. Dominant score, which indicates the degradation of the three dominant subsystems in GIS in tropics; 2. Non-dominant score, which shows the degradation of the secondary and construction subsystems of GIS; and 3. Surge Arrester readiness score, which describes the readiness of the surge arresters in GIS. The last score is important, because the lightning is severe under tropical conditions, and sometimes this component is neglected during the assessment of a complete GIS. This work considers only the externally installed surge arrester. Table 10 presents the scoring of the Health Index for all subsystems in GIS. The worst parameter score, i.e. the highest score in one subsystem, defines the score of each subsystem.

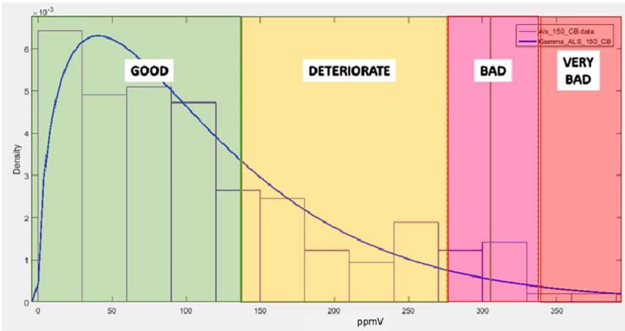

Fig. 3. Boundary values for humidity limit in the CB enclosure for GIS from Manufacturer A. The fitted distribution is the Gamma distribution. The humidity limit for "Deteriorate", "Bad", and "Very Bad", respectively are 135, 277, and 336 ppmV.

Table 9
Norm for humidity content (h, in ppmV) in 150 kV GIS from Manufacturer A in the case study.

Score	Status	CB	Non-CB
1	Good	≤ 135	≤ 209
10	Deteriorate	$135 < h \leq 277$	$209 < h \leq 660$
30	Bad	$277 < h \leq 336$	$660 < h \leq 804$
100	Very Bad	> 336	> 804

3.3.1. HI scoring at the component/enclosure layer

HI score at the component-layer, is the summation of the worst condition parameter score of subsystems in the component (or in the enclosure), as follows:

$$HI_{C\text{-}DOM.} = MAX(HI_{Primary}) + MAX(HI_{Dielectric}) + MAX(HI_{Driving}) \quad (9)$$

$$HI_{C-NON-DOM.} = MAX(HI_{Secondary}) + MAX(HI_{Construction\ \&\ Supports}) \quad (10)$$

Consequently, the dominant-score ranges from 3 to 300, while the non-dominant-score ranges from 2 to 200. The higher the score, the worse the condition.

3.3.2. HI scoring at the bay and substation layer

By using a similar approach, the worst bay-score establishes the score at the substation-layer.

3.3.3. Surge arrester readiness score

The critical part of the surge arrester consists of the zinc oxide blocks. The two factors define the life-limiting factor of these blocks, i.e., the aging of the metal blocks, which is mostly due to the moisture ingress and the number of operations of the surge arrester.

Table 11 presents the condition parameters and the health index score for an air insulated surge arrester. The worst condition parameter determines the score of the surge arrester. Furthermore, the surge arrester readiness score in one GIS is decided by the worst score among the surge arresters installed in a similar substation:

$$SA_{readiness} = MAX(HI_{SA1}, HI_{SA2}, HI_{SA3}, ..., HI_{SAn}) \quad (11)$$

4. Risk assessment model

4.1. Methodology

Risk deals with the uncertainty. It is defined as the product of the probability of an event and its consequences:

$$Risk = likelihood\ of\ an\ event\ x\ consequences \quad (13)$$

The risk assessment model is limited to the risk of having a major failure at the three dominant subsystems of GIS in tropics. The development consists of three stages: 1. the determination of the probability of GIS failure; 2. The decision of consequences based on the business values of network utility; and 3. The development of the risk acceptance matrix based on the probability and the consequences.

In the model, the risk calculation is at the GIS bay-layer. The reason is that the hazard rate curves are elaborated at this layer. As in the HI model, the risk for the whole GIS is determined by the worst risk among the bays.

4.2. Probability of GIS failure in tropics

The probability of a GIS failure depends not only on the condition (health status) of the asset, but also the other parameters, known as the susceptibilities to failure or risk indicators. In the current work, there are six risk indicators increasing the probability of GIS failure in tropics, namely: 1. The condition of critical subsystems of GIS; 2. The hazard rate at particular service time; 3. The number of interruptions per year; 4. The maintenance history; 5. The pollutants level; and 6. The surge arrester readiness (i.e. condition) in substation (see Fig. 4).

