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Health Indexing for High Voltage Gas-Insulated Switchgear (HVAC GIS)

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Health Indexing for High Voltage Gas-Insulated Switchgear (HVAC GIS)

Proefschrift

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To my parents, Sana, and my children

Summary

High voltage alternating current gas-insulated switchgear (HVAC GIS) substations have been in use for more than 40 years. Compared to other types of high-voltage substations, i.e. air-insulated switchgear (AIS) and hybrid substations, GIS substations have proven to be very reliable and resistant to environmental conditions. In addition, GIS substations can offer physical compactness and lower life cycle costs.

Notwithstanding, failures in GIS have been reported. A failure in GIS can have a significant impact on cost and performance.

It is the main task of the asset manager to identify and schedule necessary maintenance actions in a timely fashion. Such decision making is important in minimising operating costs by preventing failures, especially those that would have a significantly negative impact. It is also important in meeting the lifetime expectation of the GIS. Expected future constraints, such as increased asset performance and savings, will demand further reduction in the maintenance cost and further extension of the GIS lifetime.

The main objective of this thesis therefore was to investigate how a health indexing methodology can be obtained to support maintenance decisions for GIS that allows GIS to meet lifetime expectations. The study investigated how dedicated diagnostics should be selected based on knowledge of GIS failure modes and risk assessment of those modes. It also investigated how diagnostic data should be used to derive the health indicators.

The risk assessment has shown that the highest level of risk at the GIS components level is “*Medium*” (3 on a scale from 1 to 7, where 1 equals “*Negligible*” and 7 equals “*Extreme*”). The “*Medium*” level results from the failure mode “*Dielectric breakdown*”. However, due to the low frequency of occurrence of failures at the GIS level, the risk level for the complete shutdown of the GIS substation is Negligible (1 on the same scale).

Our analysis shows that the most efficient set of diagnostic techniques consists of 12 out of the commonly available 25 diagnostic techniques in GIS. It was shown that partial discharge detection and the stored energy are within the top five efficient diagnostics in use. Those two diagnostics were therefore further investigated. Overlapping diagnoses, which are diagnoses that detect the same failure mode, have been considered critically as these diagnoses can increase the diagnostics cumulative costs without significantly increasing the number of detected failures.

The detectability and interpretation of critical insulation defects was verified by empirical investigations. The results have provided the information that was needed to establish effective knowledge rules for partial discharge. For stored energy and partial discharge measurements, we also succeeded in formulating the required knowledge rules. These knowledge rules enable a suitable interpretation of diagnostic data in terms of technical statuses at the GIS component level.

Stress factors on GIS, like switching operations and gas leakage in the presence of an insulation defect, have also been considered as they may change the overall health index result.

The health index at the component level has been derived by combining the technical statuses. Using the fault tree analysis, the health index at busbar and bay level is derived

from the health indexes of the components. Finally, the overall health index at GIS level is derived from the health indexes at bay level using fault tree analysis again.

Furthermore, the GIS health index is utilised along with the assessed impact on the business values in the case of a failure for go/no go maintenance decision making. Once the maintenance need is assessed, deferred maintenance and immediate maintenance actions are scheduled on the basis of the remaining time to failure and time needed to plan the maintenance.

In conclusion, we have introduced a health indexing methodology with tools for selecting an optimal set of diagnostic techniques that improves maintenance scheduling and actions to reach the optimal technical and economic performance of AC high voltage gas-insulated switchgear.

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Chapter 1 Introduction

CHAPTER 1 INTRODUCTION

1.1 *GIS: A general overview*

High-voltage alternating current gas-insulated switchgear (HVAC GIS) substations have been in operation for more than 40 years. Compared to other types of high-voltage substations, i.e. air-insulated switchgear (AIS) and hybrid substations, GIS substations have proven to be very reliable and resistant to environmental conditions. In addition, GIS substations can offer physical compactness and lower life cycle costs [1].

Gas-insulated switchgear (GIS) is a compact, multiple component assembly enclosed in a grounded metallic housing in which the primary insulating medium is a compressed gas. GIS normally consists of busbars, switching components, and associated equipment [2]. Due to its suitable electrical and thermal properties, sulphur hexafluoride (SF_6 gas) is usually used as the primary insulating medium in GIS. Figure 1-1 shows our case study A, a typical example of a 380 kV double-busbar GIS substation in Meeden, TenneT TSO B.V. the Netherlands.

Figure 1-1: Part of a typical 380 kV GIS substation (case study A)

High-voltage GIS substations are mainly applied in the range of voltage classes of 52 kV and higher. They operate in electricity distribution and transmission applications. Up to 2009, more than 80,000 GIS bays in service operation have been reported, and this number increases annually [1].

Although GIS substations are said to be very reliable, failures in GIS are reported in [3], [4], and [5]. Based on the results published in these surveys, the causes of major failures which result in the cessation of one or more fundamental GIS functions can be classified into three groups [6]:

1- pre-service causes, which are introduced during a period before putting the GIS into service (e.g. design fault, engineering fault, incorrect transport or installation, and failure during commissioning);

2- in-service causes, which are introduced during service and include any excess in the operating conditions beyond the specified values and limits (e.g. load, voltage, and switching overvoltage exceeding the ratings; mechanical and environmental stress exceeding the ratings; corrosion; wear / ageing; incorrect operation; incorrect monitoring; electrical failure of adjacent equipment; mechanical failure of adjacent equipment; human error; and incorrect maintenance);

3- unknown or other causes.

The causes for major failures in GIS are summarised in Figure 1-2. Pre-service causes still account for a portion of the reported failures in GIS, but failures due to pre-service causes have been reduced over the years. Manufacturers are using stricter testing procedures. Quality controls have been improved, and more attention is paid to adequate transportation. The quality controls, for instance, ensure the removal of moving particles bigger than 1-2 mm during the manufacturing process. Therefore, pre-service failures in GIS have not been considered in this thesis. In maintenance practice, however, particles with lengths over a centimetre have been found. In this thesis, the relevance of such particles to failure initiation has been further investigated experimentally.

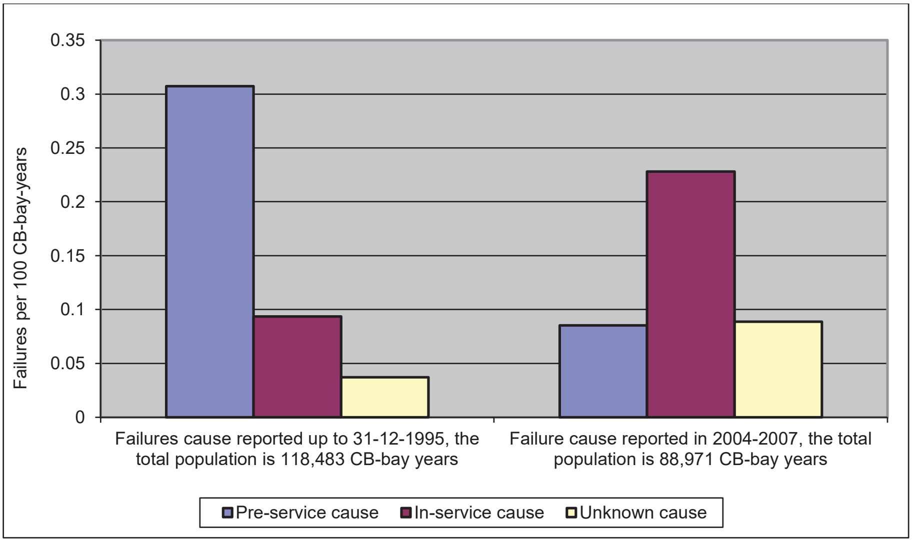


Figure 1-2: Distribution of primary cause of major failures in GIS [4] [5]

Unlike pre-service causes, in-service causes have increased over the years as shown in Figure 1-2. In-service causes are therefore selected as the topic of this thesis.

A failure in GIS can be very costly, time consuming to repair, and impactful on safety and the environment. If a failure requires a long time to be repaired, additional costs for the non-delivered power and penalty costs should be considered as well (e.g. when there is a lack in the system redundancy). A maximum downtime of 42 days and an average of 12 days has been reported[1] to clear circuit breaker failures in indoor GIS of voltage class 300 kV < U < 500 kV (class 4) [4].

[1] This time includes the repair downtime and time to get spare parts.

In addition to the failure impact, the failure frequency is important. Some failures can have a relatively low impact but can occur very frequently. Such failures affect the long-term reliability. Usually, a risk matrix expresses risk levels by plotting the failure frequency versus the failure impact.

The GIS has to operate reliably throughout its designed lifetime. Therefore, in-service failures have to be prevented as much as possible. Diagnostic techniques can be used to predict upcoming failures. Based on the diagnostic outcomes and risk assessment, maintenance activities can be initiated to correct upcoming failures preventively whenever possible and necessary.

Assigning diagnostics and maintenance work can be a challenging task. While the GIS reliability has to be ensured highly at a predefined level, the total costs have to be kept at a low level, creating a difficult balancing act.

Increasing the maintenance work will increase the system reliability but also will increase the total costs, and vice versa. However, there is an optimum level between the total costs and the system reliability. This relationship is illustrated in Figure 1-3.

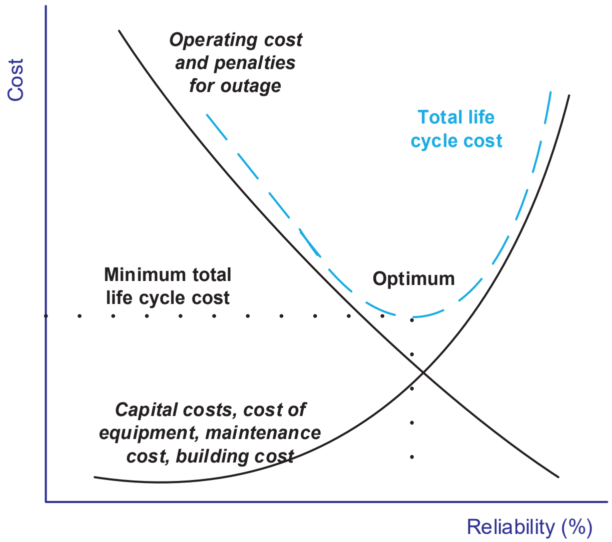


Figure 1-3: Reliability vs. cost [11]

During the useful lifetime of an existing GIS, costs like capital cost, cost of equipment, and building cost are already spent and cannot be further controlled. Diagnostic and maintenance costs, operating cost, and penalties can be controlled.

To achieve adequate control over when expenditure in terms of diagnostics and maintenance is required to keep the desired reliability, an effective method is to develop one overall indicator that describes the asset condition. That overall indicator can be used to start and prioritise the needed maintenance actions. Such an indicator of the asset condition is referred to as the health index [7].

The following questions have to be considered to control the diagnostic and maintenance costs:

1. Which GIS components should be diagnosed?
2. Which diagnostic methods have to be used?
3. Should the selected diagnostic methods be performed separately or be integrated in a package of measures?
4. How should the condition data be interpreted and the component's actual condition and the time to failure be estimated?
5. How should the health index for the GIS, which helps in prioritising and scheduling maintenance activities, be developed?

These questions are further addressed in the objectives in the next section. Hereafter, the term GIS includes reference to all switchgear components.

1.2 *Objectives of this thesis*

The main goal of this thesis is to obtain a health indexing methodology which can support maintenance decisions for GIS on site. For such methodology, it has to be investigated how dedicated diagnostics should be selected based on the knowledge of GIS failure modes and their risk assessment, and how diagnostic interpretations can be verified and used to derive the condition indicators. Accordingly, the research approach has been defined into the following specific objectives:

1. To analyse and assess the risks related with failure modes in GIS at three different levels, namely the component, busbar and bay, and GIS level.
2. To explore among commonly available diagnostic techniques for GIS an adequate set of diagnostics able to reveal risky failure modes in GIS. Subsequently to develop a ranking methodology that prioritises the selected diagnostics, namely a methodology which relates the failure risk to both the diagnostic costs and the diagnostic detection ability of failure modes.
3. To verify the detectability and interpretation of critical insulation defects by empirical observations.
4. To understand how the status of GIS can be assessed by suitable interpretation of condition data. To formulate accordingly a set of knowledge rules that implement this interpretation from condition data into statuses.
5. To express concisely the actual condition of the GIS based on its status through the use of health indexes at the components level, busbar and bay level, and GIS level and, finally, to show how the health indexes are used to initiate maintenance.

1.3 *Approach*

The approach adopted for this thesis is schematically shown in Figure 1-4. It consists of the following steps:

1. Determine the risk of failures of GIS. For this purpose, we performed a Failure Mode Effects and Criticality Analysis (FMECA). Firstly, the failure impact of various failure modes in GIS is determined (refer to Chapter 2). Secondly, the impact results are combined with the GIS failure frequency reported by Cigré to estimate the risk related with these failure modes (refer to Chapter 3).
2. Investigate how to select and prioritise proper diagnostics based on risk level, cost of diagnostics, and the detection ability to reduce the risk estimated for GIS (refer to Chapter 4).
3. Collect sufficient data and information through the laboratory experiments and publications for the selected and prioritised diagnostics (refer to Chapter 5).
4. Obtain/derive insight into the interpretation of diagnostics result in order to formulate knowledge rules. These rules process the diagnostic data into three technical statuses: "*Normal*", "*Deviated*", and "*Faulty*" (refer to Chapter 6).
5. Build up a risk-based condition assessment system that processes the GIS status into a multiple level health index for the components level, the busbar and bay level, and the GIS level. The health index provides a tool to support maintenance decisions in time (refer to Chapter 7).

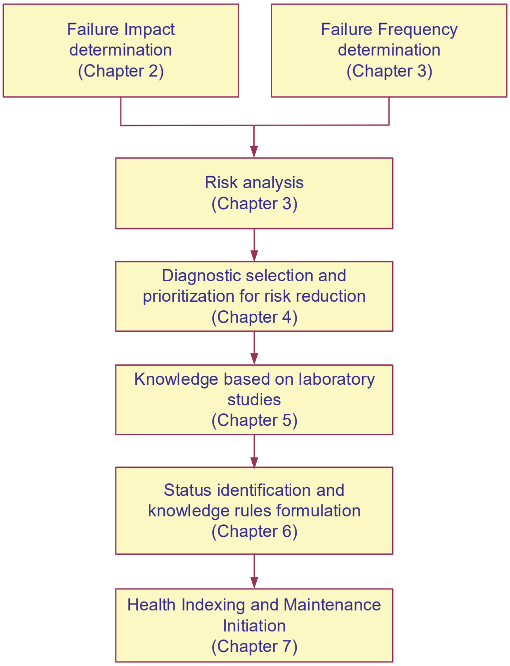


Figure 1-4: Stepwise approach towards health index for GIS

1.4 *Outline of the thesis*

Following this introduction, this thesis is divided into several chapters.

- ***Chapter 2*** describes the reported GIS failures and discusses the possible failure modes and the effects of failures by subjecting the GIS to a FMECA.
- ***Chapter 3*** assesses the risk of failure modes in GIS and its components by combining the FMECA results from Chapter 2 with the reported failures data of international surveys.
- ***Chapter 4*** derives a methodology to distinguish and to prioritise the necessary diagnostic techniques required to reduce the rate of risky failure modes in GIS.
- ***Chapter 5*** presents and discusses the laboratory investigations. Dielectric breakdown initiated by free moving particles and protrusions in GIS under various voltage shapes and voltage amplitudes has been investigated. The experimental results are necessary to develop the knowledge rules discussed in Chapter 6.
- ***Chapter 6*** illustrates how to implement a set of knowledge rules for indexing the status of the GIS and its components based on condition data. The performance of the GIS and its components has been classified into three statuses, i.e. "*Normal*", "*Deviated*", and "*Failed"* Operation.
- ***Chapter 7*** processes the statuses of the GIS and its components to obtain a multiple level health index. The initiation of maintenance actions based on the health index results is also discussed.
- ***Chapter 8*** presents conclusions and recommendations for future work.

Chapter 2 Failure Mode Impact Analysis

CHAPTER2 FAILURE MODE IMPACT ANALYSIS

2.1 *Introduction*

Post-failure investigation is usually performed to understand the origin of failure, failure frequency, and consequences of failure. In addition, the statistical analysis of failure data may offer estimations on future expectation based on past failure behaviour.

Identifying the causes of failure in GIS is important both for the manufacturer as well as the user. Identification helps the manufacturer improve GIS design by taking the causes of the failure into account. Moreover, identification of failure helps the user in developing proper maintenance strategies and/or requiring new specifications in future.

In GIS, the failure modes and their effects are identified based on reported failure data in the international surveys of Cigré [3], [4], and [18]. To analyse the failure modes and determine the severity or impact of failure, we subjected the GIS in Case Study A, as shown in Figure 2-1, to a Failure Mode, Effects, and Criticality Analysis (FMECA).

FMECA is a step-by-step structured method suitable for identifying significant failures, failure consequences, and failure risks based on the frequency and impact of the failures [15], [16]. Further details are given in Appendix A.

GIS failure modes are determined in this chapter, whereas the failure risk are focused on in the following chapter

To improve readability, the style "*italic font between quotation marks*" was used for thesis-specific definitions, such as the results of the technical status and risk assessment throughout the thesis chapters.

2.2 *Failure Mode, Effects, and Criticality Analysis application in GIS*

The installations in a GIS substation can be sub-divided into primary and secondary components [11]. The primary components include measurement transformers, connections (e.g. bushings), and switching devices. Secondary components include control and protection devices. In this thesis, only the management of primary components is investigated.

The primary components are arranged in bays in GIS. Based on bay functionality, three bay types can be distinguished, namely feeding bay, transverse bay, and sectionalising bay. GIS bays are mutually connected through the busbar system. The common arrangements of GIS installations in a substation are as follows [20]:

- Single busbar
- Double busbar
- Double busbar with double circuit breaker
- One and a half circuit breaker scheme
- Ring busbar (meshed and cross arrangement)

Over 90 per cent of existing GIS are either single busbar arrangements (prevailing in voltage ranges below 200 kV) or double busbar arrangements (prevailing in voltage ranges higher than 300 kV) [20].

In this thesis, the double busbar arrangement is the focus, and the FMECA has been applied to the typical double busbar GIS substation of our study case A, for which the circuit diagram is shown in Figure 2-1. In principle, the FMECA method described here can be applied to any GIS arrangement.

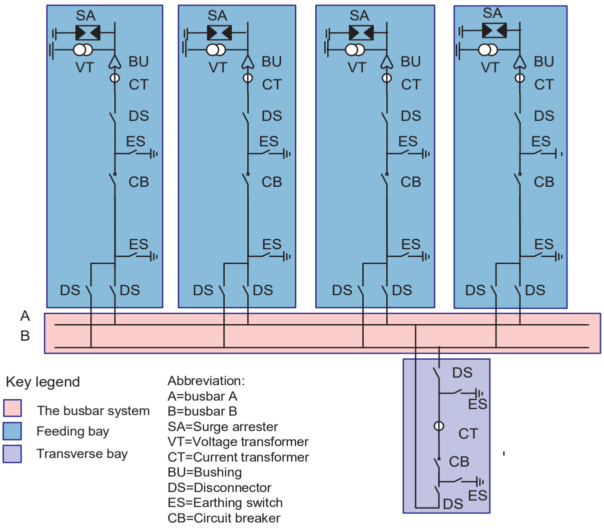


Figure 2-1: Circuit diagram of a typical double busbar GIS substation arrangement (Case Study A)

The typical GIS substation, as shown in Figure 2-1, consists of four feeding bays and one transverse bay. These bays are connected by a double busbar system. The typical components included in GIS bays are also listed in Figure 2-1.

FMECA was applied, as described in [16]. In our study case A, we decomposed the GIS installation into five indenture levels, as shown in Figure 2-2. The resulting indenture levels are as follows:

1. The GIS level
2. The busbar and the GIS bay level
3. The primary components level
4. The sub-components level
5. The basic building components level

The last indenture level is determined when all basic building components are reached. The basic building components are the basic building units or components that are not further subdivided into the next indenture level once they reach a certain (lowest) functional level.

As an example, the FMECA application to indenture level 3 is illustrated in the following sections. FMECA results for all other indenture levels are listed in Appendix A1 to A5.

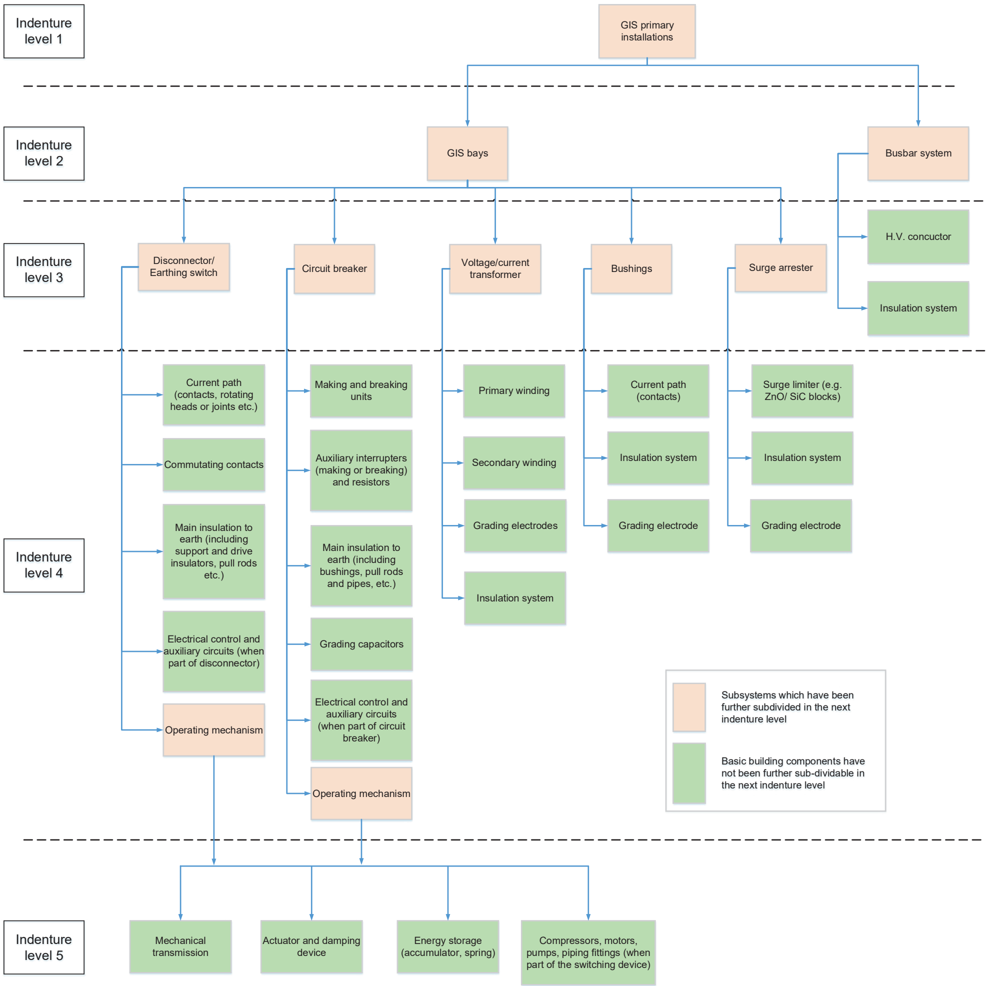


Figure 2-2: The five indenture levels distinguished in the primary GIS system

2.3 *The primary components level*

At indenture level 3, the following GIS substation primary components are identified: circuit breakers, disconnecting/earthing switches, current and voltage transformers, bushings, and surge arresters. Each of these components can have different failure modes. Therefore, different effects and consequences of failures are defined. GIS primary component functions, failure modes, and effects are defined in the FMECA worksheet (Appendix A) . For example, the circuit breaker function, failure modes, failure effects, and the failure impact are defined as the following:

Function

The circuit breaker's main function is to interrupt fault currents. A failure is defined when the circuit breaker is not able (or will not be able in the future) to perform its functionality.

Failure mode

Six failure modes have mainly been defined by Cigré [21] for the circuit breaker as follows:

- Does not operate on command (DNOC)
- Locking in open or closed position (LOCP)
- Dielectric breakdown (DBD)
- Loss of mechanical integrity (mechanical damages to different parts, such as insulators, etc.) (LMI)
- Open without command (OWC)
- Other/unknown (OTHER)

Failure effect

Once the failure mode has been determined, a distinction is made between local and system effects. A local effect is intended to describe the effect of failure on the component function itself, which includes circuit breaking. Meanwhile, a system effect is intended to describe the failure effect on the system, which is the GIS bay of which the circuit breaker comprises.

As an example, the local effect of the failure mode "*Dielectric breakdown*" is "*Circuit is unintentionally closed with possible safety and economic damage issues*", while the system effect is "*Phase-to-ground fault with possible safety and economical damage that required interruption/isolation of the bay*".

Failure impact

Besides the estimation of failure modes and effects, the failure impact must also be assessed and quantified. This process is conducted in three stages:

1. Determining the business values of interest to GIS owner

   The following six business values are typically considered important to GIS owners: safety issues, environmental issues, system performance (including non-deliverance of electricity), repair costs, regulatory compliance, and owner reputation.

2. Constructing impact levels

   Failure impacts must be determined and ranked structurally, and so impact levels are used. As an example, seven levels of failure impact are described in Table 2-1. These levels range from "*Very low*" to "*Extreme*".

3. Estimating the impact level to business values for each failure mode

   The impact level on different business values is determined.

Based on expert discussions, we developed the seven levels of failure impact, as shown in Table 2-1. This rating of impact levels has been used to indicate the failure impact in the FMECA worksheets at all indenture levels described in this thesis.

Failure impact can differ according failure mode. For example, failure mode "*Dielectric breakdown*" would have a failure impact and level, as shown in Table 2-2. Results of other failure modes can be found in Appendix A. However, the failure impact and its level may change as the situation changes. For instance, the impact of the failure mode "*Dielectric breakdown*" on environment would be different if gas is released due to disc rupture.

An overview of the failure impact of the primary components at level 3 is shown from Figure 2-3 until Figure 2-7.

Overall failure impact

After the level of impact is determined for each business value, an overall impact level must be determined. In this work, we define overall failure impact level using the highest individual level of impact.

It has been noticed that failure modes have mainly impact on cost and system performance among the selected business values. Less impact is evaluated on safety, company reputation, environment and regulatory compliance. Five failure modes on indenture level 3 have been distinguished as having high to extreme impact on the business values:

- Dielectric breakdown
- Loss of electrical/mechanical integrity
- Does not operate on command
- Locking in open or closed position
- Opens without command

For all other indenture levels, FMECA has been constructed similarly to how it has been described above and in Section 2.2. FMECA results of other indenture levels than indenture level 3 are listed in Appendix A.

Table 2-1: An example of seven levels failure impact table

	Business values					
Impact level	***Safety***	***Performance (outage time)***	***Repair cost (10^3 €)***	***Company reputation***	***Environment (Effect on the ecosystem in m^2)***	***Regulatory compliance***
Very low	No impact	Less than 1 hour	<1	No impact	< 0.1	No impact
Low	Minor injury with/without first aid	Between 1 and 4 hours	1-10	Internal unrest without media attention	0.1-1	Individual/grouped complaint of violating rules
Moderate	Medical treatment required from a general practitioner (GP)	Between 4 and 8 hours	10-100	Unrest in sector without media attention	1-10	Formal request for information
High	Moderate injury (absence due to injury of ≤7 weeks)	Between 8 and 12 hours	100-1,000	Regional media attention	10-100	Formal warning or investigation
Very high	Absence due to injury of >7 weeks	Between 12 and 16 hours	1,000-10,000	Limited national media attention Political attention on local level	100-1,000	Fine ≤ 10×10^6 euro
Serious	Permanent physical incapacitation	Between 16 and 24 hours	10,000-100,000	Considerable national media attention Political treatment on national level	1,000-10,000	Fine > 10×10^6 euro or binding regulations and Criminal law procedure
Extreme	Vital accident of an employee	More than 24 hours	>100,000	Long-term national media attention or international media attention Political treatment on national level	>10,000	Repeal License to Operate and Criminal law sanction

Table 2-2: Impact and level of impact of dielectric breakdown in GIS

	Business values					
	Safety	***Performance (outage time)***	***Repair cost ($\times 10^3$ €)***	***Company reputation***	***Environment (Effect on the ecosystem in square meter)***	***Regulatory compliance***
Situation	GIS substations are normally unmanned, and no injuries are expected.	A dielectric breakdown will terminate the circuit breaker functionality and will result in a long-time outage. Where the GIS station is a part of a redundant grid, the outage time will be short.	Opening the GIS, failure investigation, cleaning, repairing, etc. are required.	It is not expected that the company reputation will be affected.	Where no rupture disc is released, no environmental impact is expected	No regulatory compliance issue is expected
Impact	No impact	Less than 1 hour	100-1,000	No impact	No impact	No impact
Impact level	Very low	Very low	High	Very low	Very low	Very low

From Figure 2-3 to Figure 2-7, the following abbreviations are used:

DNOC: does not operate on command

LOCP: locking in open or closed position

DBD: dielectric breakdown

LMI: loss of mechanical integrity (mechanical damages of different parts like insulators, etc.)

LOIM: leakage of insulation medium

OWC: open without command

Other: Other/unknown

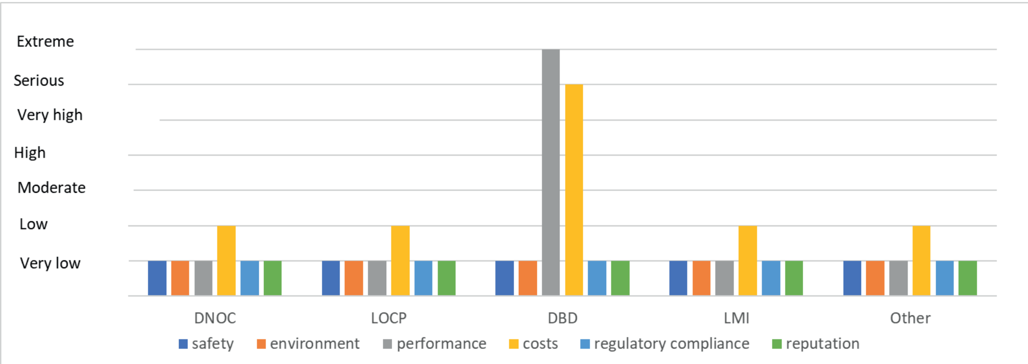


Figure 2-3: Impact on business values due to DS/ES failure modes at bay level

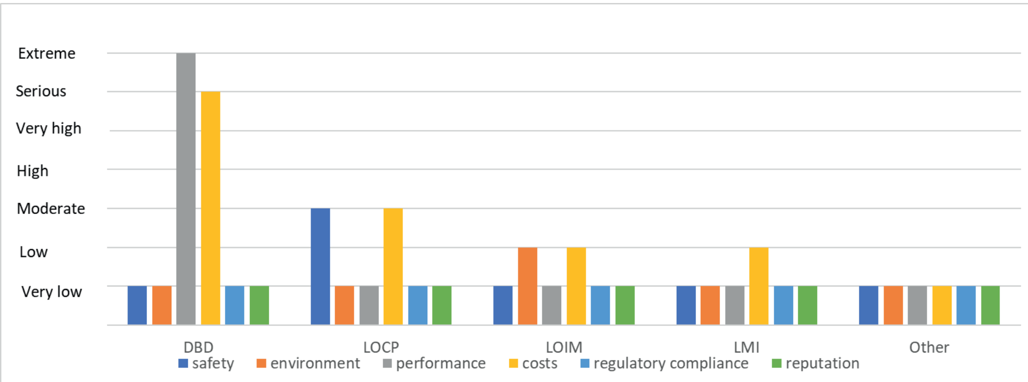


Figure 2-4: Impact on business values due to current /voltage transformer failure modes at bay level

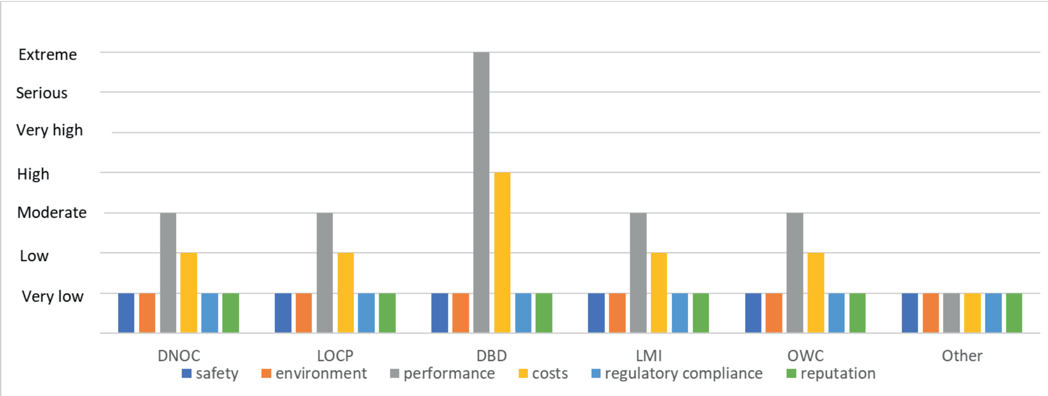


Figure 2-5: Impact on business values due to CB failure modes at bay level

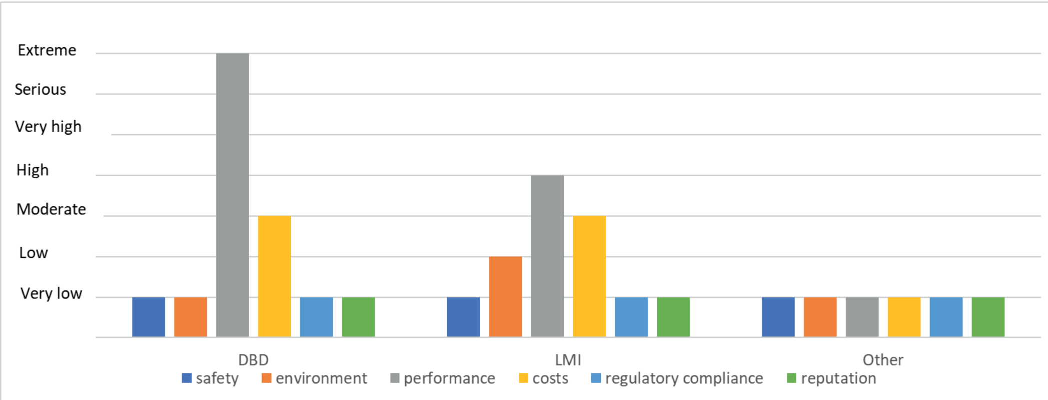


Figure 2-6: Impact on business values due to bushing/ termination failure modes at bay level

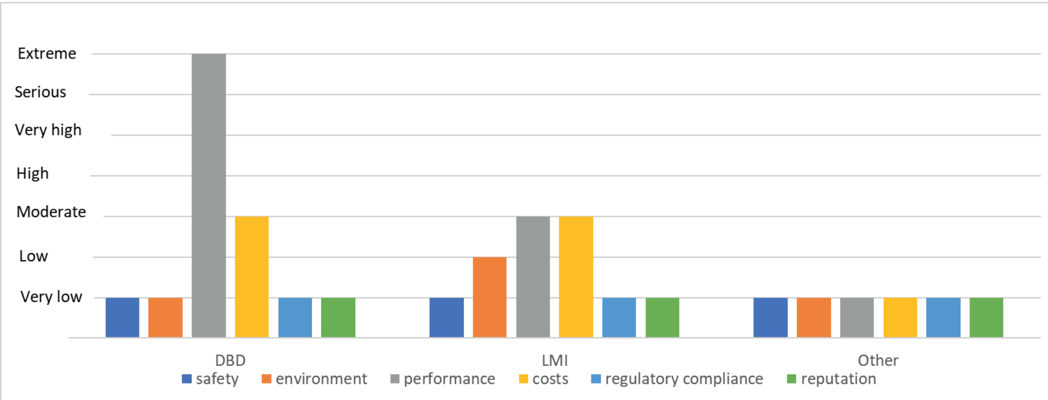


Figure 2-7: Impact on business values due to surge arrester failure modes at bay level

An alternative method to determine overall failure impact is to calculate a value instead of describing the highest individual level of the failure impact.

This method is a bit more complicated, and special care should be taken to select a proper scale that reflects the actual impact level on each business value.

Calculating a value for the overall failure of impact is achieved by

1- Assigning numbers to rank the seven levels of failure impact described in Table 2-1. A linear and logarithmic scales can be selected for this purpose.

2- Determining the overall failure of impact. One way to make this determination is to add the individual ranks as given in equation 2-1.

$$O = \sum_{i=1}^{n} K_i \qquad \text{……...} \quad 2\text{-}1$$

Where

O = the overall value of impact,

n = total number of business values and is equal to 6 in our case, and

K = the individual rank of each business value.

Equation 2-1 is used when all business values are of the same importance. However, when it is necessary to distinguish between more and less important business values, a weighting factor is used, and Equation 2-1 becomes

$$O = \sum_{i=1}^{n} W_i K_i, \qquad \text{……...} \quad 2\text{-}2$$

where (W) is a weighting factor and its sum should equal to 1 i.e. $\sum_{i=1}^{n} W_i = 1$.

2.4 Overall impacts per indenture level

The overall failure impacts for all GIS levels derived in Appendix A and are summarised in Table 2-3 till Table 2-7. Failure modes with very low and low impact levels have not been included in these tables.

Table 2-3: A summary of failure modes and impacts at GIS level, indenture level 1

System	*Sub- system*	*Failure mode*	*Overall Failure impact*
High-voltage grid	GIS substation	Losing three feeders due to any reason e.g. dielectric breakdown, failure to perform requested operation, etc.	High
		Losing the complete busbar system	High

Table 2-4: A summary of failure modes and impacts at the busbar and GIS bay level, indenture level 2

System	*Sub- system*	*Failure mode*	*Overall Failure impact*
GIS substation	GIS bays	Failing to perform requested operation	Moderate
		Dielectric breakdown	High
		Loss of electrical/mechanical integrity	Moderate
	The busbar system	Dielectric breakdown in one busbar	High
		Loss of electrical/mechanical integrity in one busbar	Moderate
		Dielectric breakdown in both busbars	Extreme
		Loss of electrical/mechanical integrity in both busbars	Very high

Table 2-5: A summary of failure modes and impacts at the primary component level, indenture level 3

System	*Sub- system*	*Failure mode*	*Overall Failure impact*
GIS bays	Disconnector/earthing switch	Does not operate on command	Low
		Locking in open or closed position	Low
		Dielectric breakdown	Extreme
		Loos of Mechanical integrity	Low
	Circuit breaker	Does not operate on command	Moderate
		Locking in open or closed position	Moderate
		Dielectric breakdown	Extreme
		Loos of Mechanical integrity	Moderate
		Opens without command	Moderate

Table 2-5 Continued: A summary of failure modes and impacts at the primary component level, indenture level 3

System	*Sub- system*	*Failure mode*	*Overall Failure impact*
GIS bays	Current/voltage transformer	Dielectric breakdown	Extreme
		Loss of electrical integrity in primary and secondary	Moderate
		Leakage of insulation medium	Low
		Loss of mechanical integrity (e.g. insulator damage)	Low
	Bushing/ Termination	Dielectric breakdown	Extreme
		Loss of mechanical/electrical integrity	High
	Surge arrester	Dielectric breakdown	Extreme
		Loss of mechanical/electrical integrity	Moderate

Table 2-6: A summary of failure modes and impacts at the sub-component level, indenture level 4

System	*Sub-system*	*Failure mode*	*Overall Failure impact*
Circuit breaker	Making and breaking units	Cracks, loose parts, broken parts, wear, burn in contacts	Extreme
	Auxiliary interrupters (making or breaking) and resistors	Cracks, loose parts, broken parts, wear, burn in contacts	Extreme
	Main insulation to earth (including bushings, pull rods and pipes, etc.)	Aging, wear, overload, loose parts, broken parts, cracks, dielectric failure	Extreme
	Grading capacitors	Leaks, corrosion, dielectric failure, and damaged electric connections from the capacitor stack to the terminals	Extreme
	Electrical control and auxiliary circuits (when part of circuit breaker)	Defective components, e.g. coil, limiting resistor, auxiliary switch or relay. Non-continuity of the circuit, incorrect blocking (lockout), earth fault in the close/opening circuit	Moderate
	Operating mechanism	Aging, wear, overloaded, leak, loose parts and broken parts	Moderate
Disconnector/ Earthing switch	Current path (contacts, rotating heads or joints, etc.)	Overload, wear, loose parts and broken parts	Extreme
	Commutating contacts	Aging, wear, overload, loose parts, broken parts, cracks, burn in contacts	Extreme

Table 2-6 Continued: A summary of failure modes and impacts at the sub-component level, indenture level 4

System	*Sub-system*	*Failure mode*	*Overall Failure impact*
Disconnector/ Earthing switch	Main insulation to earth (including support and drive insulators, pull rods, etc.)	Aging, wear, overload, loose parts, broken parts, cracks, dielectric failure	Extreme
	Electrical control and auxiliary circuits (when part of disconnector)	Defects of a component e.g. coil, auxiliary switch or relay. Non-continuity of the circuit, earth fault in the close/opening circuit	Moderate
	Operating mechanism	Aging, wear, overload, leak, loose parts and broken parts	Moderate
Current transformer	Secondary winding	Aging, wear, overload, loose parts, broken parts, short circuit	Extreme
	Grading electrodes	Damage, getting loose	Extreme
	Insulation	Aging, wear, overloaded, loose parts, broken parts, cracks, dielectric failure	Extreme
Voltage transformer	Primary winding	Wear, loose parts, broken parts, short circuit	Extreme
	Secondary winding	Wear, overload, loose parts, broken parts, short circuit	Extreme
	Grading electrodes	Damage, getting loose	Extreme
	Insulation	Aging, wear, overloaded, loose parts, broken parts, cracks, dielectric failure	Extreme
Surge arrester	Surge limiter (e.g. ZnO/ SiC blocks)	Damage, wear, overloaded, loose parts and broken parts	Extreme
	Insulation	Aging, wear, overloaded, loose parts, broken parts, cracks, dielectric failure	Extreme
	Grading electrode	Damage, getting loose	Extreme
Bushing/ Termination	Current path (contacts)	Overload, wear, loose parts, broken parts, burn in contacts	Extreme
	Insulation	Aging, wear, overloaded, loose parts, broken parts, cracks, dielectric failure	Extreme
	Grading electrode	Damage, getting loose	Extreme

Table 2-7: A summary of the failure modes and impacts at the basic building components level, indenture level 5

System	*Sub-system*	*Failure mode*	*Overall Failure impact*
Operating mechanism	Compressors, motors, pumps, piping fittings (when part of the switching device)	Any failure mode e.g. incorrect operation, wear / ageing, corrosion, leakage that would cause a malfunction of the sub-component	Moderate
	Energy storage (accumulator, spring) (when part of the switching device)		
	Actuator and damping device (when part of the switching device)		
	Mechanical transmission (when part of the switching device)		

2.5 Conclusions

Based on the discussion of this chapter, the following can be concluded:

1. We divided the GIS substation into a maximum of five indenture levels to achieve the basic building components.
2. The failure modes that have been distinguished have impact escalation mainly on cost and system performance among the selected business values.