The Total Failure Probability factor, TFP, is being introduced, which unifies all failure probabilities from the six risk indicators mentioned above. The TFP factor ranges from 0 to 100, where the higher score means, the higher the failure probability. The calculations of the failure probability based on the six influencing parameters are given in the following sub-subsections.

4.2.1. Probability of failure based on the Health Index Score (P1)

The dominant score from the HI is included as one parameter in the probability calculation. The classification is given in Table 12.

4.2.2. Probability of failure based on the Hazard Rate of GIS population (P2)

The calculation for this parameter, follows this procedure:

Given x, which is the service time of a bay in GIS, at certain voltage level and installation (indoor/outdoor); the hazard rate (h_x) is firstly determined from the curves shown in Fig. 1. The calculation for the 500 kV indoor GIS follows the indoor 150 kV GIS.

If the "dominant-score" from point 1 gives a failure probability of "HIGH" or "VERY HIGH", then it takes the upper-boundary of the hazard curve. If the "dominant-score" is "LOW", the it takes the lower-boundary, otherwise it takes the middle one.

Following this step, if N_x is the number of the bay in the population at a particular service time; the number of failure in the upcoming year, N_f, follows this equation:

$$N_f = N_x \times h_x \quad (14)$$

The probability of failure is then determined based on the N_f value as presented in Table 13.

4.2.3. Probability of failure based on number of interruptions (P3)

In the case study, 19% of fault interruptions in GIS were triggered by the lightning strokes on the connected overhead lines. These interruptions generate overvoltage transients in the insulation system. Our field investigation has shown that breakdown is likely to occur under voltage transients. It is even more likely if the surge arrester fails to protect and in a degraded insulation system. Other interruptions might occur due to, e.g., the system manuever and the clearance of faults.

In the model, the probability of failure is calculated based on the average number of interruptions per year as seen in Table 14. The norm is set based on the interruption statistics in the case study.

4.2.4. Probability of failure based on the maintenance history (P4)

It is assumed that the probability of failure is higher, if: 1. There is a delay of major inspection (overhaul) of the GIS and 2. If there is any history of repetitive corrective maintenance in GIS, for example: due to the hydraulic compression flaws, loss of mechanical integrity, etc. The

Table 10
Scoring of the Health Index for Subsystems in GIS.