Chapter 3 Risk Assessment of Failures in GIS

CHAPTER 3 RISK ASSESSMENT OF FAILURES IN GIS

3.1 Introduction

In service, major GIS failures can occur due to different types of stress, such as electrical, mechanical, and thermal stress resulting from operating GIS e.g. beyond specifications. Diagnostic methods can be used to foresee upcoming failures and reveal their symptoms.

Currently, it is difficult to detect all the kinds of GIS failures due to e.g. a lack of suitable diagnostics, inappropriate diagnostic selection, limited diagnostic detection ability, misinterpretation of diagnostic outcomes, and the limited time available to detect the occurrence of sudden failures. It may also be decided to accept certain failures, such as when the consequences of the failure are negligible, or when the required diagnostic technique is very expensive or impractical.

Therefore, a risk assessment must be performed of all possible GIS failure modes in order to identify risky components, recognise how risk at one indenture level might impact another level, and provide concise information and analysis to decide how to treat a particular failure.

Generally, the probability of occurrence of failure and the failure impact to the business values is defined as risk. Risk can be represented as [23]

$$Risk = \quad failure\ frequency \times failure\ impact \qquad \ldots\ldots\ldots \quad 3\text{-}1$$

The failure impact to business values (as discussed in Chapter 2) has been combined with failure frequency to assess the risk associated with failures in GIS and its components.

In the next sections, we performed a risk assessment of the first three GIS indenture levels, i.e. the GIS system level, the bay level, and the primary components level.

We did not include the FMECA worksheet for indenture level 4 (the sub-component level) and level 5 (the basic building component level) due to the lack of published data from users on failure probability (failure frequency). Once this data is available, the critical basic components can be added in the same way. The risk assessment results for indenture levels 1 to 3 are listed in Appendix B.2. Also, if new data for failure frequency became available or GIS user's specific data is used, the risk results can deviate from our results obtained for the first three GIS indenture levels.

3.2 *Risk assessment at the primary components level*

The indenture level 3 contains all GIS primary components. The failure frequency of these components is estimated, categorised into frequency classes, and combined with the failure impact (as discussed in Chapter 2). A risk matrix has been used to categorise risk values into risk levels.

3.2.1 Failure frequency estimation at the primary component level

Failure frequency (λ) refers to the average number of failures observed during a given period, typically one year. The failure frequencies of primary GIS components (indenture level 3) and the failure modes have been taken as reported in the international surveys [5] [24]. The failure frequency for the GIS primary components are summarised in Table 3-1.

Table 3-1: Failure frequency for the primary components in GIS

Primary components	$\lambda_{GIS\ component}$ *(failures per CB-bay-year)*	*Reference*
Circuit breaker (λ_{CB})	1.40×10^{-3}	[21]
Disconnector/earthing switch (λ_{DE})	1.30×10^{-3}	[22]
Instrument transformer (λ_{IT})	0.90×10^{-3}	[24]
SF_6 bushing ($\lambda_{Bushing}$)	0.10×10^{-3}	[5]
Surge arrester (λ_{SA})	0.04×10^{-3}	

At the primary component level, different failure modes have been distinguished for each component. The failure frequency for the individual failure modes is calculated as follows:

$$\lambda_{fm} = \lambda_{GIS\ component}\ x_{fm}, \quad \text{……..} \quad 3\text{-}2$$

Where

λ_{fm} = the failure frequency per failure mode per primary component,

$\lambda_{GIS\ component}$ = the total failure frequency per primary component, refer to Table 3-1,

x_{fm} = the contribution of the individual failure mode as a percentage of the total number of failures (these values are listed in Appendix B.1).

As an example, the failure frequencies for the circuit breaker's individual failure modes have been calculated by equation 3-2, and the results are listed in Table 3-2.

Table 3-2: Failure frequency of circuit breaker failure modes

Failure mode	x_{fm} **(%) [21]**	λ_{fm} *(failures per CB-bay-year)*
Does not operate on command	46.0	6.44×10^{-4}
Locking in open or closed position (alarm has been triggered by the control system)	19.4	2.71×10^{-4}
Electrical breakdown	19.4	2.71×10^{-4}
Loss of mechanical integrity (mechanical damages of different parts like insulators, etc.)	7.2	1.01×10^{-4}
Opens without command	2.4	3.36×10^{-5}
Other/Unknown	5.6	7.84×10^{-5}
Total	**100**	$\mathbf{1.40\times10^{-3}}$

For the circuit breaker, the failure mode "*Does not operate on command*" was found to have the highest failure frequency, followed by "*Locking in open or closed position*" and

"*Electrical breakdown*", which have the same failure frequency. Other failure modes with lower failure frequency followed.

3.2.2 Failure frequency classification at the primary components level

To avoid overestimating or underestimating risk, ranking of the impact level, selection of the proper frequency class and determining the acceptable risk level are based on experts' judgement. Failure impact has been discussed in further detail in the previous chapter. Seven classes have been selected for failure frequency, as shown in Table 3-3 [25].

10 failures per CB-bay-year or more have been interpreted as the worst-case scenario and are categorised in the frequency class "*Very often*". A failure frequency less than 10^{-4} failures per CB-bay-year has been interpreted as the lowest expected failure frequency and categorised in the frequency class "*Almost impossible*". Failure frequency between 10 and 10^{-4} failures per CB-bay-year has been interpreted, as shown in Table 3-3. The failure frequency class table, which is based on discussions with asset managers and experts, is shown in Table 3-3 and used for all GIS indenture levels.

Table 3-3: Failure frequency class table

Failure frequency (failures per CB-bay-year)	***Frequency class***
$F < 10^{-4}$	Almost impossible
$10^{-3} > F \geq 10^{-4}$	Unlikely
$10^{-2} > F \geq 10^{-3}$	Possible
$10^{-1} > F \geq 10^{-2}$	Probable
$1 > F \geq 10^{-1}$	Frequently
$10 > F \geq 1$	Often
$F \geq 10$	Very often

The failure frequencies of the circuit breaker failure modes have been categorised in classes, as shown in Table 3-4.

Table 3-4: Failure frequency classification of circuit breaker failure modes at indenture level 3

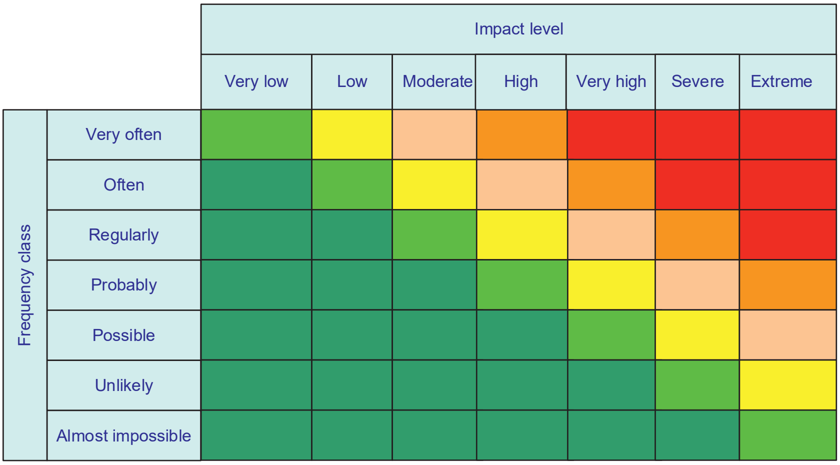
Failure mode	λ_{fm} ***(failures per CB-bay-year)***	***Frequency class***
Does not operate on command	6.44×10^{-4}	Unlikely
Locking in open or closed position (alarm has been triggered by the control system)	2.71×10^{-4}	Unlikely
Electrical breakdown	2.71×10^{-4}	Unlikely
Loss of mechanical integrity (mechanical damages of different parts like insulators, etc.)	1.08×10^{-4}	Unlikely
Opens without command	3.36×10^{-5}	Almost impossible
Other/Unknown	7.84×10^{-5}	Almost impossible

3.2.3 Risk calculation and interpretation at the primary components level

Risk is calculated by multiplying failure frequency by failure impact. The resulting values for risk do not indicate risk acceptance. Risk acceptability is categorised by experts [16]. A risk matrix tends to be used for this purpose and shows acceptable risk level by using colours. An example risk matrix is shown in Table 3-5, which has in this case a dimension of 7×7 [27].

The exemplar risk matrix combines failure impact level with frequency class and relates results to actual failure risk to all business values by colours.

Table 3-5: An example risk matrix



In this example, the risk matrix indicates risk acceptance with green. The risk levels and their corresponding ranges are summarised in Table 3-6.

Table 3-6: An overview of the colours used in Table 3-5 and their corresponding risk level of acceptance

Risk color	Risk level
	Unacceptable
	Very high
	High
	Medium
	Low
	Negligible

The risk matrix, as shown in Table 3-5, is used to estimate risk level for failure modes of the circuit breaker listed in Table 3-4. The results are listed in Table 3-7. The highest risk level calculated for GIS circuit breaker is "*Medium*" for failure mode "*Dielectric breakdown*".

Table 3-7: Risk assessment results for circuit breaker failure modes at primary component level, indenture level 3

System	*Sub-system*	*Function*	*Failure mode*	*Function Impact*		*Overall level of impact*	*Frequency class*	*Risk*
				Sub-system Function	*System function*			
GIS CB-Bay i.e. Transverse bay, Feeding bay	Circuit breaker	Interrupt fault currents	Does not operate on command	Switching operation failed	Failure to fulfil the bay functionality	Moderate	Unlikely	Negligible
			Locking in open or closed position (alarm has been triggered by the control system)	Switching operation failed	Failure to fulfil the bay functionality	Moderate	Unlikely	Negligible
			Dielectric breakdown	Circuit is unintentionally closed with possible safety and economic damage issues.	Phase-to-ground fault with possible safety and economical damage; interruption required to the bay	Extreme	Unlikely	Medium
			Loss of mechanical integrity (mechanical damages of different parts like insulators, etc.)	Switching operation failed	Failure to fulfil the bay functionality	Moderate	Unlikely	Negligible
			Opens without command	Unattended switching operation	Circuit is unintentionally interrupted with possible safety and economic damage issues	Moderate	Almost impossible	Negligible
			Other/ Unknown	Other/ Unknown	Other/ Unknown	Very low	Almost impossible	Negligible

3.2.4 Risk results for GIS primary component level

The risk assessment for the other primary components of indenture level 3 is performed similarly to how it is described for the circuit breaker in previous sections. Details can be found in Appendix B.2.

Table 3-8 shows that only the failure mode characterised by “*Dielectric breakdown*” results for the switching devices and instrument transformer in a “Medium” risk level. All other failure modes of the primary components in GIS have “Negligible” to “Low” levels of risk at the adapted setting in Table 3-6.

Table 3-8: A summary of the risk levels estimated for primary components failure modes

Primary component	***Failure mode***	***Risk level***
Circuit breaker, Disconnector/earthing switch, Instrument transformer	Dielectric breakdown	Medium
SF_6 bushing, surge arrester	Dielectric breakdown	Low
All Components	Other failure modes	Negligible

.

3.3 *Risk assessment at the busbar system and the GIS bay level*

The GIS bay level covers feeding bays, the transverse bay, and the busbar system. The failure frequencies at GIS bay level (indenture level 2) have been calculated and categorised in frequency classes similarly to how is described in Section 3.2. The failure frequency class has been combined with failure impact level, as discussed in Chapter 2, to determine the risk level.

3.3.1 Failure frequency estimation at the busbar system and the GIS bay level

The failure frequencies for GIS bays and the busbar are 13.4×10^{-3} and 2.1×10^{-4} failures per CB-bay-year, respectively [5]. To calculate the failure frequency of the individual failure modes, the failure frequency of the GIS bay and the busbar, respectively, have been multiplied with their fraction x_{fm} by Equations 3-3 and 3-4. The calculation results are listed in Table 3-9 and Table 3-10.

$$\lambda_{fm,GIS\ busbar} = \lambda_{GIS\ busbar}\, x_{fm,GIS\ busbar} \quad \text{........} \quad 3\text{-}3$$

$$\lambda_{fm,GIS\ bay} = \lambda_{GIS\ bay}\, x_{fm,GIS\ bay} \quad \text{........} \quad 3\text{-}4$$

Where

$\lambda_{fm,GIS\ busbar}$ = the failure frequency per failure mode in GIS busbar,

$\lambda_{GIS\ burbar}$ = the total failure frequency of GIS busbar,

$x_{fm,GIS\ busbar}$ = the contribution of the individual failure mode as a percentage of the total number of failures in GIS busbar

$\lambda_{fm,GIS\ bay}$ = the failure frequency per failure mode in GIS bay,

$\lambda_{GIS\ bay}$ = the total failure frequency of GIS bay,

$x_{fm,GIS\ bay}$ = the contribution of the individual failure mode as percentage of the total number of failures in GIS bay.

Table 3-9: the failure frequencies for the busbar system major failure modes

Failure mode	% $x_{fm,GIS\ busbar}$ ***(Contribution to the total number of failures) [5]***	$\lambda_{fm,GIS\ busbar}$ ***(failures per CB-bay-year)*** [2]
Dielectric breakdown	84.2	1.76×10^{-4}
Loss of mechanical / electrical integrity	15.8	3.31×10^{-5}
Total	**100**	$\mathbf{2.1\times10^{-4}}$

[2] It is assumed that the double busbar system failure frequency is equal to the squared value of the failure frequency of the single busbar.

Table 3-10: the failure frequencies for the GIS bays major failure modes

Failure mode	% $x_{fm,GIS\ bay}$ ***(Contribution to the total number of failures) [5]***	$\lambda_{fm,GIS\ bay}$ ***(failures per CB-bay-year)***
Failing to perform requested operation, function respectively	63.4	8.49×10^{-3}
Dielectric breakdown	22.5	3.01×10^{-3}
Loss of mechanical / electrical integrity	5.4	7.23×10^{-4}
Other/Unknown	8.7	1.16×10^{-3}
Total	**100**	$\mathbf{13.40\times10^{-3}}$

3.3.2 Failure frequency classification for the busbar system and GIS bay level

The failure frequencies calculated for GIS bays and the busbar system failure modes have been categorised into classes based on Table 3-3. The failure frequency classification results are listed in Table 3-11 and Table 3-12.

Table 3-11: Failure frequency classification for the busbar failure modes

Failure mode	$\lambda_{fm,GIS\ busbar}$ ***(failures per CB-bay-year)***	***Failure frequency class***
Dielectric breakdown	1.76×10^{-4}	Unlikely
Loss of mechanical/electrical integrity	3.31×10^{-5}	Almost impossible

Table 3-12: Failure frequency classification for the GIS bays failure modes

Failure mode	$\lambda_{fm,GIS\ bay}$ ***(failures per CB-bay-year)***	***Failure frequency class***
Failing to perform requested operation, function respectively	8.49×10^{-3}	Possible
Dielectric breakdown	3.01×10^{-3}	Possible
Loss of mechanical/electrical integrity	7.23×10^{-4}	Unlikely
Other/Unknown	1.16×10^{-3}	Possible

3.3.3 Risk calculation and interpretation at the busbar system and the GIS bay level

The failure frequency classification results listed in Table 3-11 and Table 3-12 have been combined with failure impact on business values (for indenture level 2) to calculate risk value. Thereafter, the risk acceptability is determined by the risk matrix, as shown in Table 3-5. The complete risk results at GIS bay level are listed in the FMECA work sheet, as shown in Table 3-13.

3.3.4 Risk results for the busbar system and GIS bay level

Table 3-13 shows that the possible failure modes of GIS bays and the busbar both have a “*Low*” to “*Negligible*” risk level across GIS on the whole.

Table 3-13: Risk assessment results for indenture level 2

System	Sub-system	Function	Failure mode	Function Impact		Overall level of impact	Frequency class	Risk
				Sub-system Function	System function			
GIS primary installation	GIS Bay i.e. Transverse bay, Feeding bay	Current transfer between the different busbars, and current transfer to the grid	Failing to perform requested operation, function respectively	No current transfer is possible from one busbar to another	Affect the GIS redundancy and reliability	Moderate	Possible	Negligible
			Dielectric breakdown	Circuit is unintentionally closed with possible safety and economic damage issues	Phase-to-ground fault with possible safety and economical damage; interruption required to the bay	High	Possible	Negligible
			Loss of electrical/mechanical integrity	No current transfer is possible from one busbar to another	Failure to fulfil the bay functionality	Moderate	Unlikely	Negligible
			Other /Unknown	Other /Unknown	Other /Unknown	Very low	Possible	Negligible
	The busbar (the example GIS consists of a double busbar system)	Connect the GIS bays	Dielectric breakdown in one busbar section	Circuit is unintentionally closed with possible safety and economic damage issues	Phase-to-ground fault with possible safety and economical damage; interruption required to the busbar	High	Unlikely	Negligible
			Loss of electrical/mechanical integrity in one busbar section	No current transfer is possible from one busbar to another	Failure to fulfil the busbar functionality	Moderate	Almost impossible	Negligible
			Dielectric breakdown in a both busbar sections	Circuit is unintentionally closed with possible safety and economic damage issues	Phase-to-ground fault with possible safety and economical damage; interruption required to the busbar	Extreme	Almost impossible	Low
			Loss of electrical/mechanical integrity in a both Busbar sections	No current transfer is possible from one busbar to another	Failure to fulfil the busbar functionality	Very high	Almost impossible	Negligible
			Other /Unknown	Other /Unknown	Other /Unknown	Very low	Almost impossible	Negligible

3.4 Risk assessment at GIS level

At indenture level 1, the risk has been aggregated across the complete GIS substation

3.4.1 Failure frequency estimation at GIS level

The study case A consists of four feeding bays, one transverse bay, and a double busbar system. This structure results in 128 possible failure combinations. Among these situations, the highest failure frequency occurs in the following two situations and can lead to a complete shutdown of the GIS in case study A.

1. When 3 of the 4 feeding bays fail
2. When the double busbar system fails i.e. both busbar 1 and busbar 2 fail.

The calculations of the failure frequency of these two situations are shown in Table 3-14 in the fourth column.

Table 3-14: Failure frequency calculation for the worst two possible failure situations in GIS

Situation	*description*	*Failure mode*	*The overall failure frequency (failures per CB-bay-year)*	*Remarks*
1	When 3 of the 4 feeding bays fail	Fail to perform the requested operation	9.60×10^{-6}	The overall failure frequency = $4\times(13.4\times10^{-3}\times13.4\times10^{-3}\times13.4\times10^{-3})$
2	When busbars 1 and 2 fail	Dielectric breakdown	4.4×10^{-8}	The overall failure frequency = $2.1\times10^{-4}\times2.1\times10^{-4}$

3.4.2 Failure frequency classification at GIS level

The failure frequency classes determined for GIS levels are categorised based on Table 3-3. The failure frequency classification results are listed in Table 3-15.

Table 3-15: Failure frequency classes at GIS level

Situation	*description*	*Failure mode*	*The overall failure frequency (failures per CB-bay-year)*	*Failure frequency class*
1	When 3 of the 4 feeding bays fail	Fail to perform the requested operation	9.6×10^{-6}	Almost impossible
2	When busbars 1 and 2 fail	Dielectric breakdown	4.4×10^{-8}	Almost impossible

3.4.3 Risk calculation and interpretation at the GIS level

Risk level is determined as has been described in Section 3.2.3 based on the failure frequency class and the level of the failure impact on business values and the risk matrix shown in Table 3-5. Risk assessment results are shown in Table 3-16.

3.4.4 Risk results at GIS level

Risk assessment results for GIS level, as seen in Table 3-16, show that a complete shutdown of the GIS substation has a "*Negligible*" risk at the adopted setting of the used risk matrix.

Table 3-16: Risk assessment at GIS level

System	***Sub-system***	***Function***	***Failure mode***	***Function Impact***		***Overall level of impact***	***Failure frequency class***	***Risk***
				Sub-system Function	***System function***			
High-voltage grid	GIS primary installation	Electricity transfer and distribution between the GIS input and output sides	Losing three feeders to any reason e.g. dielectric breakdown, failure to perform requested operation, etc.	Complete power interruption at the output side	Could affect the grid redundancy/reliability	High	Almost impossible	Negligible
			losing of the complete busbar system			High	Almost impossible	Negligible

3.5 Summary

The risk assessment results obtained in this chapter across the indenture levels are summarised in Table 3-17.

Table 3-17: A summary of the assessed risk level

Indenture level identification	***system***	***Sub- system***	***Failure mode***	***Risk level***
Indenture level 1: The GIS level	High-voltage grid	GIS station	Losing three feeders due to any reasons	Negligible
			losing of the complete busbar system due to any reasons	Negligible
Indenture level 2: The busbar system and the GIS bay level	GIS station	GIS bays	Failing to perform requested operation, function respectively	Negligible
			Dielectric breakdown	Negligible
			Loss of electrical/mechanical integrity	Negligible
		Single busbar system	Dielectric breakdown	Negligible
			Loss of electrical/mechanical integrity	Negligible
		Double busbar system	Dielectric breakdown	Low
			Loss of electrical/mechanical integrity	Negligible
Indenture level 3: The primary components level	GIS bay	Disconnector/earthing switch	Does not operate on command	Negligible
			Locking in open or closed position	Negligible
			Dielectric breakdown	Medium
			Loss of mechanical integrity	Negligible
		Circuit breaker	Does not operate on command	Negligible
			Locking in open or closed position	Negligible
			Dielectric breakdown	Medium
			Loss of mechanical integrity	Negligible
			Opens without command	Negligible
		Current/ voltage transformer	Dielectric breakdown	Medium
			Loss of mechanical/electrical connections integrity	Negligible
			Leakage of insulation medium	Negligible
		SF_6 Bushing	Dielectric breakdown	Low
			Loss of mechanical/electrical integrity	Negligible
		Surge arrester	Dielectric breakdown	Low
			Loss of mechanical/electrical connections integrity	Negligible

1. For the GIS substation of case study A, "*Negligible*" risk level has been estimated for possible GIS failure modes at indenture level 1. This probability is due to the low frequency of occurrence of the failure modes.
2. A "*Negligible*" to "*Low*" risk level has been estimated for GIS bays and the busbar system's failure modes identified at indenture level 2. The GIS substation consists of many bays and a double busbar system. Such arrangement of the GIS provide redundancy. Whenever redundancy is applicable, decreased failure frequency is expected.

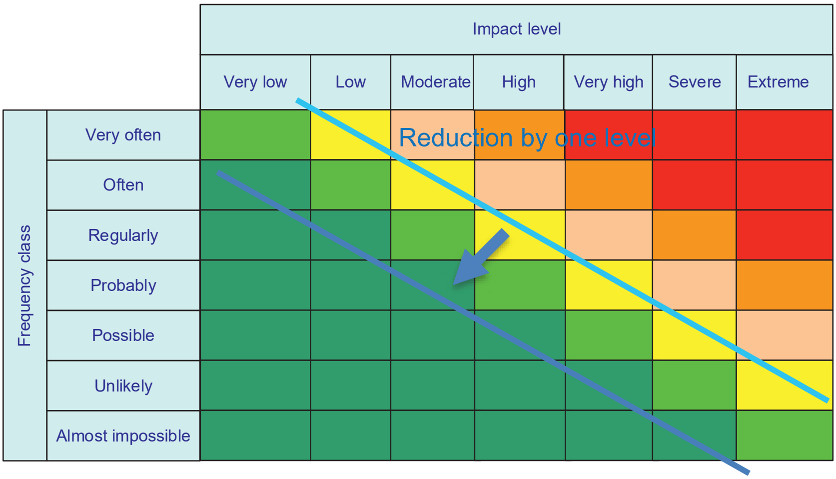
   A low failure frequency and/or low failure impact or a combination thereof will result in a "*Negligible*" to "*Low*" risk level for the GIS substation at the busbar system and GIS bay level.

3. At the primary components level, major failure modes have a "*Negligible*" to "*Low*" risk level. "*Medium*" risk level has been assessed for the failure mode, which is characterised by "*Dielectric breakdown*" in the GIS switching components and instrument transformers.

3.6 Changes in risk level

Risk is assessed using the acceptance levels of Table *3-6*. Risk may change when the defined scale for failures impact on the business values is changed or when frequency information changes i.e. new data for the failure frequency became available. Changes in risk due to simultaneous uncertainties in both coordination are evaluated by reducing the defined acceptable risk level in the adopted risk matrix by one level as schematically shown in Table 3-18.

Table 3-18: One- and two-level reduction in acceptable risk levels



The risk results at component level, as summarised in Section 3.5, are mapped in Table 3-19. The failure mode "*Dielectric breakdown*" is assessed as having the risk level "*Medium*" in the GIS switching components and instrument transformers, while other failure modes have "*Negligible*" to "*Low*" risk levels.

Reducing the acceptable risk level by one level has shown that (see Table 3-19)

1- The failure mode "*Dielectric breakdown*" will have risk levels "*Very High*" in GIS switching components and instrument transformers and "*Medium*" in the other GIS components

2- Other failure modes at the primary component level will have "*Negligible*" risk levels.

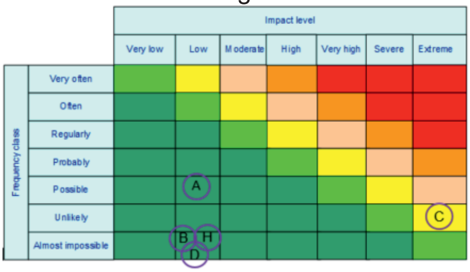
However, multifunctional failure modes aren't in the model, a circuit breaker can fail to trip the fault current when it "*Does not operate on commend*" or is "*Locked in closed position*", and the back-up circuit breaker (protection system) does not act. In such cases, the failure impact on business values is "*Extreme*", which results in risk level "*Medium*".

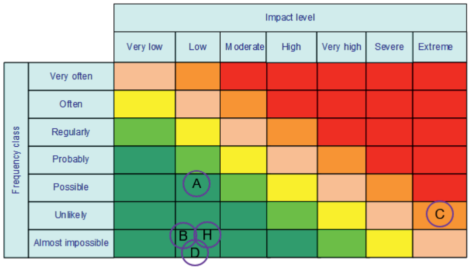
Table 3-19: Mapping of assessed risk level at component level. Does not operate on command (A), Locking in open or closed position (B), Dielectric breakdown (C), Loss of mechanical integrity (D), Opens without command (E), Leakage of insulation medium (F), Loss of electrical connections integrity (G), and Other/Unknown (H)

Initial Risk

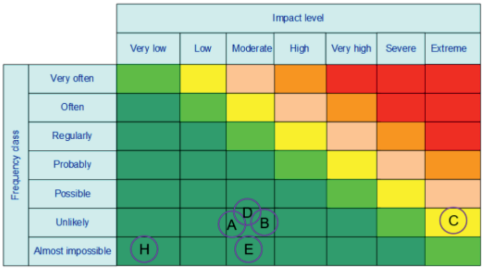
Change of risk acceptance level by one levels

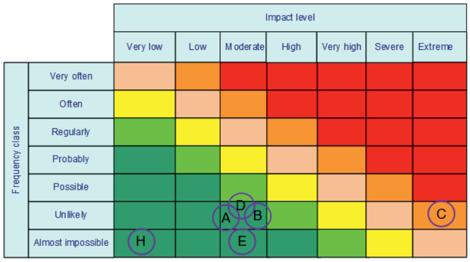
Disconnector/earthing switch



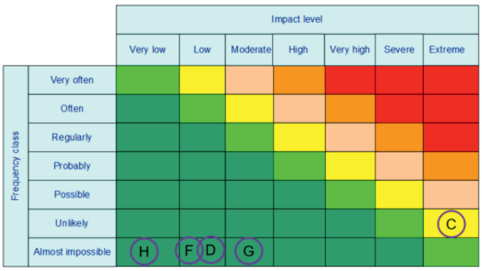


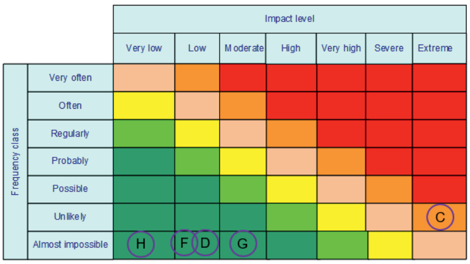
Circuit breaker



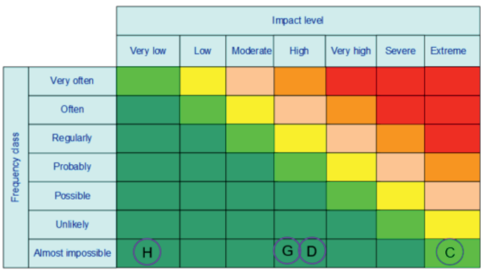


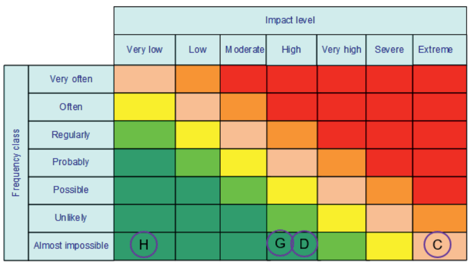
Instrument transformer





Bushing





Surge arrester

Frequency class		Impact level						
		Very low	Low	Moderate	High	Very high	Severe	Extreme
	Very often							
	Often							
	Regularly							
	Probably							
	Possible							
	Unlikely							
	Almost impossible	H		G D				C

Frequency class		Impact level						
		Very low	Low	Moderate	High	Very high	Severe	Extreme
	Very often							
	Often							
	Regularly							
	Probably							
	Possible							
	Unlikely							
	Almost impossible	H		G D				C

3.7 Conclusion

Except "*Dielectric breakdown*" in switching components and instrument transformers of GIS, all failure modes are of a "*Low*" risk level. Reducing the acceptable risk level of the adopted risk acceptance table by one level further results in "*Very High*" risk level of the failure mode "*Dielectric breakdown*". Other failure modes at the primary component level still have a "*Negligible*" risk level under the same circumstances.

The failure modes "*Does not operate on command*" and "*Locking in open or closed position"* can result in "*Medium*" risk level under multifunctional failure modes.

To prevent "*Dielectric breakdown*" and other risky failure modes in GIS substations, it is important to address diagnostics that can detect and provide early warnings when such failure modes become active.

Chapter 4 Condition Diagnostics Selection for Risk Reduction

CHAPTER 4 CONDITION DIAGNOSTICS SELECTION FOR RISK REDUCTION

4.1. *Introduction*

Risk can be mitigated either by reducing the failure impact on the business values or by reducing the failure frequency. In some cases, it might be necessary to reduce both.

Reducing the failure impact on the business values in GIS can be achieved by increasing the GIS redundancy, for example, by using a double busbar system. Increasing the redundancy may increase the cost and the GIS complexity. However, it is not always feasible to increase the redundancy. Other ways to reduce the failure impact are, for instance, using proper protection systems, fast localisation, and replacement and emergency plans.

Performing diagnostic measurements could unveil upcoming failure modes. By preventing these upcoming failure modes by means of maintenance, whenever necessary and possible, the mean time between failures would increase, and the failure frequency would decrease. Therefore, applying diagnostics can be seen as a preparatory step in mitigating or reducing risk. It should be remembered that detecting a failure does not mean that failure frequency has been reduced; failure frequency is only reduced if the failure is prevented by immediate or planned maintenance. The initiation and planning of maintenance is the topic of Chapter 7.

The challenge is to select an appropriate set of diagnostic techniques out of the many available techniques, ensuring sufficient detection ability but preventing overlapping diagnostics for the same failure mode. The commonly available GIS diagnostics are summarised in Appendix C. This selection procedure is the main topic of this chapter. A method to prioritise the different diagnostics by priority numbering, will be introduced. In this way, it is possible to select the required diagnostics which can reveal critical failure modes in GIS.

In Chapter 3, the failure mode "*Dielectric Breakdown*" is assessed to have the highest risk level relative to the other failure modes. The other failure modes at the primary components level have shown a "*Negligible*" to "*Low*" risk level even when the acceptable level of risk was reduced by one level. However, the failure modes "*Does not operate on command*" and "*Locking in open and closed position*" have the highest failure frequency and can result in "*Medium*" risk level under inadvertent condition.

In this chapter, we will therefore focus on the latter three failure modes, namely "*Does not operate on command*", "*Locking in open and closed position*", and "*Dielectric breakdown*", in order to select the diagnostics required to reduce risk.

4.2. *Available diagnostics to reveal failures in GIS*

In total, 25 commonly available diagnostics have been identified which could reveal upcoming failures in GIS and its components. The description of these diagnostics and the GIS components with which these diagnostics are to be used is given in Appendix C.

Eleven diagnostics can be applied to detect the GIS failure modes "*Does not operate on command*" and "*Locking in open and closed position*". Four diagnostics reveal "*Dielectric breakdown*" in GIS components. The remaining diagnostics foresee other upcoming failures in GIS which are not considered in this thesis.

Table 4-1 shows that some of the 15 relevant diagnostics overlap in that they detect failure modes caused by one or different failure origins. For instance, a failure in the compressors, motors, pumps, piping fittings, or energy storage devices (accumulator, spring) can reduce the contact travel speed and lead to the failure mode "*Locking in open or closed position*". Such a failure can be examined by measuring the stored energy (spring position, pressure) but also by measuring the contact travel characteristic.

To minimise such overlaps, the effectiveness of the diagnostics needs to be estimated. Therefore, the business risk associated with these failure modes is estimated. Thereafter, the estimated risk values are revised by including how the detection ability of each of the 15 diagnostics can reduce the failure frequency. In the next section, the diagnostics will be prioritised along this way.

Table 4-1: Components responsible for failures and failure origins identified for the failure modes "*Dielectric breakdown*", "*Does not operate on command*", and "*Locking in open and closed position*"

Failure mode	*Components responsible for failures*	*Failure origin*	*Available diagnostic*
– Does not operate on command – Locking in open or closed position	Operating mechanism [21][18]	– Compressors, motors, pumps, piping fittings – Energy storage (accumulator, spring)	– Visual inspection – Number of motor pump running times – State of motor/pump (current, voltage, etc.) – Stored energy (spring position, pressure) – Contact travel characteristic – Status of auxiliary switches – Coil current profile
		Actuator and damping device	– Vibration signature – Contact travel characteristic
		Mechanical transmission	– Visual inspection – Vibration signature – Contact travel characteristic
		Other and unknown	– Other or unknown
	Electrical control and auxiliary circuits [36]	– Coils – Relays	– Visual inspection – Coil current profile – Circuit continuity – Voltage measurements at the terminals
		Density monitoring System (with piping)	– Visual inspection – Leak detection techniques
		Energy Limit Supervision	– Visual inspection – Number of motor/pump running times

Table 4-1 Continued: Components responsible for failures and failure origins identified for the failure modes "*Dielectric breakdown*", "*Does not operate on command*", and "*Locking in open and closed position*"

Failure mode	*Components responsible for failures*	*Failure origin*	*Available diagnostic*
– Does not operate on command – Locking in open or closed position	Electrical control and auxiliary circuits [36]	Auxiliary Switch	– Visual inspection – Status of auxiliary switches – Coil current profile
		Wiring & joints	– Visual inspection – Circuit continuity – Voltage measurements at the terminals
		Other and unknown	– Other or unknown
Dielectric breakdown [34]	Component at service voltage	Poor contacts	– Partial discharge (PD) – Contact resistance
		– Particles and foreign bodies – Bulk insulation of spacer – Bad shield and electrostatic contacts – Protrusion/Particle on HV conductor	– Partial discharge (PD)
		Moisture	– SF_6 gas moisture – SF_6 contamination
		Dielectric failures resulting from mechanical failures occurring outside the insulation	– See operating mechanism
		Other and unknown	– Other or unknown

4.3. *Diagnostics selection by means of risk revision*

Diagnostics offer different abilities to detect a particular failure mode. To illustrate how the detection ability can affect the diagnostics selection, the risk associated with the GIS failure modes "*Dielectric breakdown*", "*Does not operate on command*", and "*Locking in open and closed position*" has been firstly estimated and then revised after using diagnostics.

Thereafter, diagnostics have been prioritised based on the revised risk level, cost for diagnostics, and the diagnostics detection ability.

4.3.1. *Diagnostics selection*

We define the detection ability of a diagnostic as the likelihood that a particular failure mode is being detected by the selected diagnostic. Examples of the detection ability and the corresponding detection criteria are shown in Table 4-2 [16]. The detection ability ($D_{ability}$) is introduced in the last column of the table.

A range is selected to quantify the detection likelihood with an overlap between the different levels of detection ability.

Table 4-2: Detection criteria and the corresponding detection ability

Level of $D_{ability}$ *[16]*	***Criteria [16]***	***Range of $D_{ability}$***
Almost certain	The diagnostic methods will almost certainly detect a potential failure mode	>80%
Very high	Very high chance the diagnostic methods will detect the failure mode	60%-80%
High	High chance the diagnostic methods will detect the failure mode	50%-70%
Moderately high	Moderately high chance the diagnostic methods will detect the failure mode	40%-60%
Moderate	Moderate chance the diagnostic methods will detect the failure mode	30%-50%
Low	Low chance the diagnostic methods will detect the failure mode	20%-40%
Negligible	Very low chance the diagnostic methods will detect the failure mode	<20%

Let $D_{ability}$ [3] be the likelihood to detect a particular failure mode at a particular failure origin, and let $\lambda_{revised}$ be the revised failure frequency. $\lambda_{revised}$ indicates the reduced failure frequency of a failure mode due to the use of diagnostics. $\lambda_{revised}$ is determined by multiplying the failure frequency (λ) and the likelihood of failing to detect the failure mode. Mathematically, $\lambda_{revised}$ is determined as shown in equation 4-1.

$$\lambda_{revised} = \lambda \times (1 - D_{ability}/100) \qquad \text{........} \quad 4\text{-}1$$

[3] The $D_{ability}$ is the likelihood of the diagnostic to detect a particular failure mode as usual. In other words, $D_{ability}$ does not consider the probability of the diagnostic to fail to detect the failure mode due to, for example, defective measuring equipment, bad signal transfer, improper interpretation of the diagnostic data or adopting improper time window to use the diagnostic.

The classification of the revised failure frequency ($\lambda_{revised}$) is determined in a similar way as in Chapter 3 by using Table 3-3. The failure impact on the business values and the level of the impact is determined as discussed in Chapter 2 in Section 2.3. Thereafter, the revised risk ($R_{revised}$) is determined by the class of the failure frequency and the level of the failure impact on the business values using Table 3-6.

The risk associated with the GIS failure modes "*Dielectric breakdown*", "*Does not operate on command*", and "*Locking in open and closed position*" has been revised to illustrate how the detection ability can influence the diagnostics selection. The risk and the revised risk results are listed in Table 4-4.

The revised risk has been determined by estimating the diagnostic's detection ability for different failure modes per failure origin (see Table 4-4, column 10). The diagnostic's detection ability is set to 40% to indicate a "*Low*" to "*Moderate*" detection ability. It is set to 50% to indicate a "*Moderate*" to "*Moderately high*" detection ability, to 70% to indicate a "*High*" to "*Very high*" detection ability, and to 80% to indicate "*Very high*" and "*Almost certain*" detection ability.

Thereafter, the revised failure frequency is calculated by equation 4-1, and the results have been set to classes in a similar way as has been explained in Chapter 3, Table 3-3. The values of the revised failure frequency and its corresponding class are listed in Table 4-4 in column 11 and column 12. Finally, the revised risk has been determined, and the complete results for the revised risk are shown in the last column in Table 4-4.

It should be noted that the failure modes "*Does not operate on command*" and "*Locking in open and closed position*" have been estimated to have a "*Negligible*" risk level in Chapter 3 despite these modes have the highest failure frequency. However, their risk under multifunctional failure mode (called worst case in Table 4-5) has been considered, and the overall impact for these two failure modes is exaggerated by setting to the worst case of "*Extreme*" in column 8 in Table 4-4. The impact of failures and the impact level is already discussed in Chapter 2 and Table A-4 in Appendix A.

The results are shown for the failure modes "*Dielectric breakdown*", "*Does not operate on command*", and "*Locking in open and closed position*" firstly when the impact of the latter two is ranked at "*Moderate*" (as in Chapter 3) and, secondly, when their impact is exaggerated by setting to the worst case of "*Extreme*".

- The revised risk level shows that partial discharge measurement is the most efficient diagnostic to identify the failure mode "*Dielectric breakdown".*
- A set of 12 diagnostics out of the available 15 diagnostics are the most effective to identify the failure modes "*Dielectric breakdown*, "*Does not operate on command*", and "*Locking in open and closed position*".

These efficient diagnostics have reduced the failure frequency class. As a result, a reduction in the risk level has been indicated in Table 4-4 and Table 4-5 by a change in the risk colour from yellow to green. A change in the colour from yellow to green indicates a reduction from the "*Medium*" to the "*Low*" risk level. Table 4-3 summarises the 12 diagnostics found this way.

Table 4-3: Diagnostics required to foresee "*Dielectric breakdown*", "*Does not operate on command*", and "*Locking in open and closed position*" failure modes

Diagnostics
1. Visual inspection
2. Coil current profile
3. Stored energy (spring position, pressure)
4. Contact travel characteristic
5. State of motor/pump (current, voltage, etc.)
6. Circuit continuity
7. Status of auxiliary switches
8. Voltage measurements at the terminals
9. Vibration signature
10. Partial discharge (PD)
11. Number of motor pump running times
12. Leak detection techniques

In the next section, these 12 diagnostics are prioritized to indicate which diagnostics offer to detect maximum number of failures, have lowest diagnostic cost and achieve maximum reduction of risk.