Code	Cond. Parameter	Health Score: 1	Health Score: 10	Health Score: 30	Health Score: 100	Sub-system Score
Dominant Subsystem – Primary Subsystem						
P1.1	Cumulative Short Circuit Current	≤30% of limit	30% < limit ≤ 70%	70% < limit ≤ 100%	> Limit	$HI_{Primary\text{-}CB}$ = Max (P1.1, P1.2, P2.1, P2.2) … (1) $HI_{Primary\text{-}Switches}$ = Max (P2.1, P2.2) … (2) $HI_{Primary\text{-}NonSwitching}$ = P2.2 … (3)
P1.2	Number of Short Circuit Interruption	≤30% of limit	30% < limit ≤ 70%	70% < limit ≤ 100%	> Limit	
P2.1	Static Contact Resistance Measurement	$\Delta R_{st\text{-}contact} \le 5\%$	$5\% < \Delta R_{st\text{-}contact} \le 10\%$	$10\% < \Delta R_{st\text{-}contact} \le 20\%$	$\Delta R_{st\text{-}contact} > 20\%$	
P2.2	Hot Spot on the Enclosure	No Hot Spot			With Hot Spot	
Dominant Subsystem – Dielectric Subsystem						
D1.1	Gas Pressure	Up to 0.5%	> 0.5% up to 4%	> 4% up to 7%	> 7%	$HI_{Dielectric}$ = Max ((D1.1 *OR* D1.2), D2.1, D2.2, D2.3, D2.4, D2.5, D2.6) … (4)
D1.2	Gas Density	Up to 0.5%	> 0.5% up to 4%	> 4% up to 7%	> 7%	
D2.1	SF_6 Purity	$G_{pur} \ge 98.7\%$	$97.8\% \le G_{pur} < 98.7\%$	$97\% \le G_{pur} < 97.8\%$	< 97%	
D2.2	SO_2 content	$G_{SO2} \le 1$ ppmV	$1 < G_{SO2} \le 4.6$ ppmV	$4.6 < G_{SO2} \le 10$ ppmV	> 10 ppmV	
D2.3	SF_6 by-products other than SO_2	Air ***OR*** CF_4 < 1% Vol. ***OR*** $SOF_4 + SO_2F_2 + SOF_2 + HF < 50$ ppmV			Air ***OR*** CF_4 ≥ 1% Vol. ***OR*** $SOF_4 + SO_2F_2 + SOF_2 + HF \ge 50$ ppmV	
D2.4	PD Pattern & PD Growth	No PD		PD exist, No Growth	PD exist + Growth	
D2.5	Humidity content in SF_6	See sub Section 3.2				
D2.6	Dew point in SF_6 at gas pressure	Follows the Humidity Limit (by translating ppmV from D2.5 into dew point)				
Dominant Subsystem – Driving Mechanism Subsystem						
E1.1	Number of mechanical works	≤ 10% limit	$10\% < N_{CB} \le 50\%$ limit	$50\% < N_{CB} \le 100\%$ limit	> 100% limit	$HI_{Driving\text{-}CB}$ = MAX (E1.1, E1.2, E2.1, E2.2) … (5) $HI_{Driving\text{-}Switches}$ = MAX (E1.1, E2.3) … (6)
E1.2	Compress. (if any)	No Leak	Month ly reple-nish	Weekly replenish	Daily replenish	
E2.1	Contact timing Open & Close	$\|\Delta t_{contact}\| \le 2\%$	$2\% < \|\Delta t_{contact}\| \le 5\%$	$5\% < \|\Delta t_{contact}\| \le 10\%$	$\|\Delta t_{contact}\| > 10\%$	
E2.2	Contact travel record	Good result			Problem Observed	
E2.3	Motor Current	$\|\Delta I_{motor}\| \le 2\%$	$2\% < \|\Delta I_{motor}\| \le 5\%$	$5\% < \|\Delta I_{motor}\| \le 15\%$	$\|\Delta I_{motor}\| > 15\%$ OR Motor fails	
Non-Dominant Subsystem – Secondary Subsystem						
S1.1	Wiring & Relays Conditions in Local	No corro-sion	Slight corro-sion	Severe corro-sion	Mas-sive Corro-sion & Dust	$HI_{Sec.}$ = Max (S1.1, S1.2, S2.1, S2.2) … (7)
S1.2	Control Cubicle (LCC)	No dust	Slight dust	Severe Dust		
S2.1	Hot Spot in wiring in LCC	No Hot Spot			With Hot Spot	
S2.2	Relay & control function; Indicators check	All OK		Any indi-cator fails	Any relay fails	
Non-Dominant Subsystem – Construction and Support Subsystem						
C1.1	Corrosion level	Slight Corro-sion, No Leaks	Mode-rate Corrosion, No Leaks	Severe Corro-sion, Small Leaks	Catas-tro-phic; Big Leaks	$HI_{C\&S}$ = MAX (C1.1, C1.2, C1.3, C2.1) … (8)
C1.2	Deposited Pollutants	Slightly Pollu-ted	Mode-ratelly Polluted	Highly Pollu-ted	Catas-trophic	
C1.3	Foundation integrity	No crack			With crack, **OR** Misa-ligned enclo-sure	
C2.1	% error with reference gauge	< 1%	1 ≤ err. < 5%	5 ≤ err. < 10%	> 10%	

Table 11
Health Index Scoring for Surge Arrester.

Code	Cond. Parameter	Health Score				Sub-system Score
		1	*10*	*30*	*100*	
Surge Arrester						
A1.1	Number of SA operations	$5 < N_{SA} \le 10$	$10 < N_{SA} \le 15$	$15 < N_{SA} \le 30$	$N_{SA} > 30$	HI_{SA} = MAX (A1.1, A1.2, A1.3) … (12)
A1.2	Leakage Current	$I_{SA} <$ 120% of the min. of the other phases	150% $> I_{SA} \ge$ 120% of the min. of the other phases	200% $> I_{SA} \ge$ 150% of the min. of the other phases	$I_{SA} \ge$ 200% of the min. of the other phases	
A1.3	Service Time	$A_{SA} \le$ 10 years	$10 < A_{SA} \le$ 15 years	$15 < A_{SA} \le$ 20 years	$A_{SA} >$ 20 years	

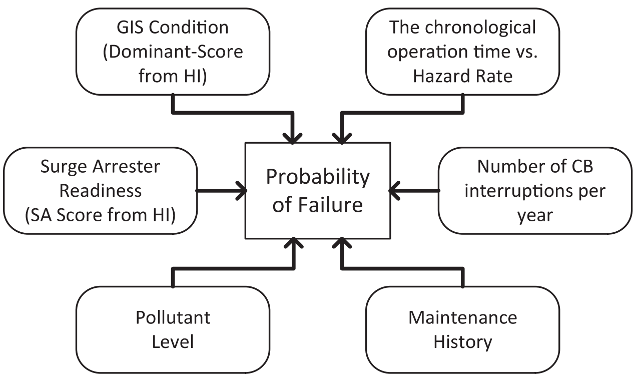

Fig. 4. Various parameters influencing the probability of failure of a GIS in tropics.

Table 12
Probability of failure based on HI Dominant Score (P1).