Table 4-4: The effect of using different diagnostic techniques to foresee the failure mode "*Dielectric breakdown*"
AI: Almost impossible, UL: Unlikely, EX: Extreme, MO: Moderate, L: Low, M: Medium, N: Negligible

Components responsible for failures	Failure mode	Failure origin	Available diagnostic	Contribution to the total failure, N (%)	λ	Failure frequency class	$Impact$	$Risk\ (R)$	$D_{ability}$	$\lambda_{revised}$	Revised failure frequency class	$R_{revised}$
Component at service voltage	Dielectric breakdown [34]	Poor contacts	Contact resistance	1.89	5.68E-05	AI	EX	L	90	5.68E-06	AI	L
			Contact temperature		5.68E-05	AI	EX	L	20	4.54E-05	AI	L
		Poor contacts	[4]Partial discharge (PD)	9.09	2.74E-04	UL	EX	M	80	5.47E-05	AI	L
		Particles and foreign bodies				UL	EX	M	80	5.47E-05	AI	L
		Bulk insulation of spacer				UL	EX	M	30	1.92E-04	UL	M
		Bad shield and electrostatic contacts				UL	EX	M	80	5.47E-05	AI	L
		Protrusion/ Particle on HV conductor				UL	EX	M	30	1.92E-04	UL	M
		Moisture	SF_6 gas moisture	1.20	3.61E-05	AI	EX	L	90	3.61E-06	AI	L
			SF_6 contamination		3.61E-05	AI	EX	L	40	2.17E-05	AI	L
		Dielectric failures resulting from mechanical failures occurring outside the insulation	See operating mechanism	1.37	4.13E-05	AI	EX	L	20	3.30E-05	AI	L

[4] The $D_{ability}$ for PD measurement is based on [34]

Table 4-4 Continued: The effect of using different diagnostic techniques to foresee the failure mode "*Dielectric breakdown*"

Components responsible for failures	Failure mode	Failure origin	Available diagnostic	Contribution to the total failure, N (%)	λ	Failure frequency class	$Impact$	$Risk\ (R)$	$D_{ability}$	$\lambda_{revised}$	Revised failure frequency class	R_{revise}
Operating mechanism [21]	Does not operate on command	Compressors, motors, pumps, piping fittings	Visual inspection	16.64	1.75E-04	UL	MO	N	40	1.05E-04	UL	N
			State of motor/pump (current, voltage, etc.)		1.75E-04	UL	MO	N	70	5.26E-05	AI	N
			Number of motor pump running times		1.75E-04	UL	MO	N	50	8.77E-05	AI	N
			Stored energy (spring position, pressure)		1.75E-04	UL	MO	N	70	5.26E-05	AI	N
			Contact travel characteristic		1.75E-04	UL	MO	N	50	8.77E-05	AI	N
			Status of auxiliary switches		1.75E-04	UL	MO	N	40	1.05E-04	UL	N
			Coil current profile		1.75E-04	UL	MO	N	40	1.05E-04	UL	N
		Energy storage (accumulator, spring)	Visual inspection	14.92	1.57E-04	UL	MO	N	20	1.26E-05	AI	N
			State of motor/pump (current, voltage, etc.)		1.57E-04	UL	MO	N	50	7.87E-05	AI	N
	Locking in open or closed position		Number of motor pump running times		1.57E-04	UL	MO	N	70	4.72E-05	AI	N
			Stored energy (spring position, pressure)		1.57E-04	UL	MO	N	70	4.72E-05	AI	N
			Contact travel characteristic		1.57E-04	UL	MO	N	50	7.87E-05	AI	N
			Status of auxiliary switches		1.57E-04	UL	MO	N	50	7.87E-05	AI	N
			Coil current profile		1.57E-04	UL	MO	N	40	9.42E-05	AI	N
		Actuator and damping device	Vibration signature	9.26	9.77E-05	AI	MO	N	70	2.93E-05	AI	N
			Contact travel characteristic		9.77E-05	AI	MO	N	50	4.88E-05	AI	N
		Mechanical transmission	Visual inspection	15.27	1.61E-04	UL	MO	N	50	8.05E-05	AI	N
			Vibration signature		1.61E-04	UL	MO	N	60	6.44E-05	AI	N
			Contact travel characteristic		1.61E-04	UL	MO	N	60	6.44E-05	AI	N

Table 4-4 Continued: The effect of using different diagnostic techniques to foresee the failure mode "*Dielectric breakdown*"

Components responsible for failures	Failure mode	Failure origin	Available diagnostic	Contribution to the total failure, N (%)	λ	Failure frequency class	Moderate	$Risk\ (R)$	$D_{ability}$	$\lambda_{revised}$	Revised failure frequency class	$R_{revised}$
Electrical control and auxiliary circuits [36]	Does not operate on command	Coils	Visual inspection	1.89	8.49E-05	AI	MO	N	40	5.10E-05	AI	N
			Coil current profile		8.49E-05	AI	MO	N	70	2.55E-05	AI	N
			Circuit continuity		8.49E-05	AI	MO	N	90	8.49E-06	AI	N
			Voltage measurements at the terminals		8.49E-05	AI	MO	N	70	6.49E-05	AI	N
		Relays	Visual inspection	4.80	2.16E-04	UL	MO	N	50	1.08E-04	UL	N
			Coil current profile		2.16E-04	UL	MO	N	50	1.08E-04	UL	N
			Circuit continuity		2.16E-04	UL	MO	N	70	6.49E-05	AI	N
			Voltage measurements at the terminals		2.16E-04	UL	MO	N	70	3.24E-05	AI	N
		Density monitoring system (with piping)	Visual inspection	2.40	1.08E-04	AI	MO	N	90	1.08E-05	AI	N
	Locking in open or closed position		Leak detection techniques		1.08E-04	AI	MO	N	70	3.24E-05	AI	N
		Energy limit supervision	Visual inspection	2.40	1.08E-04	AI	MO	N	50	5.41E-05	AI	N
			Number of motor pump running times		1.08E-04	AI	MO	N	70	3.24E-05	AI	N
		Auxiliary switch	Visual inspection	2.40	1.08E-04	AI	MO	N	40	6.49E-05	AI	N
			Status of auxiliary switches		1.08E-04	AI	MO	N	70	3.24E-05	AI	N
			Coil current profile		1.08E-04	AI	MO	N	70	3.24E-05	AI	N
		Wiring & joints	Visual inspection	1.72	7.72E-05	AI	MO	N	30	5.41E-05	AI	N
			Circuit continuity		7.72E-05	AI	MO	N	70	2.32E-05	AI	N
			Voltage measurements at the terminals		7.72E-05	AI	MO	N	70	2.32E-05	AI	N

Table 4-5: The effect of using different diagnostic techniques to foresee "*Dielectric breakdown*", "*Does not operate on command*", and "*Locking in open and closed position*" with impact ranked at worst case for the latter two failure modes
AI: Almost impossible, UL: Unlikely, EX: Extreme, MO: Moderate, L: Low, M: Medium, N: Negligible

Components responsible for failures	Failure mode	Failure origin	Available diagnostic	Contribution to the total failure, N (%)	λ	Failure frequency class	*Impact*	*Risk (R)*	$D_{ability}$	$\lambda_{revised}$	Revised failure frequency class	$R_{revised}$
Component at service voltage	Dielectric breakdown [34]	Poor contacts	Contact resistance	1.89	5.68E-05	AI	EX	L	90	5.68E-06	AI	L
			Contact temperature		5.68E-05	AI	EX	L	20	4.54E-05	AI	L
		Poor contacts	[5]Partial discharge (PD)	9.09	2.74E-04	UL	EX	M	80	5.47E-05	AI	L
		Particles and foreign bodies				UL	EX	M	80	5.47E-05	AI	L
		Bulk insulation of spacer				UL	EX	M	30	1.92E-04	UL	M
		Bad shield and electrostatic contacts				UL	EX	M	80	5.47E-05	AI	L
		Protrusion/ Particle on HV conductor				UL	EX	M	30	1.92E-04	UL	M
		Moisture	SF_6 gas moisture	1.20	3.61E-05	AI	EX	L	90	3.61E-06	AI	L
			SF_6 contamination		3.61E-05	AI	EX	L	40	2.17E-05	AI	L
		Dielectric failures resulting from mechanical failures occurring outside the insulation	See operating mechanism required diagnostics	1.37	4.13E-05	AI	EX	L	20	3.30E-05	AI	L

[5] The $D_{ability}$ for PD measurement is based on [34].

Table 4-5 Continued: The effect of using different diagnostic techniques to foresee "*Dielectric breakdown*", "*Does not operate on command*", and "*Locking in open and closed position*" with impact ranked at worst case for the latter two failure modes

Components responsible for failures	Failure mode	Failure origin	Available diagnostic	Contribution to the total failure, N (%)	λ	Failure frequency class	*Impact*	*Risk (R)*	$D_{ability}$	$\lambda_{revised}$	Revised failure frequency class	R_{revise}
Operating mechanism [21]	Does not operate on command	Compressors, motors, pumps, piping fittings	Visual inspection	16.64	1.75E-04	UL	EX	M	40	1.40E-04	UL	M
			State of motor/pump (current, voltage, etc.)		1.75E-04	UL	EX	M	70	6.99E-05	AI	L
			Number of motor pump running times		1.75E-04	UL	EX	M	50	1.16E-04	UL	M
			Stored energy (spring position, pressure)		1.75E-04	UL	EX	M	70	6.99E-05	AI	L
			Contact travel characteristic		1.75E-04	UL	EX	M	50	1.16E-04	UL	M
			Status of auxiliary switches		1.75E-04	UL	EX	M	40	1.40E-04	UL	M
			Coil current profile		1.75E-04	UL	EX	M	40	1.40E-04	UL	M
		Energy storage (accumulator, spring)	Visual inspection	14.92	1.57E-04	UL	EX	M	20	1.67E-04	UL	M
			State of motor/pump (current, voltage, etc.)		1.57E-04	UL	EX	M	50	1.04E-04	UL	M
	Locking in open or closed position		Number of motor pump running times		1.57E-04	UL	EX	M	70	6.27E-05	AI	L
			Stored energy (spring position, pressure)		1.57E-04	UL	EX	M	70	6.27E-05	AI	L
			Contact travel characteristic		1.57E-04	UL	EX	M	50	1.04E-04	UL	M
			Status of auxiliary switches		1.57E-04	UL	EX	M	50	1.04E-04	UL	M
			Coil current profile		1.57E-04	UL	EX	M	40	1.25E-04	UL	M
		Actuator and damping device	Vibration signature	9.26	9.77E-05	AI	EX	M	70	3.89E-05	AI	L
			Contact travel characteristic		9.77E-05	AI	EX	M	50	6.48E-05	AI	L
		Mechanical transmission	Visual inspection	15.27	1.61E-04	UL	EX	M	50	1.07E-04	AI	M
			Vibration signature		1.61E-04	UL	EX	M	60	8.55E-05	AI	L
			Contact travel characteristic		1.61E-04	UL	EX	M	60	8.55E-05	AI	L

Table 4-5 Continued: The effect of using different diagnostic techniques to foresee "*Dielectric breakdown*", "*Does not operate on command*", and "*Locking in open and closed position*" with impact ranked at worst case for the latter two failure modes

Components responsible for failures	Failure mode	Failure origin	Available diagnostic	Contribution to the total failure, N (%)	λ	Failure frequency class	Extreme	$Risk\ (R)$	$D_{ability}$	$\lambda_{revised}$	Revised failure frequency class	$R_{revised}$
Electrical control and auxiliary circuits [36]	Does not operate on command	Coils	Visual inspection	1.89	8.49E-05	AI	EX	L	40	5.10E-05	AI	L
			Coil current profile		8.49E-05	AI	EX	L	70	2.55E-05	AI	L
			Circuit continuity		8.49E-05	AI	EX	L	90	8.49E-06	AI	L
			Voltage measurements at the terminals		8.49E-05	AI	EX	L	70	6.49E-05	AI	L
		Relays	Visual inspection	4.80	2.16E-04	UL	EX	M	50	1.08E-04	UL	M
			Coil current profile		2.16E-04	UL	EX	M	50	1.08E-04	UL	M
			Circuit continuity		2.16E-04	UL	EX	M	70	6.49E-05	AI	L
			Voltage measurements at the terminals		2.16E-04	UL	EX	M	70	3.24E-05	AI	L
	Locking in open or closed position	Density monitoring System (with piping)	Visual inspection	2.40	1.08E-04	AI	EX	M	90	1.08E-05	AI	L
			Leak detection techniques		1.08E-04	AI	EX	M	70	3.24E-05	AI	L
		Energy Limit Supervision	Visual inspection	2.40	1.08E-04	AI	EX	M	50	5.41E-05	AI	L
			Number of motor pump running times		1.08E-04	AI	EX	M	70	3.24E-05	AI	L
		Auxiliary Switch	Visual inspection	2.40	1.08E-04	AI	EX	M	40	6.49E-05	AI	L
			Status of auxiliary switches		1.08E-04	AI	EX	M	70	3.24E-05	AI	L
			Coil current profile		1.08E-04	AI	EX	M	70	3.24E-05	AI	L
		Wiring & joints	Visual inspection	1.72	7.72E-05	AI	EX	L	30	5.41E-05	AI	L
			Circuit continuity		7.72E-05	AI	EX	L	70	2.32E-05	AI	L
			Voltage measurements at the terminals		7.72E-05	AI	EX	L	70	2.32E-05	AI	L

4.3.2. *Diagnostics prioritisation*

For further selection among diagnostics, a priority index is introduced in this section. To prioritise diagnostics, the following factors have been considered:

- Diagnostic cost, which includes the cost of labour and skill costs. An example of cost evaluation criteria and the corresponding ranks are shown in Table 4-6. Diagnostics showing lower costs get a higher rank.
- Detection ability, which indicates the diagnostic's ability to detect the particular failure mode. The detection ability example shown in Table 4-2 has been taken from [16] and has been ranked as shown in Table 4-7. Diagnostics showing better detection ability get a higher rank.
- Number of failures, diagnostics that are able to detect a larger part of the total number of failures N (%) as listed in Table 4-4, column 5 hence score higher.
- Risk level. The possible risk level related with a particular failure mode is determined (Section 3.2). Higher risk gets a higher rank as shown in Table 4-8.

The values proposed for the diagnostic cost, detection ability, and risk level can vary per company from the ones shown in Table 4-6, Table 4-7, and Table 4-8.

Table 4-6: An example cost ranking table

Level of cost	*Cost (C) (Man-hour)*	*Rank of cost*
Very low	$C < 0.5$	7
Low	$0.5 \leq C < 1.0$	6
Moderate	$1.0 \leq C < 1.5$	5
High	$1.5 \leq C < 2.0$	4
Very high	$2.0 \leq C < 2.5$	3
Serious	$2.5 \leq C < 3.0$	2
Extreme	$C \geq 3.0$	1

Table 4-7: An example diagnostics detection ability and rank of detection ability

Level of $D_{ability}$ [16]	*$D_{ability}$ (%)*	*Rank of $D_{ability}$*
Almost certain	> 80	7
Very high	60 - 80	6
High	50 - 70	5
Moderately high	40 - 60	4
Moderate	30 - 50	3
Low	20 - 40	2
Negligible	< 20	1

Table 4-8: Ranking of the levels of risk

Level of risk	*Rank of risk*
Unacceptable	6
Very high	5
High	4
Medium	3
Low	2
Negligible	1

To combine the diagnostics cost, the diagnostics detection ability, the number of failures, and the risk level, we introduced the diagnostics priority index value (P_{prior}).

The P_{prior} is determined by multiplying the rank of the diagnostic detection ability, the rank of the diagnostic costs, the failure mode contribution to the total number of failures, and the risk rank. A higher P_{prior} indicates a higher diagnostic priority as represented in equation 4-2.

$$P_{prior} = D_{ability\_Rank} \times C_{rank} \times N \times R_{rank} \quad \text{……...} \quad 4\text{-}2$$

Where

C_{rank} = the diagnostic cost rank (see Table 4-6).

$D_{ability\_rank}$ = the detection ability rank (see Table 4-7).

N = the number of failures N (%) per failure mode (see Table 4-4).

R_{rank} = risk rank (see the tables in Appendix B.2 for risk level and Table 4-8 for the ranking of the risk level).

Some diagnostics can reveal a single failure mode originated from multiple failure origins. For example, partial discharge detection can be used to foresee "*Dielectric breakdown*" originated from particles and protrusions. Therefore, the number of failure origins (k) is incorporated in equation 4-2, which in turn results in equation 4-3:

$$P_{prior} = \sum_{j=1}^{k} D_{ability\_rank}(j)\, C_{rank}(j)\, N(j)\, R_{rank}(j) \quad \text{……...} \quad 4\text{-}3$$

Where

k = the total number of failure origins for which a particular diagnostic method can be used and which can be discriminated.

Other diagnostics are able to discriminate multiple failure modes. For example, identifying the state of the motor can reveal problems with the operating mechanism such as the failure modes "*Not operating on command*" or "*Locked in open or closed position*". Such overlap has also been taken into account in equation 4-4 as shown by the summation over (n) below:

$$P_{prior} = \sum_{i=1}^{n}\sum_{j=1}^{k}\left(D_{ability\_rank}(ij)\, C_{rank}(ij)\, N(ij)\, R_{rank}(ij)\right) \quad \text{……...} \quad 4\text{-}4$$

Where

n = the total number of failure modes for which a particular diagnostic method can be used.

The P_{prior} has been determined by equation 4-4 for the failure modes "*Dielectric breakdown*", "*Does not operate on command*", and "*Locking in open and closed position*". The calculation results are listed in Table 4-9.

Table 4-9: Diagnostics order of priority

Diagnostic	Failure Mode	Failure origin	N (%)	$D_{ability}$	Rank of $D_{ability}$	Rank of R	Rank of C	P_{prior}	Order of priority
State of motor	Does not operate on command	Compressors, motors, pumps, piping fittings	16.64	70	6	1	6	10.47	2
		Energy storage (accumulator, spring)	14.92	50	5	1	6		
Number of motor pump running times	Does not operate on command	Compressors, motors, pumps, piping fittings	16.64	50	5	1	7	12.09	1
		Energy storage (accumulator, spring)	14.92	70	6	1	7		
Stored energy (spring position, pressure)	Does not operate on command	Compressors, motors, pumps, piping fittings	16.64	70	6	1	5	9.47	5
		Energy storage (accumulator, spring)	14.92	70	6	1	5		
Contact travel characteristic	Does not operate on command	Compressors, motors, pumps, piping fittings	16.64	50	5	1	4	9.98	4
		Energy storage (accumulator, spring)	14.92	50	5	1	4		
		Mechanical transmission	15.27	60	6	1	4		
Coil current profile	Does not operate on command	Compressors, motors, pumps, piping fittings	16.64	40	4	1	4	6.01	7
		Energy storage (accumulator, spring)	14.92	40	4	1	4		
		Relays	4.80	50	5	1	4		
Vibration signature	Does not operate on command	Mechanical transmission	15.27	60	6	1	4	3.66	9
Circuit continuity	Does not operate on command	Relays	4.80	70	6	1	5	1.44	11
Voltage measurement at the terminals	Does not operate on command	Relays	4.80	70	6	1	7	2.02	10
Status of auxiliary switches	Does not operate on command	Energy storage (accumulator, spring)	14.92	50	5	1	6	4.48	8
Visual inspection	Does not operate on command	Energy storage (accumulator, spring)	14.92	20	1	1	6	6.48	6
		Mechanical transmission	15.27	50	5	1	6		
		Density monitoring system (with piping)	2.40	90	7	1	6		

Table 4-9 Continued: Diagnostics order of priority

Diagnostic	Failure Mode	Failure origin	N (%)	$D_{ability}$	$Rank$ of $D_{ability}$	Rank of R	$Rank$ of C	P_{prior}	$Order$ of $priority$
Leak detection techniques	Does not operate on command	Density monitoring System (with piping)	2.4	70	6	1	6	0.86	12
Partial discharge (PD)	Dielectric breakdown	Poor contacts	1.89	80	6	3	6	10.00	3
		Particles and foreign bodies	3.43	80	6	3	6		
		Bulk insulation of spacer	1.72	30	2	3	6		
		Bad shield and electrostatic contacts	3.09	80	6	3	6		
		Protrusion/Particle on HV conductor	0.86	30	2	3	6		

Thereafter, the diagnostics are ordered based on their diagnostic priority values in Table 4-10. The table shows that number of motor pump running times, state of motor, partial discharge measurement, contact travel characteristics and stored energy are in the top five orders of priority respectively among the 12 diagnostics.

Table 4-10: Ordered diagnostics based on their priority

Diagnostic	***Order of priority (numbers 1 to 12 indicate the order of priority from highest to lowest respectively)***
Number of motor pump running times	1
State of motor	2
Partial discharge	3
Contact travel characteristic	4
Stored energy (spring position, pressure	5
Visual inspection	6
Coil current profile	7
Status of auxiliary switches	8
Vibration signature	9
Voltage measurements at the terminals	10
Circuit continuity	11
Leak detection techniques	12

However, some diagnostics can overlap for the same failure mode. Such an overlap unnecessary increases the diagnostic costs and has to be prevented while selecting diagnostics.

To illustrate the comparative analysis of the diagnostics and their impact on costs, the diagnostics along with their failure modes, failure origins, and detection ability are arranged in Table 4-12. The diagnostic costs and the diagnostic cumulative costs are estimated in terms of man-hours per circuit breaker bay in Table 4-12. The detection ability in the table is the same as in Table 4-5. The costs we used are based on the expert experience listed in Table 4-11. The suggested man-hours cover only the diagnostic time and exclude variables such as travel time to substation, isolation and grounding activities, safety instructions, etc.

Table 4-11: A typical example diagnostic costs estimation

Diagnostic	*Estimated man-hours per CB Bay*	*Description*
Partial discharge (PD)	0.5	2 men need 5 minutes per sensor assuming a CB bay has 3 sensors
Number of motor pump running times	0.17	2 men need 5 minutes to check the number of motor pump running times
State of motor	0.67	2 men need 20 minutes per CB bay
Stored energy (spring position, pressure)	1	2 men need 30 minutes per CB bay to check the stored energy
Voltage measurements at the terminals	0.17	2 men need 5 minutes per CB bay to check the terminal voltage
Status of auxiliary switches	0.67	2 men need 20 minutes per CB bay
Circuit continuity	1	2 men need 30 minutes per CB bay to check the circuit continuity
Vibration signature	1.5	2 men need 45 minutes per CB bay to check the vibration signature
Contact travel characteristic	1.67	2 men need 50 minutes per CB bay to check the contact travel characteristic
Visual inspection	0.67	2 men need 20 minutes per CB bay
Coil current profile	1.5	2 men need 45 minutes per CB bay to check the coil current profile
Leak detection techniques	0.5	2 men need 30 minutes per CB bay

In Table 4-12, we introduce the overlap index between diagnostics. The overlap index is calculated by dividing the detection ability of a diagnostic by the detection ability of the diagnostic which has the highest order of priority (in a set of diagnostics used for the same failure mode and failure origin) as represented in equation 4-5.

$$\%\ Overlap\ index = \frac{D_{ability}\ of\ the\ current\ diagnostic}{D_{ability}\ of\ the\ diagnostic\ with\ the\ highest\ order\ of\ priority} \times 100 \ \ldots\ldots \quad 4\text{-}5$$

The overlap index = 0 when the diagnostics have non-common failure mode and non-common failure origin as shown in Figure 4-1 (A). Such situation occurs for example for stored energy and partial discharge measurements. The overlap index is > 100 if a diagnostic has a higher detection ability than the diagnostic with the highest order of priority as shown in Figure 4-1 (B). Intermediate cases occur for 0 < overlap index ≤ 100 when a diagnostic has a lower detection ability than the diagnostic with the highest order of priority as shown in Figure 4-1 (C). The overlap index results are shown in Table 4-12.

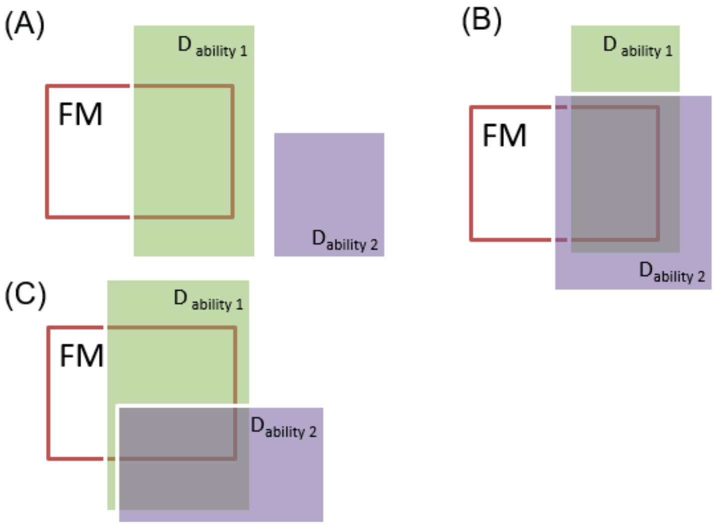


Figure 4-1: Examples of overlap between diagnostics. $D_{ability\ 1}$ is the $D_{ability}$ of the diagnostic with the highest order of priority. $D_{ability\ 2}$ is the $D_{ability}$ of other diagnostics. (A) No overlap between diagnostic 1 and diagnostic 2 (B) Overlap is larger than 100% (diagnostic 2 has a higher detection ability than diagnostic 1), (C) Overlap is larger than zero and less equal to 100 (as index is equal larger that 100 as diagnostic 2 has a lower detection ability than diagnostic 1)

The overlap results and the diagnostic cumulative costs, which are listed in Table 4-12, are presented in blue columns and an orange line respectively in Figure 4-2. The partial discharges detection, number of motor pump running times, contact travel characteristic measurements at mechanical transmission, visual inspection at density monitoring system, and coil current profile at relays are diagnostics with no overlap.

Table 4-12 shows that these five diagnostics could detect up to 39.5%[6] of the reported failures, with the risk level "*Medium*" as shown in Table 4-5, based on their detection ability and contribution to the total failure, as highlighted in red in Table 4-13.

Adding another diagnostic, such as the stored energy measurement, could increase the ratio of the detected failures by 3.3%[7] to 42.8%. However, another diagnostic could also increase the cumulative cost (man-hours per CB-bay) by 30% (i.e. from 4.67 to 6.67 hours).

If cost is not a factor, about 44.3% of the reported failures can be detected by using the diagnostics with the highest detection ability based on Table 4-12. Performing

---

6 (1.89+3.40+3.09)*0.8+(1.72+0.86)*0.3+16.64*0.5+14.32*0.7+15.27*0.6+4.80*0.5+2.40*0.9)=39.5%

7 16.64*(70-50)+14.32*(70-70)=3.3%

diagnostics without overlap would result in the minimum cost. Including other diagnostics may reveal more failures but will increase the costs.

It should be mentioned that diagnostic overlap can be seen as a way to ensure quality by double checking for the same failure mode. Nevertheless, it is important to consider the diagnostic overlap while selecting diagnostics to maximise the ratio of the detected failures and achieve budgeting.

Table 4-12: Diagnostic cumulative cost and overlap index

Priority order	Diagnostic	Failure Mode	Failure origin	Contribution to the total failure (in %)	Detection ability	Overlap index (in %)	Man-hours per CB bay	Cumulative cost (man-hours per CB bay)
1	Number of motor pump running times	Does not operate on command	Compressors, motors, pumps, piping fittings	16.64	50	0[8]	0.17	0.17
			Energy storage (accumulator, spring)	14.92	70	0		
2	State of motor	Does not operate on command	Compressors, motors, pumps, piping fittings	16.64	70	140	0.67	0.83
			Energy storage (accumulator, spring)	14.92	50	71		
3	Partial discharge (PD)	Dielectric breakdown	Poor contacts	1.89	80	0	0.50	1.33
			Particles and foreign bodies	3.40	80			
			Bulk insulation of spacer	1.72	30			
			Bad shield and electrostatic contacts	3.09	80			
			Protrusion/Particle on HV conductor	0.86	30			
4	Contact travel characteristic	Does not operate on command	Compressors, motors, pumps, piping fittings	16.64	50	100	1.67	3.00
			Energy storage (accumulator, spring)	14.92	50	71		
			Mechanical transmission	15.27	60	0		
5	Stored energy (spring position, pressure)	Does not operate on command	Compressors, motors, pumps, piping fittings	16.64	70	140	1.00	4.00
			Energy storage (accumulator, spring)	14.92	70	100		

[8] The overlap index is set to zero for the diagnostic with the highest order of priority among the set of diagnostics used for the same failure mode and failure origin.

Table 4-12 Continued: Diagnostic cumulative cost and overlap index

Priority order	Diagnostic	Failure Mode	Failure origin	Contribution to the total failure (in %)	Detection ability	Overlap index (in %)	Man-hours per CB bay	Cumulative cost (man-hours per CB bay)
6	Visual inspection	Does not operate on command	Energy storage (accumulator, spring)	14.92	20	29	0.67	4.67
			Mechanical transmission	15.27	50	83		
			Density monitoring System (with piping)	2.40	90	0		
7	Coil current profile	Does not operate on command	Compressors, motors, pumps, piping fittings	16.64	40	80	1.50	6.17
			Energy storage (accumulator, spring)	14.92	40	57		
			Relays	4.80	50	0		
8	Status of auxiliary switches	Does not operate on command	Energy storage (accumulator, spring)	14.92	50	71	0.67	6.83
9	Vibration signature	Does not operate on command	Mechanical transmission	15.27	60	100	1.50	8.33
10	Voltage measurements at the terminals	Does not operate on command	Relays	4.80	70	140	0.17	8.50
11	Circuit continuity	Does not operate on command	Relays	4.80	70	140	1.00	9.50
12	Leak detection techniques	Does not operate on command	Density monitoring System (with piping)	2.40	70	78	0.50	10.00

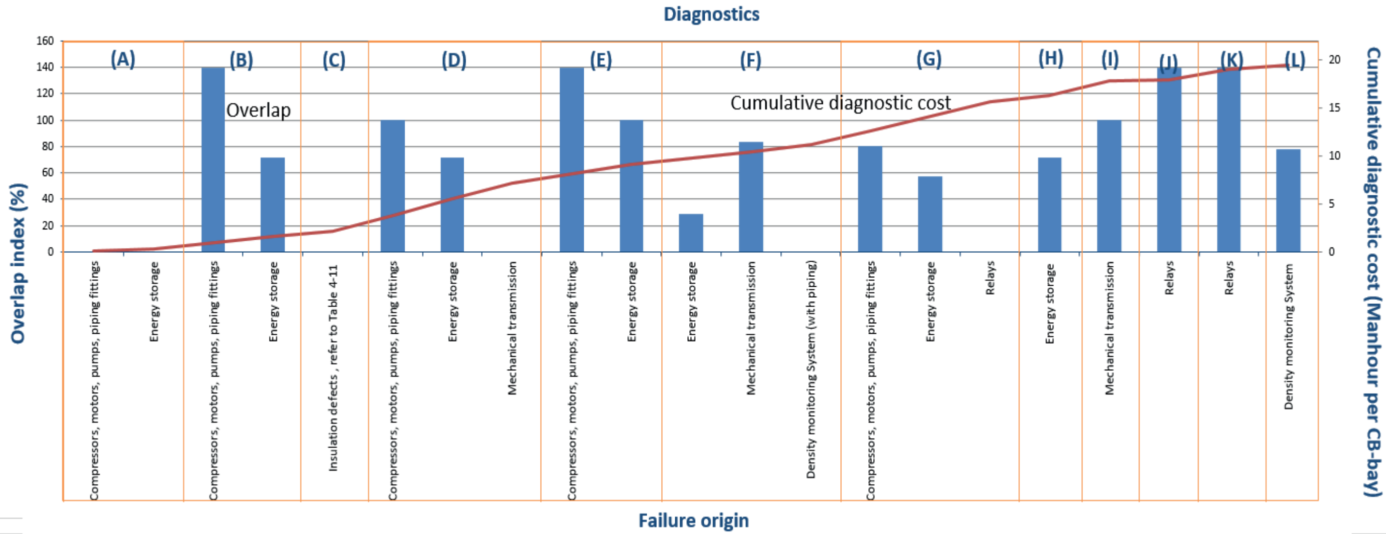


Figure 4-2: Diagnostic cumulative cost and overlap index based on Table 4-12

Number of motor pump running times (A), State of motor (B), Partial discharge (C), Contact travel characteristic (D), Stored energy (E), Visual inspection (F), Coil current profile (G), Status of auxiliary switches (H), Vibration signature (I), Voltage measurements at the terminals (J), Circuit continuity (K), Leak detection techniques (L)

Table 4-13: Detection ability and contribution to the total failure of the selected diagnostics

Components responsible for failures	Failure mode	Failure origin	Available diagnostic	Contribution to the total failure (in percentage)	$D_{ability}$
Component at service voltage	Dielectric breakdown [34]	Poor contacts	-Contact resistance	1.89	90
			-Contact temperature		20
		Poor contacts	-Partial discharge (PD)	1.89%	80
		Particles and foreign bodies		3.40	80
		Bulk insulation of spacer		1.72	30
		Bad shield and electrostatic contacts		3.09	80
		Protrusion/Particle on HV conductor		0.86	30
		Moisture	-SF_6 gas moisture	1.20	90
			-SF_6 contamination		40
		Dielectric failures resulting from mechanical failures occurring outside the insulation	-See operating mechanism required diagnostics	1.37	-
Operating mechanism [21]	Does not operate on command Locking in open or closed position	Compressors, motors, pumps, piping fittings	-Visual inspection	16.64	40
			-State of motor/pump (current, voltage, etc.)		70
			-Number of motor pump running times		50
			-Stored energy (spring position, pressure)		**70**
			-Contact travel characteristic		50
			-Status of auxiliary switches		40
			-Coil current profile		40
		Energy storage (accumulator, spring)	-Visual inspection	14.32	20
			-State of motor/pump (current, voltage, etc.)		50
			-Number of motor pump running times		70
			-Stored energy (spring position, pressure)		**70**
			-Contact travel characteristic		50
			-Status of auxiliary switches		50
			-Coil current profile		40
		Actuator and damping device	-Vibration signature	9.26	70
			-Contact travel characteristic		50
		Mechanical transmission	-Visual inspection	15.27	50
			-Vibration signature		60
			-Contact travel characteristic		60

Table 4-13 Continued: Detection ability and Contribution to the total failure of the selected diagnostics

Components responsible for failures	Failure mode	Failure origin	Available diagnostic	Contribution to the total failure (in percentage)	$D_{ability}$
Electrical control and auxiliary circuits [36]	Does not operate on command Locking in open or closed position	Coils	-Visual inspection	1.89	40
			-Coil current profile		70
			-Circuit continuity		90
			-Voltage measurements at the terminals		70
		Relays	-Visual inspection	4.80	50
			-Coil current profile		50
			-Circuit continuity		70
			-Voltage measurements at the terminals		70
		Density monitoring system (with piping)	-Visual inspection	2.40	90
			-Leak detection techniques		70
		Energy Limit Supervision	-Visual inspection	2.40	50
			-Number of motor pump running times		70
		Auxiliary Switch	-Visual inspection	2.40	40
			-Status of auxiliary switches		70
			-Coil current profile		70
		Wiring & joints	-Visual inspection	1.72	30
			-Circuit continuity		70
			-Voltage measurements at the terminals		70

4.4. *Conclusions*

Many diagnostics are available to unveil possible failure modes in GIS. Diagnostics have different costs and can offer different ability to detect a particular failure mode. Moreover, diagnostics can overlap, revealing similar failure modes. Therefore, in this chapter we introduced methods which give the ability to select and to prioritise certain diagnostics.

- Based on experience from experts of different institutions we were able to assess the diagnostic detection ability and the effect on the risk level, by which it was possible to systematically select the most efficient set of diagnostic techniques amongst the available diagnostic techniques for the failure modes "*Dielectric breakdown*", "*Does not operate on command*", and "*Locking in open and closed position*".
- To prioritise the selected diagnostic techniques, a ranking methodology has been developed. This ranking methodology relates the revised failure risk to the diagnostic costs and the diagnostic detection ability for failure origins and failure modes.
- We have shown that number of motor pump running times, state of motor, partial discharge, contact travel characteristic, and stored energy are the top five diagnostics respectively in level of priority.
- When selecting diagnostics, we learned that the overlap between diagnostics has to be considered. Overlapping failure mode diagnoses can increase the diagnostics' cumulative costs but may not increase the amount of detected failures significantly. We have shown that the diagnostics for partial discharges detection, number of motor pump running times, contact travel characteristic measurements at mechanical transmission, visual inspection at density monitoring system, and coil current profile at relays form an efficient set, having minimum overlap for the series of the risky failure modes.
- We introduced methods to select and prioritise diagnostics in GIS. These methods can be generalised for failure modes other than "*Dielectric breakdown*", "*Does not operate on command*", and "*Locking in open and closed position*" as well.

Chapter 5 Experimental Investigation: Dielectric Breakdown Initiated by Moving Particles and Protrusions

CHAPTER 5 EXPERIMENTAL INVESTIGATION: DIELECTRIC BREAKDOWN INITIATED BY MOVING PARTICLES AND PROTRUSIONS

5.1 *Introduction*

Diagnostics have been proposed in the previous chapter based on their priority and overlap in detectability for failure modes. The highest top five priorities among the other diagnostics respectively in level of priority are number of motor pump running times, state of motor, partial discharge, contact travel characteristic, and stored energy.

Sufficient data and information to develop the required knowledge rules for the latter five diagnostics are available in the literature [28][36], however more empirical information is still needed to establish effective knowledge rules despite the fact that many partial discharge interpretations in case of GIS have been published in [40] to [63].

For sound GIS, the different types of voltage and overvoltage stresses (Appendix D) are covered by the standard Lightning Impulse Withstand Level (LIWL) [59]. However, the situation is different in the presence of critical insulation defects and Very Fast Transient Overvoltages (VFTO) and superposed voltages. An insulation defect in GIS can result in a locally increased electric field, which may disturb and finally breakdown the insulation system.

The critical insulation defects have been classified into five types by Cigré A3, as summarised in Table 5-1 [34]. In general, these types of defects become critical to the insulation system for certain dimension and voltage stress as shown in Table 5-1.

Table 5-1: Important insulation defects and their critical length and voltage stress for GIS at 170 kV and higher [34].

Defect	***Critical defect length***	***Voltage stress***
Free moving particle	3 mm to 5 mm	AC, DC, Lightning Impulse (LI), Very Fast Transient Overvoltage (VFTO)
Protrusion on the high-voltage conductor	1 mm	LI, VFTO
Particle on insulators	1 mm to 2 mm	LI, VFTO
Floating elements	Undefined	AC
Voids and cavities in the GIS insulators and spacers	3 mm to 4 mm (diameter)	AC

In this chapter, we further investigate in particular the behaviour of the free moving particles and protrusions under VFTO and superposed voltage stresses.

These experiments are conducted to provide answers to the following two questions:

- Would the defect cause dielectric breakdown?
- Can such a defect already be detected under AC operational voltage stress?

Therefore we have investigated the breakdown possibility initiated by

- free moving particles in GIS under AC, lightning impulse, and VFTO stress;
- protrusions in GIS under lightning impulse voltage stress and lightning impulse superposed on AC voltage stress.

Table 5-2 lists in which section the above mentioned questions are discussed for each type of defect.

Table 5-2: An overview table of the sections on how the possibility of breakdown and detection regarding free moving particles and protrusions in GIS.

Voltage stress	***Free moving particles***		***Fixed protrusions***	
	Examined particle length (5 mm to 30 mm)		***Examined protrusion length (1 mm to 4 mm)***	
	Breakdown possibility	***Detection***	***Breakdown possibility***	***Detection***
AC	See Sections 5.2.1 and 5.4.4	See Section 5.6.1	See Sections 5.2.1 and 5.5.1	See Section 5.6.2
TOV[9]	See Section 5.4.4	-	See Section 5.5.1	-
LI	See Sections 5.2.1 and 5.4.5	-	See Sections 5.2.1 and 5.5.2	-
LI+AC	See Section 5.4.5	-	See Sections 5.2.1 and 5.5.3	-
VFTO	See Sections 5.2.2 and 5.4.6	-		

[9] Temporary Over Voltage

5.2 *Test setups for breakdown initiated by free moving particles*

Moving particles in GIS can lift off under AC voltage and get close to the high-voltage conductor, which can result in breakdown. In addition, breakdown can also occur in case VFTO or lightning voltage stress occurs.

GIS manufacturers use a quality control that aims to eliminate moving particles in newly installed GIS. In practice, however, relatively long moving particles are still found in GIS. Such particles are possibly caused by GIS operation and/or lapses in quality control during maintenance activities. In maintenance practice, particles up to a few centimetres in length have been found (see Figure 5-1). Therefore, particles of 5-30 mm length were investigated during the laboratory investigation in this research.

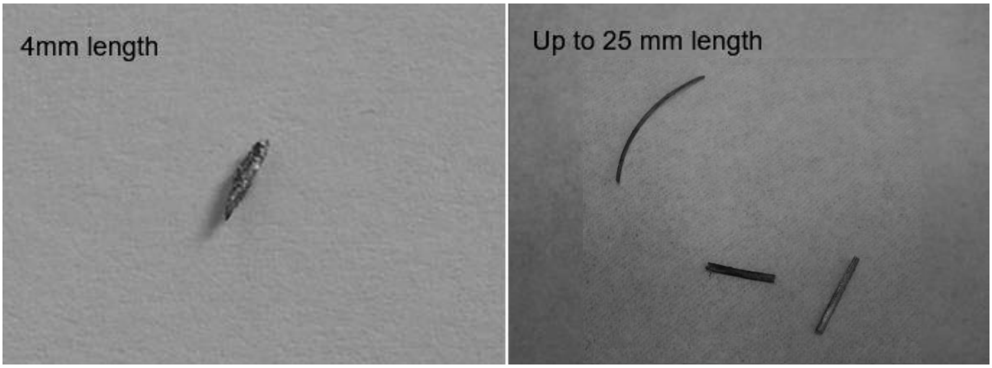


Figure 5-1: Moving particles found on site

To investigate the breakdown behaviour of free moving particles in GIS under AC, VFTO, and lightning voltage stresses, two different test setups have been used.

The first test setup was used to

- determine the maximum height that moving particles of 5-30 mm length can jump under AC voltage stress;
- investigate if breakdown occurs under AC voltage stress when moving particles reach their maximum jump height;
- investigate if breakdown occurs under lightning voltage stress for moving particles which approach the maximum jump height and haven't initiated a failure under AC voltage stress.

The second test setup was used to investigate the breakdown when a moving particle jumps to its maximum jump height while VFTO stress is simultaneously occurring. Only particles that have initiated no breakdown under AC voltage stress at their maximum jump height were subjected to VFTO voltage stress successively in our investigations. Particles up to 30 mm in length were selected during the experimental investigation.

5.2.1 Test setup for AC and lightning impulse breakdown investigation

A partial discharge-free GIS test section has been used to perform the breakdown experiments under AC and lightning impulse voltage stress. The high-voltage conductor and the enclosure are made of aluminium with a 35-mm and 150-mm inner and outer radius respectively.

The GIS test section has been connected via a bushing to the voltage source as shown in Figure 5-2 for AC and in Figure 5-3 for Lightning Impulse (LI). To protect the AC source from the high current surge in case of breakdown, a protection resistance is used. The voltage has been measured through a capacitive or resistive voltage divider.

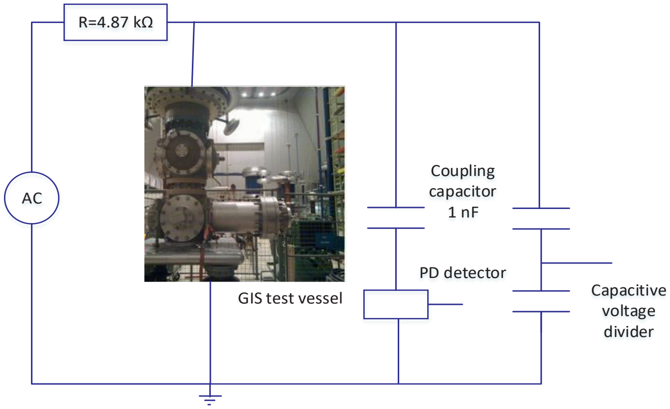


Figure 5-2: The AC test setup

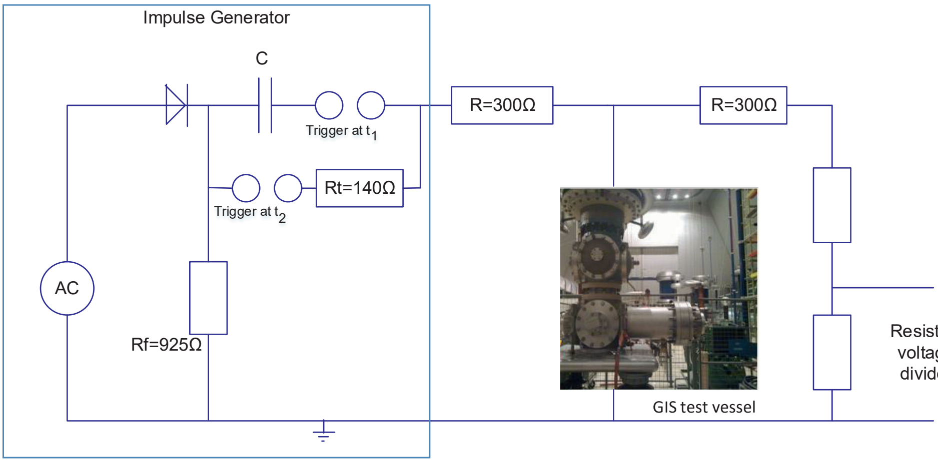


Figure 5-3: The lightning impulse test setup

Aluminium wire particles were placed on the inner surface of the GIS enclosure in the test section during the AC experiments. During the lightning impulse experiments, the particles were placed at various heights including their maximum height of jump using a cotton thread as shown in Figure 5-4.

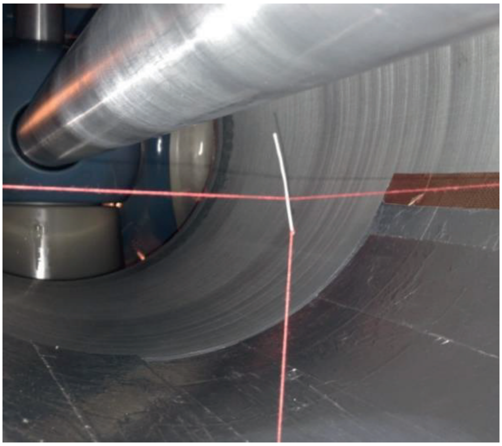


Figure 5-4: Aluminium wire particles at a pre-defined height in the test compartment

The particles are 5, 10, 15, 20, and 30 mm in length. The particles' radius is 0.25 mm. An example of a 10-mm length cylindrical aluminium particle is shown in Figure 5-5.

Figure 5-5: Aluminium wire particle of 10-mm length and 0.25-mm radius

During the tests, the AC voltage was slowly increased up to 1.08 p.u. (130 kV_{rms}), which is the maximum achievable voltage for this setup. The voltage value was maintained for about 100 seconds whenever required to allow partial discharge measurements by means of the UHF-PD method. PD was also measured by means of conventional partial discharge detection as described in the IEC 60270 standard.

The lightning impulse voltage was increased up to 3.5 pu (600 kV) in steps of 20 kV during the lightning impulse tests. Once breakdown occurs, the particle was replaced.

5.2.2 Test setup for VFTO breakdown investigation

VFTO measurements have been performed in fruitful cooperation with the High Voltage Laboratory of the Institute of Power Transmission and High Voltage Technology (IEH) at Stuttgart University. The test setup used to perform the VFTO measurements is a 550 kV GIS section. A picture of the GIS test setup is shown in Figure 5-6.

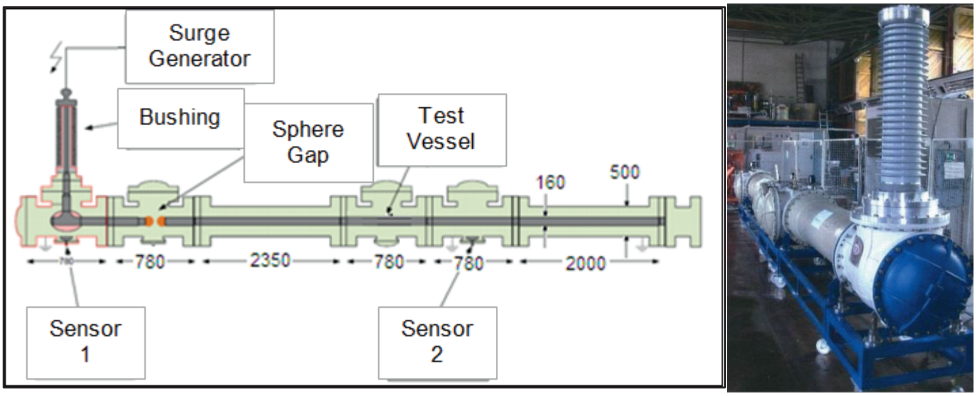


Figure 5-6: VFTO test setup (550-kV GIS) in the laboratory of Stuttgart University of Technology

The VFTO stress is generated by means of a sphere gap subjected to a lightning impulse. The lightning impulse is generated by a standard impulse generator and injected into the GIS via the connected bushing. The breakdown of the sphere gaps result in VFTO waves.

The VFTO waves reflect at the far end of the GIS. When the inner conductor is not grounded, the reflection coefficient is approximately +1. When the inner conductor is connected to the ground, the reflection coefficient is approximately -1.

This test setup is suitable to generate VFTO waves of amplitude up to 800 kV with an approximate basic frequency of about 15 MHz (when the HV conductor is open ended) and about 7.5 MHz (when the HV conductor is grounded). The VFTO basic frequency depends on the reflection at the ends and the total length of the GIS (refer to Figure 5-6).

The amplitude of the VFTO is controlled by adjusting the sphere gap distance and the gas pressure in the sphere gap compartment.

The test setup is occupied with two capacitive sensors integrated at each side of the GIS. These two sensors are especially developed by IEH to measure VFTO in GIS (see Figure 5-6) [35].

During the experiments, the sphere gap distance was fixed to 10 mm, and the gas pressure was varied from 1 to 5 bars. The maximum amplitude of the generated VFTO is 645 kV, with a frequency of approximately 15 MHz (the HV conductor is open ended) and rise time of about 26 ns as shown in Figure 5-7. The blue line in Figure 5-7 indicates the measured waveform at sensor 1, and the green line indicates the measured waveform at sensor 2.

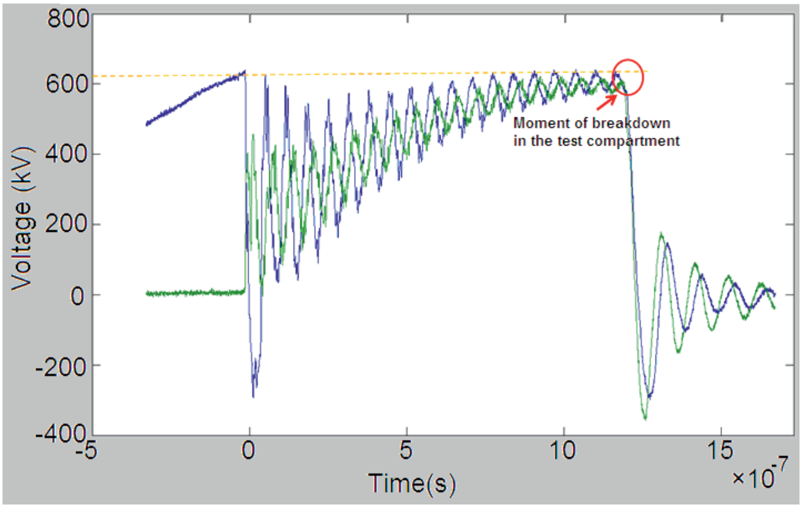


Figure 5-7: Maximum VFTO measured in the GIS test setup. The blue and the green lines are respectively the measured waveforms at sensors 1 and 2, see Figure 5-6

During the experiments, the aluminium particles were placed at a predefined height including their maximum height of jump by using a cotton thread as shown in Figure 5-8.

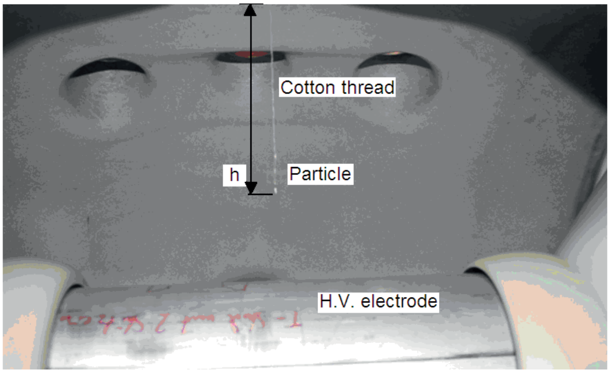


Figure 5-8: A cotton thread is used to hold the particles at a pre-defined height (h) in the test compartment

5.3 *Test setups for breakdown initiated by protrusions*

Three different test setups have been used to investigate breakdown in GIS initiated by protrusions:

1. The AC test setup was used to distinguish protrusion lengths that initiate breakdown under AC voltage stress.
2. The lightning test setup was used to distinguish protrusion lengths that initiate breakdown under lightning impulse voltage stress. Protrusions which initiated no breakdown under AC voltage stress were subjected to lightning impulse.
3. The superposed test setup was used to distinguish protrusion lengths that initiate breakdown under lightning impulse superposed on AC voltage stress. Only protrusions which initiated no breakdown under lightning impulse were subjected to this test.

5.3.1 Test setup for AC breakdown investigation

Critical protrusion lengths that initiate breakdown under AC voltage stress in GIS have been investigated. A test vessel filled with 4.5-bar (absolute) SF_6 gas, as shown in Figure 5-9, was used. The test vessel was connected to the AC source through 1 kΩ resistance to protect the AC source from the high current surge in case of breakdown. A coupling capacitor of 1 nF and a partial discharge detector was used to measure the partial discharges as described in the IEC 60270 standard.

Protrusions of 1 mm up to 4 mm length and 70-90 μm tip were placed between two Rogowski electrodes. The distance between the electrodes was 5 mm.

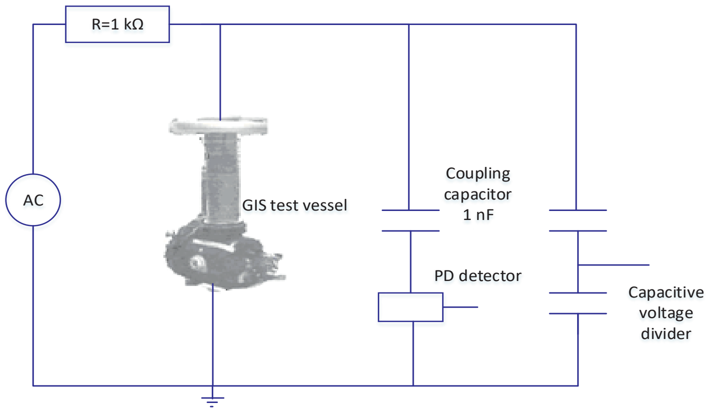


Figure 5-9: Circuit diagram for breakdown under AC voltage stress in GIS due to protrusions

5.3.2 Test setup for lightning impulse breakdown investigation

The test setup shown in Figure 5-10 was used to perform the breakdown test under lightning impulse in the presence of protrusions. A discharge capacitance of 2 μF, a front resistor of (180 Ω+600 Ω), and a tail resistor of 6.14 kΩ were used to obtain the standard lightning impulse shown in Figure 5-11. Rogowski electrodes were used during the experiments. The distance between the electrodes was 5 mm.

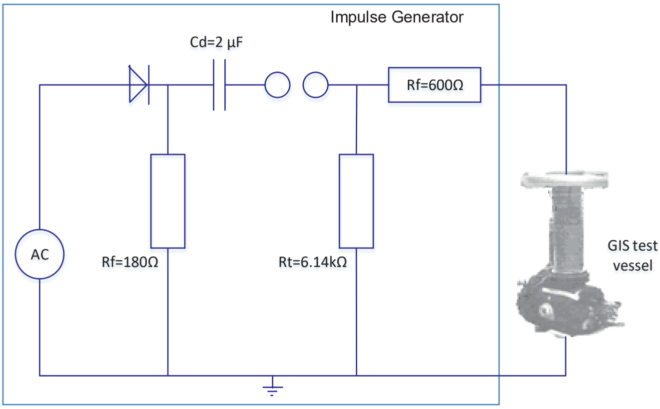


Figure 5-10: Circuit diagram for breakdown under lightning voltage stress due to protrusions

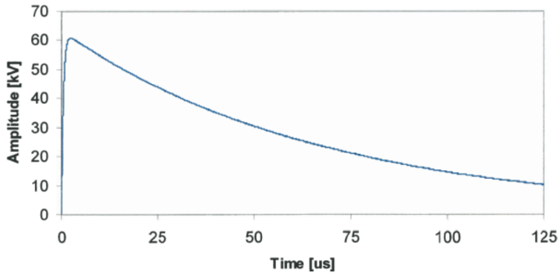


Figure 5-11: Lightning impulse (1.42 µs, 50.4 µs) obtained by the circuit diagram shown in Figure 5-10, these values are within the acceptable limits of standard LI of 1.2 µs (±30%), 50 µs (20%) specified in IEC 60060-1

5.3.3 Test setup for superposed voltage breakdown investigation

The breakdown voltage of protrusions in GIS under lightning impulse superposed on AC voltage stress has been investigated by using the test setup shown in Figure 5-12.

Rogowski electrodes were used during the experiments. The distance between the electrodes was 5 mm.

The AC source was connected to the LV electrode (GIS enclosure), and the lightning impulse generator was connected to the HV electrode. The circuit shown in Figure 5-12 was designed to protect the AC source from the steep surges of the impulse generator and also to protect the impulse generator and the AC source during a breakdown by using a sphere gap.

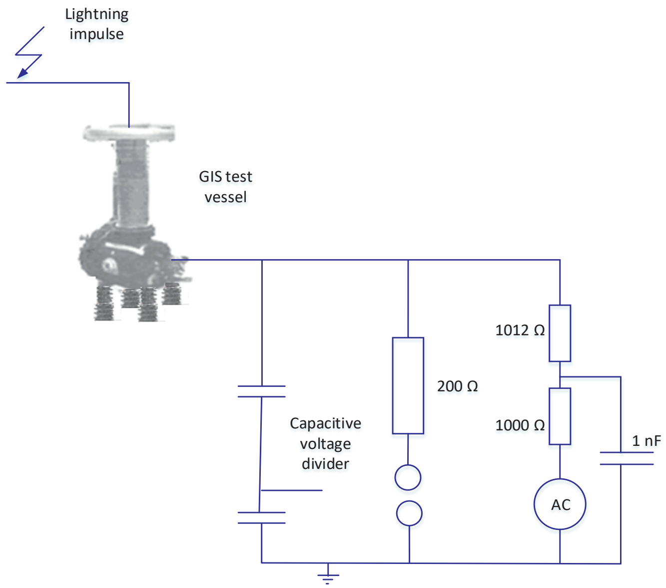


Figure 5-12: Circuit diagram for breakdown under superposed voltage stresses in GIS due to protrusions

Standard lightning impulse has been superposed on the AC voltage. The maximum electric field stress occurs when the voltages support each other, i.e. when the negative lightning impulse is superposed on the positive peak of the AC voltage and vice versa (see Figure 5-13).

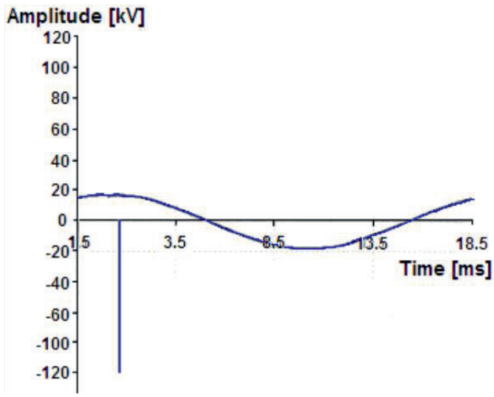


Figure 5-13: Lightning voltage stresses superposed on AC voltage stress. Worst case situations occur when the superposed voltages enhance each other.

5.4 *Dielectric breakdown initiated by free moving particles*

Free moving particles laying on the inner side of the GIS enclosure start moving when the electrostatic (lifting) force exceeds the gravitational force. The magnitude of the electrostatic force depends on the value of the electric field, the particle's dimensions, the type of particle material, and the particle's orientation [40].

Moving particles can also lift off by means of sufficient mechanical impact, even when the electrostatic force is less than the gravitational force [40]. Therefore, the effect of a mechanical impact on GIS was investigated during the experiments as well.

Aluminium wire particles with a 0.25-mm radius and a length from 5 mm up to 30 mm were placed on the inner surface of the GIS test vessel and subjected to AC voltage stress.

Besides the partial discharge and the breakdown measurements under AC voltage stress, the maximum jump height of the particles was measured. Thereafter, the particles were placed at their maximum jump height by means of a cotton thread (see Figure 5-8) and subjected to AC, lightning, and VFTO voltage stresses to assess the lowest breakdown level.

5.4.1 Basic principle behind particle lift-off

The motion of particles laying on the inner side of the GIS enclosure, under the influence of the applied electrical field, can be estimated by calculating the forces acting on the particle[44]. The electrostatic force F_e and the gravitational force F_g are the main forces affecting a particle's movement thereby the image and the drag forces were neglected. A moving particle starts moving mainly if the electrostatic force F_e exceeds the gravitational force F_g [44] [48]. In first approximation, F_e is calculated by multiplying the net charge on the particle with the value of the electric field[44]. F_g is calculated by multiplying the mass of the particle with the gravitational acceleration. F_e and F_g are determined by equations 5-1 and 5-2. During the calculation of F_e, the worst case is considered when the voltage is at its peak value. The calculation results are shown in Table 5-3.

$$F_e = Q\hat{E}$$

$$= 2\,\pi\,\varepsilon_0\, r\, l\, \hat{E}^2$$

$$= 2\,\pi\,\varepsilon_0\, r\, l\, \left(\frac{\hat{V}}{r_o\, ln\frac{r_o}{r_i}}\right)^2 \quad \text{........ 5-1}$$

$$F_g = m\,g \quad \text{........ 5-2}$$

The ratio (F_e/F_g) is as follows:

$$\frac{F_e}{F_g} = \frac{2\,\pi\,\varepsilon_0\, r\, l_{particle}\left(\frac{\hat{V}}{r_o\, ln\frac{r_o}{r_i}}\right)^2}{9.81\,\pi\,\rho\, l_{particle}\, r_{particle}^2}$$

$$\frac{F_e}{F_g} = \frac{2\,\varepsilon_0\,\left(\frac{\hat{V}}{r_o\,ln\frac{r_o}{r_i}}\right)^2}{9.81\,\rho\,r_{particle}} \quad \text{……...} \quad 5\text{-}3$$

Where

$\hat{E}$ = peak value of the electric field (V/m);

ε_0 = permittivity of free space= 8.85×10^{-12} F/m;

$l_{particle}$ = particle length (m);

r = particle radius = 0.25×10^{-3} (m);

$\hat{V}$ = peak voltage = 130 kV;

r_o = outer radius of GIS = 0.15 m;

r_i = inner radius of GIS = 0.035 m;

m = particle mass = π ρ $l\,r^2_{particle}$ (kg);

ρ = particle density = 2700 kg/m^3 (Aluminium); and

g = gravitational acceleration = 9.81 m/s^2 or N/kg.

Table 5-3: The calculated electrostatic and gravitational forces for different particle lengths

l (mm)	F_e (N)	F_g (N)	F_e/F_g
5	2.10×10^{-5}	2.60×10^{-5}	0.8
10	4.20×10^{-5}	5.20×10^{-5}	0.8
15	6.30×10^{-5}	7.79×10^{-5}	0.8
20	8.40×10^{-5}	10.4×10^{-5}	0.8
25	10.5×10^{-5}	13.0×10^{-5}	0.8
30	12.6×10^{-5}	15.6×10^{-5}	0.8

The ratio (F_e/F_g) in the first approximation is independent of the particle's length. The ratio (F_e/F_g) is fixed for the particular GIS dimensions, applied voltage, and particle's radius.

Even when manufacturers are using proper quality control in an effort to eliminate contamination during manufacturing of GIS, the ratio (F_e/F_g) can be used by the GIS manufacturers to adjust their design and manufacturing process to produce a more reliable GIS. For instance, the movement of particles of a critical radius in GIS of a particular dimension and voltage level can be estimated, and the particles can get trapped by gravity by adjusting the GIS dimensions during the design process or by constructing a field trap. Such trapping techniques are being used by the GIS manufacturers.

As noted, the image charges and the drag force also influence the particle's movement [41] [42]. A particle laying on or close to the GIS enclosure senses an attractive force due to the image charges in the GIS enclosure [41]. A decrease in F_e of 30% due to the image charges has been reported in [41]. The drag force also acts in the opposite direction of the particle motion and originates from the skin friction along the particle surface [41]. Refer to Appendix E for the calculation of maximum and minimum jump heights and drag force.

5.4.2 Laboratory results of particle movement in GIS

Under AC voltage, the motion of particles has been confirmed by visual inspection using a video camera placed close to an inspection window of the GIS test vessel.

During the experiments, particles showed no movements even when the voltage increased up to 1.08 pu. The reason behind the immobility of the particles is explained by equation 5-3. For the values used during the experiments, the ratio (Fe/Fg) is approximately equal to 0.8. The electrostatic force is thus 20% less than the gravitational force. This clarifies why the particles did not start to move under the AC voltage stress. To initiate particle movements, a hammer was used to simulate the mechanical forces generated fromswitching components in GIS.

The frequencies and the G-force levels generated by the hammer are in the range 0.8 kHz. The amplitude can be adjusted to 15–40 G in the range of circuit breaker vibration [43]. The resulting G-force from the hammer was measured during the experiments by a commercial accelerometer (Monitran 1010) which can measure up to 80 G.

After applying the mechanical impact, the particles showed some movement. For example, 5-mm particles have shown some movements before they welded vertically to the inner surface of the GIS enclosure[10]. Longer particles clearly showed shuffling, moving, and even jumping. Table 5-4 lists the particles' observed movements.

Table 5-4: Particles movement in GIS after mechanical impact [11,12]

		Electric field at the low voltage conductor (pu)			
		0,67	***0,83***	***1,00***	***1,08***
Particle length (mm)	***5***	Jumped and welded to the inner surface of the GIS enclosure	welded to the inner surface of the GIS enclosure	welded to the inner surface of the GIS enclosure	welded to the inner surface of the GIS enclosure
	10	Shuffling	Increased Shuffling	Increased Shuffling	Moving and jumping away
	15	Shuffling	Shuffling and jumping	Moving and jumping away	Moving and jumping away
	30	Shuffling	Moving and jumping away	Moving and jumping away	Moving and jumping away

In the performed experiments, it was observed that prior to applying a mechanical impact the particles showed no movements under the applied electric field. Supported by the mechanical impact, particles of 5 mm jumped and were welded to the inner surface of

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[10] Influenced by the mechanical impact, particles of 2-mm length also jumped and welded vertically to the inner side of the GIS enclosure.

[11] The light grey text indicates that the observed movement did not change when the voltage increased.

[12] More description of the terms *shuffling*, *moving*, and *jumping* (mentioned in this table) are described in Section 5.6.1.

the GIS enclosure. Longer particles were shuffling, moving, and jumping towards the high-voltage conductor.

5.4.3 Particles' jump height

Simulations have been performed to estimate the particles' jump height based on the calculation of the electrostatic force, the gravity force, and the drag force. To confirm the simulation results, the particles' time of flight was measured by the acoustic AIA analyser, and the particles' jump height was determined [43]. The acoustic measurement results are listed in Appendix E. The simulations and the acoustic measurements are shown in Figure 5-14.

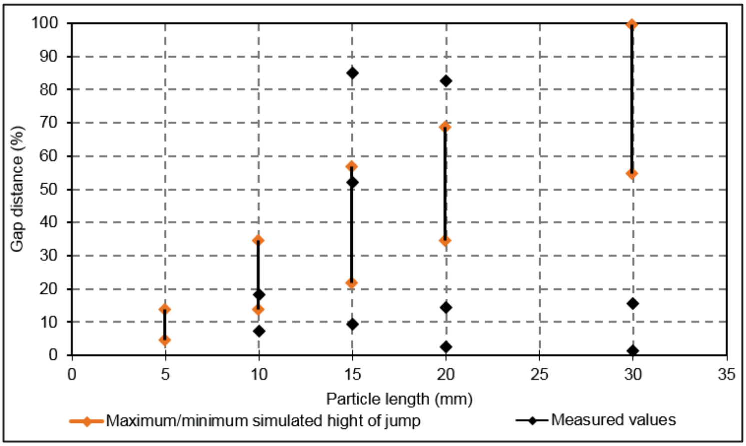

Figure 5-14: The jump height measurements of aluminium particles of various length and 0.25-mm radius under 1.08 pu AC voltage stress (after mechanical impact)

Some deviations can be observed between the measured and the simulated values in Figure 5-14. This deviation be caused by initial value of non-zero charge on the particle at lift-off. It could also be due to neglecting the inflight corona [44]. Indeed, it has been reported in [44] that the actual charges at lift-off are approximately 20% higher than the value obtained by equation 5-1.

Despite the deviation between the simulation and experimental results, the jump height measurements obtained from the simulations and measurements were used during the following breakdown experiments.

5.4.4 Dielectric breakdown initiated by moving particles under AC voltage stress

Once a particle approaches the HV conductor, the particle may exchange (part of) its charges by means of partial discharges. Such charge exchanges result in a decrease or reversal in the force acting on the particle, and thus the particle is forced back towards the enclosure.

Instead of a partial discharge, particles in the vicinity of the high-voltage conductor can cause a full breakdown. It has been reported by [41] that under AC voltage stress, the highest probability that a particle can cause breakdown occurs at the voltage peak and when the particle is close (<2 mm) to the high-voltage conductor.

However, not all particles can reach the vicinity of the high-voltage conductor and cause breakdown. During the AC experiments, the particles were placed initially at various jump heights including the maximum jump height or even higher (i.e. even closer to the HV conductor) by using a cotton thread as shown in Figure 5-4.

No breakdown was initiated by particles of 30- and 20-mm length in SF_6 gas at 3 bars (absolute) and 1.08 pu. Breakdown was observed for 30-mm particles at low SF_6 gas pressure of 1 bar (absolute) and elevated test voltage (1.23 pu) when the particles were only at a short distance from the HV conductor.

The experimental results are listed in Table 5-5.

Table 5-5: The measurement results under AC voltage stress

Defect length (mm)	*The gap distance crossed by the particle (in percentage)*	*Voltage (pu)*	*Gas pressure (bars absolute)*	*Breakdown*
30	70	1,08	3	No
30	90	1,08	3	No
30	95	1,08	3	No
30	95	1,08	2	No
30	95	1,08	1	No
30	98	1,13	1	No
30	98	1,17	1	No
30	98	1,23	1	Yes
30	98	1,25	1	Yes
20	98	1,25	1	No
20	98	1,26	1	No

These results are in line with the experimental results published by Cooke et al. and Hattori et al. in [60] and [61]. We have re-calculated the breakdown stress values from these two studies in a GIS test setup with similar dimensions. The results are presented in Figure 5-15. The dashed red line in Figure 5-15 indicates the electric field strength of 1 pu in the AC test setup. 1 pu electric field strength is below the required electric field strength to cause breakdown in the presence of particles from 5 mm up to 30 mm in length in the test setup under AC voltage stress. It should be noted that the particles were fixed by a cotton thread to the gap distance mentioned in Table 5-5.

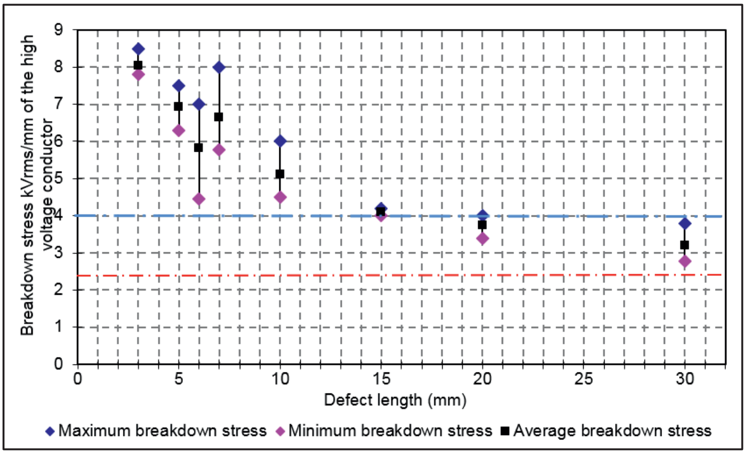

Figure 5-15: AC breakdown stress in the presence of moving particles in GIS at 4 bars (absolute) [60][61]. The red line in the figure indicates the electric field strength in the laboratory test setup (1 pu=2.62 kV$_{rms}$/mm[13]).

In case of a temporary overvoltage, a voltage increase of up to 1.7 pu (i.e. a value of 1.7 × 2.62 kV$_{rms}$/mm = 4.45 kV$_{rms}$/mm) can be expected. By shifting the red line in Figure 5-15 up to this value (see the blue line in the figure), it can be concluded that particles of 15 mm and longer would become critical to the GIS since they may cause breakdown if a temporary overvoltage were to occur.

[13] This level is similar to the electric field strength in a 380 kV GIS installation in Meeden.

5.4.5 Dielectric breakdown initiated by moving particles under lightning impulse

For breakdown results initiated by particles under lightning impulse which is superposed on AC voltage stress, we refer to Hattori et al. [61]. We have re-calculated the breakdown stress values given by Hattori et al. in a GIS test setup of similar dimension like ours. The results are plotted in Figure 5-16.

At 3.5 pu electric field strength, i.e. 11.6 kV_{peak} / mm, particles of 10 mm and longer might cause breakdown while particles shorter than 10 mm long might not cause breakdown. We performed HV experiments in order to confirm the estimated values using our set-up, as well as to relate the particle length to the particle's maximum height of jump and to the breakdown strength.

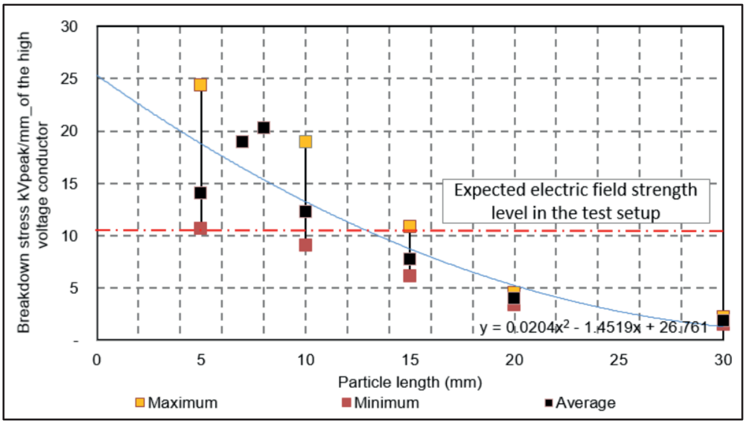

Figure 5-16: Breakdown initiated by moving particles under lightning superposed on AC voltage stress at 4 bars (absolute) [61]

Aluminium particles from 5 mm to 30 mm were placed in the same way as in the test vessel described in Section 5.2.1, namely at their maximum jump altitude by means of a cotton thread. The particles were subjected to a standard lightning impulse. The lightning impulse was increased in steps from 20 kV up to a maximum value of 600 kV, which corresponds to 3.5 pu [43]. Our results are summarised in Table 5-6 [43].

Table 5-6: Breakdown initiation results in the presence of moving particles under lightning impulse at 4 bars (absolute) [43][1]

	The distance from the particle tip to the GIS enclosure in percentage[2,3]								
Particle length	***10%***	***20%***	***30%***	***40%***	***50%***	***60%***	***70%***	***80%***	***90%***
5 mm									
10 mm									
15 mm									
20 mm									
25 mm									
30 mm									

[1]The green colour indicates no breakdown has occurred during the experiments under positive and negative lightning impulse. The yellow colour indicates no breakdown has occurred under only positive impulse (in these cases, no experiments were performed under negative impulse lightning). The red colour indicates that breakdown has occurred under positive and negative lightning impulse.

[2] The distance expressed in the table is the distance from the inner surface of the GIS enclosure to the particle tip. Therefore the distance is the thread and the particle length (see Figure 5-8) divided by the total gap distance expressed in a percentage.

[3] The grey colour boxes indicate that no measurement was performed since the particle length exceeds the possible gap distance.

To estimate whether a particle might cause breakdown, the points of measured breakdown at the minimum gap distance per particle (see Table 5-6), the particle's simulated jump height, and the measured jump height (as shown in Figure E-8 in Appendix E) are presented together in Figure 5-17. Black dots in the figure represent the measured height of jump, and orange dots represent simulated ones. The red triangles are the measured points of breakdown at the minimum gap distance per particle (see Table 5-6).

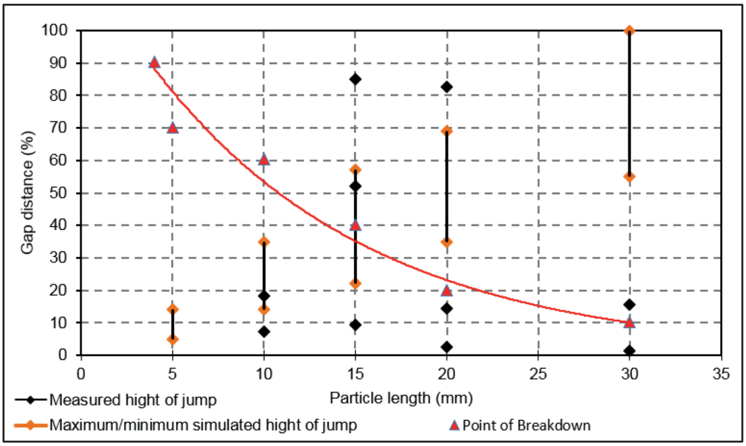

Figure 5-17: Evaluation of breakdown initiated by moving particles under lightning impulse voltage stress.

The jump's height achieved by particles of 10 mm and shorter will not enable these particles to jump beyond the breakdown trend line as shown in Figure 5-17 (the red line). Therefore, particles 10 mm long and shorter are not critical to the GIS under lightning voltage stress. Longer particles are able to jump higher than the breakdown trend line, and therefore particles of 15 mm-length and longer are critical to the GIS under lighting voltage stress.

5.4.6 Dielectric breakdown initiated by moving particles under VFTO voltage stress

A first series of experiments have been conducted to investigate the dielectric breakdown initiated by particles in GIS under VFTO voltage stress. The laboratory test setup described in Section 5.2.2 was used. The particles were placed in the test compartment at a predefined distance modelling the worst-case particle jump under AC voltage stress. A cotton thread was used to keep this distance as shown in Figure 5-8. The particle is subjected to about 2.3 pu VFTO voltage stress. In these experiments, no AC voltage was applied.

The breakdown results initiated by particles under lightning impulse superposed on AC voltage stress, as shown in Figure 5-16, were used to indicate which particle lengths could initiate breakdown under VFTO voltage stress. For this purpose, Figure 5-16 has been depicted in Figure 5-18 where 2.3 pu voltage stress is indicated by the broken red line.

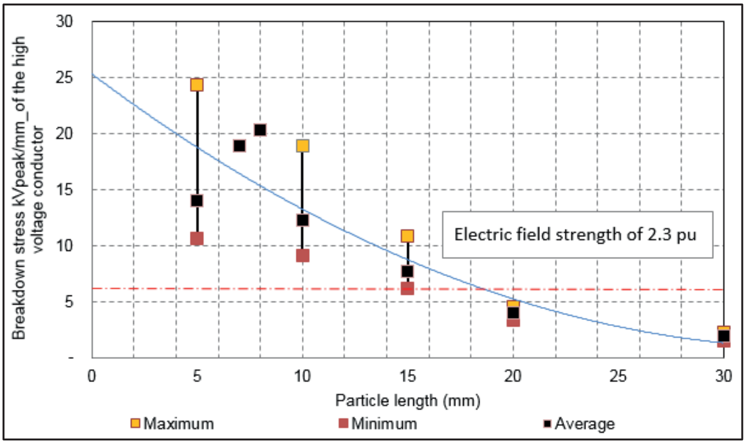

Figure 5-18: Breakdown initiated by moving particles under lightning superposed on AC voltage stress at 4 bars (absolute). The red line indicates the electric field strength in the VFTO laboratory test setup at 2.3 pu (6 kV_{peak}/mm)

The figure indicates that particles of 15 mm and longer can initiate breakdown. Therefore, to investigate the breakdown initiated by particles under VFTO voltage stress, 15-mm and 30-mm moving particles were subjected to 2.3 pu VFTO voltage stress. The experimental results are summarised in Table 5-7.

Table 5-7: Experiment results under 2.3 pu VFTO voltage stress

Particle length (mm)	*The distance from the particle tip to the GIS enclosure in percentage[14]*	*Number of attempts*	*Break down*
15	10	6	No
15	35	6	No
15	40	4	No
15	65	6	No
15	75	6	No
15	90	5	No
30	70	26	No
30	90	2	Yes

The points of the measurements, the particle's simulated height of jump, and the measured height of jump are shown together in Figure 5-19.

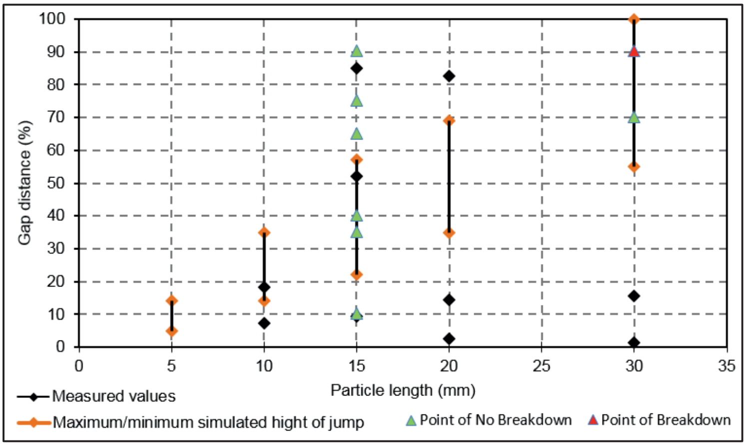

Figure 5-19: Evaluation of breakdown initiated by moving particles under VFTO voltage stress of 2.3 pu. Black and orange dots are the measured height of jump and simulated height of jump respectively.

It can be observed from Figure 5-17 and Figure 5-19 that the breakdown points observed under lightning voltage stress are shifted upwards under VFTO voltage stress due to the shorter time duration of the VFTO stress. For the same particle length, the particle has to bridge more distance of the gap towards the HV conductor to cause breakdown under VFTO voltage stress compared to the lightning voltage stress. In the case of the 30-mm particle length, the particle has to bridge 10% of the gap distance to cause breakdown under lightning impulse compared to 90% under VFTO voltage stress. Thus for the same particle length and gap distance, a higher voltage is required to have breakdown under VFTO voltage stress [50]. The breakdown voltage is higher under VFTO voltage stress.

Based on the experimental results, as shown in Figure 5-19, the following conclusions can be drawn:

[14] The distance expressed in the table is the distance from the inner surface of the GIS enclosure to the particle tip, i.e. it includes the thread and the particle length (see Figure 5-8).

1. Particles of 15-mm length and shorter cause no breakdown under VFTO voltage stress.
2. Particles of 30-mm length and shorter cause no breakdown under VFTO voltage stress at a gap distance less than 70%.
3. Particles of 30-mm length and longer cause breakdown under VFTO voltage stress at a gap distance equal or bigger than 90%.
4. More experiments are required to evaluate the breakdown behaviour in-between the range in particle length of 15–30 mm at a gap distance which exceeds 70%.

5.5 *Dielectric breakdown initiated by protrusions*

5.5.1 Dielectric breakdown initiated by protrusions under AC voltage stress

Breakdown initiated by protrusion defects of lengths from 1 to 4 mm has been investigated in our GIS setup under AC voltage stress (section 5.3.1). The breakdown results are shown in Figure 5-20. The breakdown values are given in per unit with respect to the electric field strength at the HV conductor in a 380 kV GIS with 270-mm and 65-mm outer and inner radii of conductor respectively [47].

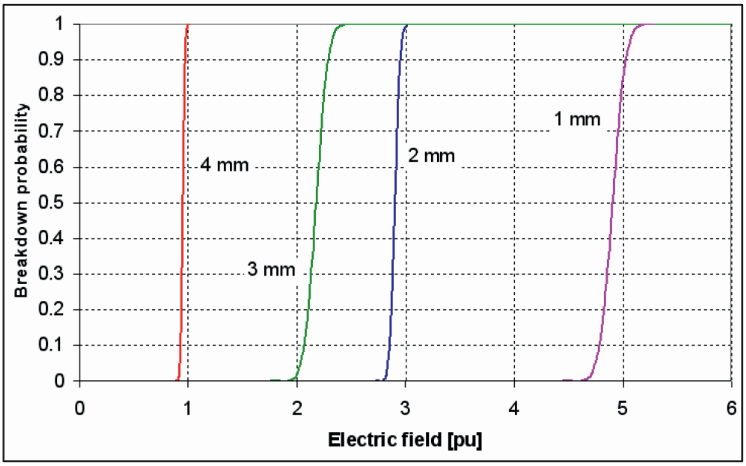

Figure 5-20: Protrusion-initiated breakdown under AC voltage stress. Breakdown probability versus the electric field strength of the HV electrode in pu (1 pu is 3.7 kVpeak/mm) [47]

Figure 5-20 shows the following:

- The breakdown voltage decreases as the protrusion length increases.
- Protrusion of 4 mm would initiate breakdown slightly below 1 pu under AC voltage stress. Protrusions of 1, 2, and 3 mm would cause no breakdown under 1 pu AC voltage stress as well as under temporary overvoltage where the voltage may increase up to 1.7 pu.

5.5.2 Dielectric breakdown initiated by protrusions under lightning impulse voltage stress

Breakdown initiated by protrusion defects 1–4 mm in length have been investigated using the test setup discussed in section 5.3.2 for standard lightning impulse. The breakdown voltage was investigated under positive as well as under negative lightning impulse. The up-and-down method was used to determine the breakdown voltage, and 20 impulses were used each time [49].

The experimental results are summarised in Table 5-8. It can be observed that, as we expected, that the negative lightning impulse polarity is more critical [50].

Table 5-8: Dielectric breakdown values in GIS initiated by protrusions 1–4 mm in length under lightning impulse voltage stress [47]

Protrusion length (mm)	*LI (positive) [pu]*	*LI (negative) [pu]*
1	5.53±0.15	-5.07±0.53
2	3.49±0.11	-2.35±0.15
3	2.69±0.08	-1.92±0.09
4	1.32±0.04	-1.13±0.05

Lightning impulse of amplitude up to about 3.5 pu can occur in GIS. Therefore, values less than 3.5 pu in Table 5-8 would indicate breakdown. In conclusion, protrusions of 1-mm length will not cause a breakdown under lightning impulse. Protrusions 2 mm long are likely to cause breakdown under positive lightning impulse since they are within the scatter. Longer protrusions of 3 mm and 4 mm will cause breakdown under lightning impulse.

5.5.3 Dielectric breakdown initiated by protrusions under lightning impulse superposed on AC voltage stress

The test setup discussed in Section 5.3.3 was used to investigate protrusion-initiated breakdown under lightning impulse superposed on AC voltage stress. Protrusions of 1-mm and 2-mm length were used during the experiments since the first length caused no breakdown under lightning impulse and the second length is likely to cause breakdown under positive lightning impulse (see Table 5-8). Longer protrusions have not been considered as these will cause a breakdown regardless.

A standard lightning impulse was superposed on AC voltage. The up-and-down method was used to determine the breakdown voltage where 20 impulses were used in each time.

The experiments results are summarised in Table 5-9 [47].