Dominant Score	Interpretation	Probability of Failure
3	All subsystems have score equal to 1	LOW
3 < up to 30	MAX. 3 subsystems with score of 10	MODERATE
30 < up to 90	MAX. 3 subsystems with score of 30	HIGH
> 90	MIN. 1 subsystem with score of 100	VERY HIGH

Table 13
Probability of failure based on hazard rate (P2).

N_f	Interpretation	Probability of Failure
< 0.1	1 CB-bay fails in > 10 years	LOW
≥0.1–0.2	1 CB-bay fails in 5–10 years	MODERATE
≥0.2–0.5	1 CB-bay fails in 2–5 years	HIGH
≥0.5	1 CB-bay fails in < 2 years	VERY HIGH

Table 14
Probability of failure based on number of interruptions per year (P3).

Average Interruption/year	Probability of Failure
< 1.23	LOW
$1.23 < x \le 1.98$	MODERATE
$1.98 < x \le 2.32$	HIGH
≥ 2.32	VERY HIGH

calculation procedure is as follows.

Firstly, the maximum time for the major inspection in GIS ($t_{MAX\text{-}TO}$) is determined by two factors: 1. The B5-lives from the statistical life-time-assessment; and 2. The "dominant-score" from the HI assessment. The B5-lives has the upper and lower boundaries (see Table 6). The time to major inspection follows these boundaries accordingly to the dominant score of the bay (see Table 15).

Secondly, the "remaining time to the major inspection" is calculated by using the following equation:

Table 15
Maximum time to major inspection based on the B5-lives from statistical life-time assessment.

Voltage Level	GIS Installation	Dominant Score	Time to Major Inspection (in years, $t_{Max\text{-}TO}$)
500 kV	Indoor and Outdoor	3 ≤ up to 30	25
		30 < up to 90	19
		> 90	15
150 kV	Indoor	3 ≤ up to 30	30
		30 < up to 90	25
		> 90	21
	Outdoor	3 ≤ up to 30	22
		30 < up to 90	15
		> 90	10

$$t_{TMO} = (t_{ST} - t_{Max\text{-}TO})/t_{Max\text{-}TO} \quad (15)$$

where

t_{TMO}: the remaining time to the major inspection
t_{ST}: the service time of the bay in GIS from the first operation or from the last major inspection
$t_{Max\text{-}TO}$: the maximum estimated time-to-major overhaul

Finally, the probability of failure is defined based on the t_{TMO} and the existence of repetitive flaws in GIS as shown in Table 16 below.

4.2.5. Probability of failure based on pollutants level (P5)

The probability of failure due to pollutants is determined based on the location of GIS as seen in Table 17. Following the observation in the case study, the outdoor GIS is more susceptible to corrosion, and it has more steep hazard rate than the indoor GIS.

4.2.6. Probability of failure based on surge arrester readiness (P6)

The probability of the insulation breakdown under the lightning stroke is higher if the surge arrester fails to protect [13]. Therefore, the surge arrester readiness score from the HI is elaborated in the probability of failure. The classification is shown in Table 18. This calculation is applicable only for GIS equipped with surge arrester (i.e., GIS connected to the overhead lines).

4.2.7. Total Failure Probability (TFP) score

The procedure to obtain the TFP is as follows: Firstly, a score of 1/

Table 16
Probability of failure based on maintenance history (P4).

N_f	Repetitive Flaws?	Probability of Failure
$t_{TMO} < (-0.5)$	YES	MODERATE
	NO	LOW
$(-0.5) \le t_{TMO} < 0$	YES	HIGH
	NO	MODERATE
$t_{TMO} \ge 0$	YES	VERY HIGH
	NO	HIGH

Table 17
Probability of failure based on pollutants level.

GIS Installation	Location	Probability of Failure
OUTDOOR	Seashore	VERY HIGH
	Industrial Area	VERY HIGH
	Big Cities	VERY HIGH
	Benign	HIGH
INDOOR	Seashore	HIGH
	Industrial Area	HIGH
	Big Cities	MODERATE
	Benign	LOW

Table 18
Probability of failure based surge arrester readiness (P6).

Surge Arrester Score from HI Assessment	Probability of Failure
1	LOW
10	MODERATE
30	HIGH
100	VERY HIGH

10/30/100 is assigned into each risk indicator (P1 to P6) to represent sequentially, “LOW”, “MODERATE”, “HIGH”, and “VERY HIGH” failure probability. Secondly, each score is multiplied by a weighting factor. The weighting factor is decided by the Delphi method based on the heuristics sense of the local experts. It has been agreed that P1 to P4 have a higher degree of criticality than P5 and P6. Meanwhile, P1 and P2 have a slightly higher influence than P3 and P4. The following TFP equation was decided based on that qualitative agreement:

For GIS without surger arrester:

$$TFP_{NO\text{-}SA} = 0.25x(P1) + 0.25x(P2) + 0.2x(P3) + 0.2x(P4) + 0.1x(P5) \quad (16)$$

For GIS with surger arrester:

$$TFP_{SA} = 0.2x(P1) + 0.2x(P2) + 0.2x(P3) + 0.2x(P4) + 0.1x(P5) + 0.1x(P6) \quad (17)$$

where P1 to P6 are squentially the probability of failure mentioned in points 1–6 above.