Table 5-9: Dielectric breakdown values in GIS initiated by protrusions 1 mm and 2 mm in length under lightning impulse superposed on AC voltage stress [47]

Protrusion length (mm)	*Voltage stress (pu)*	
	AC (negative) and LI (positive) [pu]	*AC (positive) and LI (negative) [pu]*
1	4.6-4.9	3.3-3.7
2	2.8-3.1	1.6-1.8

A 3.5 pu lightning impulse superposed on 1 pu AC voltage stress would result in a voltage stress of 4.5 pu. Based on Table 5-9, it can be concluded that protrusions as short as 1 mm in length would cause dielectric breakdown in GIS under superposed voltage stresses in the case of 3.5 pu lightning impulse.

5.6 *Partial discharge detection of moving particles and protrusions*

In the previous sections, it has been shown that insulation defects can initiate breakdown. Therefore, it is of importance to detect insulation defects on time, before those defects can actually trigger the breakdown. Partial discharges often precede a breakdown and can therefore be a useful tool to detect insulation defects. The question to be answered is whether partial discharge measurements are sensitive enough to detect the critical defects. For this purpose, the following sections look back at the PD measurement results obtained in an earlier stage of our research. This previous stage employed the conventional method in accordance to IEC 60270 in the presence of protrusion defects [51] and the so-called UHF method in the presence of free moving particles in GIS under AC voltage stress. The test setups used for the partial discharge measurements are shown in Figure 5-2 and Figure 5-9.

5.6.1 Moving particles detection

The PD magnitudes measured for particles 5–30 mm long are summarised in Figure 5-21. The partial discharge measurements have shown that particles of 5 mm and longer show a detectable PD magnitude exceeding 5 pC apparent discharge. A threshold detection level of 5 pC is specified by Cigré as the minimum required detection level in GIS [53].

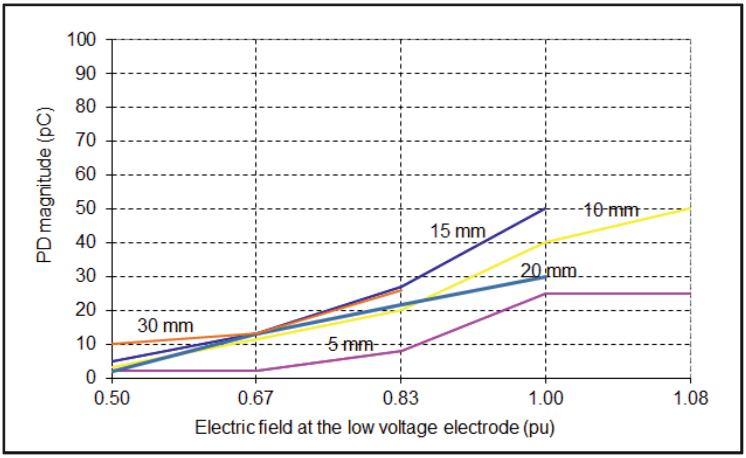

Figure 5-21: PD magnitude versus the eclectic field strength for different particle lengths

Besides the possibility to detect particles of 5 mm length and longer, three stages in the behaviour of the moving particles can be distinguished based on the UHF frequency spectra and the three Phase Resolved Partial Discharge (PRPD) patterns as shown in [51] and [52]:

1. Shuffling stage

   The particle starts to shuffle and discharge. This stage is characterised by

   - a PD spectrum with a low amplitude and low selective intensity as shown in Figure 5-22 (A);

- a PRPD pattern with a low amplitude and high intensity as shown in Figure 5-22 (B).

2. Moving stage

   The particle starts to move. This stage is characterised by

   - a PD spectrum with a high amplitude and high and full intensity as shown in Figure 5-22 (C);
   - a PRPD pattern with a high amplitude and less intensity as shown in Figure 5-22 (D).

3. Jumping stage

   The particle is jumping. This stage is characterised by

   - a PD spectrum with a high amplitude and high and selective intensity, i.e. with gaps that can be observed in the spectrum as shown in Figure 5-22 (E);
   - a PRPD pattern with a high amplitude and less intensity as shown in Figure 5-22 (F).

At the jumping stage, a particle can reach the high-voltage conductor, and therefore this stage is the most dangerous one [51][52].

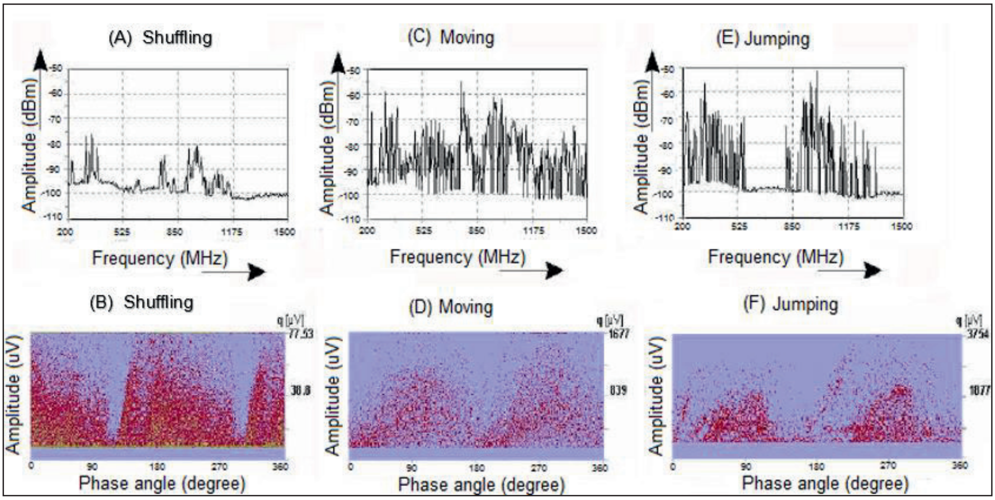

Figure 5-22: An example of the different stages in the behaviour of a moving particle in GIS [52]

5.6.2 Protrusions detection

The PD's of protrusion defects in GIS were measured versus the electric field strength in Figure 5-23. The figure shows the following [47]:

- The PD magnitude is significantly increased just before breakdown.
- A sensitivity of 10 pC or less is required to detect the defect in time.

- Protrusions 2, 3, and 4 mm in length give a detectable PD magnitude at 1 pu.
- A 1-mm protrusion gives a detectable PD magnitude at 2.1 pu. Hence, it is not possible to detect 1-mm protrusions in service under 1 pu AC voltage stress.

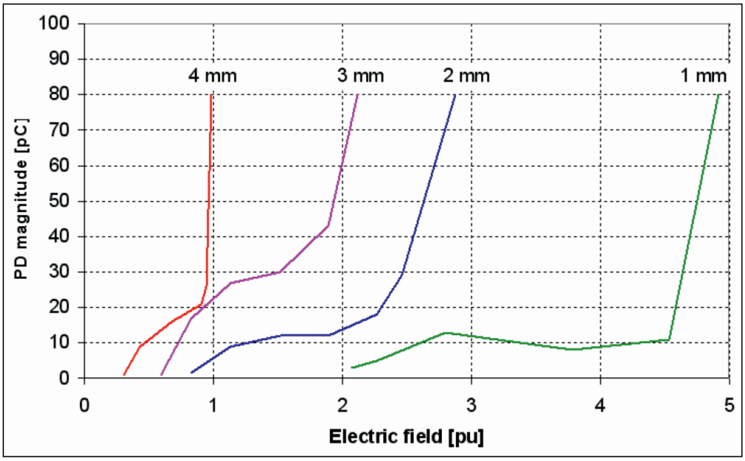

Figure 5-23: Partial discharge magnitude versus the electric field strength in pu initiated by protrusion defect in GIS under AC voltage stress

From the PD measurements, it follows that the development of the PRPD pattern is similar for all protrusions. It has been observed that three stages occur before breakdown [51]. To illustrate how the three stages are related to the breakdown voltage, the PD magnitude has been plotted in Figure 5-24 as a function of the test voltage related to the breakdown voltage for each protrusion.

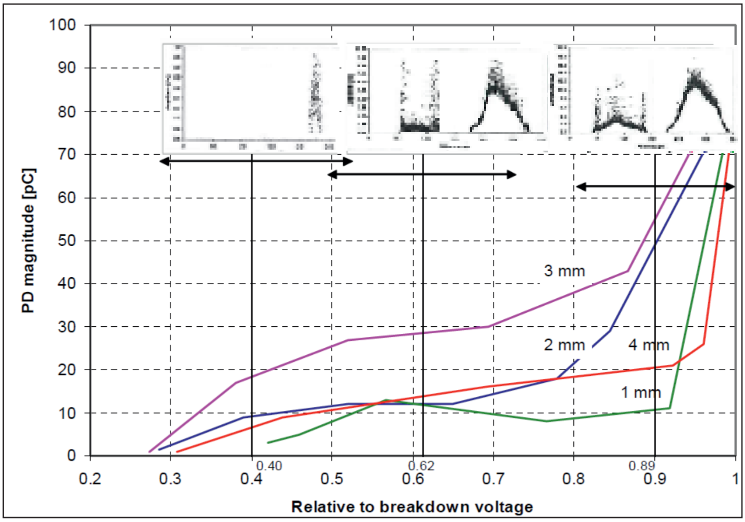

Figure 5-24: Partial discharge magnitude vs. the voltage related to the breakdown voltage of each protrusion

Based on the PD patterns shown in Figure 5-24, three stages in the protrusion behaviour have been distinguished:

1. Stage 1: In the initial stage, 28–46% of the breakdown voltage occurs and the first PD activity is taking place at one half of the sinus waveform in the PD pattern.
2. Stage 2: In the intermediate stage, 44–80% of the breakdown voltage occurs and the PD activity is starting to take place at the other half of the sinus waveform in the PD pattern.
3. Stage 3: In the stage closest to breakdown, 78–100% of the breakdown voltage occurs and the PD activity is taking place at both halves of the sinus waveform in the PD pattern with high intensity.

It can be concluded based on the PD results that the PD process is almost independent of the protrusion length. In addition, the upcoming breakdown can be predicted based on the measured PRPD pattern.

To illustrate the usefulness of this predictive ability, let a protrusion indicate a pattern of stage 1 with a relative breakdown voltage of 46%. If the test voltage increases beyond 2.17 pu (1 pu / 0.46), a breakdown can be expected. Hence, in the case of a temporary overvoltage, where the voltage can increase to around 1.7 pu, breakdown is unlikely. Meanwhile a breakdown would be expected in the case of a lightning impulse since the voltage may rise to 3.5 pu.

5.7 *Conclusions*

This chapter can draw the following conclusions:

A. Breakdown in gas-insulated switchgear (GIS):

1. No dielectric breakdown was initiated by particles 5–30 mm in length under 1 pu AC voltage during the experiments in electrical field similar to the one in 380 kV GIS.
2. It was estimated that particles 15 mm in length and longer can cause dielectric breakdown under temporary overvoltage stress if the voltage can reach 1.7 pu.
3. It was estimated that particles 15 mm in length and longer can cause dielectric breakdown under 3.5 pu lightning impulse.
4. No dielectric breakdown was initiated by particles 15 mm in length and shorter under 2.3 pu VFTO voltage stress. Particles of 30-mm length cause no breakdown under VFTO voltage stress at a gap distance less than 70%.
5. Particles 30 mm in length and longer cause breakdown under VFTO voltage stress at a gap distance equal to or bigger than 90%.
6. Protrusions of 3 mm and shorter initiate no dielectric breakdown under 1 pu AC voltage stress and temporary overvoltage stresses.
7. Protrusions 2 mm in length and longer cause dielectric breakdown under lighting impulse of 3.5 pu. A 1 mm protrusion would initiate breakdown under lightning impulse of 3.5 pu superposed on 1 pu AC voltage stress.

B. Detectability of defects by partial discharge measurements:

1. Mobile particles of 5 mm and longer produce a detectable PD level at 1 pu AC voltage stress. Three stages in the particles' behaviour are distinguished based on the PD patterns.
2. Protrusions 2–4 mm in length produce detectable PD levels at 1 pu. A 1-mm protrusion produces a detectable PD level at 2.1 pu, which makes the protrusion undetectable under 1 pu AC voltage stress. Based on the PD patterns, three stages in the protrusion behaviour have been distinguished.

These conclusions are used as the base in the following chapters to develop the required knowledge rules for partial discharge measurements.

Chapter 6 Technical Status Identification Methodology

CHAPTER 6 TECHNICAL STATUS IDENTIFICATION METHODOLOGY

6.1 *Introduction*

To fulfil its function according to the specifications, GIS and its components need to operate within specified limits. These limits have been indicated as the normal operation region in Figure 6-1. A region of deviation which can be positive or negative (as shown in Figure 6-1) is defined as the region in which the operation of the GIS or one of its components crosses the limits of the normal operation region but without a failure. The failure region appears whenever the GIS or one of its components is not able to perform its main function properly, as shown in Figure 6-1.

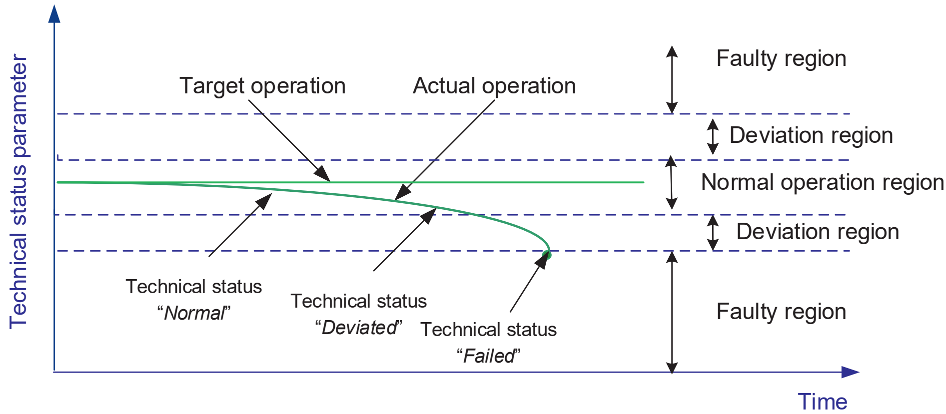

Figure 6-1: Regions of "*Normal*", "*Deviated*", and "*Failed*" operation

We introduce a three-status technical index to characterise the operation of GIS and its components in the above regions. These statuses are "*Normal*", "*Deviated*", and "*Failed*".

The technical status of GIS and its components is evaluated by performing inspections and diagnostic measurements. Knowledge rules are used to convert diagnostic data into status indices in a structured way.

Knowledge rules can be based on the manufacturer's specified values and limits, international standards and recommendations, user's experience, and expert's opinions. Knowledge rules are expressed by a mathematical equation, a decision table, a decision flowchart, or a statement. The knowledge rules have to be as easy as possible to apply to the diagnostic data to give a clear and unambiguous interpretation of the diagnostics' outcomes.

The development of effective knowledge rules required conversion of measurement data into a technical status index. That conversion is the topic of this chapter and will be illustrated firstly for the measurements of stored energy in operating mechanisms as applied for circuit breakers and secondly for partial discharge measurements.

The knowledge rules for other selected GIS diagnostics are presented in Appendix F.

6.2 *Knowledge rules for stored energy measurements*

The amount of stored energy in the operating mechanism of a circuit breaker or disconnector should be sufficient for moving the main contacts. A decrease in the stored energy below a critical value results in a delay of the main contacts' movement and could lower the switching device's interrupting ability [28][36].

The basic operating principles use hydraulic, pneumatic, or spring mechanisms.

In hydraulic operating mechanisms, a hydraulic system is used to pressurise nitrogen gas to store the energy. In pneumatic operating mechanisms, the energy is stored as a pressurised air by using a motor compressor. Therefore, gas pressure is monitored to indicate the amount of the stored energy. If hydraulic oil is used in the operating mechanism, the oil can be monitored.

The energy stored in a circuit breaker operating mechanism is maintained at a nominal pressure to ensure a safe and successful switching operation [28][36]. An alarm is ignited if the stored energy either drops below a predetermined level, i.e. the alarm pressure, or increases above the maximum pressure. When the stored energy drops below the alarm level, the circuit breaker is locked out to prevent an unsafe and non-successful switching operation.

The stored energy in a spring operating mechanism is supplied by an electric motor. Therefore, in addition to the spring position, the motor current and the motor running times can be used to indicate indirectly the level of the stored energy. However, this method is not very accurate [28].

The various levels described for the stored energy are schematically shown in Figure 6-2.

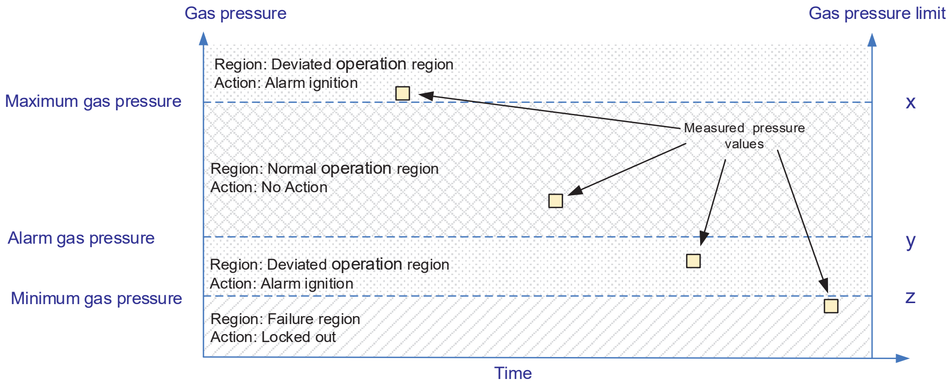

Figure 6-2: Schematic of pressure limits and operational regions

Operating limits are determined based on the stored energy levels in the circuit breaker operating mechanism. These limits are indicated in percentages as x, y, and z in Figure 6-2 and can be calculated as indicated in Table 6-1.

Table 6-1: Knowledge rules for the gas pressure, mathematical representation

Knowledge rules	*Criteria*	*Technical status*
P ≥ x	$x = \left(1 + \frac{maximum\ pressure - nominal\ pressure}{nominal\ pressure}\right) \times 100\%$ Where x is the gas pressure in percentage at which the status deviation is distinguished	Deviated
y < P < x	$y = \left(1 + \frac{alarm\ pressure - nominal\ pressure}{nominal\ pressure}\right) \times 100\%$ Where y is the pressure in percentage at which an alarm signal is generated	Normal
z < P ≤ y	$z = \left(1 + \frac{minimum\ allowable\ pressure - nominal\ pressure}{nominal\ pressure}\right) \times 100\%$ Where z is the gas pressure in percentage at which the status failure is distinguished	Deviated
P ≤ z		Failed

The technical status of the operating mechanism is "*Normal*" when the gas pressure value is equal to or less than x and bigger than y. The status is "*Failed*" when the gas pressure is equal to or less than z. Otherwise the status of the operating mechanism is defined as "*Deviated*" (see Table 6-1).

As an example, the knowledge rules of Table 6-1 have been applied to a real circuit breaker having a hydraulic operating mechanism with the specifications shown in Table 6-2.

Table 6-2: An application example of the stored energy values in a hydraulically operated circuit breaker

Gas level	*Gas pressure value (bar)*
Nominal pressure	355
Minimum breaking pressure	255
Maximum pressure (breaking/making)	370
Alarm pressure	314

The resulting operating limits are shown in Table 6-3.

Table 6-3: An application example of the stored energy knowledge rules

Knowledge rules	*Technical status*	*Description*
P ≥ 104.0%	Deviated	The pressure value equals to or exceeds the breaking/making (maximum) pressure limit
88.4% < P < 104.0 %	Normal	The pressure value lies within the specified limits
71.8% < P ≤ 88.4%	Deviated	The pressure value is equal to or less than the alarm level (but still higher than the lockout level)
P ≤ 71.8%	Failed	The pressure value is equal to or less than the lockout level

The table indicates that a pressure level bigger than 88.4% and less than 104.0% would not disturb the operating mechanism's functionality.

A pressure level equal to or less than 88.4% but bigger than 71.8% indicates a deviation in the operating mechanism. Similarly, a deviation in the operating mechanism would be indicated when the pressure became equal to or exceeds 104.0%. A gas pressure equal to or less than 71.8 % would lock out the circuit breaker operation.

In this way, we can indicate the status of the operating mechanism based on the level of the stored energy.

6.3 *Knowledge rules for partial discharge measurements*

The presences of insulation defects in GIS can influence the electric field distribution by means of local electrical field concentrations, which finally can lead to a dielectric breakdown of the insulation. Before total breakdown, often partial breakdowns occur at the location of the insulation defect as was demonstrated in Chapter 5. This phenomenon is known as partial discharge (PD) activity. Therefore, PD detection provides an indication of elevated risk for dielectric breakdown of the insulation system.

Many techniques have been established to measure partial discharges [12] [13]. The conventional PD measurement technique is standardised in IEC 60270, and nonconventional methods include the Ultra High Frequency (UHF) method, acoustic method, and chemical method.

Among these methods, the UHF method has proven to be very suitable for on-line PD detection in GIS due to the method's relatively simple measuring setup, its high signal-to-noise ratio, and its high detection ability [34].

After performing the PD measurements, three steps are important to identify the source of the measured signals [34]: The first is feature extraction, in which the relevant information from the PD data is captured to produce the PD defects' fingerprint. The second is classification of the extracted features to recognise the defects. The third is determination of the confidence interval to recognise doubtful PD classification for which an expert estimation is needed.

As a result, the partial discharge signals can be classified either as acknowledged PD, noise or unknown signals.

To determine the status of the insulation system in GIS based on PD measurements in service, in addition to the insulation defect type and location, the GIS operating conditions have to be taken into account. Chapter 5 showed that some defects can be harmful under normal operating voltage, whereas others are harmful under transient overvoltages. The defect type and the defect location can be identified from analysing the PD measurement results [34] [66]. The operating conditions can be obtained from the GIS operator and Supervisory Control And Data Acquisition (SCADA) system.

The flowchart shown in Figure 6-3 describes how we assessed the status of the insulation system based on the PD measurement results. The flowchart consists of the following three main blocks:

1. <u>Noise signals</u>

   The insulation system is defect free when the measured signals are identified as noise signals originating from a source located outside the GIS. In such cases, the status of the insulation system is set to "*Normal Operation*" as illustrated in block number 1 in the flowchart shown in Figure 6-3.

2. <u>Unknown signals</u>

   It is possible that the measured signals cannot be identified as PD signals or noise signals due to, for instance, lack of knowledge in extracting the useful PD features or inaccurate classification of the PD data. In such cases, the location of the signal source has to be determined to distinguish whether the source of the signals is located inside or outside GIS.

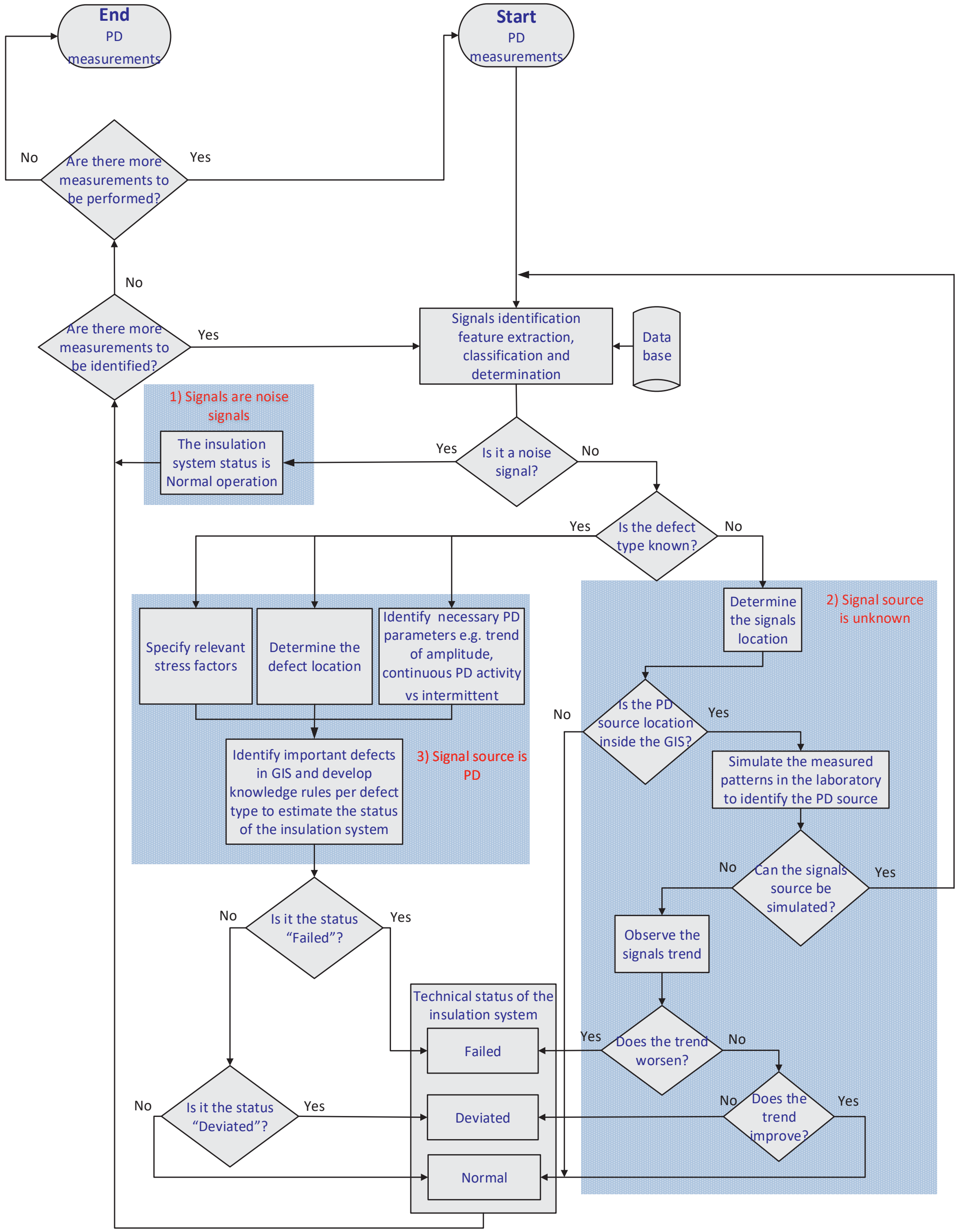

Figure 6-3: A flowchart to determine the insulation system status in GIS based on the PD diagnosis in service

Sources of unknown signals located outside the GIS do not indicate a defect in the GIS insulation system. Therefore, the technical status of the insulation system is set to "*Normal*".

When the signal's source is located inside the GIS, an attempt has to be made to identify the type of source to determine whether the signal is originating from an insulation defect or another origin. This knowledge can come from past operation's experiences or knowledge can be gained by simulating different GIS defects in the high-voltage laboratories. When it is hard to determine the source of the PD signals, two options are available:

- A decision can be made to open GIS and reveal the signal's source. New knowledge will be gained when opening GIS, and care should be taken to capture this knowledge for future reference.
- A decision can be made to keep observing the trend of the measured signals before a decision is made to open GIS. With this option, the possible consequences, such as a sudden breakdown, have to be fully considered.

For unknown signals, an increasing trend of the observed signals can indicate a serious danger level. Therefore, the technical status of the insulating system is set to "*Failed*" to indicate the worst case. In general, if the PD trend for unknown signals is decreasing, the technical status of the insulating system is set to "*Normal*". Otherwise the technical status is set to "*Deviated*", as indicated in block number 2 in the decision flowchart shown in Figure 6-3.

3. <u>PD signals</u>

   Once the signal source is identified as an insulation defect, it is important to estimate whether dielectric breakdown of the insulation system can occur. Therefore the type of the insulation defect and location as well as the operating conditions are taken into account as shown in block number 3 in Figure 6-3 [34][66]. Also, any changes in the operating conditions and the trend of the PD amplitude have to be considered.

The following five types of insulation defects have been identified to be important and may put GIS at risk [34]:

1. Free moving particles
2. Protrusions
3. Particles on insulators
4. Floating electrodes
5. Voids and cavities in the GIS insulators and spacers

In the following sub-sections, we estimate the status of the insulation system in the presence of each of these five types of defect by collecting information on partial discharge phenomena from relevant experiments and literature. The knowledge rules are formulated in the form of tables.

6.3.1 Free moving particles

As has been discussed in Section 5.6.1, three stages in the behaviour of the moving particles can be distinguished based on the UHF frequency spectra and the PRPD patterns: shuffling stage, moving stage, and jumping stage.

Besides the ability to distinguish the behaviour of the particles in three stages furthermore the particle length can be estimated by acoustic measurements [54][34]. Lundgaard's estimation of the particle length in [54] assumes that the particle is elongated and either moving or jumping during the acoustic measurements. In addition, he shows that a maximum error of 40% can be expected by estimating the particle length by acoustic measurements [54].

On the basis of the particle behaviour and the operating conditions, the expected technical status of the insulation system is estimated in the following subsections. Estimations are made when the particle is shuffling, moving, and jumping as shown in the basic flowchart of Figure 6-4.

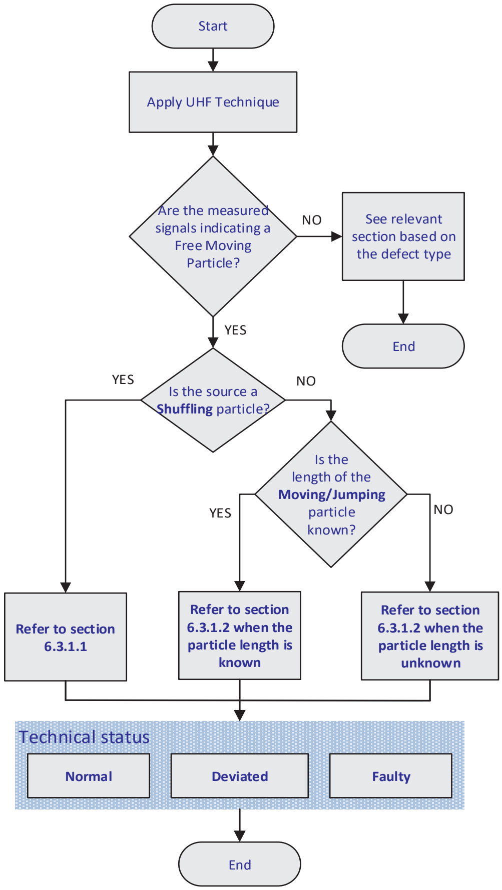

Figure 6-4: Basic flowchart to assess the insulation status in the presence of free moving particles in the GIS

6.3.1.1 Shuffling particles

It is not possible to estimate the particle length when the particle is in the shuffling stage. Therefore, the particle length is not part of the decision chain when the insulation status is estimated. The decision chain considers the below voltage stresses. The statuses can be summarised as follows:

- AC voltage stress

  No dielectric breakdown was initiated by particles under AC voltage during the experiments as illustrated in Section 5.4. Therefore, the technical status of the insulation is set to "*Normal*" under AC voltage in Table 6-4. We assume that this is applicable for all GIS of the same voltage class as ours or whenever the electric field strength is the same at the GIS enclosure where the particle is laying.

- TOV stress

  Due to the increase in the applied voltage, a shuffling particle under TOV stress may acquire the required electrostatic force and lift off and attach to the HV conductor. Protrusions of 4 mm would cause breakdown under TOV stress as discussed in Section 5.5. It can be expected that certain shuffling particles would initiate breakdown under TOV stress once these particles attach to the HV conductor. Therefore, we set the technical status of the insulation system to "*Failed*".

- LI impulse superposed on AC voltage stress

  Based on the breakdown results obtained for protrusion-initiated breakdown under lightning impulse and lightning impulse superposed on AC voltage stress (see Section 5.5.2), it can be concluded that certain shuffling particles of 1-mm diameter or more are likely to cause breakdown. Therefore, we set the technical status of the insulation system to "*Failed*".

- VFTO stress

  Breakdown under VFTO voltage stress occurs when the particle bridges a big portion of the gap distance between the enclosure and the HV conductor. Since the particle is shuffling, it is not possible to bridge the gap distance. Therefore, breakdown is not likely to occur, and the technical status of the insulation is set to "*Normal*".

- DC voltage stress

  DC voltage in AC GIS occurs as a result of the trapped charges, for instance, when a floating part of the GIS is disconnected [37]. DC voltage can reach a value of up to 1.2 pu [37]. Under DC voltage, particles as short as 1 to 6 mm can be lifted off [60]. After they lift off, particles can keep moving towards the HV conductor. Once the moving particle gets close enough to the HV conductor, the particle will acquire almost the full potential [59]. Then the remaining gap between the particle upper tip and the HV conductor is bridged, and the particle acquires the full potential of the HV conductor [59]. Therefore, particles approaching or attached to the HV conductor under DC voltage stress would behave as protrusions under AC voltage stress. Protrusions of 4 mm and longer would initiate breakdown even slightly below 1 pu under AC voltage stress.

Hence, it would be expected that certain shuffling particles would initiate breakdown under DC voltage stress, and therefore the technical status of the insulation is set to "*Failed*".

Based on the previous discussion the status of the insulation system in the presence of a free particle in the shuffling stage is summarised in Table 6-4.

Table 6-4: The technical status of the insulation system in the presence of a free particle in the shuffling stage

[15]PD trend	Voltage stress								
	AC (1pu)			TOV (1.7pu)			LI+AC (4.5pu)		
	Possibility for insulation breakdown	Technical status	Remarks	Possibility for insulation breakdown	Technical status	Remarks	Possibility for insulation breakdown	Technical status	Remarks
PD spectrum has low amplitude and low selective intensity PRPD pattern has low amplitude and high intensity (see Section 5.6.1)	No	Normal	Particles would show a moving and jumping behaviour before they would cause breakdown. Such transition in the particle movement can be assessed based on the PD results (see Section 5.6.1). If the particle starts moving or jumping, Section 6.3.1.2 is applicable.	Yes	Failed	In the case of a temporary overvoltage stress, driven by the increase in the (quasi) electrostatic force, the particle may reach the HV conductor. When the particle is 4 mm or longer, breakdown is expected to follow.	Yes	Failed	Protrusions of 1 mm or longer are likely to cause breakdown under LI superposed on AC voltage stress (see Section 5.5.3). Based on that section, it can be estimated that shuffling particles of 2-mm diameter or more are likely to cause breakdown.

Table 6-4 Continued: The technical status of the insulation system in the presence of a free particle in the shuffling stage

PD trend	Voltage stress					
	VFTO (2.3pu)			DC (1pu)		
	Possibility for insulation breakdown	Technical status	Remarks	Possibility for insulation breakdown	Technical status	Remarks
PD spectrum has low amplitude and low selective intensity PRPD pattern has low amplitude and high intensity (see Section 5.6.1)	No	Normal	-	Yes	Failed	Particles as short as 1 mm can get lifted off and attach to the high-voltage conductor. Particles that get close or attach to the high-voltage conductor would behave as protrusions. In such cases, Section 6.3.2 is applicable.

[15] When a mechanical vibration takes place, the particle may keep shuffling, transition to another stage (i.e. start moving or jumping), or weld to the inner surface of the GIS enclosure as has been discussed in Section 5.4.2.

6.3.1.2 Moving or jumping particles

The technical status of the insulation medium is discussed in the presence of moving or jumping particles firstly when the particle length is known and, secondly, when the particle length is unknown.

Assessment of the insulation technical status when the particle length is known

The experiments discussed in Chapter 5 were achieved by using particles of different lengths under various voltage stresses. Based on the particle length and the type of voltage stress, the status of the insulation medium is estimated as shown in Table 6-5. The statuses can be summarised as follows:

- AC voltage stress

  Up to 1 pu AC voltage stress, no breakdowns were observed during the experiments as discussed in Section 5.4.4. Therefore, the insulation technical status is set to "*Normal*".

- TOV stress

  Moving particles about 15 mm in length and longer are likely to cause dielectric breakdown in GIS under TOV stress, as discussed in Section 5.4.4. Therefore, the technical status of the insulation is set to "*Failed*" if the particle length exceeds 15 mm.

- LI impulse superposed on AC voltage stress

  It has been estimated that moving particles of 15 mm and longer can cause breakdown under lightning impulse (see Section 5.4.5). The technical status of the insulation is set to "*Failed*" for particles of 15 mm and longer.

- VFTO stress

  Moving particles of 30 mm and longer would cause breakdown under VFTO voltage stresses (see Section 5.4.6). Therefore, the technical status of the insulation is set to "*Failed*" if the particle length exceeds 30 mm.

- DC voltage stress

  Particles as short as 1 to 6 mm can be lifted and attach to the HV conductor, thereafter behaving as protrusions. The experimental results presented in Section 5.5 have shown that protrusions 4 mm in length and longer would cause dielectric breakdown under AC voltage stress. Therefore, under DC voltage stress, it can be expected that free moving particles of 4 mm would cause breakdown under DC voltage stress. The insulation technical status is set to "*Failed*" for particles of 4 mm and longer.

Attempts have been made by [54] and [64] to estimate particle lengths. The results have shown a limited accuracy in estimating particle lengths due to the unknown exact particle shape.

Table 6-5: The technical status of the insulation system in the presence of a free particle in the moving and the jumping stages when the particle length is known

Defect length (mm)	Voltage stress					
	AC (1 pu)		TOV (1.7 pu)		LI +AC (4.5 pu)	
	Possibility for insulation breakdown	Technical status	Possibility for insulation breakdown	Technical status	Possibility for insulation breakdown	Technical status
1≤l<4	No	Normal	No	Normal	No	Normal
4≤l<6	No	Normal	No	Normal	No	Normal
6≤l<15	No	Normal	No	Normal	No	Normal
15≤l<30	No	Normal	Yes	Failed	Yes	Failed
l=30	No	Normal	Yes	Failed	Yes	Failed

Defect length (mm)	Voltage stress			
	VFTO (2.3 pu)		DC (1 pu)	
	Possibility for insulation breakdown	Technical status	Possibility for insulation breakdown	Technical status
1≤l<4	No	Normal	No	Normal
4≤l<6	No	Normal	Yes	Failed
6≤l<15	No	Normal	Yes	Failed
15≤l<30	No	Normal	Yes	Failed
l=30	Yes	Failed	Yes	Failed

Assessment of the insulation technical status when the particle length is unknown

In practice, the particle's shape and dimension are unknown. Therefore, the status of the insulation system has to be estimated independent from the particle length. In other words, the status has to be estimated based only on the amplitude, the shape of the PRPD pattern, the frequency spectrum [67], and the type of voltage stress. We categorised the trends of the partial discharge activity mentioned in Section 5.6.1 into four types based on the behaviour of the moving particles as shown schematically in Figure 6-5:

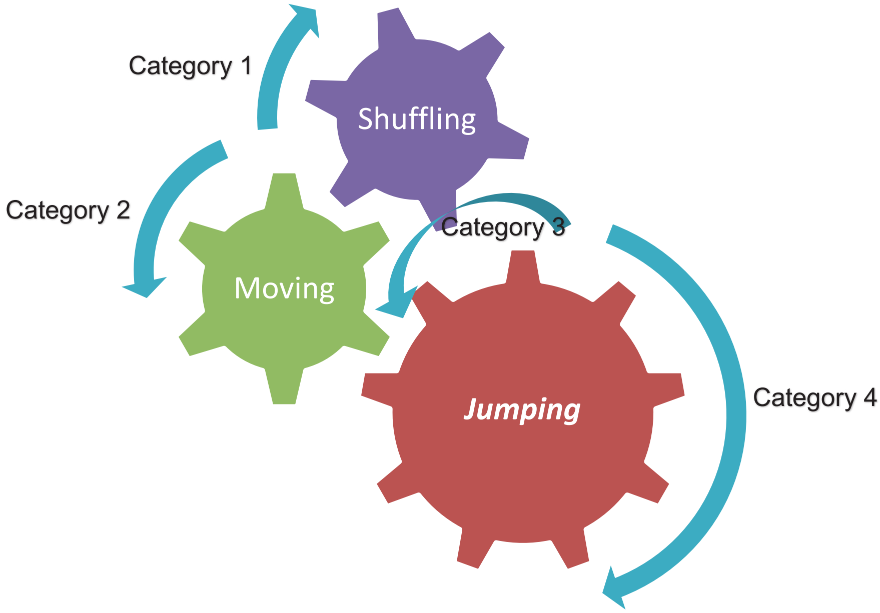

Figure 6-5: Four categories of the behaviour of the moving particles where the particle length is unknown (in practice)

- Category 1

  The particle tends to transition from the moving stage back to the shuffling stage. Section 6.3.1.1 is applicable.

- Category 2

  The particle tends to stay at the moving stage or transitions to the jumping stage.

  PD trend: Some gaps might be observed in the frequency spectrum, and the PRPD pattern show stable or increasing amplitude and low or decreasing intensity.

- Category 3

  The particle tends to transition from the jumping stage back to the moving stage.

PD trend: The gaps in the frequency spectrum width become narrow, and fewer gaps might be observed in the frequency spectrum. The PRPD pattern shows decreasing amplitude and increasing intensity.

- Category 4

  The particle tends to stay at the jumping stage and jumps higher.

  PD trend: Gaps are observed in the frequency spectrum and become wider as the particle jumps higher. The PRPD pattern shows stable or increasing amplitude and less intensity.

The insulation technical status has been estimated by considering the particle behaviour in categories 2 to 4 and the type of voltage stress as follows:

- AC voltage stress

  During the breakdown experiments, for the used GIS test section and the applied voltage level, no breakdown occurred under 1 pu AC voltage stress initiated by particles even when the particles were placed at their maximum possible jump height (see Section 5.4). Therefore, the technical status of the insulation system is set to "*Normal*".

- TOV stress

  In the case of TOV stress, driven by the increase in the quasi electrostatic force, particles may reach the HV conductor and breakdown could follow. It has been estimated that particles of 15 mm may cause breakdown under TOV voltage stress (see Section 5.4.4). Therefore, the technical status of the insulation is set to "Failed".

- LI impulse superposed on AC voltage stress

  Particles of 15 mm can initiate dielectric breakdown under lightning impulse, as discussed in Section 5.4.5. Therefore, the insulation technical status is set to "*Failed*".

- VFTO stress

  Breakdown can be observed under VFTO voltage stress when the particle is 30 mm and when the particle can bridge about 90% of the gap distance (see Section 5.4.6). Therefore, it can be estimated that no breakdown is expected for category 2, breakdown is possible for category 3, and breakdown is more likely to occur for category 4. Hence, the technical status of the insulation is set to "*Normal*" for category 2, "*Deviated*" for category 3, and "*Failed*" for category 4.

- DC voltage stress

  Under DC voltage, particles of 4 mm long can lift off and cause breakdown under DC voltage stress. Hence the technical status of the insulation is set to "*Failed*" for all categories.

The corresponding technical status of the insulation system for these different situations has been summarised in Table 6-6.

Table 6-6: The technical status of the insulation system in the presence of a free particle in the moving and the jumping stages when the particle length is unknown (in practice)

Category	***Voltage stress***					
	AC (1 pu)		***TOV (1.7 pu)***		***LI+AC (4.5 pu)***	
	Possibility for insulation breakdown	***Technical status***	***Possibility for insulation breakdown***	***Technical status***	***Possibility for insulation breakdown***	***Technical status***
Category 1	Section 6.3.1.1 is applicable					
Category 2	No	Normal	Yes	Failed	Yes	Failed
Category 3	No	Normal	Yes	Failed	Yes	Failed
Category 4	No	Normal	Yes	Failed	Yes	Failed

Category	***Voltage stress***			
	VFTO (2.3 pu)		***DC (1 pu)***	
	Possibility for insulation breakdown	***Technical status***	***Possibility for insulation breakdown***	***Technical status***
Category 1	Section 6.3.1.1 is applicable			
Category 2	No	Normal	Yes	Failed
Category 3	Possible	Deviated	Yes	Failed
Category 4	Yes	Failed	Yes	Failed

.