Eq. (15) has 1024 possible combinations with 347 distinguished outputs. Meanwhile, Eq. (16) has 4096 possible combinations with 264 differentiated outputs. The possible outputs are thend divided equally into four intervals to classify the TFP into four probability levels, i.e., “LOW”, “MODERATE”, “HIGH”, and “VERY HIGH” (see Tables 19 and 20).

4.3. Consequences matrix

In this work, the consequence matrix from the case study is used as seen in Table 21 [14]. The case study is a state-owned company. The consequence from each business value has been classified into five severity levels, namely, “LOW”, “MODERATE”, “SERIOUS”, “SEVERE”, and “CATASTROPHIC”. The importance of the business values follows the order in Table 21.

People from various backgrounds should elaborate on the development of the consequences-matrix. The purpose is to obtain the objectivity.

Table 19
Total Failure Probability Group for GIS without Surge Arrester.

$TFP_{NO\text{-}SA}$ Score	Probability of Failure
≤18.15	LOW
18.2–32.95	MODERATE
33–49.5	HIGH
49.6–100	VERY HIGH

Table 20
Total Failure Probability Group for GIS with Surge Arrester.

$TFP_{NO\text{-}SA}$ Score	Probabilityof Failure
≤ 19	LOW
19.1–32	MODERATE
32.2–49.1	HIGH
49.3–100	VERY HIGH

It was found that the measure of the consequences among different business values might be not comparable. One of the reasons is due to the historical experience owned by the utility.

4.4. Risk acceptance matrix

The risk acceptance matrix is made in two-dimensional of rows and columns as shown in Appendix B. The horizontal scale is the severity level of the consequence, while the vertical is the TFP. The risk for the whole GIS is defined by the worst risk of the bays in a substation.

The risk is classified into four categories, i.e., “VERY HIGH”, “HIGH”, “MODERATE”, and “LOW”. At what level the company can accept the risk is called the “risk acceptance”. Its level depends on the risk attitude of the utility, whether it is a risk taker or a risk avoider.

5. Model verification

The models are verified on a 150 kV GIS from the case study. The GIS is located indoor, with single-phase configuration and it has double busbars with 8 CB-bays (see Appendix C). The service time of the GIS is 23 years, and it has never been overhauled. This article reports only the summary of calculation.

5.1. Health index calculation

The calculation started on subsystems of component following the enclosure configurations. Fig. 5 shows the enclosure configuration for the line feeder and the bus coupler. The transformer and line feeders are merely similar.

As seen in the figure, the CB has a dedicated enclosure. The other enclosures contain more than one component, for example, the enclosure G1 contains a Bus-1 segment, a DS, and a CT bus. The HI scores at the component-layer have been summarized in Tables 22 and 23 based on the enclosure segmentation.

From both tables below, it can be seen that the non-dominant score for both CB and non-CB components have a score of 31. This is due to the defective indicators in the Local Control Cubicle (LCC) in all bays. Meanwhile, in the CB, the highest dominant score is 140 (in Line-1B), this score is due to the high humidity content (score of 100) and the increase of the contact-resistance over 10% in 2 years (score of 30).

In the non-CB components, the dielectric-score for G9 enclosures in all bays is above 100. This is because the high humidity content and the findings of SO_2 which is indicating the PD activity.

Table 24 summarizes the HI scores for all bays following the procedure discussed in Section 3.3 of this article. As seen from this table, Line 1A and 1B have the worst score of 140. Line-1B is the worst because two enclosures are having a score of 140 (i.e., CB and G9). Meanwhile, the non-dominant score for all bays equals to 31.

All Surge Arresters in the GIS have a service time over 20 years (score of 100) with the number of operations in between 20 and 30 times (score of 30). All leakage current monitors were damage so that the leakage current is deducted from the number of operations, i.e., equals to 30. Following Eqs. (11) and (12), the surge arrester readiness score is 100.

Finally, the HI scores at the substation-layer, are as follows: 140 for

Table 21
The consequences matrix based on the business values of a network utility in case study [14].