6.3.2 Protrusions

The PD process is almost independent of the protrusion length, and the upcoming breakdown can be predicted based on the measured PRPD pattern as has been discussed in Section 5.6.2 [52] [62]. Three stages in the protrusion behaviour have been distinguished in Section 5.5, i.e. the initial stage, intermediate stage, and close-to-breakdown stage. These stages can be recognised based on the shape of the PRPD patterns [52].

In addition to these three stages, it has been evaluated experimentally in Section 5.5 that protrusions of 3 mm and shorter cause no dielectric breakdown under 1 pu AC voltage stress [62]. Under transient voltage stresses superposed on AC voltage stress, it has been shown that protrusions of 1 mm and longer do cause dielectric breakdown [62].

In practice, it is not possible to measure the protrusion length. Therefore, the technical status of the insulation system in the presence of a protrusion defect in GIS has been estimated based only on the three stages in the protrusion behaviour and the type of voltage stress, as has been discussed in Section 5.5. The results are summarised in Table 6-7 for the following cases:

- AC voltage stress
    - The technical status of the insulation system is set to "*Normal*" when the protrusion shows the behaviour of the initial stage.
    - The technical status of the insulation system is set to "*Deviated*" when the protrusion shows the PD behaviour of the intermediate stage since a dielectric breakdown may occur.
    - The technical status is set to "*Failed*" when the protrusion shows the behaviour of the close-to-breakdown stage since dielectric breakdown is likely to occur.
- TOV stress
    - The technical status of the insulation system is set to "*Deviated*" when the protrusion shows the behaviour of the initial stage since breakdown is likely to occur, as has been discussed in Section 5.6.2.
    - The technical status is set to "*Failed*" when the protrusion shows the behaviour of either the intermediate stage or the close-to-breakdown stage since breakdown is very likely to occur.
- LI impulse superposed on AC voltage stress

  The technical status of the insulation is set to "*Failed*" whenever a lightning impulse can occur during normal operation since a breakdown is most likely to occur under this condition.
- DC voltage stress

  The minimum breakdown voltage level under AC and DC voltage stresses is similar when a particle is placed on or near the HV conductor [60]. Therefore, under DC voltage, the technical status of the insulation system would be similar to the technical status assigned under AC voltage, as has been discussed above.

- The technical status of the insulation system is set to "*Normal*" when the protrusion shows the behaviour of the initial stage.
- The technical status is set to "*Deviated*" when the protrusion shows the PD behaviour of the intermediate stage since a dielectric breakdown may occur.
- The technical status is set to "*Failed*" when the protrusion shows the behaviour of the close-to-breakdown stage since dielectric breakdown is likely to occur.

Table 6-7: The technical status of the insulation system in the presence of a protrusion in GIS when the protrusion length is unknown (in practice)

Stage	***Voltage stress***							
	AC (1 pu)		***TOV (1.7 pu)***		***AC+LI (4.5 pu)***		***DC (1 pu)***	
	Possibility for insulation breakdown	***Technical status***	***Possibility for insulation breakdown***	***Technical status***	***Possibility for insulation breakdown***	***Technical status***	***Possibility for insulation breakdown***	***Technical status***
[16]**Stage I: Initial stage**	No	Normal	Possible	Deviated	Yes	Failed	No	Normal
Stage II: Intermediate stage	Possible	Deviated	Yes	Failed	Yes	Failed	Possible	Deviated
Stage III: Close-to-breakdown stage	Yes	Failed	Yes	Failed	Yes	Failed	Yes	Failed

[16] Stages 1, 2, and 3 are described in Section 5.6.2.

6.3.3 Particles on insulators

Particles attached to the insulator surface are discussed in [55], from which the following criteria were derived:

- Particles as small as 2 mm, adhering to a spacer surface, can cause a reduction in the withstand voltage of about 50% under lightning voltage stress.
- Particles of 4 mm can cause a reduction of 50% in the withstand voltage under AC voltage stress. The withstand voltage is further reduced for longer particles.

It has been reported that a particle of 12 mm or longer on a spacer surface near the HV conductor shows a PD magnitude of 1 to 2 pC under 1 pu AC voltage stress [65]. Such a PD level is hard to detect onsite due to the background noise level.

Besides the length of the particle, the reduction of the withstand voltage depends on the particle's distance from the HV electrode [55] [56]. The withstand voltage decreases with decreasing distance from the HV electrode [55] [56].

In practice, the particle length and the particle's exact location on the spacer and its orientation cannot be determined. However, if PD measurements show the presence of a particle fixed to the insulator, the PD measurement results and the applied voltage shape can be used to estimate the technical status of the insulation (summarised in Table 6-8) in the following cases:

- AC voltage stress

  The technical status of the insulation system under AC voltage stress is set to "*Failed*" only when the PDs show continuous activity and increasing PD amplitude. Such behaviour would indicate that the particle is close to causing a dielectric breakdown. The technical status is set to "*Deviated*" when the PD amplitude increases and non-continuous PD activity is measured. Otherwise, the technical status of the insulation system is set to "*Normal*".

- LI impulse superposed on AC voltage stress

  Under lightning voltage stress, the technical status of the insulation is set to "*Failed*" irrespective of the trend of the PDs, since a dielectric breakdown is likely to occur in all situations.

Table 6-8: A decision table to estimate the technical status of the insulation system in the presence of a particle on the GIS insulator

PD trend of magnitude [34]	***PD activity***	***Voltage stress***			
		AC (1 pu)		***LI+AC (4.5 pu)***	
		Possibility for insulation breakdown	***Technical status***	***Possibility for insulation breakdown***	***Technical status***
Decreasing	Intermittent PD activity	No	Normal	Yes	Failed
	Continuous/ Unknown PD activity	No	Normal	Yes	Failed
Stable	Intermittent PD activity	No	Normal	Yes	Failed
	Continuous/ Unknown PD activity	No	Normal	Yes	Failed
Increasing	Intermittent PD activity	Possible	Deviated	Yes	Failed
	Continuous/ Unknown PD activity	Yes	Failed	Yes	Failed

6.3.4 Floating electrodes

Shield electrodes are used at locations where electric field concentrations can occur. Sometimes electrodes become electrically disconnected (floating electrode) during operation for different reasons, such as vibrations. Between the electrically disconnected electrode and the conductor (it was shielding), PD activity occurs when the floating electrode voltage exceeds the withstand voltage of the SF_6 gas. Discharges of floating electrodes can become critical under AC voltage, but they would require a long time to cause breakdown (months to years) and high PD amplitude.

The activity of the PD and the PD trend in magnitude is used to estimate the technical status of the insulation system as shown in Table 6-9 [34].

SF_6 by-products are formed when the PD is occurring continuously for a sufficiently long time. SF_6 by-products can be corrosive and diffuse away from the arc vicinity. They can impact GIS components, and breakdown may occur as a result.

Continuous PD activity indicates that the floating element is close to causing a dielectric breakdown, especially if a spacer or a solid insulator is nearby. Therefore, the technical status of the insulation system in these situations is set to "*Failed*".

When the PD trend is increasing but with intermittent PD activity, insulation breakdown is possible, and therefore the technical status of the insulation is set to "*Deviated*". Otherwise, the technical status of the insulation is set to "*Normal*".

Table 6-9: A decision table to estimate the insulation system status in the presence of a floating electrode in GIS

PD trend of magnitude [34]	***PD activity***	***Voltage stress***	
		AC (1 pu)	
		Possibility for insulation breakdown	***Technical status***
Decreasing	Intermittent PD activity	No	Normal
	Continuous/ Unknown PD activity	Yes	Failed
Stable	Intermittent PD activity	No	Normal
	Continuous/ Unknown PD activity	Yes	Failed
Increasing	Intermittent PD activity	Possible	Deviated
	Continuous/ Unknown PD activity	Yes	Failed

6.3.5 Voids and cavities in the GIS insulators and spacers

Voids can persist for years before they develop into electrical trees and cause electrical breakdown. Voids from 3 mm to 4 mm diameter have been shown to be critical to GIS [34]. In practice, it is not possible to estimate the shape, diameter, and exact location of the voids and cavities inside the insulators and spacers. However, information regarding the PD trend, the PD activity, and the applied voltage can be gathered to estimate the technical status of the insulation system. For instance, voids and cavities are not critical to the insulators and spacers if they show a PD level of about 1 pC after the manufacturing process [34].

Many stages have been distinguished in the PRPD patterns resulting from voids and cavities at the nominal operating voltage [57]. However, three main stages can be identified: the initial stage, the conditioned stage, and the final stage. In the final stage, electric treeing occurs and is followed by dielectric breakdown [57].

During the transition from the initial stage, through the conditioned stage, and towards the final stage, the PD trend decreases [63]. In addition, continuous PD activity of a void is known to be more critical than intermittent activity [63][34]. Therefore, it can be estimated that electrical breakdown may occur when the void shows a decreasing PD trend of magnitude and continuous PD activity, i.e. when the void shows the PD pattern of the final stage. In such situations, the technical status of the insulation is set to "*Failed*".

As a result, if a void is detected in the insulator, the technical status of "*Deviated*" is assigned to the insulation system when a pattern of:

- The final stage is distinguished, and the PD magnitude shows
    - intermittent activity but a decreasing trend,
    - continuous activity and a stable trend, or
    - continuous activity and an increasing trend.
- The conditioned stage is distinguished, and the PD magnitude shows a decreasing trend and continuous activity.

The technical status is set to "*Normal*" for all other operations. A summary overview is given in Table 6-10.

Table 6-10: A decision table to estimate the technical status of the insulation system in the presence of a void in the GIS insulator and spacer

Stage in the protrusion behaviour	*PD trend of magnitude ([8] annex a)*	*PD activity*	*Voltage stress*	
			AC (1 pu)	
			Possibility for insulation breakdown	*Technical status*
Stage 1: Initial stage	Decreasing PD magnitude	Intermittent PD activity	No	Normal
		Continuous/ Unknown PD activity	No	Normal
	Stable PD magnitude	Intermittent PD activity	No	Normal
		Continuous/ Unknown PD activity	No	Normal
	Increasing PD magnitude	Intermittent PD activity	No	Normal
		Continuous/ Unknown PD activity	No	Normal
Stage 2: Conditioned stage	Decreasing PD magnitude	Intermittent PD activity	No	Normal
		Continuous/ Unknown PD activity	Possible	Deviated
	Stable PD magnitude	Intermittent PD activity	No	Normal
		Continuous/ Unknown PD activity	No	Normal
	Increasing PD magnitude	Intermittent PD activity	No	Normal
		Continuous/ Unknown PD activity	No	Normal
Stage 3: Final stage	Decreasing PD magnitude	Intermittent PD activity	Possible	Deviated
		Continuous/ Unknown PD activity	Yes	Failed
	Stable PD magnitude	Intermittent PD activity	No	Normal
		Continuous/ Unknown PD activity	Possible	Deviated

6.3.6 Summary of the knowledge rules developed for partial discharge diagnosis

We assessed the technical statuses of the insulation system in GIS based on the knowledge rules developed for the partial discharge measurements as summarised in Appendix F.2. Based on the count of the resulting technical statuses for the studied situations, the shares in percentage between the statuses "*Normal*", "*Deviated*", and "*Failed*" are shown in Figure 6-6. The figure also shows the type of voltage stress at which "*Deviated*" and "*Failed*" statuses occur.

It can be concluded from Figure 6-6 (A) that the presence of partial discharge activity is critical to the insulation in about 47% of the cases. And in 53% of the cases, the partial discharge activity does not directly lead to critical situations. This means that if partial discharge is detected successfully, it is a significant tool to assess the status of the insulation in GIS.

67% of cases that received the technical status "*Deviated*" occurred under AC voltage stress despite the fact that this type of stress should be normal voltage stress for GIS, as shown in Figure 6-6 (B).

Figure 6-6 (C) shows that lightning impulse superposed on AC voltage stress is responsible for the highest share (42%) of the technical status "*Failed*", followed by temporary overvoltage stress (19%). In reviewing the technical status "*Failed*", attention has to be given to insulation defects, which initiate breakdown especially under lightning impulse superposed on AC voltage stress and temporary overvoltage. These defects respectively are moving particles, protrusions, and particles located on insulators.

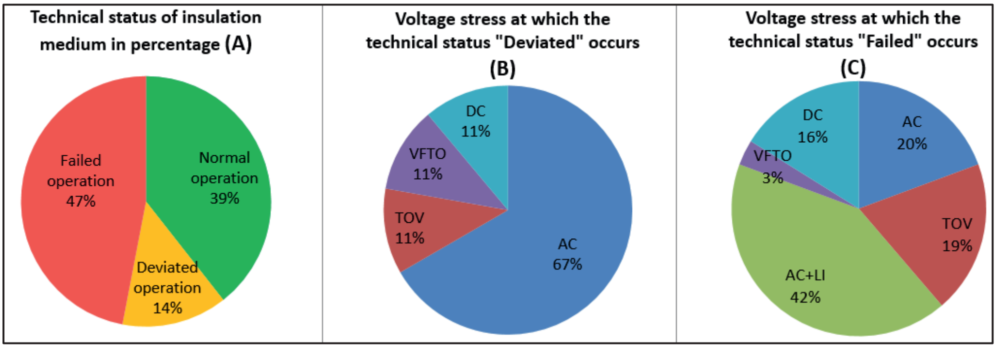

Figure 6-6: Number of situations (in percentage) which can result in the technical statuses "*Normal*", "*Deviated*", and "*Failed*" (A) with voltage shared in the cases of the technical statuses "*Deviated*" (B) and "*Failed*" (C)

6.4 *Conclusions*

There is no unique way to formulate and present knowledge rules for the technical status assessment of GIS. To maximise the utilisation of the knowledge rules, the rules have to be clear, as simple as possible, and offer an unambiguous interpretation of the diagnostics outcomes.

In this chapter, we proposed to develop the necessary knowledge rules for GIS based on the following:

- manufacturer data, as in the case of the circuit breaker's stored energy; and
- the literature and the knowledge collected from experiments, as in the case of partial discharges.

Sufficient knowledge is available to estimate the technical status of the insulation system in a more accurate way when the size and dimension of the insulating defects, like moving particles and protrusions, are known. The currently available methods to estimate the size of defects located inside GIS are often inaccurate, impractical, or simply non-existent.

The main share of the technical status "*Failed*" is initiated by moving particles, protrusions, and particles located on insulators under lightning superposed on AC voltage stress and temporary overvoltage. Special attention therefore has to be paid to these types of insulation defects during the design, manufacturing, and operation of the GIS.

Chapter 7 Health Indexing and Maintenance Initiation

CHAPTER 7 HEALTH INDEXING AND MAINTENANCE INITIATION

7.1 *Introduction*

GIS performance is influenced by multiple types of stress (i.e. electrical, mechanical, thermal, chemical, and environmental). This stress may deteriorate GIS, increase its failure probability, and decrease its lifetime.

To maintain GIS and its components, it is necessary to understand the actual conditions of GIS by establishing a health index based on the diagnostic outcomes through knowledge rules. We aim to scientifically support the asset manager by timely establishment of maintenance actions.

Hence, the diagnostic data is the input for the knowledge rules. Knowledge rules are used to identify the technical status of GIS components, which in turn are combined to indicate the condition as health index. Based on the results of the health index, we assess the need for and timing of maintenance.

The sequence starting from diagnostics selection to maintenance decision through the knowledge rules, technical status identification, and health indexing is illustrated schematically in the diagram in Figure 7-1.

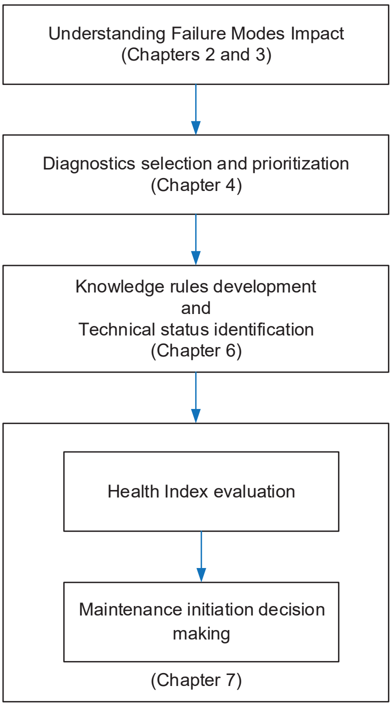

Figure 7-1: The sequence of actions from diagnostic selection through knowledge rules development and health index generating to maintenance decision-making

The following two points are discussed in this chapter:

1- The health index of the GIS at;

   a. the primary component level;

   b. the busbar and GIS bay level;

c. the GIS level.

2- Maintenance decision-making, which is based on the health index results.

7.2 *Health index evaluation*

In Chapters 2 and 3, GIS was categorised into indenture levels. The health index assessment of GIS starts from the lowest level and goes until the highest indenture level, taking into account the health index of GIS inner components and subsystems. In this process, the possible impact on the higher levels until the highest level are addressed.

Three indexes, "*Good*", "*Fair*", and "*Poor*" are used in this chapter to express the healthiness of the GIS and its components at

1- Component level, by the combination of the technical statuses, the remaining time to failure (TTF), and time until next examination by diagnostics or inspection (TTI). GIS operating conditions, such as switching operations and gas leakages in the presence of an insulation defect, have also been considered as they may change health index results.

2- Busbar and bay level, thereby combining the health index of GIS primary components considering the busbar and GIS bay arrangement. A fault tree analysis (FTA) is used for this purpose.

3- GIS level by using the FTA to combine the health index of the busbar and individual GIS bays according to the busbar and bay arrangement in GIS.

The evaluation of the health index at these three levels is schematically shown in Figure 7-2.

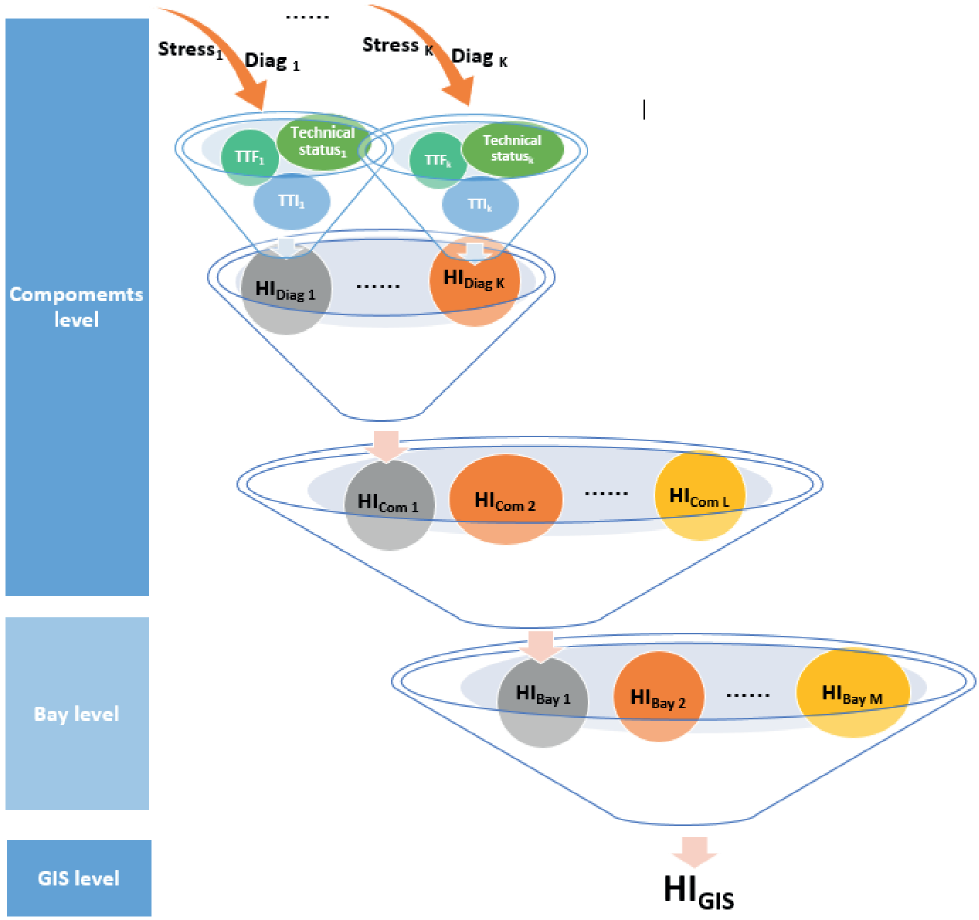

Figure 7-2: The evaluation of the health index at the primary components level, the busbar and the GIS bay level and the GIS level, a schematic representation. Diag $_1$ to Diag $_k$ refer respectively to the first and last diagnostic

7.3 *Health index evaluation at GIS primary component level*

The health index of GIS at the primary component level is evaluated by first estimating the technical status of the GIS primary components i.e. "*Normal*", "*Deviated*", and "*Failed*" through the knowledge rules, as discussed in Chapter 6. Secondly, the remaining time to failure (TTF) is estimated, and the result is combined with the technical status in the case of "*Deviated*". When TTF is estimated, the stress factors, such as drop in gas pressure and switching operation of GIS, should be considered since they may lengthen or shorten TTF, which is discussed further in Sections 7.3.1 and 7.3.2.

7.3.1 Time to failure estimation

The remaining time to failure (TTF) can be estimated statistically using expert opinions or calculations. As illustrative examples of expert opinions and calculations, determination of TTF in case of SF_6 gas leak and PD activity are discussed below:

7.3.1.1 Determination of TTF in case of SF_6 leakage

The time to failure in the case of a leak is the time needed to reach the minimum gas pressure at which failure occurs. The leak rate is determined as the following [68]:

$$q_l = \frac{\Delta\,(P.V)}{\Delta t}, \qquad \text{……...} \quad 7\text{-}1$$

Where

q_l: leak rate, pa.m²/s,

P: pressure, pa,

V: volume, m³,

t: time, s.

By determining the actual value of the gas pressure drop (ΔP) and time interval (Δt), the leak rate can be determined by Equation 7-1. It is preferable to have at least three measurement points to confirm the shape and slope of the leak rate. A schematic example of TTF determination in case of a leak is shown in Figure 7-3.

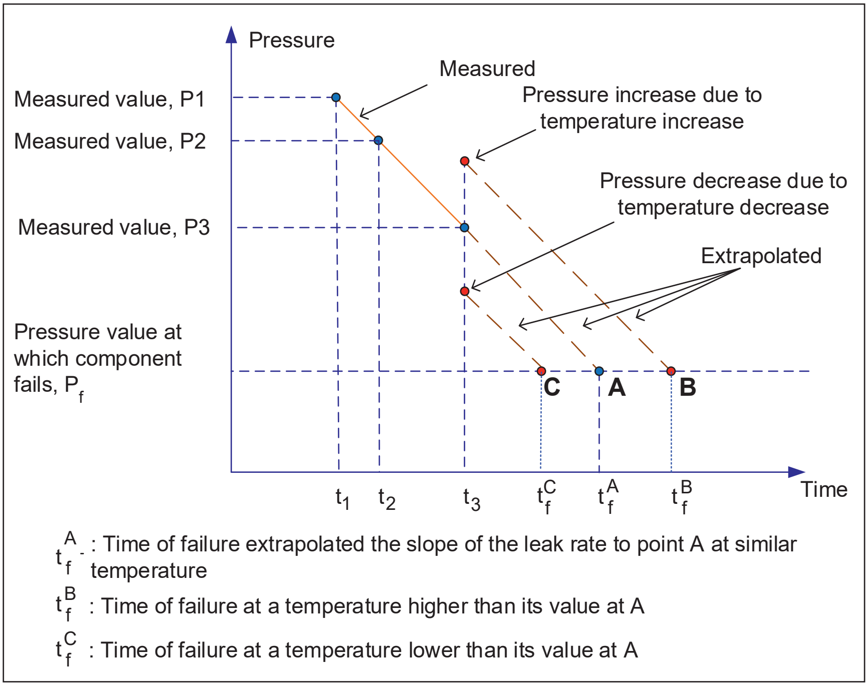

Figure 7-3 Determination of TTF in case of leak

Let t_f^A, t_f^B, and t_f^C be time of failure at points A, B, and C in Figure 7-3, and time to failure (t_f) is the time at which the pressure drops to the value that results in component failure. t_f^A is determined by a linear regression of the leak rate to point A. In fact, time of failure can be derived from Equation 7-1, and the measured values of gas pressure as the following:

$$t_f = \frac{(P_f - P_3)}{Leakage\ rate}.V + t_3, \qquad \text{.........} \qquad 7\text{-}2$$

Where

P_f: gas pressure value at which the component fails,

P_2: measured gas pressure value at time t_2,

P_3: measured gas pressure value at time t_3.

TTF is the difference between time of failure and time of last measurement, and when referring to Figure 7-3, TTF will be:

$$TTF = t_f - t_3$$

The leakage rate is calculated from the last pressure measurements by Equation 7-1 i.e. at t_2 and t_3, TTF became

$$TTF = \frac{(P_f - P_3)}{(P_3 - P_2)}.(t_3 - t_2) \qquad \text{........} \qquad 7\text{-}3$$

In its general form, equation 7-3 can be re-written as

$$TTF = \frac{P_f - P_i}{P_i - P_{(i-1)}}.(t_i - t_{(i-1)}), \qquad \text{........} \qquad 7\text{-}4$$

Where

P_i : current pressure value,

$P_{(i-1)}$: pressure value measured prior to the last measurement,

t_i : date of P_i,

$t_{(i-1)}$: date of $P_{(i-1)}$.

Changes in temperature, particularly seasonal and daily changes in temperature, may impact the gas pressure and finally TTFs in case of leakage.

[17]The relationship between temperature and gas pressure is experimented as being linear according to Equation 7-5. An increase of about 11% in gas pressure would result from a temperature increase from 0^oC to 30^oC, as shown in Equation 7-6.

$$P.V = n.R.T, \qquad \text{........} \qquad 7\text{-}5$$

$$\frac{P_{(at 30^oC)}}{P_{(at\ 0^oC)}} = \frac{T_{(at\ 30^oC)}}{T_{(at\ 0^oC)}} = \frac{303}{273} = 1.11\ , \qquad \text{........} \qquad 7\text{-}6$$

Where

n: number of mol ,

R: gas constant, 8.314 J / mol. K,

T: temperature, K .

An increase in gas pressure will increase TTF (point A in Figure 7-3 to be shifted towards point B). A drop in the temperature will decrease TTF (point A to be shifted towards point C).

7.3.1.2 Determination of TTF in case of PD

In the case of partial discharge, the impact of voltage stress is considered in estimating TTF. For instance, the technical status of the insulation medium containing a protruding defect in the initial stage is set to (refer to Section 6.3.2)

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[17] SF_6 gas is non-ideal gas, however equation 7-5 gives about the same results as Döring formula that shows an increase of 12.4 % in the gas pressure when temperature increases from 0^oC to 30^oC.

- "*Normal"* under AC voltage stress
- "*Deviated*" under temporary overvoltage stress
- "*Failed*" under lightning impulse superposed on AC voltage stress

As long as the protrusion does not change behaviour to that of the intermediate stage or the close-to-breakdown stage, we consider that TTF is long under AC voltage stress. Once the protrusion behaviour is changed to one of the other two stages, or temporary overvoltage stress or lightning impulse is expected, we consider TTF short, and that the protrusion possibly or will cause insulation breakdown. In the next section, we compare TTF to TTI as a reference value.

7.3.2 Single diagnostic health index evaluation

To evaluate the health index based on a single diagnostic of a GIS primary component, TTF is firstly compared with time until next examination by diagnostic inspection (TTI). TTI is normally defined based on best practices, manufacturer recommendations, and/or expert opinions.

The health index is evaluated for each GIS primary component as follows:

- The health index is set to "*Good*" if the technical status is "*Normal*", which is the case when no deviation is observed in technical status outputs.
- The health index is set to "*Fair*" when
    - the component has the technical status "*Normal*", but a deviation in the measured values is observed that may impact TTF. For example, TTF should be estimated when a gas leakage (refer to Section 7.3.1.1) is observed to ensure that TTF is larger than TTI, or
    - the component has the technical status "*Deviated*", and TTF is estimated to be larger than TTI under all possible operating conditions.
- The health index is set to "*Poor*" if
    - the component technical status is "*Failed*", or
    - TTF is estimated to be shorter or equal to TTI.

The process of evaluation of the health index at GIS primary component level is schematically shown in Figure 7-4. In the following section, the health index is derived where multiple diagnostics are used, or there exist multiple stresses that may simultaneously interact and impact technical status and/or TTF.

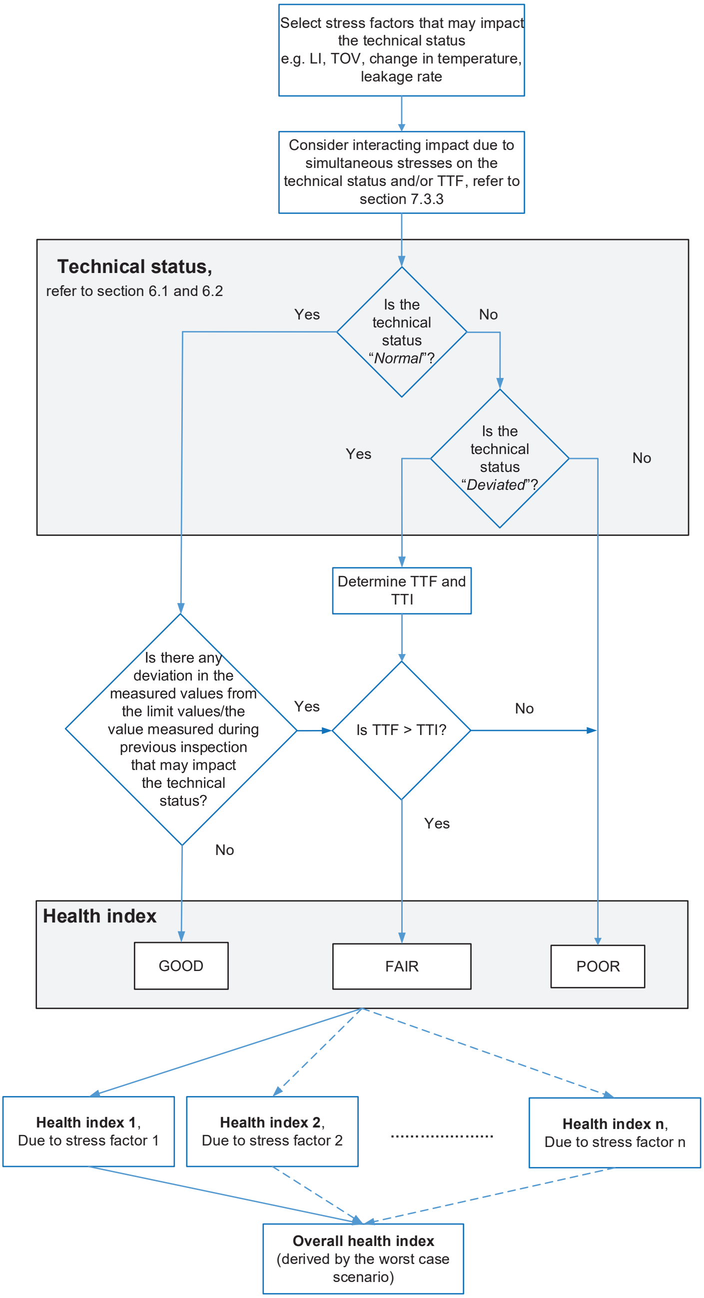

Figure 7-4: The health index evaluation considering one component status, TTF and operational conditions

7.3.3 Multiple diagnostic health index evaluation

In reality, multiple diagnostics can be used on a GIS component, or the component can be subjected to different stress factors, such as LI, TOV, changes in temperature, and increased leakage rate. Therefore, the health index is derived for each individual technical status (refer to Section 7.3.2), and the resulting health indexes are combined to obtain the overall health index of that GIS component, as shown in Figure 7-5.

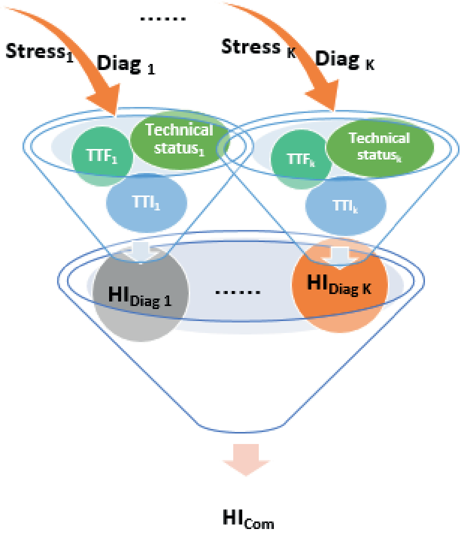

Figure 7-5: Multiple diagnostic health index evaluation

The following application example illustrates how to combine health indexes resulting from different diagnostics to evaluate the overall health index of GIS components.

Let a gas drop from 6 bara to 5.8 bara be detected after having two measurements in 6 weeks, knowing that the next inspection is in 12 weeks. Also, let partial discharge (PD) activity indicating a protrusion defect in the initial stage be observed in that GIS component knowing that the next PD measurement is after one year.

The health index of that GIS component is determined by estimating the technical status and TTF per diagnostic and evaluating the health index per diagnostic according to Figure 7-4. Finally, the individual health indexes are combined to evaluate the overall health index of the GIS component in this example.

Step 1: Status estimation per diagnostic

As an application example, assume that the GIS component has the following gas specifications:

Table 7-1: An application example of gas pressure specification of a GIS component

Gas level	Gas pressure value (bara)
Nominal pressure	6
Alarm pressure	5.5
Locking pressure	5

The knowledge rules developed in Section 6.2 result in the limiting values and corresponding technical status, as listed in Table 7-2.

Table 7-2: An application example of a gas pressure knowledge rules and corresponding technical status

Description	Knowledge rules	
	Criteria	Technical status
The pressure value lies within the specified limits	P > 91.6%	Normal
The pressure value is equal to or less than the alarm level (but higher than the lockout level)	83.3% < P ≤ 91.6%	Deviated
The pressure value is equal to or less than the lockout level	P ≤ 83.3%	Failed

The gas pressure has dropped from 6 bara to 5.8 bara i.e. dropped to 96.6% in 6 weeks. Since the pressure value is larger than 91.6% in the example, the technical status is set to "*Normal*" based on gas pressure criteria listed in Table 7-2.

Due to PD detecting activity originating from a protrusion in the initial stage, the technical status of the insulation depends on applied voltage stress. Based on Table 6.7 in Section 6.3.2, the possible technical status under numerous voltage stresses are listed in Table 7-3:

Table 7-3: The technical status of the insulation in the presence of a protrusion in GIS

	Technical status		
	AC	TOV	AC+LI
Protrusion in stage I: Initial stage	Normal	Deviated	Failed

The technical status thus depends on the type of applied voltage stress and can change from "*Normal*" under AC voltage stress, to "*Deviated*" under temporary overvoltage stress, to "*Failed*" under lightning stress superposed on AC voltage stress.

Step 2: Estimation of time to failure per diagnostic

For the GIS component, the remaining time to failure (TTF) in the example case of a gas leak is 24 weeks, as determined based on Equation 7-4:

$$TTF^{18} = \frac{(P_f - P_i)}{(P_i - P_{(i-1)})}\left(t_i - t_{(i-1)}\right)$$

$$TTF = \frac{(5.0 - 5.8)}{(5.8 - 6.0\ )}(6 - 0)$$

$$= 24\ weeks \qquad \ldots\ldots.. \qquad 7\text{-}7$$

It is more of a challenge to estimate accurately TTF in case of PD since many factors must be considered, such as defect type and length, voltage stress type and level, and PD trend. Therefore, calculation of TTF is not feasible, and only the subject expert can provide an estimation.

TTF, in case of a PD, which originates from a protrusion defect in its initial stage, is long under AC voltage stress, and no dielectric breakdown is expected. Meanwhile, when temporary overvoltage or lightning impulse superposed on AC voltage stress occurs, TTF becomes short, and dielectric breakdown is expected. TTF also becomes short when the protrusion behaviour changes to that of the intermediate or close-to-breakdown stages.

Influence of changes of stress factors on TTF

The interactive impact of a drop in SF_6 gas pressure on PDs originating from a protrusion defect has been investigated [51][55][69]. The results have shown that the PD amplitude in general increases as pressure decreases. An increase from 25 pC to 40 pC in PD amplitude has been recorded for a 5 mm protrusion located in a high-voltage electrode when the pressure drops from 6.5 to 4.5 bara [69]. An increased PD amplitude originating from a protrusion can indicate the tendency to cause dielectric breakdown and hence a shorter TTF. Changes in PD behaviour and more accurate estimations of TTF can be achieved through monitoring of PD behaviour, refer to Section 5.6.

The health index of a GIS component is evaluated based on the individual health index per diagnostic, as shown in Figure 7-4, by using the worst-case scenario, as discussed in the following paragraphs.

Step 3: Single health index evaluation per diagnostic

1- Gas leak detection: the health index is set to "*Fair*" for the gas leak since a deviation is first observed in the gas pressure with respect to the last measured value during the previous inspection, and TTF (24 weeks) is larger than TTI (12 weeks). The impact of temperature changes on TTF are determined by Equation 7-6, Assume that this impact is limited and will not reduce TTF below TTI, as seen in Section 7.3.1.1.

[18] Pressure is measured in Bara and time in weeks rather than in Pascal and seconds. As indicated in Section 7.3.1.1, such changes have no impact on the final results.

2- PD measurement: the health index for the insulation system based on PD results has the following two possibilities:

   a. "*Fair*" if PD activity is observed. However, no dielectric breakdown is expected under AC voltage stress, and the protrusion behaviour does not change to that of the intermediate or close-to-breakdown stages, or if TTF is assumed to be bigger than TTI since no dielectric breakdown is expected.

   b. "*Poor*" for all other situations where the voltage changes or drops in gas pressure will cause the PD behaviour to change from that in the initial stage to the behaviour in the intermediate or close-to-breakdown stages.

Step 4: Overall health index evaluation for the GIS component

It cannot be guaranteed that switching and lightning or a drop in gas pressure will not take place, or that the PD behaviour will not change until next inspection. Therefore, under these conditions, the worst health index shall indicate the overall health index of a GIS component.

$$Overall\ health\ condition = Worst\ case\ (Health\ index_{diagnoscic\ 1}\ , \ldots\ldots, Health\ index_{diagnoscic\ n})$$

As a result, the health index of the GIS component is determined as "*Poor*" for the case example based on PD results.

An overview of the complete situation and an evaluation of the health index for the GIS example component is shown in Table 7-4.

Table 7-4: An example result of the overall health index

Diagnostic Name	Situation description	Status	Time to failure	[19]Health index per diagnostic	Overall health index
Gas leak	Gas leak detected. p_i =5.4 bara, $p_{(i-1)}$ =5.5 bara, measurement period is 6 weeks. Next inspection is after **3 months.**	**Normal operation**	**TTF > TTI** TTF is 30 weeks based on the leakage rate calculation whereas TTI is 12 weeks	**Fair**	**Poor**
Partial discharge	PD activity detected originated from protrusion in the initial stage. Next PD measurement is after **one year.**	**Normal operation** under AC voltage stress (refer to Section 6.3.2)	**TTF > TTI** (in the case that neither temporary overvoltage nor lightning impulse superposed on AC voltage stress takes place and the protrusion behaviour does not change to intermediate stage or close-to-breakdown stage)	**Fair**	
		Deviated operation under temporary over voltage stress (refer to Section 6.3.2	**TTF < TTI** (in the case that either temporary overvoltage or lightning impulse is superposed on AC voltage stress or in the case that the protrusion behaviour changes to intermediate stage or close-to-breakdown stage)	**Poor**	
		Failed operation under lightning impulse superposed on AC voltage stress (refer to Section 6.3.2)			

[19] This figure is estimated based on the status and time to failure, as described in Table 7-1.

7.4 *Health index evaluation at the busbar system and the GIS bay level*

The overall health index of a GIS bay is determined by combining the health indexes of the individual components in said bay. The TTF of a GIS bay is equal to the minimum TTF of the bay's individual components. However, bay arrangement should be considered when TTF is determined, as is explained in Equation 7-9.

The health index and TTF of each bay component is estimated similarly to the description provided in Section 7.3.

The components in GIS bays can be arranged in a way so that the bay has redundancy. The number of the components and their arrangement must be taken into account when the health index of the bay is to be determined. To achieve this purpose, the Fault Tree Analysis (FTA) is used, which is usually used to determine the probability of failure occurrence. In this chapter, the FTA has been used to determine the health index of different GIS bays.

To conduct the FTA diagram, the general rules include

1. GIS components connected in series in a bay circuit diagram are connected by an OR gate in the FTA diagram. OR gate passes the worst health index of the components it connects. A summary of the possible OR gate's resulting health index of two components is provided in Table 7-5

Table 7-5: OR gate and possible resulting health indexes for two components

		Health index component 1		
		Good	Fair	Poor
Health index component 2	Good	Good	Fair	Poor
	Fair	Fair	Fair	Poor
	Poor	Poor	Poor	Poor

2. Components connected in parallel in a bay circuit diagram are connected by an AND gate in the FTA diagram. AND gate passes the best health index of all components it connects. A summary of the possible resulting health indexes of the two components are listed in Table 7-6

Table 7-6: AND gate and possible resulting health indexes for two components

		Health index component 1		
		Good	Fair	Poor
Health index component 2	Good	Good	Good	Good
	Fair	Good	Fair	Fair
	Poor	Good	Fair	Poor

As an example, the circuit diagram of a typical feeding bay is shown in Figure 7-6, and the corresponding FTA is shown in Figure 7-7. The earthing switch is used to connect GIS components to ground for numerous purposes, such as safety during maintenance work. Prior to using the earthing switch, GIS components should be disconnected from service otherwise an electrical short circuit will occur. In case of the technical status "*Deviated*" or "*Failed*" of the earthing switch, the purpose for which GIS must be grounded, such as maintenance work, is delayed. However, GIS functionality is not affected since the GIS is already out of service. Therefore, the earthing switches have not been considered in the corresponding FTA diagram of the feeding bay provided in Figure 7-7.

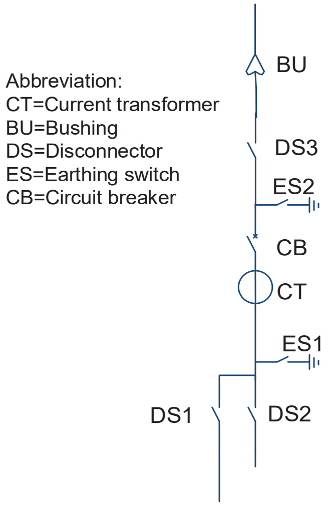

Figure 7-6: Circuit diagram of an example feeding bay

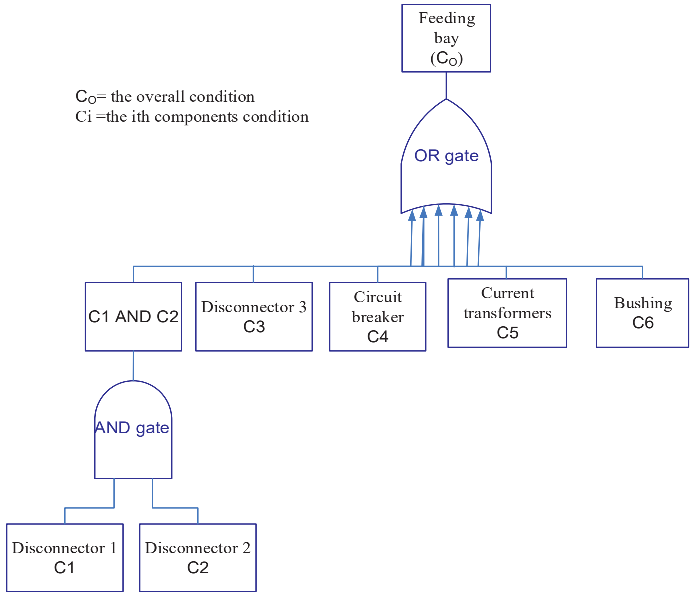

Figure 7-7: The FTA diagram corresponding to the feeding bay shown in Figure 7-6

Based on the FTA diagram, the health index of the feeding bay is determined by the following equation:

$$C_o = \quad (C_1 \; AND \; C_2) \; OR \; C_3 \; OR \; C_4 \; OR \; C_5 \; OR \; C_{6,} \quad \ldots\ldots\ldots \qquad 7\text{-}8$$

Where

C_o *: the overall health index,*

C_i *: the i^{th} components health index.*

The TTF of a GIS bay is equal to the minimum TTF of the bay's individual components, which can be expressed as shown in Equation 7-9. It should be noted that C_1 and C_2 are AND connected. Therefore, the maximum TTF of these two components should be considered.

$$TTF_{Bay} = \quad Min\ ((Max\ TTF\ (C_1\ , C_2\ ), C_3\ , C_4\ , C_5\ , C_6) \quad \ldots\ldots\ldots \qquad 7\text{-}9$$

Where

TTF: *time to failure.*

The bay's health index is categorised as "*Good*" when all of its components connected in series are categorised as "*Good*", and at least one of the components connected in parallel has the health index "*Good*". The bay's health index is set to "*Poor*" when at least one of the individual bay components (connected in series) has the health index "*Poor*", or when all components connected in parallel have the health index "*Poor*". Otherwise, the bay's health index is set to "*Fair*" when at least one of the components connected in series has the health "*Fair*", or when all components connected in parallel have the health index "*Fair*". The health index of the GIS busbar and other bay types are similarly determined.

7.5 *Health index evaluation at GIS level*

In this section, the health index at GIS level is determined. GIS level is the highest level at which GIS is considered one unit.

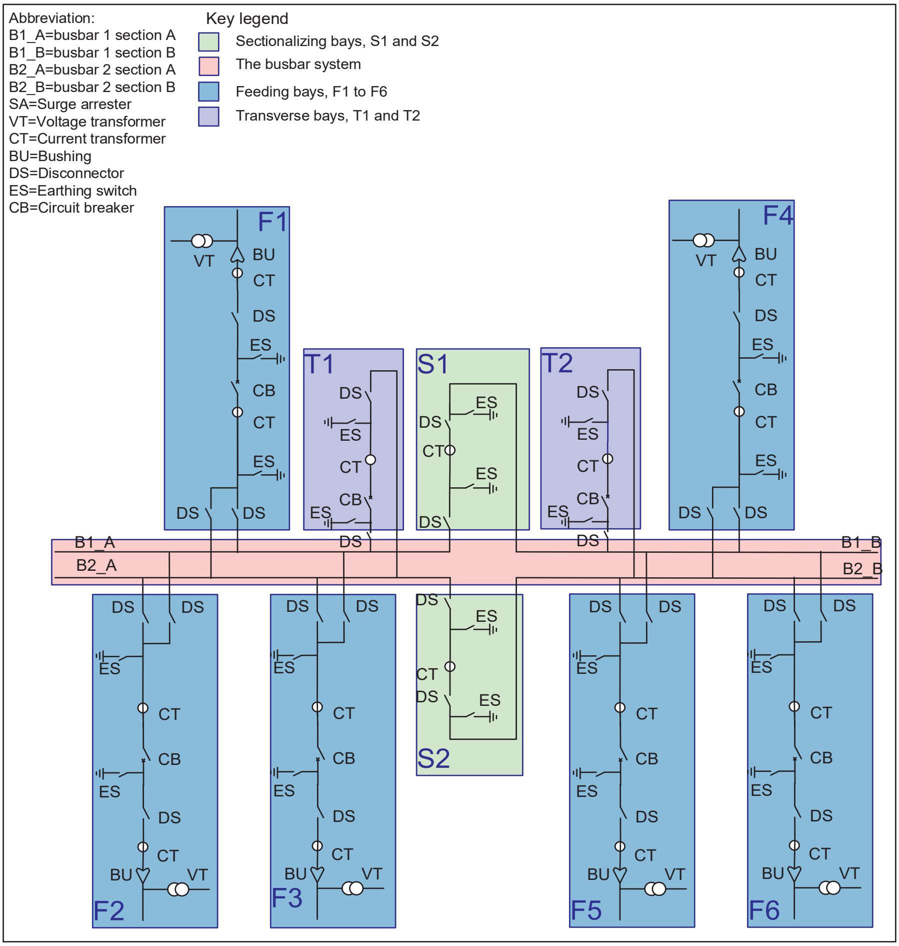

Figure 7-8: GIS substation (case study B)

The GIS health index is estimated using a similar approach to that described in Section 7.4, by combining the health indexes of individual GIS bays. TTF at GIS level is calculated based on the TTF of GIS' individual bays and taking into account bay arrangement.

The GIS substation arrangement (Case Study B) shown in Figure 7-8 is used to illustrate the evaluation of the health index and TTF at GIS level. The exemplar GIS substation is an expansion of the typical GIS shown in Figure 2-1 (Case Study A).

The construction of the FTA is not straightforward because of the complicated arrangement of the GIS substation example. The GIS substation is therefore, alternatively represented as shown in Figure 7-9. The GIS substation has been divided into three sections, of which the left and right sections are connected through the middle section. The left and the right sections each consist of one incoming bay (F1 and F4), two outgoing bays (F2, F3, F5 and F6), one transverse bay (T1 and T2), and two busbar sections (B1_A, B1_B, B2_A and B2_B). The middle section consists of two sectionalising bays (S1 and S2).

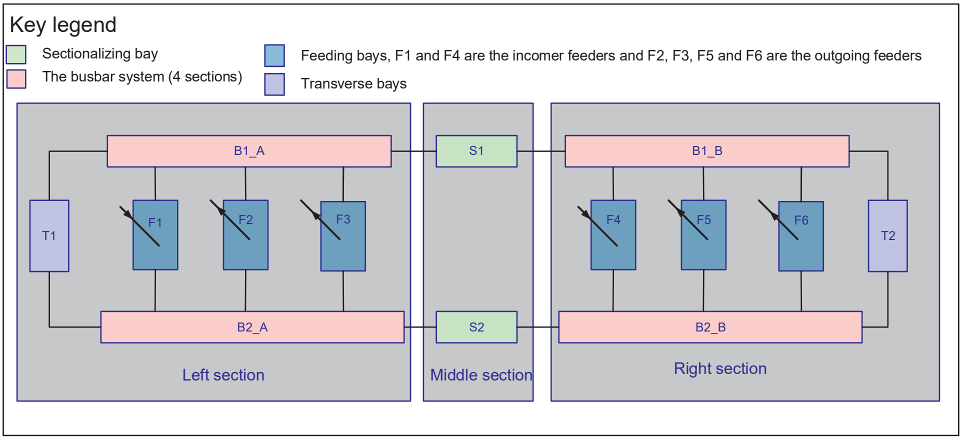

Figure 7-9: An alternative way to represent the example GIS substation

The GIS substation task is not only to distribute power, but also for protection by de-energising bays to allow maintenance work to be conducted and clear faults downstream. To ensure that the GIS tasks are conducted properly, the busbar system and GIS bays are arranged in a way that allows the GIS substation to have redundancy, resulting in high reliability. A failure can therefore disturb GIS service or reliability. Hence, the health index at the GIS level is classified as follows:

- The health index is classed as "*Good*" when both service and reliability are undisturbed. This classification implies that the substation feeders and busbar system have the health index "*Good*".
- The health index is classed as "*Fair*" when reliability is disturbed, but the service is not. An example of this classification is when an incoming bay is classified "*Poor*" assuming that the other incoming bay is able to feed all outgoing feeders hence reduced reliability (through reduced redundancy). Another example of this classification is when an outgoing bay is classified as "*Fair*", which implies reduced reliability.
- The health index is "*Poor*" when the service is disturbed, and when at least one of the outgoing GIS bays has the index "*Poor*".

Based on Figure 7-9, there are 10 bays and 4 busbar sections that can result in (3^{14}) combinations. However, since the health index "*Poor*" of one of the outgoing feeders results in the health index "*Poor*" of GIS, the total number of possible combinations is (3^{11}).

The following number of situations is the smallest list of events that can lead to "*Poor*" i.e. service interruption at least at one of the outgoing feeders:

1- Both incomers fail,

   i.e. F1 AND F4

2- One of the outgoings feeders fails

   i.e. F2 OR F3 OR F5 OR F6

3- The busbar left section or right section fails

   i.e. B1_A AND B2_A

   B1_B AND B2_B

4- Incomer feeder and both bus sectionalising bays fail,

   i.e. F1 AND S1 AND S2

   F4 AND S1 AND S2

5- Incomer feeder, sectionalising bay and busbar section fail

   i.e. F1 AND S1 AND B2_A

   F1 AND S2 AND B1_A

   F4 AND S1 AND B2_B

   F4 AND S2 AND B1_B

TTF can be determined knowing that AND indicates the maximum TTF of its inputs, and that OR indicates the minimum TTF of its inputs. As an example, for Situation 1, the overall TTF = Maximum TTF (F1, F4), whereas in Situation 2, overall TTF = Minimum TTF (F2, F3, F5, F6).

To prevent these situations, the health index can trigger maintenance, as is discussed in the following section.

7.6 *Health index based maintenance*

The health index can be used to initiate maintenance. However, some of the "*Fair*" and "*Poor*" health indexes have an acceptable impact on business values, and so no maintenance actions are required. Topics such as "when" and "how" to schedule maintenance activities are discussed in this section.

Normally, the GIS health index changes the health index from "*Good*" to "*Poor*" through the health index "*Fair*". This change is an indication of deterioration in GIS primary components' condition that may impact the higher levels up to the highest level. The impact depends on type of failure and redundancy in terms of GIS arrangement. In general, the transition of the health index allows for planning and performing of maintenance whenever possible and applicable. Hence, the health index helps in maintenance decision-making, particularly in terms of necessity and time of maintenance.

When the health index of a GIS or its components deviates from the health index "*Good*", the impact on business values must be evaluated. Based on the comparison of the estimated level of impact against the acceptable level of impact, a go/no go decision to perform maintenance should be made.

The suitable maintenance course must be selected in case of a positive maintenance decision. The action restores the deviated or failed component to an improved status in order to meet acceptance criteria, such as the reliability or budget limitations.

To schedule a maintenance action, the remaining time to failure (TTF) can be used. Sufficient time to failure allows for the use of scheduled maintenance. Figure 7-10 summarises four steps towards initiating maintenance. Steps 1 and 2 have already been discussed in this thesis, and steps 3 and 4 are discussed in further detail in the following sections.

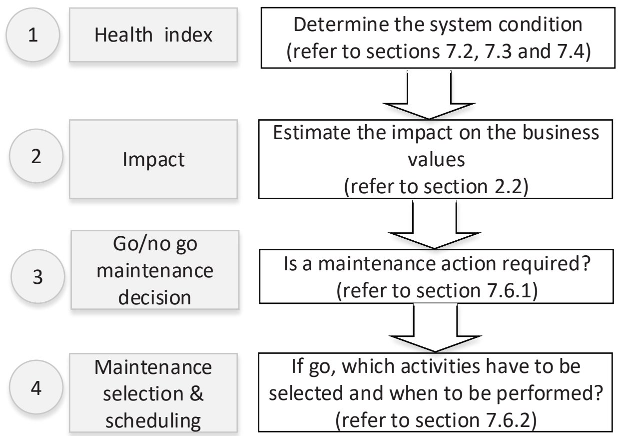

Figure 7-10: Four steps towards starting maintenance

7.6.1 A Go/no go maintenance decision

To make a go/no go maintenance decision, the health index is combined with the impact of possible failure.

Six business values in total are typically considered to be important to GIS, as described in Chapter 2, namely safety, system performance, repair and compensation costs, company reputation, environment, and regulatory compliance.

The failure impact is determined and ranked individually for the business values. The failure impact's overall value is determined by the highest individual level of impact, as discussed in Chapter 2. The overall failure impact is classified into seven levels. These levels are very low, low, moderate, high, very high, serious, and extreme.

The overall failure impact is divides into two groups: "*Acceptable*" and "*Not-acceptable*". The "*Acceptable*" impact of a failure may indicate failures with low-moderate impact, while the "Not-acceptable" impact may indicate failures with higher impact.

By combining the overall impact of a failure with the health index of GIS, the following four areas can be distinguished:

1- Area A: In this area, there is no indication of failure, and the GIS health index is "*Good*". Therefore, no additional maintenance is required.

2- Area B: In this area, the health index is "*Fair*", which implies that time to failure is longer than time until the next inspection. In addition, in this area, the impact of failure is "*Acceptable*" , so there is no need for additional maintenance.

3- Area C: In this area, the health index is "*Poor*", which implies that time to failure is shorter than the time until the next inspection. However, the failure impact is "*Acceptable*". In such situations, a decision can be made to perform maintenance or to run to failure.

4- Area D: In this area, the health index is either *"Fair"* or "*Poor*", and the failure impact is "*Not-acceptable*". Therefore, there is a need for additional maintenance. Two maintenance actions can be performed, immediate or scheduled maintenance. The maintenance action can be based on the impact and GIS health index, as is discussed in the following section.

This go/no go maintenance decision procedure is applicable at the three different levels of GIS i.e. the primary component level, busbar system and GIS bay level, and GIS level, refer to Figure 7-11. Care should be taken when the "*Acceptable*" and "*Not-acceptable*" levels of impact on business values are defined at the three levels of GIS, which are all different. For example, a circuit breaker failure that needs a certain repair time would interrupt circuit breaker functionality be considered "*Not-acceptable*" at GIS component level. Meanwhile, such a failure at component level may not interrupt the functionality of GIS and may be considered "*Acceptable*" at higher levels, such as GIS level.

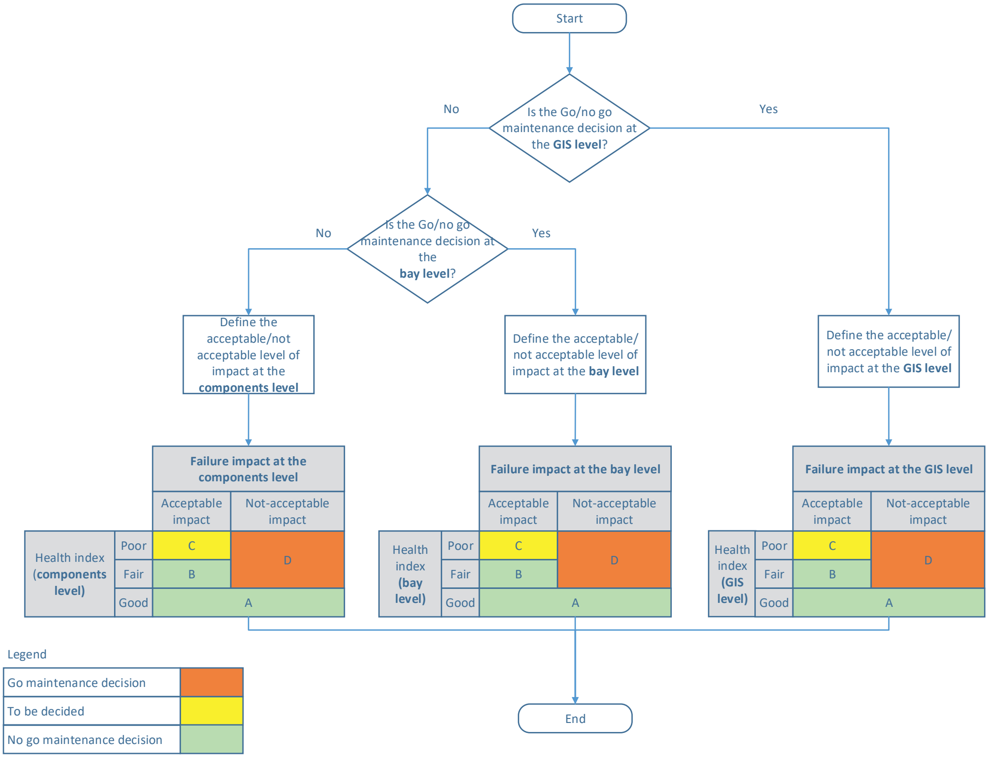

Figure 7-11: A go/no go maintenance decision flowchart

7.6.2 Maintenance selecting and scheduling

Maintenance activities must be selected to retain GIS and its components in or restore it to a state in which it can perform its required function. If maintenance is feasible and applicable, maintenance is scheduled or performed immediately.

No maintenance actions are required for region A (sine the health index is *"Good"*) and for region B (since health index is *"Fair"*, and the failure impact on business values is "*Acceptable*").

Scheduled maintenance is introduced whenever time to failure is longer than the time required to plan maintenance, otherwise immediate maintenance is initiated. Immediate and scheduled maintenance are discussed in the following sections firstly, maintenance is discussed in terms of when the health index is "*Poor*", and the failure impact is "*Acceptable*" (region C). Secondly, maintenance is discussed in terms of when the health index is "*Fair*" and "*Poor*", and the failure impact is "*Not-acceptable*" (region D).

Health index "*Fair*" and non-acceptable impact of the failure at region D

The health index "*Fair*" indicates a deviated GIS operations or (one of) its components, though the possible failure may not occur prior to the next inspection period i.e. remaining time to failure (TTF) ≥ time until next examination by diagnostics or inspection (TTI). The tipping point occurs when the component fails exactly at the end of this stage i.e. at the end of the "*Fair*" stage, see Figure 7-12. This occurrence implies that TTF = TTI.

Scheduling maintenance needs time to prepare maintenance and time to perform it. During maintenance, the component is switched off, and no failure can occur. Therefore, only minimum time to plan the maintenance (TTP) is of importance.

- If TTF>TTP, it is possible to schedule a maintenance action.
- If TTF≤TTP, scheduled maintenance is impractical. In such situations, immediate maintenance is performed, or the GIS primary component is taken out of service during the planning phase.

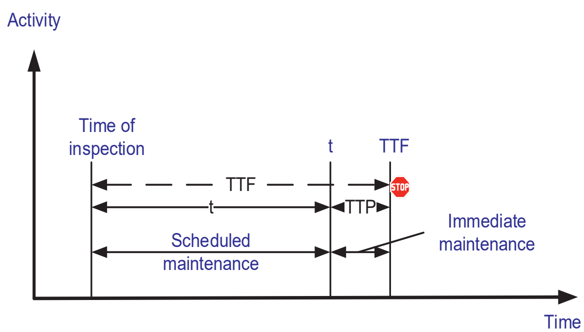

Figure 7-12: Estimating maintenance type

Health index "*Poor*" at regions C and D

The health index "*Poor*" of GIS or its components implies the technical status "*Failed*" or "*Deviated*" as the possible failure may occur prior to next inspection, i.e. remaining time to failure (TTF) < time till next examination by diagnostics or inspection (TTI)

Based on the total impact of failure, two possibilities have been distinguished:

1. When the health index is "*Poor*", and the failure impact is "*Not-acceptable*", immediate maintenance is required.
2. When the health index is "*Poor*", but with a failure results in an "*Acceptable*" total impact, if a decision in made to perform maintenance, it is possible to schedule maintenance in case that the remaining time to failure (TTF) can be estimated. Otherwise, immediate maintenance is initiated. When TTF is known, the following situations can be distinguished:
    a. TTF > TTP: Remaining time to failure is longer than maintenance planning time. Therefore, it is possible to schedule maintenance after which scheduled maintenance is impractical, refer to Figure 7-13 (A).
    b. TTF ≤ TTP: Time to failure is shorter than or equal to maintenance planning time. Hence, no sufficient time is available to schedule maintenance, and therefore immediate maintenance is required, refer to Figure 7-13 (B).
    c.

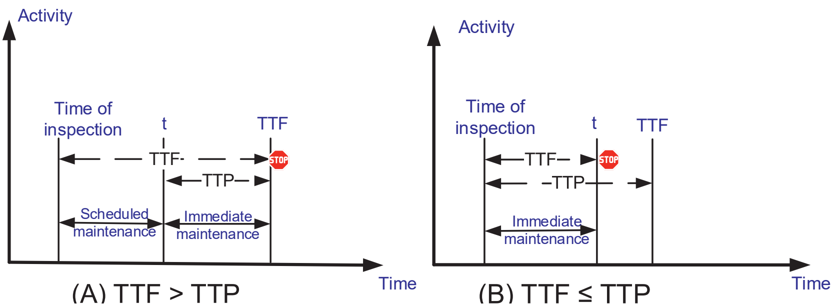

Figure 7-13: Immediate and scheduled maintenance when TTF>TTP (A) and TTF≤TTP (B)

7.7 Summary

Three basic health indexes, "*Good*", "*Fair*", and "*Poor*", have been used to express the "healthiness" of GIS and its components at three different levels: primary component level, busbar and bay level, and system level.

Examples have been provided to illustrate how the health index can be determined from a single diagnostic. In the case of multiple diagnostics, the results of each diagnostic have been combined to evaluate multiple diagnostic health indexes.

Thereafter, the health index maintenance is discussed in terms of "go/no go" maintenance decisions and maintenance selecting and scheduling.

7.8 Conclusions

From the discussion presented in this chapter, the following can be concluded:

1. To indicate the health index at each level, we advise combining the status (the results from the knowledge rules) with the remaining time to failure (TTF) and time until next examination by diagnostics or inspection (TTI). The worst case-scenario is adopted to estimate overall health index.
2. To bridge the arrangement's complexity at a typical GIS substation, we divide GIS substation into sections to determine the health index at GIS level.
3. We advise a go/no go maintenance decision based on the health index results and the expected failure impact.
4. Deferred maintenance and immediate maintenance are scheduled by considering the remaining time to failure (TTF) and time to plan the maintenance (TTP).

Chapter 8 Conclusions and recommendations

CHAPTER 8 CONCLUSIONS AND RECOMMENDATIONS

8.1 *Conclusions*

In this thesis, the health indexing for high-voltage AC gas-insulated switchgear (HVAC GIS) substations has been developed using a risk-based condition assessment methodology. This methodology processed the GIS technical status obtained at the component level in combination with the remaining time to failure and the time until next examination by diagnostics or inspection. The results were used to derive health indexes at the higher levels which are the busbar and GIS bay level, and GIS level. We also discussed how to use the derived health index to initiate maintenance. To achieve the systematic health index, several stages were necessary, as represented by the order of Chapter 2 to 7[20] in this thesis, from which we derive the following conclusions:

Failure mode impact analysis

The failure modes distinguished for GIS have an impact mainly on cost and system performance among all selected business values.

Failure frequency analysis

Switching components in GIS have the highest relative failure frequency among all GIS components.

Failure risk assessment in GIS

The risk assessment showed that the highest level of risk at GIS component level is "*Medium*" (3 on a scale from 1 to 7, where 1 equals "*Negligible*" and 7 equals "*Extreme*") resulting from failure mode "*Dielectric breakdown*". Due to the low frequency of failures at GIS level, the risk level for the complete shutdown of the GIS substation is "*Negligible*" (1 on the same scale).

Condition diagnostic selection for risk reduction

We systematically select the optimal set of 12 diagnostic techniques amongst the commonly available 25 GIS diagnostic techniques. We developed a ranking methodology to prioritise the selected diagnostic techniques. As a result, we have shown that "*Number of motor pump running times*", "*State of motor*", "*Partial discharge detection*", "*Contact travel characteristic*", and "*Stored energy*" are ranked highest among all diagnostics.

We have shown that diagnoses for overlapping failure mode can increase the cumulative costs of diagnostics but may not decrease the amount of undetected failures significantly. The diagnostics for "*Partial discharges detection*", "*Number of motor pump running times*", "*Contact travel characteristic measurements at mechanical transmission*", "*Visual inspection at density monitoring system*", and "*Coil current profile at relays*" form an efficient set with minimum overlap.

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[20] To improve readability, the style "*italic font between quotation marks*" has been used for thesis-specific definitions, such as the results of the technical status and risk assessments throughout the thesis chapters. The same style choice is applicable here and in the following sections.

Breakdown Initiated by free moving particles and protrusion defects in GIS

With the aim of collecting sufficient data and information as reference for the selected and prioritised diagnostics, we observed that further empirical information was needed to establish effective knowledge rules for “*Partial discharge*”, which is within the top five diagnostics. Therefore, we derived the required information for the knowledge rules based on “*Partial discharge*” measurements in GIS and analysed, and obtained new experimental results.

The breakdown initiated by protrusion defects of lengths from 1 to 4 mm and aluminium wire particles of 0.25-mm radius and length from 5 mm to 30 mm were investigated in laboratory experiments. The detectability of these insulation defects was also investigated. The following can be concluded based on the obtained results:

Breakdown in gas-insulated switchgear

No dielectric breakdown was initiated by moving particles of 5–30 mm under 1 pu AC voltage during the experiments in electrical field similar to the one in 380 kV GIS. It was estimated that moving particles of 15 mm and longer can cause dielectric breakdown under temporarily overvoltage stress at which point voltage can reach 1.7 pu. Moving particles of 15 mm and longer can cause dielectric breakdown when 3.5 pu lightning impulse is applied.

Furthermore, no dielectric breakdown was initiated by moving particles of 15-mm length and shorter when 2.3 pu very fast transient overvoltage (VFTO) is applied. Particles of 30 mm length cause no breakdown under VFTO voltage stress at a gap distance less than 70%. Moving particles of 30 mm and longer cause breakdown when VFTO voltage is applied with the particle at a gap distance equal to or larger than 90%.

Protrusions of 3 mm or shorter initiate no dielectric breakdown under 1 pu AC voltage stress or temporary overvoltage stress. Protrusions of 2 mm and longer cause dielectric breakdown under lighting impulses of 3.5 pu. A protrusion of 1 mm would initiate breakdown under lightning impulses of 3.5 pu superposed on 1 pu AC voltage stress.

Detectability of free moving particles and protrusions by partial discharge measurement

Moving particles of 5 mm and longer produce a detectable PD level at 1 pu AC voltage stress. In addition, three stages of particle behaviour are distinguished based on PD patterns. Protrusions of 2-4 mm produce detectable PD levels at 1 pu. A protrusion of 1 mm produces a detectable PD level at 2.1 pu, which makes it undetectable under 1 pu AC voltage stress. Similarly, three stages of protrusion behaviour have been distinguished based on PD patterns.

Status Identification Methodology

To characterise the operation of GIS components, we developed knowledge rules to convert measurement data into three technical status indexes. These indexes are the technical statuses “*Normal*”, “*Deviated*”, and “*Failed*”. Knowledge rules were formulated for the diagnostic data of “*Stored energy*” and “*Partial discharge*” measurements. These knowledge rules allowed for suitable interpretation of the condition data into statuses at GIS component level.

It can be concluded from the counted results of the technical statuses “*Normal*”, “*Deviated*”, and “*Failed*” for “*Partial discharge*” in GIS that 47% of the studied cases were considered critical to insulation. the remaining 53% of the cases do not directly lead to critical situations. This finding means that if "*Partial discharge*" is detected successfully, it is a significant tool in providing early warning for a critical status of GIS insulation. A large share of the critical cases is initiated by moving particles, protrusions and particles located on insulators under lightning superposed on AC voltage stress, and temporary overvoltage.

Health Indexing and Maintenance Initiation

For asset health, we used three basic health indexes, "*Good*", "*Fair*", and "*Poor*", to express the healthiness of GIS at different levels, namely the primary component level, the busbar and bay level, and system level.

The health index at the component level has been derived through the combination of the technical statuses, the remaining time to failure (TTF), and time until the next examination by diagnostics or inspection (TTI). Stress factors on GIS, such as switching operations and gas leakages in the presence of an insulation defect have also been considered as they may change the health index result.

Using the fault tree analysis, the health index at busbar and bay level is derived from the components' health indexes. Finally, the overall health index at GIS level is derived from the health indexes at busbar and bay level using the fault tree analysis again.

The GIS health index is utilised along with assessed impact on business values in the case of a failure for a go/no go maintenance decision-making. Once the maintenance need is decided, deferred or immediate maintenance actions are successfully scheduled on the basis of TTF and time to plan the maintenance (TTP), where planned maintenance is possible if TTF>TTP, and only immediate maintenance is possible if TTF≤TTP.

8.2 *Revisiting thesis objectives*

The main objective of this thesis, as outlined in Section 1.2, is to obtain a health indexing methodology that supports GIS maintenance decision-making. It must be investigated how dedicated diagnostics should be selected based on the knowledge of GIS failure modes and their risk assessments, and how diagnostic interpretations can be verified and used to derive condition indicators. For that purpose, the research approach has been categorised into five specific objectives.

In this section, we revisit these five specific objectives and discuss their respective results.

1. **To analyse and assess the risks related with failure modes in GIS at three different levels, namely the component, busbar and bay, and GIS level.**

   The risk assessment has shown that the highest level of risk at GIS component level is "*Medium*" (3 on a scale from 1 to 7, where 1 equals "*Negligible*", and 7 equals "*Extreme*") resulting from failure mode "*Dielectric breakdown*". Due to the low frequency of failures at GIS level, the risk level for the complete shutdown of the GIS substation is "*Negligible*" (1 on the same scale).

2. **To select among commonly available diagnostic techniques for GIS an adequate set of diagnostics able to reveal risky failure modes in GIS. Subsequently to develop a ranking methodology that prioritises the selected diagnostics, namely a methodology which relates the failure risk to both the diagnostic costs and the diagnostic detection ability of failure modes.**

   We developed a methodology to systematically select the most efficient set of diagnostic techniques amongst the commonly available GIS diagnostic techniques. "*Number of motor pump running times*", "*State of motor*", "*Partial discharge detection*", "*Contact travel characteristic*" and "*Stored energy*" were ranked the highest among all diagnostics.

   We have shown that overlapping failure mode diagnoses can increase diagnostic cumulative costs but may not increase the amount of the detected failures significantly.

3. **To verify the detectability and interpretation of critical insulation defects by empirical observation.**

   The detectability and interpretation of critical insulation defects was verified through empirical observation. The results have provided information needed to establish effective knowledge rules for the condition data for "*Partial discharge measurements*".

4. **To understand how the status of GIS can be assessed by suitable interpretation of condition data. To formulate accordingly a set of knowledge rules that implement this interpretation from condition data into statuses.**

   Knowledge rules were successfully formulated for the condition data of "*Stored energy*" and "*Partial discharge measurements*". These knowledge rules have enabled suitable interpretation of the condition data into technical statuses.

5. **To express concisely the actual condition of the GIS based on its status through the use of health indexes at the components level, busbar and bay level, and GIS level and, finally, to show how the health indexes are used to initiate maintenance.**

   The health index at component level has been derived by the combination of the technical statuses, the remaining time to failure (TTF), and time until next examination by diagnostics or inspection (TTI). Stress factors, such as lightning, switching operations, and gas leakages in the presence of an insulation defect have also been considered as they may change the health index results.

   Using the fault tree analysis, the health index at busbar and bay level is successfully derived from the components health index. Finally, the overall health index at GIS level is derived from the health indexes at busbar and bay level using the fault tree analysis. The redundancy of the GIS was considered in terms of GIS arrangement.

   Furthermore, the GIS health index is utilised along with the assessed impact on business values for a go/no go maintenance decision making. Once the maintenance need is decided, deferred or immediate maintenance is scheduled on the basis of the remaining time to failure (TTF) and time to plan the maintenance (TTP). It has been shown that it is possible to plan maintenance if TTF>TTP, and only immediate maintenance is possible if TTF≤TTP.

8.3 Technical relevance

The principle task of the asset manager is to decide what maintenance is to be performed and to plan it timely. This decision-making is important to minimise the operating costs by preventing failures, particularly those with a negative impact and to meet GIS lifetime expectations. Expected future constraints, such as increased asset performance and savings, will demand further reduction in the maintenance cost and further extension of the GIS lifetime.

This work is intended to provide the required health indexing methodologies to support maintenance decision-making in order to allow for the GIS asset manager to complete tasks and meet future expectations through the use of most efficient diagnostics for failure prevention and timely mitigation.

In a broader view, these methodologies also enable appropriate risk management and support in achieving the organisation’s target objectives and plans, which are two corner stones of asset management system models such as ISO 55000.

8.4 Recommendations for future work

During the progress of this thesis, a number of questions were raised as recommended for further investigation. These questions are related to currently available data (e.g. Cigré), maintenance selection, prioritisation techniques in use, and available monitoring systems for GIS. The following topics are recommended for further research with respect to

Data collection and surveying

1. It is not possible to accomplished FMECA at the most detailed (lower) indenture levels due to the lack of published probability of failures (failure frequencies). A survey is recommended to consider these detail, as critical basic components can be better identified and diagnosed to decrease risk level and increase GIS reliability.
2. It has been noted that different GIS users have different acceptance levels for failure impact on business values and for the frequency of failure. A survey or benchmark may be helpful in understanding and analysing these differences in the accepted levels by GIS users for a more effective risk assessment and more detailed go/no go maintenance decisions.

Insulation defects behaviour under aggressive atmospheric conditions

GIS substations are often in operation in conditions where GIS is functioning under aggressive atmospheric conditions. A change in SF_6 gas quantity or quality can be expected under such conditions due to factors such as the deterioration of the GIS sealing system.

It is therefore recommended to further investigate the behaviour of insulation defects in GIS under these conditions. In considering another combination of temperature, humidity, and gas pressure, the knowledge developed will allow managers to develop adequate knowledge rules, which allow for more accurate health indexing of GIS under these conditions.

Maintenance

We discussed the principles of health index maintenance initiation in terms of a “go/no go” maintenance decision and scheduling. It is recommended to specify the boundaries of the four regions (A to D) to determine when the GIS owner should initiate maintenance to ensure GIS reliability at a predefined level and keep total costs at a low level, which is a complex equilibrium.

Monitoring and data integration

The currently available monitoring systems monitor individual parameters of GIS, such as PD and gas pressure. The output of such systems are alarms based on pre- defined set values. This finding implies that information sources are segmented in reality, whereas the task of the asset manager is to make a firm maintenance decision by considering all information sources. Therefore, it is recommended to implement the knowledge presented in this thesis into a comprehensive GIS asset management health index, upon which a maintenance decision support system can be based.

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HVDC GIS management

Electricity transmission by Direct Current (DC) already exists and expected to grow in significance in the future. It requires the use of HVDC (High Voltage Direct Current) GIS. Similar to other types of assets, HVDC GIS should be properly managed to meet the expected level of performance and life span. Therefore, it is recommended to investigate how the methodologies developed in this thesis can be applied to HVDC GIS.

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List of Abbreviations and Symbols

Abbreviation and Symbol	Meaning	Unit
AC	Alternating current	V
Al	Aluminium	-
BU	Bushing	-
C	Capacitance	F
C (Chapter 4)	Diagnostic cost	-
CB	Circuit breaker	-
C_i	The i[th] components health index	-
Cigré	The International Council on Large Electric Systems (in French: Conseil International des Grands Réseaux Électriques)	-
C_o	Overall health index	-
Com	GIS primary component	-
C_{rank}	Diagnostic cost rank	-
CT	Current transformer	-
$D_{ability}$	Detection ability	-
$D_{ability\_rank}$	Detection ability rank	-
DC	Direct current	V
DS	Disconnector	-
DBD	Dielectric breakdown	-
DNOC	Does not operate on command	-
ES	Earthing switch	-
$\hat{E}$	Peak value of the electric field	V/m
ε_0	Permittivity of free space	F/m
F_g	Gravitational force	N
F_e	Electrostatic force	N
FMECA	Failure Mode Effects and Criticality Analysis	-
FTA	Fault tree analysis	-
GIS	Gas-insulated switchgear	-
g	Gravitational constant	m/s^2
IEC	The International Electrotechnical Commission	-
IEEE	Institute of Electrical and Electronics Engineers	-
K (Chapter 2)	Individual rank of each business value	-
K (Chapter 4)	Total number of failure origins a particular diagnostic method can be used for	-
l	Particle length	m
LI	Lightning Impulse	V
LMI	Loss of mechanical integrity (mechanical damages of different parts like insulators, etc.)	-
LOCP	Locking in open or closed position	-
LOIM	Leakage of insulation medium	-
m	Particle mass	kg
N	Number of failures per failure mode per failure origin	-
N (Chapter 4)	Total number of failure modes a particular diagnostic method can be used for	-
n (Chapter 2)	Total number of business values	-

Abbreviation and Symbol	Meaning	Unit
n (Chapter 7)	Number of mol	
O	Overall value of impact	-
OWC	Open without command	-
P	Pressure	-
PD	Partial discharge	pC and V
P_{prior}	Diagnostics priority index value	-
PRPD	Phase Resolved Partial Discharge	-
pu	Per unit	-
ρ	Particle material density	kg/m^3
q_l	Leak rate	$pa.m^2/s$
R	Resistance	Ω
R (FMECA)	Risk	-
R (chapter 7)	Gas constant	J / mol. K
R_{rank}	Risk rank	-
R_f	Front resistance	Ω
R_t	Tail resistance	Ω
r	Particle radius	m
r_i	Inner radius of GIS	m
r_o	Outer radius of GIS	m
S	Severity	
SCADA	Supervisory control and data acquisition	-
T	Temperature	K
t	Time	-
TTI	Time till next examination by diagnostics or inspection	weeks
TTF	Time to failure	weeks
TTP	Minimum time to plan maintenance	weeks
UHF	Ultra-High Frequency	-
$\hat{V}$	Peak voltage	V
V	Volume	-
VFTO	Very Fast Transient Overvoltage	V
W	Weighting factor	-
x	Contribution of the individual failure mode as a percentage of the total number of failures	-
$x_{fm,GIS\ busbar}$	Contribution of the individual failure mode as a percentage of the total number of failures in GIS busbar	-
$x_{fm,GIS\ bay}$	Contribution of the individual failure mode as a percentage of the total number of failures in the GIS bay	-
λ	The failure frequency	failures per CB-bay-year
λ_{fm}	Failure frequency per failure mode per primary component	failures per CB-bay-year
$\lambda_{fm,GIS\ bay}$	Failure frequency per failure mode in GIS bay	failures per CB-bay-year
$\lambda_{fm,GIS\ busbar}$	Failure frequency per failure mode in GIS busbar	failures per CB-bay-year
$\lambda_{GIS\ bay}$	Total failure frequency of the GIS bay	failures per CB-bay-year
$\lambda_{GIS\ burbar}$	Total failure frequency of the GIS busbar	failures per CB-bay-year
$\lambda_{GIS\ component}$	Total failure frequency per primary component	failures per CB-bay-year
$\lambda_{revised}$	Revised failure frequency	failures per CB-bay-year

Definitions

For the sake of clarity and avoiding ambiguity in interpreting terms used throughout the chapters of this PhD thesis, some terms are defined.

Switchgear is a general term covering switching devices and their combinations with associated control, measuring, protective and regulating equipment, as well as the assemblies of such devices and equipment with associated interconnections, accessories, enclosures, and supporting structures, intended in principle for use in connection with generation, transmission, distribution, and conversion of electric energy [1].

Circuit-Breaker Bay a 3-phase assembly consisting of one circuit-breaker per phase, and its associated isolating and earthing switches, instrument transformers, interconnecting bus up to and including the line disconnect switch (if applicable), and the section of main bus (if applicable) [12]

Reliability is the ability of an item to perform a required function under given conditions for a given time interval [12]

Failure is the termination of the ability of an item to perform a required function [12]

Notes

1. After failure, the item has a fault.
2. "*Failure*" is an event, as distinguished from *'Fault*" which is a state.

Major failure (MF) is failure of a switchgear and controlgear that causes the cessation of one or more of its fundamental functions. A major failure will result in an immediate change in system operating conditions, such as the backup protective equipment being required to remove the fault or a mandatory removal from service within 30 minutes for unscheduled maintenance [14].

Minor failure (mf) is any failure of a constructional element or a sub-assembly that does not cause a major failure of the switchgear or controlgear [14]. For example, a small SF_6 leakage is a minor failure, as long as it does not affect GIS functions. An electrical breakdown due to reduction in SF_6 gas pressure is a major failure and will result in an immediate change in GIS condition.

Fault is the state of an item characterised by inability to perform a required function, excluding the inability during preventive maintenance or other planned actions, or due to lack of external resources [12]

Note: A fault is often the result of a failure of the item itself.

Failure mode is the manner by which a failure is observed and generally describes the way the failure occurs.

Failure effect comprises the consequences of a failure on operation, function or functionality, or status of the component.

Maintenance is the combination of all technical and administrative actions, including supervision actions, intended to retain an item in, or restore it to, a state in which it can perform a required function [14]

Diagnostic techniques are all kinds of inspection, measurement and/or monitoring, without actions of dismantling, even with the equipment in service, to indicate the condition of the equipment and/or to detect abnormalities and determine the optimum overhaul programme [12]

Diagnostics can be performed on a periodic basis or continuously and can be performed on-line or off-line.

Inspection is the periodic visual investigation of the principal features of the switchgear and controlgear in service without dismantling. This investigation is generally directed toward pressures and/or levels of fluids, tightness, position of relays, pollution of insulating parts. Actions such as lubricating, cleaning, washing, etc., which can be carried out with the switchgear and controlgear in service, are also included [14].

Monitoring is observation of the operation of a system or part of a system to verify correct functioning by detecting incorrect functioning. This process is carried out by measuring one or more variables of the system and comparing the measured values with specified values [14].

Continuous monitoring is monitoring in which the gathered data is transmitted continuously [12].

Periodic monitoring is monitoring in which the gathered data is transmitted non-continuously or periodically [12].

Mean time between failures (MTBF) is the time interval that may be expected between failures of a piece of operating equipment [2].

Failure mode, effects and criticality analysis (FMECA): The identification of significant failures, their consequences, and their criticality. Analysing failure criticality involves classifying or prioritising the level of importance for each failure based on failure rate and the severity of the effect of failure [15].

Severity is a non-dimensional number that stands for severity, i.e. an estimate of how strongly the effects of the failure will affect the system or user [16] p 41.

Appendices

Appendix A FMECA Application to the GIS, Failure Impact

Risk analysis methodologies use different types of data and information as inputs, e.g. probability and frequency of failures, issues related to company policy, and management and environmental issues. The output data of the risk analysis methodologies is also diverse and may include recommendations, lists, risk levels, and index and event frequencies [17].