Importance Rank	Business Value	Severity Level				
		Catastrophic	Severe	Serious	Moderate	Low
1	Safety	Cause death (Fatality)	Cause permanent disability	Cause temporary disability	First aid injury, medical and injury	Near miss
2	Extra Fuel Cost	> 750,000 USD	> 75,000–750,000 USD	> 7,500–75,000 USD	> 750–7500 USD	≤750 USD
3	Energy not Served	> 4000 MWh	> 400–4,000 MWh	> 40–400 MWh	> 4–40 MWh	≤4 MWh
4	Equipment Cost	> 2,000,000 USD	> 200,000–2,000,000 USD	> 20,000–200,000 USD	> 2000–20,000 USD	≤2000 USD
5	Customer Satisfaction	Very High Potential Riot	High Potential Riot	Moderate Potential Riot	Low Potential Riot	No Potential Riot
6	Leadership	Committed to law/ legal action	Top management and government officials are involved	Other external bodies are involved	Handled by middle managerial level	Handled by local substation supervisor
7	Environment	Catastrophic contamination, National warning	Severe contamination, National/Regional warning	High contamination, Regional warning	Medium contamination, local warning	Low contamination

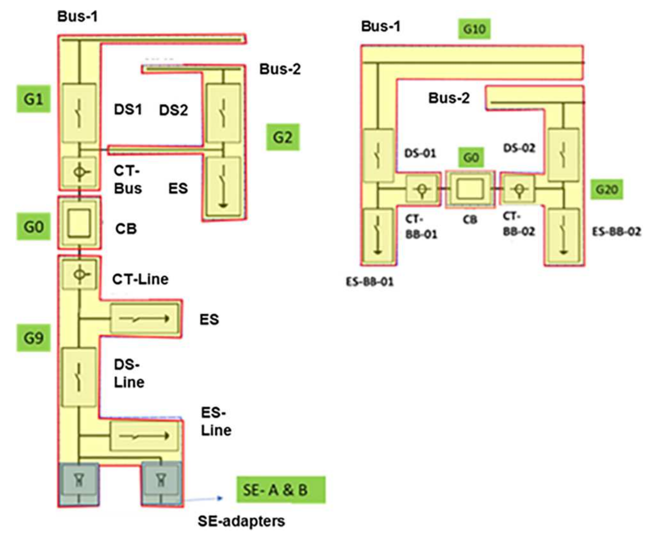

Fig. 5. The enclosure segmentation in the GIS sample: (left) the line-feeder (with the Surge Arrester installed outdoor) and (right) the bus coupler.

Table 22
HI Scores of CB from all bays in GIS sample.

Score	Feeder							
	1A	*1B*	*2A*	*2B*	*T1*	*T2*	*T3*	*BC*
DOM.	50	**140**	21	21	21	30	41	12
Non DOM.	31	31	31	31	31	31	31	31

Table 23
HI Scores of Non-CB components from all bays in GIS sample.

Encl.	Feeder							
	1A	*1B*	*2A*	*2B*	*T1*	*T2*	*T3*	*BC*
Dominant Score								
G1/10	111	12	21	12	12	12	12	12
G2/20	21	12	21	12	12	12	12	21
G9	**140**	**140**	111	111	111	111	111	–
Non-Dominant Score								
G1/10	31	31	31	31	31	31	31	31
G2/20	31	31	31	31	31	31	31	31
G9	31	31	31	31	31	31	31	–

Table 24
HI Score of bays in GIS sample.

Score	Feeder							
	1A	*1B*	*2A*	*2B*	*T1*	*T2*	*T3*	*BC*
DOM.	140	140	111	111	111	130	111	21
Non DOM.	31	31	31	31	31	31	31	31

the Dominant score, 31 for the Non-dominant score, and 100 for Surge Arrester readiness score. Any score with a minimum of 100 is indicating a catastrophic level in one of the GIS subsystems.

5.2. Risk calculation

It is worth to underline that the risk calculation is conducted at the bay-layer. The probability of failure based on the six influencing parameters are the following:

Table 25
Scores of failure probability factors in all bays in GIS Sample.

Bay	P1	P2	P3	P4	P5	P6	TFP	Prob.
1A	100	1	1	30	1	100	36.5	HIGH
1B	100	1	10	30	1	100	**38.3**	HIGH
2A	100	1	1	30	1	100	36.5	HIGH
2B	100	1	10	30	1	100	**38.3**	HIGH
T1	100	1	10	30	1	100	**38.3**	HIGH
T2	100	1	1	30	1	100	36.5	HIGH
T3	100	1	1	30	1	100	36.5	HIGH
BC	10	1	1	1	1	100	12.7	LOW

Table 26
Summary of the consequences in the GIS Sample.

Business Values	Consequence Possibility	Severity Level
Safety	Permanent disability on the respiratory system	SEVERE
Extra Fuel Cost	No extra fuel cost	LOW
ENS (Energy Not Served)	80 MWh	SERIOUS
Equipment Cost	~600 k USD	SEVERE
Customer Satisfaction	Possibility to have riot is low	MODERATE
Leadership	The GIS supply the arsenal owned by the military department	SERIOUS
Environment	Cleaning the contamination may take weeks, penalty by the local authority may apply	MODERATE

1. The HI dominant scores for all bays in GIS sample has been given in Tables 21 and 22. The probability of failure based on these scores (P1) follows the classification in Table 12.
2. The hazard rate is low, this is because the GIS is indoor. It is found that the expected number of failure (N_f) in the upcoming year is 0.069, which means “LOW” probability of failure (P2) for all bays.
3. The average number of interruptions per year in this GIS ranges from 1 up to 1.6, which means “LOW to MODERATE” probability of failure due to interruptions at various bays in GIS Sample (P3).
4. The GIS has no repetitive flaws, but the major inspections have been delayed. Consequently, the probability of failure for majority bays is “HIGH” (P4).
5. The GIS is located indoor in a benign area. Following the values in Table 17, the probability of failure is “LOW” (P5).
6. As mentioned in HI calculation, the surge arrester readiness score is 100. Therefore, the failure probability from the surge arrester readiness factor is “VERY HIGH” (P6).

The scores of failure probability factors and the TFP from each bay are summarized in Table 25.

The consequences have been calculated through the field investigation and the contingency-simulation of failure. It is assumed that a major failure at any bay will result in the outage of all feeders in the GIS sample. Table 26 presents the results.

Based on the worst TFP factor, and the consequences, the risk of having a major failure in the GIS sample has been summarized in Table 27.

As seen from the table, the considered GIS has a “HIGH” risk regarding Safety, Equipment Cost, Energy Not Served, and Leadership.

In order to rank the risk among GIS from different locations, the following procedures might apply: 1. By taking into account the importance of the business values (e.g., HIGH risk on Safety is more critical than HIGH risk on Leadership); 2. By introducing the weighting factor in the multi-criteria analysis to convert all the consequences from business values into a single metric (e.g., by presenting the Total Risk Score (TRS); 3. By using the RPN (Risk Prioritisation Number) methodology [15]. The RPN is not discussed in this article.

Table 27
Risk Matrix in the GIS Sample.

Probability of Failure		Consequence Severity				
Qualitatively	TFP_{SA}	LOW	MODERATE	SERIOUS	SEVERE	CATASTHROPIC
		Extra F. Cost	- Cust. Satisfaction - Environment	- ENS - Leadership	- Safety - Eq. Cost	
VERY HIGH	49.3 - 100	M	H	H	VH	VH
HIGH	**32.2 - 49.1**	L	M	H	H	VH
MODERATE	19.1 - 32	L	M	M	H	H
LOW	≤ 19	L	L	L	M	M

6. Summary and conclusions

This article proposes health index and risk assessment models for asset management at the operational and tactical levels with a case study of GIS operating under tropical conditions. To achieve these purposes, thorough statistical analysis and forensic investigations in a case study consisting of 631 bays of GIS operating in tropics have been performed in order to find the critical condition parameters that committed to GIS failures.

Our investigation found the high failure rates in the case study, where the tropical parameters, i.e., the humid ambient and the frequent lightning incidence, have been suspected to be involved in the performance of GIS, both directly and indirectly. Also, we determined the critical subsystems of GIS in tropics, i.e., the primary, the dielectrics, and the driving mechanism subsystems. The secondary, and the construction and support subsystems, are less critical. These findings are considered in the HI and RA models.

The HI model provides a comprehensive GIS condition, which stated in three scores, i.e., 1. The dominant score; 2. The non-dominant score; and 3. The surge arrester readiness score. The scaling of the score is non-linear to stand-out the weak parameter in the result. This has been proven during verification, as any score of minimum 100 is indicating that at least a single subsystem in GIS has a catastrophic condition.

In the risk assessment model, the Total Failure Probability (TFP) factor has been introduced which unifies six risk indicators that increase the failure probability of GIS in the tropics. The consequences matrix will be characteristic of each utility, depending on their business values and historical experiences.

The presented models have been successfully implemented in a GIS sample from the case study. It is suggested to regularly review the models, particularly on the norms and weighting factors, to obtain better accuracy.

Acknowledgement

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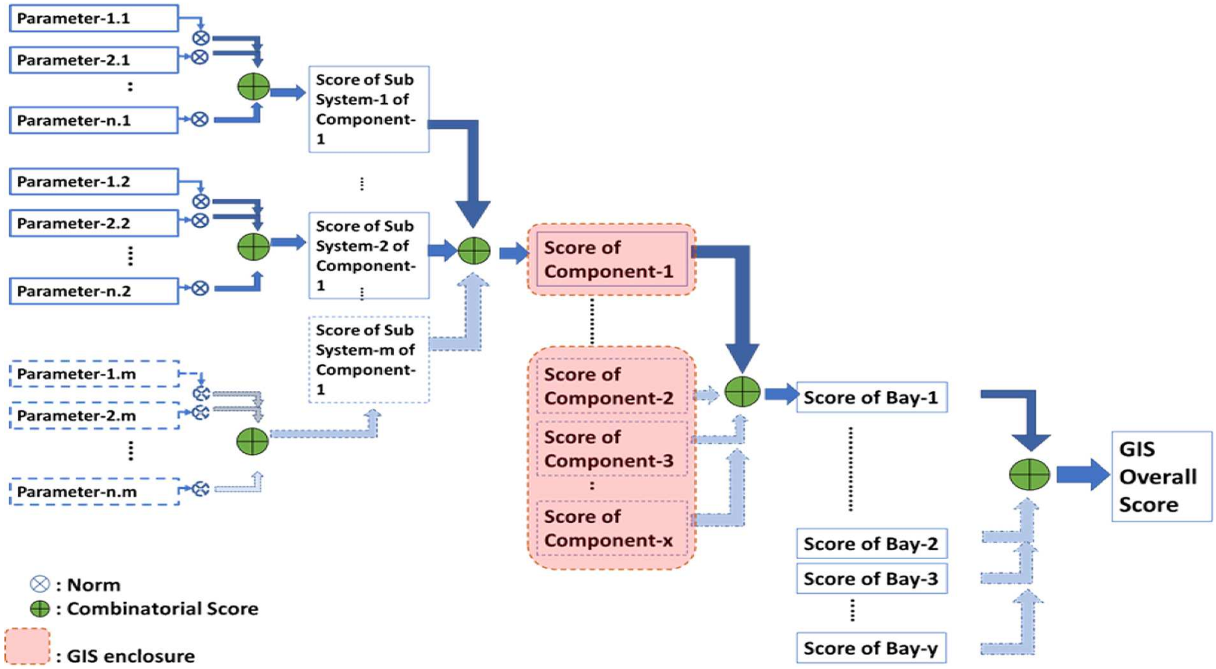
Appendix A

The hierarchical of the scoring procedure in the GIS HI Model.



Appendix B

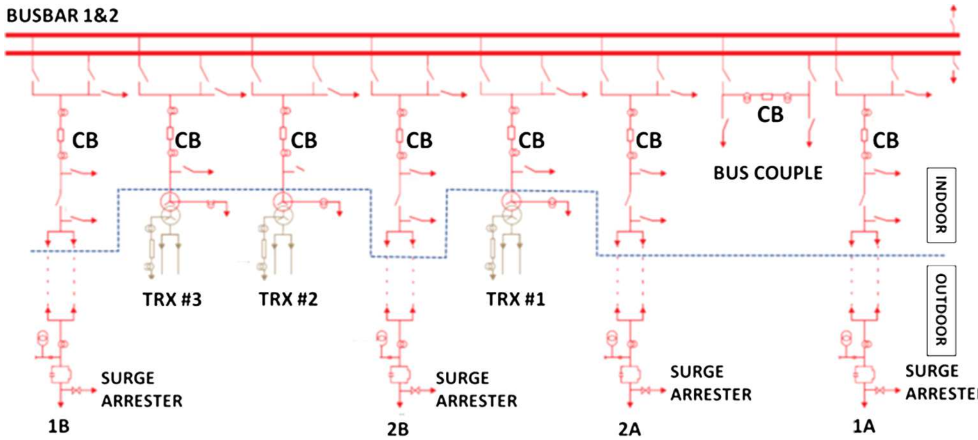
The consequence matrix based on the business values of network utility in the case study.

Probability of Failure			Consequence Severity				
Qualitatively	TFP_{NO-SA}	TFP_{SA}	LOW	MODERATE	SERIOUS	SEVERE	CATASTHROPIC
VERY HIGH	49.6-100	49.3 - 100	M	H	H	VH	VH
HIGH	33 - 49.5	32.2 - 49.1	L	M	H	H	VH
MODERATE	18.2 - 32.95	19.1 - 32	L	M	M	H	H
LOW	≤ 18.15	≤ 19	L	L	L	M	M

VH	: Very High
H	: High
M	: Moderate
L	: Low

Appendix C

The Single Line Diagram of GIS used for model verification in the case study. The GIS consists of 8 bays, i.e. 3 transformer feeders, 4-line feeders and a bus coupler. The surge arresters are installed outdoors.



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