Over sixty risk analysis methodologies were reviewed in [17]. The relationship between the different types of input data, the risk analysis methodologies themselves, and the possible output data are summarised in [17]. It has been shown that there is no unique way to perform risk analysis, and that risk methodologies depend on the depth of the analysis, area of application, and the experience of the analysts who use these methodologies [17] [19].

In [17] and [19], risk methodologies have been classified into deterministic, probabilistic, and a combination of the two types. Deterministic methods assume that failure is certain and known. Meanwhile, probabilistic methods are based on the probability and the frequency of failure occurrence. A combination of the previous two methods provides flexibility.

Furthermore, risk methodologies have been classified into qualitative, quantitative, and semi-quantitative. Qualitative methods give a simple description of major failure. These methods are performed when the risk is small and familiar. Quantitative methods are based on the estimation of failure frequency and its consequences. Quantitative methods are performed when the cost is reasonable, and the information and data are available. Semi-quantitative risk methods are a combination of these two categories.

Probabilistic and quantitative methods, such as the Fault Tree Analysis (FTA), are applied to implement a failure scenario and top event failure. These methods are based on the probability of failure occurrence. Failure Mode Effect Analysis (FMEA) is used for qualitative failure mode identification. When using these methods, failure should be known and certain.

As described in [16], FMECA is performed through the following steps:

1. Define system boundary and its main functions
2. Break the system down into subsystems (see Figure A-1)
3. Define the subsystem boundary and its main functions
4. Describe how failures can occur (failure mode)
5. Describe the effects of failures on the subsystem (local effect) and system (system effect)
6. Specify and determine the severity of the failures

Steps 1 to 6 are discussed in Chapter 3, and steps 7 and 8 are discussed in Chapter 4:

7. Specify and determine the probability of occurrence of the failures
8. Determine the risk as the multiplication of the probability of failure occurrence and the expected impact of the failure

Figure A-2 is a flowchart describing how FMECA can be performed. FMECA results are usually listed in a worksheet. The worksheet used in Appendix B.2 has been adopted to list FMECA results in this thesis.

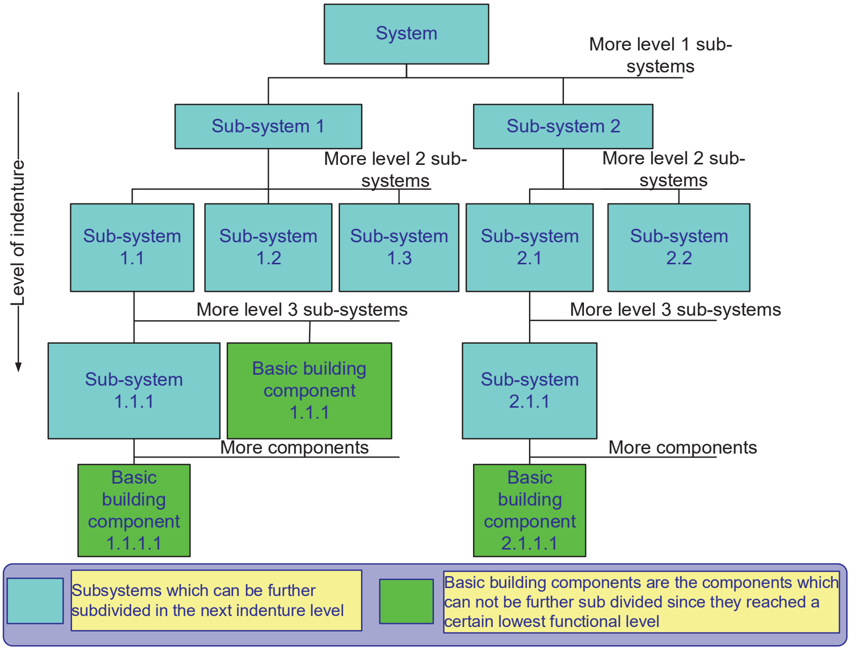

Figure A-1: System breakdown structure

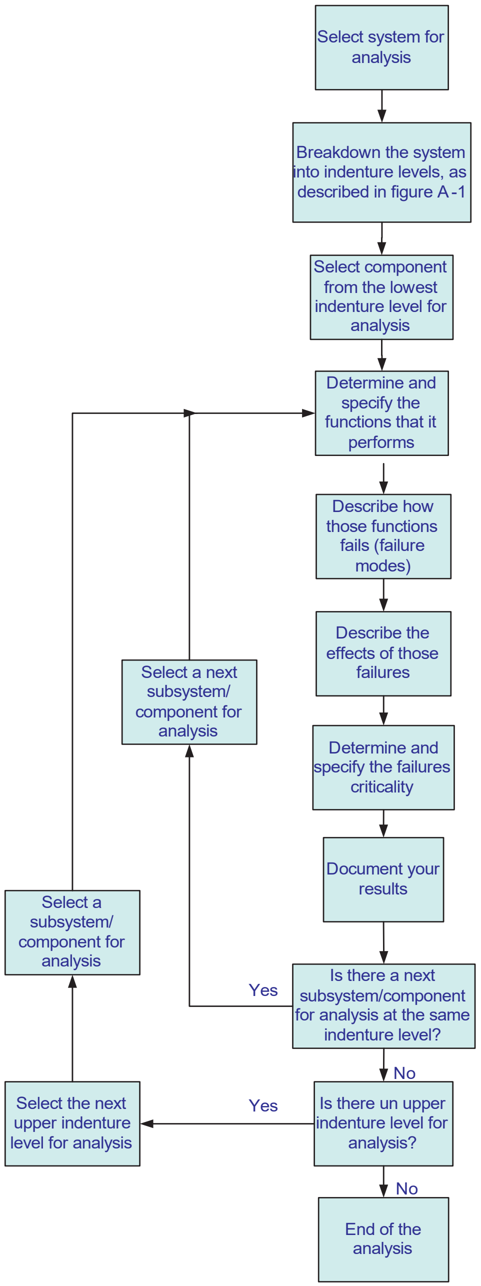

Figure A-2: FMECA performing flowchart

Failure Impact

The FMECA procedure, as described in this appendix and Section 2.3, is applied to indenture levels 1, 2, 3, 4, and 5 to estimate failure mode, failure effect, failure impact, and, calculate and rank overall failure impact while the risk is estimated for indenture levels 1, 2 and 3 in Appendix B.

Appendix A.1 GIS level, indenture level 1

Indenture level 1 is the first indenture and highest level that can be distinguished. At this level, the boundary is GIS installation. Regardless of the GIS station arrangement, the complete GIS installation (Case Study A) shown in Figure 2-1 is represented in a box with one input and one output (see Figure A-3). The input and output arrows indicate the electricity exchange within the high-voltage grid. At indenture level 1, the system boundary is the high-voltage grid, and the subsystem boundary is the GIS substation.

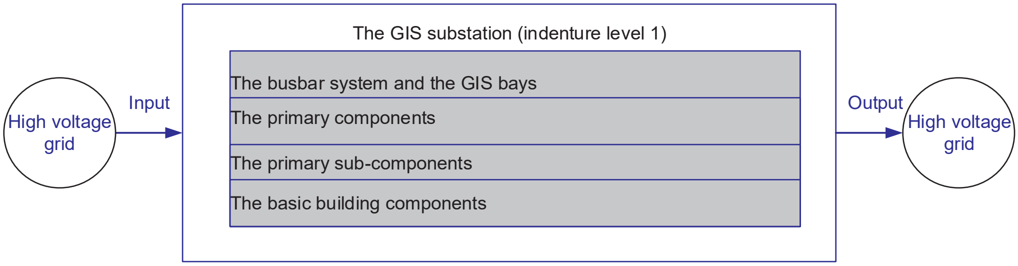

Figure A-3: The GIS installations in indenture level 1

After the identification of the system and subsystem boundaries, GIS functionality and its expected failure mode and effect must be described and listed in a FMECA worksheet.

Function: electricity transfer and electricity distribution between GIS input and output sides.

Failure mode: The GIS example used in Chapter 2 consists of four feeding bays, one transverse bay, and a double busbar system. This system allows for 28 possible combinations of failure. The worst cases, which may lead to a complete shutdown of the GIS station, are

1. When 3 of the feeding bays fail
2. When the double busbar system fails, i.e. busbar 1 and busbar 2 both fail

Failure effect: The failure effect must be estimated at system and local levels. For indenture level one, system level is the high-voltage grid, and local level is the GIS station. At system level, the failure could affect grid redundancy and reliability. At local level, the failure would cause a total power interruption at the output side of GIS.

Individual and overall level of impact: at indenture level 1, a common practice is that

- The GIS station is a part of a redundant grid
- A complete shutdown of the station is the worst possible case that may occur, (see Section 3.4 of Chapter 3).

In a redundant grid, it is a common practice that the end user has no power interruption when there is complete shutdown of the GIS substation. Therefore, the impact on the performance, company reputation, and the regulatory compliance is "*Very low*".

Dielectric breakdowns that result in no release of the rupture disk have no impact on environmental and safety issues. Hence, the failure impact is "*Very low*", which has already been considered in this thesis. The failure impact on environmental and safety issues can be substantial if breakdown is accompanied by rupture disk release. The repair cost has been estimated as "*High*".

A complete overview of failure impact of indenture level 1 is listed in Table A-1, where the overall impact of failure is set to "*High*" as it is the highest individual level of impact. If the GIS substation in not a part of a redundant grid, the failure would impact the end user and performance, company reputation, while regulatory compliance also faces the impact.

Table A-1: FMECA worksheet for indenture level 1

System	Sub-system	Function	Failure mode	Function Impact		Impact on the Individual business values						Overall level of impact
				Sub-system Function	System function	Safety	Environment	Performance	Cost	Regulatory compliance	Reputation	
High-voltage grid	GIS primary installation	Electricity transfer and distribution between the GIS input and output sides	Losing three feeders for any reason e.g. dielectric breakdown, failure to perform requested operations, etc.	Complete power interruption at the output side	Could affect grid redundancy/ reliability	Very low	Very low	Very low	High	Very low	Very low	High
			Loss of the complete busbar system	Complete power interruption at the output side	Could affect grid redundancy/ reliability	Very low	Very low	Very low	High	Very low	Very low	High

Appendix A.2 The busbar system and GIS bay level, indenture level 2

At indenture level 2, the GIS substation consists of several subsystems, namely the busbar system, transverse bays, and feeding bays, as shown in Figure A-4. These three subsystems, their functions, failure modes, failure effects, and failure impacts are summarised in the FMECA worksheet shown in Table A-2.

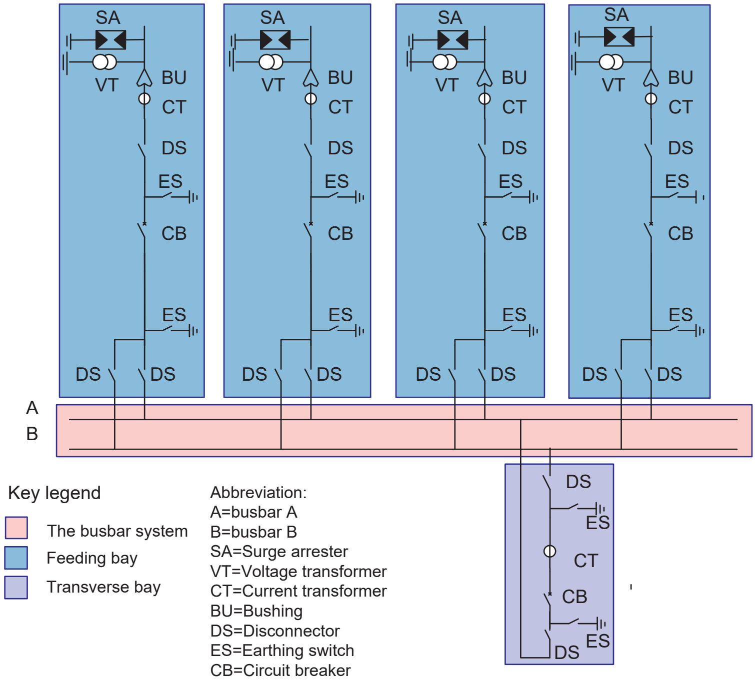

Figure A-4: Subsystems included in indenture level 2

Function: the GIS bay's function is to transfer the current between the different busbars and the grid. The function of the GIS busbar is to connect GIS bays.

Failure mode: failing to perform requested operation, function respectively, dielectric breakdown, and loss of electrical/mechanical integrity are the GIS bays' main failure modes. In the busbar, the main failure modes are dielectric breakdown and loss of electrical/mechanical integrity.

Individual and overall level of impact: different failure modes result in different impacts. To determine failure impact, we must distinguish between single failure and multiple failures. A single failure is the failure of one subsystem, whereas a multiple failure is the failure of two or more subsystems at the same time.

At indenture level 2, the failure of one busbar as well, as the failure of both busbars, has been covered in the failure modes, failure effects, and failure impacts, as listed in Table A-2.

A failure in busbar “A” or “B” of the double busbar system , or a failure in one of the GIS bays has a “*Very low*” impact on business values. One exception to this rule is that busbar failure will result in a certain repair cost. The repair cost has been estimated as *“High”* in the case of dielectric breakdown and “*Moderate*” in the case of loss of electrical/mechanical integrity. The impact on the other business values is “*Very low*”.

When the failure modes occur in busbar “A” and “B”, the failure impact on GIS performance has been estimated to result in an outage of over 24 hours. Hence, the failure impact is “Extreme”, according to Table 2-1. The overall level of impact is determined by the worst case. The results for indenture level 2 are listed in Table A-2.

Table A-2: FMECA worksheet for indenture level 2

System	Sub-system	Function	Failure mode	Function Impact		Impact on the Individual business values						Overall level of impact
				Sub-system Function	System function	Safety	Environment	Performance	Cost	Regulatory compliance	Reputation	
GIS primary installation	GIS Bay i.e. Transverse bay, Feeding bay	Current transfer between the different busbars and current transfer to the grid	Failing to perform requested operations and function respectively	No current transfer is possible from one busbar to another	Affect the GIS redundancy and reliability	Very low	Very low	Very low	Moderate	Very low	Very low	Moderate
			Dielectric breakdown	Circuit is unintentionally closed with possible safety and economic damage issues	Phase-to-ground fault with possible safety and economical damage; interruption required to the bay	Very low	Very low	Very low	High	Very low	Very low	High
			Loss of electrical/mechanical integrity	No current transfer is possible from one busbar to another	Failure to fulfil bay functionality	Very low	Very low	Very low	Moderate	Very low	Very low	Moderate
			Other /Unknown	Other /Unknown	Other /Unknown	Very low	Very low	Very low	Very low	Very low	Very low	Very low
	The busbar (the example GIS consists of a double busbar system)	Connect GIS bays	Dielectric breakdown in one busbar section	Circuit is unintentionally closed with possible safety and economic damage issues	Phase-to-ground fault with possible safety and economical damage, interruption required	Very low	Very low	Very low	High	Very low	Very low	High
			Loss of electrical/mechanical integrity in one busbar section	No current transfer is possible from one busbar to another	Failure to fulfil busbar functionality	Very low	Very low	Very low	Moderate	Very low	Very low	Moderate
			Dielectric breakdown in a both busbar sections	Circuit is unintentionally closed with possible safety and economic damage issues	Phase-to-ground fault with possible safety and economical damage, interruption required	Very low	Very low	Extreme	High	Very low	Very low	Extreme
			Loss of electrical/mechanical integrity in a both Busbar sections	No current transfer is possible from one busbar to another	Failure to fulfil busbar functionality	Very low	Very low	Very high	Moderate	Very low	Very low	Very high
			Other /Unknown	Other /Unknown	Other /Unknown	Very low	Very low	Very low	Very low	Very low	Very low	Very low

Appendix A.3 The primary component level, indenture level 3

This level has been described in Section 2.3. The results are shown in Table A-3.

Table A-3: FMECA worksheet for indenture level

System	Sub-system	Function	Failure mode	Function Impact		Impact on the Individual business values						Overall impact Level
				Sub-system Function	System function	Safety	Environment	Performance	Cost	Regulatory compliance	Reputation	
GIS CB-Bay i.e. Transverse bay, Feeding bay	Disconnector/ Earthing switch	Disconnect load current/ connect live parts to ground for certain purposes	Does not operate on command	Switching operation failed Connection to/from ground failed	Could affect the bay functionality Delay or fail in performing grounding	Very low	Very low	Very low	Low	Very low	Very low	Low
			Locking in open or closed position (alarm has been triggered by the control system)	Switching operation failed Connection to/from ground failed	Could affect the bay functionality Delay or fail in performing grounding	Very low	Very low	Very low	Low	Very low	Very low	Low
			Dielectric breakdown	Circuit is unintentionally closed with possible safety and economic damage issues	Phase-to-ground fault with possible safety and economical damage; interruption required to the bay	Very low	Very low	Extreme	High	Very low	Very low	Extreme
			Loss of mechanical integrity (mechanical damages of different parts like insulators, etc.)	Switching operation failed Connection to/from ground failed	No effect	Very low	Very low	Very low	Low	Very low	Very low	Low
			Other /Unknown	Other/Unknown	Other/Unknown	Very low	Very low	Very low	Low	Very low	Very low	Low
	Current transformer, Voltage transformer	Current/ voltage measurements	Dielectric breakdown	Circuit is unintentionally closed with possible safety and economic damage issues	Phase-to-ground fault with possible safety and economical damage; interruption required to the bay	Very low	Very low	Extreme	High	Very low	Very low	Extreme

Table A-3 Continued: FMECA worksheet for indenture level

System	Sub-system	Function	Failure mode	Function Impact		Impact on the Individual business values						Overall impact Level
				Sub-system Function	System function	Safety	Environment	Performance	Cost	Regulatory compliance	Reputation	
GIS CB-Bay i.e. Transverse bay, Feeding bay	Current or voltage transformer	Current/ voltage measurements	Loss of electrical connections integrity in primary and secondary	No transformation	No effect	Moderate	Very low	Very low	Moderate	Very low	Very low	Moderate
			Leakage of insulation medium	No effect	No effect	Very low	Low	Very low	Low	Very low	Very low	Low
			Loss of mechanical integrity (mechanical damages of different parts like insulators, etc.)	No transformation	No effect	Very low	Very low	Very low	Low	Very low	Very low	Low
			Other/ Unknown	Other/Unknown	Other/Unknown	Very low	Very low	Very low	Very low	Very low	Very low	Very low
GIS CB-Bay i.e. Transverse bay, Feeding bay	Circuit breaker	Interrupt fault currents	Does not operate on command	Switching operation failed	Failure to fulfil bay functionality	Very low	Very low	Moderate	Low	Very low	Very low	Moderate
			Locking in open or closed position (alarm has been triggered by the control system)	Switching operation failed	Failure to fulfil bay functionality	Very low	Very low	Moderate	Low	Very low	Very low	Moderate
			Dielectric breakdown	Circuit is unintentionally closed with possible safety and economic damage issues.	Phase-to-ground fault with possible safety and economical damage; interruption required to the bay	Very low	Very low	Extreme	High	Very low	Very low	Extreme
			Loss of mechanical integrity (mechanical damages of different parts like insulators, etc.)	Switching operation failed	Failure to fulfil bay functionality	Very low	Very low	Moderate	Low	Very low	Very low	Moderate
			Opens without command	Unattended switching operation	Circuit is unintentionally interrupted with possible safety and economic damage issues	Very low	Very low	Moderate	Low	Very low	Very low	Moderate
			Other/ Unknown	Other/ Unknown	Other/ Unknown	Very low	Very low	Very low	Very low	Very low	Very low	Very low

Table A-3 Continued: FMECA worksheet for indenture level

System	Sub-system	Function	Failure mode	Function Impact		Impact on the Individual business values						Overall impact Level
				Sub-system Function	System function	Safety	Environment	Performance	Cost	Regulatory compliance	Reputation	
GIS CB-Bay i.e. Transverse bay, Feeding bay	Bushing/ Termination	Connect GIS fields to the overhead lines	Dielectric breakdown	Circuit is unintentionally closed with possible safety and economic damage issues.	Phase-to-ground fault with possible safety and economical damage, interruption required	Very low	Very low	Extreme	Moderate	Very low	Very low	Extreme
			Loss of mechanical/electrical integrity (mechanical damages of different parts, big SF_6 leakage)	No or bad connection, Reduction in SF_6 density	May effect the bay functionality (it may be necessary to take the bay out of service to fix problem)	Very low	Low	High	Moderate	Very low	Very low	High
			Other/ Unknown	Other/ Unknown	Other/Unknown	Very low	Very low	Very low	Very low	Very low	Very low	Very low
	Surge arrester	Protection against lightning impulses	Dielectric breakdown	Circuit is unintentionally closed with possible safety and economic damage issues	Phase-to-ground fault with possible safety and economical damage, interruption required	Very low	Very low	Extreme	Moderate	Very low	Very low	Extreme
			Loss of electrical/mechanical connections integrity in primary and secondary	Failure in performing protection	No effect	Very low	Low	Moderate	Moderate	Very low	Very low	Moderate
			Other /Unknown	Other/ Unknown	Other/Unknown	Very low	Very low	Very low	Very low	Very low	Very low	Very low

Appendix A.4 The sub-component level, indenture level 4

The primary components that have been identified in indenture level 3 are considered systems at indenture level 4 and are further subdivided into primary sub-components and basic building components.

The basic building components are the basic building units or components that are not further subdivided into the next indenture level since they have reached a certain lowest functional level. For instance, a current transformer mainly consists of windings, insulators, and a grading electrode, which are considered its basic building components.

The primary sub-components and the basic building components, **functions**, **failure modes**, and **failure impacts** are described in the FMECA worksheet shown in Table A-4.

Individual and overall level of impact: similar to previous indenture levels, the individual and the overall levels of impact are determined.

Different failure modes at indenture level 4 have a "*Very low*" impact on company reputation, regulatory compliance, and environmental and safety issues.

A failure of the sub-primary components can result in primary component outages. The duration of these outages depends on the failure modes. An outage can be very short but may also last for an extended time. An outage time of over 24 hours is assumed for sub-components dealing with high voltage, and an outage time between 4 and 8 hours is assumed for other sub-components. The repair cost is assumed to be "*High*" for main insulation failures in circuit breakers and disconnectors. The repair cost of other sub-components dealing with high voltage is assumed to be "*Moderate*" and "*Low*" in other sub-components. The level of impact has been determined according to Table A-4.

The overall level of impact is determined by the worst case, and the results for indenture level 4 are listed in Table A-4.

The operating mechanisms of the switching devices, such as the circuit breaker and disconnector/earthing switch, are the only remaining sub-components that are to be further subdivided at the next indenture level.

Table A-4: FMECA worksheet for indenture level 4

System	Sub-system	Function	Failure mode	Function Impact		Impact on the Individual business values						Overall level of impact
				Sub-system Function	System function	Safety	Environment	Performance	Cost	Regulatory compliance	Reputation	
Circuit breaker	Making and breaking units	Breaking the fault current within a specified period of time Making and breaking the load current.	Cracking, becoming loose or breaking, wear, burn on contact	Failure in breaking the fault current Failure in breaking/making the load current	Failure in the circuit breaker performance	Very low	Very low	Extreme	Moderate	Very low	Very low	Extreme
	Auxiliary interrupters (making or breaking) and resistors	Increase interrupting abilities	Cracking, becoming loose or breaking, wear, burn on contact	Failure in breaking the fault current Failure in breaking/making the load current	Failure in the circuit breaker performance	Very low	Very low	Extreme	Moderate	Very low	Very low	Extreme
	Main insulation to earth (including bushings, pull rods and pipes, etc.)	Support and insulate live part from the ground	Aging, wear, overload, becoming loose, breaking, cracking, dielectric failure	Insulation failure	Circuit breaker has to be taken out of service	Very low	Very low	Extreme	High	Very low	Very low	Extreme
	Grading capacitors	Control the voltage distribution across each breaking unit of multi-unit circuit breakers	Leaks, corrosion, dielectric failure, damaged electric connections from capacitor stack to terminals	Failure in controlling the voltage distribution	May result in a failure in the switching operation	Very low	Very low	Extreme	Moderate	Very low	Very low	Extreme
	Electrical control and auxiliary circuits (when part of circuit breaker)	Ensure that the circuit breaker responds correctly, safely, and reliably to external commands	Defects of a component e.g. coil, limiting resistor, auxiliary switch or relay. Non-continuity of the circuit, incorrect blocking (lockout), earth fault in the close/opening circuit	Failure or deviation in the electrical control and auxiliary circuit performance	Failure or deviation in circuit breaker performance e.g. did not operate on command or spurious (unintended) operation	Very low	Very low	Moderate	Moderate	Very low	Very low	Moderate

Table A-4 Continued: FMECA worksheet for indenture level 4

System	Sub-system	Function	Failure mode	Function Impact		Impact on the Individual business values						Overall level of impact
				Sub-system Function	System function	Safety	Environment	Performance	Cost	Regulatory compliance	Reputation	
Circuit breaker	Operating mechanism	Provide the required force and speed to operate the circuit breaker	Aging, wear, overloading, leaking, becoming loose or breaking	Failure or deviation in the operating mechanism performance	Failure or deviation in the circuit breaker performance	Very low	Very low	Moderate	Moderate	Very low	Very low	Moderate
Disconnec tor / Earthing switch	Current path (contacts, rotating heads or joints etc.)	Providing the required path for the current	Overloading, wear, breaking or becoming loose	Interruption in the current path	Failure in the disconnector performance	Very low	Very low	Extreme	Moderate	Very low	Very low	Extreme
	Commutating contacts	Making and breaking the (load) current	Aging, wear, overload, becoming loose or breaking, cracking, burn on contact	Failure/deviation in making/breaking the (load) current	Failure/deviation in the disconnector performance	Very low	Very low	Extreme	Moderate	Very low	Very low	Extreme
	Main insulation to earth (including support and drive insulators, pull rods etc.)	Support and insulate live part from the ground	Aging, wear, overloading, becoming loose, breaking, cracking, dielectric failure	Insulation failure	Failure in the disconnector performance	Very low	Very low	Extreme	High	Very low	Very low	Extreme
	Electrical control and auxiliary circuits (when part of disconnector)	Ensure that the disconnector responds correctly, safely & reliably to external commands	Defects of a component e.g. coil, auxiliary switch or relay. Non-continuity of the circuit, earth fault in the close/opening circuit	Failure or deviation in the electrical control and auxiliary circuit performance	Failure or deviation in the disconnector performance e.g. did not operate on command, or spurious (unintended) operation	Very low	Very low	Moderate	Low	Very low	Very low	Moderate
	Operating mechanism	Provide the required force and speed to operate the disconnector	Aging, wear, overloading, leaking, becoming loose, breaking	Failure or deviation in the operating mechanism performance	Failure/deviation in the disconnector performance	Very low	Very low	Moderate	Low	Very low	Very low	Moderate

Table A-4 Continued: FMECA worksheet for indenture level 4

System	Sub-system	Function	Failure mode	Function Impact		Impact on the Individual business values						Overall level of impact
				Sub-system Function	System function	Safety	Environment	Performance	Cost	Regulatory compliance	Reputation	
Current measuring transformer	Secondary winding	Provide the induced voltage that has a low amplitude and can be read	Aging, wear, overloading, leaking, becoming loose, breaking, short circuit	No induces voltage i.e. no transformation	No current readings i.e. no measurement	Very low	Very low	Extreme	Moderate	Very low	Very low	Extreme
	Grading electrodes	Electric field reduction (by pushing it towards the high-voltage electrode)	Damage, becoming loose	Field concentration	May result in insulation failure	Very low	Very low	Extreme	Moderate	Very low	Very low	Extreme
	Insulation	Support and insulate live part from the ground	Aging, wear, overloading, leaking, becoming loose, breaking, cracking, dielectric failure	Insulation failure	No current readings i.e. no output	Very low	Very low	Extreme	Moderate	Very low	Very low	Extreme
Voltage measuring transformer	Primary winding	Provide the required magnetic field to the transformer	Wear, becoming loose or breaking, short circuit	No magnetic field in the transformer	No voltage readings i.e. no measurement	Very low	Very low	Extreme	Low	Very low	Very low	Extreme
	Secondary winding	Provide the induced voltage which has a low amplitude and can be read	Wear, overloading, becoming loose or breaking, short circuit	No induced voltage i.e. no transformation	No voltage readings i.e. no measurement	Very low	Very low	Extreme	Low	Very low	Very low	Extreme
	Grading electrodes	Electric field reduction (by pushing it towards the high-voltage electrode)	Damage, becoming loose	Field concentration	May result in insulation failure	Very low	Very low	Extreme	Low	Very low	Very low	Extreme
	Insulation	Support and insulate live part from the ground	Aging, wear, overloading, becoming loose, breaking, cracking, dielectric failure	Insulation failure	No voltage readings i.e. no output	Very low	Very low	Extreme	Moderate	Very low	Very low	Extreme

Table A-4 Continued: FMECA worksheet for indenture level 4

System	Sub-system	Function	Failure mode	Function Impact		Impact on the Individual business values						Overall level of impact
				Sub-system Function	System function	Safety	Environment	Performance	Cost	Regulatory compliance	Reputation	
Surge arrester	Surge limiter (e.g. ZnO/ SiC blocks)	Leading any voltage surge to a current wave passes through the surge limiter, where the surge energy is dissipated	Damage, wear, overloading, becoming loose, breaking, cracking	Failure/limited ability to dissipate the surge voltage energy	Failure of the surge arrester (failure to protect)	Very low	Very low	Extreme	Low	Very low	Very low	Extreme
	Insulation	Support and insulate live part from the ground	Aging, wear, overloading, becoming loose, breaking, cracking dielectric failure	Insulation failure	Failure of the surge arrester (failure to protect)	Very low	Very low	Extreme	Moderate	Very low	Very low	Extreme
	Grading electrode	Electric field reduction (by pushing it towards the high-voltage electrode)	Damage, becoming loose	Field concentration	May result in insulation failure	Very low	Very low	Extreme	Low	Very low	Very low	Extreme
Bushing/ Termination	Current path (contact)	Providing the required path for the current	Overloading, wear, breaking, becoming loose, burn on contact	Interruption in the current path	Bad/no connection to overhead line	Very low	Very low	Extreme	Low	Very low	Very low	Extreme
	Insulation	Support and insulate live part from the ground	Aging, wear, overloading, becoming loose, breaking, cracking, dielectric failure	Insulation failure	No connection to overhead line	Very low	Very low	Extreme	Moderate	Very low	Very low	Extreme
	Grading electrode	Electric field reduction (by pushing it towards the high-voltage electrode)	Damage, becoming loose	Field concentration	Insulation failure	Very low	Very low	Extreme	Low	Very low	Very low	Extreme

Appendix A.5 The basic building component level, indenture level 5

At indenture level 5, the circuit breaker operating mechanism and the disconnector/earthing switch operating mechanism are further subdivided. Disconnectors/earthing switches have mechanisms that are operated by a motor or manually. Circuit breakers have mainly a pneumatic, spring, or hydraulic operating mechanism. Despite some differences, the basic building components involved in the operating mechanisms of circuit breakers and disconnectors/earthing switches are similar. Their **functions**, possible **failure modes**, **failure effects**, and **failure impact** are identified and listed in Table A-5.

Individual and overall level of impact: similarly to previous indenture levels, the individual and the overall levels of impact are determined.

The failure of basic building components has a "*Very low*" impact on company reputation, regulatory compliance, and environmental and safety issues.

An outage time between 4 to 8 hours is assumed in case of failure of basic building components, and the failure impact on the system performance is "*Moderate*". The repair cost of the basic building components is assumed to be "*Low*".

The overall level of impact is determined by the worst case, and the results for indenture level 5 are listed in Table A-5.

At indenture level 5, all basic building components are identified for GIS installations. Therefore, indenture level 5 represents the final indenture level.

Table A-5: FMECA worksheet for indenture level 5

System	Sub-system	Function	Failure mode	Function Impact		Impact on the Individual business values						Overall level of impact
				Sub-system Function	System function	Safety	Environment	Performance	Cost	Regulatory compliance	Reputation	
Operating mechanism	Compressors, motors, pumps, piping fittings (when part of the switching device)	Provides the required energy to the operating mechanism	Incorrect operation, wear / ageing, corrosion, leakage	low or no energy are provided to the operating mechanism	Low or no force and speed are provided by the operating mechanism to the switching device	Very low	Very low	Moderate	Low	Very low	Very low	Moderate
	Energy storage (accumulator, spring) (when part of the switching device)	Storage the required energy which gives the necessary force for moving the switching device main contacts	Wear /ageing, corrosion, leakage	low or no energy are provided to the operating mechanism	Low or no force and speed are provided by the operating mechanism to the switching device	Very low	Very low	Moderate	Low	Very low	Very low	Moderate
	Actuator and damping device (when part of the switching device)	An actuator is used to release the switching device have to trip when a switching command is detected, and a damping device is used to limit a mechanical movement/vibration	Corrosion, wear, ageing	Deviation or failure in the actuator/damping device performance	Deviation or failure in the operating mechanism performance	Very low	Very low	Moderate	Low	Very low	Very low	Moderate
	Mechanical transmission (when part of the switching device)	The mechanical linkage transfers the movement from the hydraulic piston to the main contacts	Corrosion, wear, ageing, cracking, breaking	Deviation or failure in the mechanical transmission performance	Deviation or failure in the operating mechanism performance	Very low	Very low	Moderate	Low	Very low	Very low	Moderate

Appendix B FMECA Application to the GIS, Risk Estimation

Appendix B.1 Failure Frequency in GIS

Distribution of major failure modes for circuit breaker major failures [21]

Failure mode	$\% \, x_{fm,GIS\,CB}$ ***Contribution to the total number of failures***	$\lambda_{fm,GIS\,CB}$ ***(failures per CB-bay-year)***
Does not operate on command	46%	6.44×10^{-4}
Locking in open or closed position (alarm triggered by the control system)	19.4%	2.71×10^{-4}
Electrical breakdown	19.4%	2.71×10^{-4}
Loss of mechanical integrity (mechanical damage to different parts, such as insulators, etc.)	7.2%	1.01×10^{-4}
Opens without command	2.4%	3.36×10^{-5}
Other/Unknown	5.6%	7.84×10^{-5}
Total	100%	6.44×10^{-4}

Distribution of major failure modes for disconnector/earthing switch major failures [22]

Failure mode	$\% \, x_{fm,GIS\,DE}$ ***Contribution to the total number of failures***	$\lambda_{fm,GIS\,DE}$ ***(failures per CB-bay-year)***
Does not operate on command	79.3%	1.03×10^{-3}
Locking in open or closed position (alarm triggered by the control system)	3.6%	4.68×10^{-5}
Electrical breakdown	12.8%	1.66×10^{-4}
Loss of mechanical integrity (mechanical damage to different parts, such as insulators, etc.)	0.7%	9.10×10^{-6}
Other/Unknown	3.6%	4.68×10^{-5}
Total	100%	1.30×10^{-3}

Distribution of major failure modes for Instrument transformers major failures [24]. The data reported in the survey are for AIS and GIS

Failure mode	$\% \, x_{fm,GIS\,IT}$ ***Contribution to the total number of failures***	$\lambda_{fm,GIS\,IT}$ ***(failures per CB-bay-year)***
Dielectric breakdown	46.1%	4.14×10^{-4}
Loss of electrical connections integrity in primary and secondary	9.2%	8.28×10^{-5}
Leakage of insulation medium	13.1%	1.17×10^{-4}
Loss of mechanical integrity (mechanical damage to different parts, such as insulators, etc.)	8.2%	7.38×10^{-5}
Accuracy out of tolerances	6.0%	5.40×10^{-5}
Providing false signals	2.9%	2.61×10^{-5}
Damp circuit loss of function	0.8%	7.20×10^{-6}
Monitoring device loss of function (e.g. oil pressure, SF_6 density, or free gas detection systems	2.6%	2.34×10^{-5}
Other	11.4%	1.02×10^{-4}
Total	100%	9.00×10^{-4}

Distribution of major failure modes for the surge arrester (reported failures for surge arrester is zero in new Cigré survey [5]).

Failure mode	$\% \, x_{fm,GIS\ SA}$ ***Contribution to the total number of failures [4]***	$\lambda_{fm,GIS\ SA}$ ***(failures per CB-bay-year)***
Dielectric breakdown	50%	2.00×10^{-5}
Partial discharge	50%	2.00×10^{-5}
Other	0%	0.00
Total	100%	4.00×10^{-5}

Distribution of major failure modes for the SF_6 bushing

Failure mode	$\% \, x_{fm,GIS\ Bushing}$ ***Contribution to the total number of failures [5]***	$\lambda_{fm,GIS\ Bushing}$ ***(failures per CB-bay-year)***
Dielectric breakdown	66.7%	6.67×10^{-4}
Loss of mechanical/ electrical integrity	11.1%	1.11×10^{-4}
Other	22.2%	2.22×10^{-4}
Total	100%	0.10×10^{-3}

Appendix B.2 Risk Estimation

The FMECA procedure described in Chapter 3 is applied to indenture levels 1, 2 and 3 to estimate risk.

Table B-1: FMECA worksheet for indenture level 1

System	*Sub-system*	*Function*	*Failure mode*	*Function Impact*		*Overall level of impact*	*Frequency class*	**Risk**
				Sub-system Function	*System function*			
High-voltage grid	GIS primary installation	Electricity transfer and distribution between GIS input and output sides	Losing three feeders for any reason e.g. dielectric breakdown, failure to perform requested operation, etc.	Complete power interruption at the output side	Could affect grid redundancy/reliability	High	Almost impossible	
			Losing the complete busbar system	Complete power interruption at the output side	Could affect grid redundancy/reliability	High	Almost impossible	

Table B-2: FMECA worksheet for indenture level 2

System	Sub-system	Function	Failure mode	Function Impact		Overall level of impact	Frequency class	Risk
				Sub-system Function	System function			
GIS primary installation	GIS Bay i.e. Transverse bay, Feeding bay	Current transfer between the different busbars And current transfer to the grid	Failing to perform requested operation, function respectively	No current transfer is possible from one busbar to another	Affect the GIS redundancy and reliability	Moderate	Possible	
			Dielectric breakdown	Circuit is unintentionally closed with possible safety and economic damage issues	Phase-to-ground fault with possible safety and economical damage; interruption required to the bay	High	Unlikely	
			Loss of electrical/mechanical integrity	No current transfer is possible from one busbar to another	Failure to fulfil the bay functionality	Moderate	Unlikely	
			Other /Unknown	Other /Unknown	Other /Unknown	Very low	Unlikely	
	The busbar (the example GIS consists of a double busbar system)	Connect the GIS bays	Dielectric breakdown in one busbar section	Circuit is unintentionally closed with possible safety and economic damage issues	Phase-to-ground fault with possible safety and economical damage; interruption required to the busbar	High	Unlikely	
			Loss of electrical/mechanical integrity in one busbar section	No current transfer is possible from one busbar to another	Failure to fulfil the busbar functionality	Moderate	Almost impossible	
			Dielectric breakdown in a both busbar sections	Circuit is unintentionally closed with possible safety and economic damage issues	Phase-to-ground fault with possible safety and economical damage; interruption required to the busbar	Extreme	Almost impossible	
			Loss of electrical/mechanical integrity in a both Busbar sections	No current transfer is possible from one busbar to another	Failure to fulfil the busbar functionality	Very high	Almost impossible	
			Other /Unknown	Other /Unknown	Other /Unknown	Very low	Almost impossible	

Table B-3: FMECA worksheet for indenture level 3

System	*Sub-system*	*Function*	*Failure mode*	*Function Impact*		*Overall level of impact*	*Frequency class*	*Risk*
				Sub-system Function	*System function*			
GIS CB-Bay i.e. Transverse bay, Feeding bay	Disconnector/ earthing switch	Disconnect load current/ connect live parts to ground for certain purposes	Does not operate on command	Switching operation failed Connection to/from ground failed	Could affect the bay functionality Delay or fail in performing grounding	Low	Possible	
			Locking in open or closed position (alarm has been triggered by the control system)	Switching operation failed Connection to/from ground failed	Could affect the bay functionality Delay or fail in performing grounding	Low	Almost impossible	
			Dielectric breakdown	Circuit is unintentionally closed with possible safety and economic damage issues	Phase-to-ground fault with possible safety and economical damage, interruption required	Extreme	Unlikely	
			Loss of mechanical integrity (mechanical damages of different parts like insulators, etc.)	Switching operation failed Connection to/from ground failed	No effect	Low	Almost impossible	
			Other /Unknown	Other/Unknown	Other/Unknown	Low	Almost impossible	
	Current transformer, voltage transformer	Current/ voltage measurements	Dielectric breakdown	Circuit is unintentionally closed with possible safety and economic damage	Phase-to-ground fault with possible safety and economical damage, interruption required	Extreme	Unlikely	
			Loss of electrical connections integrity in primary and secondary	No transformation	No effect	Moderate	Almost impossible	
			Leakage of insulation medium	No effect	No effect	Low	Unlikely	
			Loss of mechanical integrity (mechanical damages of different parts like insulators, etc.)	No transformation	No effect	Low	Almost impossible	
			Other/ Unknown	Other/Unknown	Other/Unknown	Very low	Unlikely	

Table B-3 Continued: FMECA worksheet for indenture level 3

System	*Sub-system*	*Function*	*Failure mode*	*Function Impact*		*Overall level of impact*	*Frequency class*	*Risk*
				Sub-system Function	*System function*			
Impact on the Individual business values	Circuit breaker	Interrupt fault current	Does not operate on command	Switching operation failed	Failure to fulfil the bay functionality	Moderate	Unlikely	
			Locking in open or closed position (alarm triggered by control system)	Switching operation failed	Failure to fulfil the bay functionality	Moderate	Unlikely	
			Dielectric breakdown	Circuit is unintentionally closed with possible safety and economic damage	Phase-to-ground fault with possible safety and economical damage, interruption required	Extreme	Unlikely	
			Loss of mechanical integrity (mechanical damage to different parts, such as insulators, etc.)	Switching operation failed	Failure to fulfil the bay functionality	Moderate	Unlikely	
			Opens without command	Unattended switching operation	Circuit is unintentionally interrupted with possible safety and economic damage issues	Moderate	Almost impossible	
			Other/ Unknown	Other/ Unknown	Other/ Unknown	Very low	Unlikely	
	Bushing/ termination	Connect GIS fields to the overhead lines	Dielectric breakdown	Circuit is unintentionally closed with possible safety and economic damage	Phase-to-ground fault with possible safety and economical damage, interruption required	Extreme	Almost impossible	
			Loss of mechanical/electrical integrity (mechanical damage to different parts, such as big SF_6 and leakage)	No or bad connection, Reduction in SF_6 density	May effect the bay functionality (it might be required to take the bay out of service to fix the problem)	High	Almost impossible	
			Other/ Unknown	Other/ Unknown	Other/Unknown	Very low	Almost impossible	
	Surge arrester	Protection against lightning impulses	Dielectric breakdown	Circuit is unintentionally closed with possible safety and economic damage	Phase-to-ground fault with possible safety and economical damage, interruption required	Extreme	Almost impossible	
			Partial discharge	Failure in performing protection	No effect	Moderate	Almost impossible	
			Other /Unknown	Other/ Unknown	Other/Unknown	Very low	Almost impossible	

Appendix C Summary of GIS Diagnostics

This appendix summarises the commonly available diagnostics for GIS and briefly describes the goal of each diagnostic and its input and output.

Table C-1: A summary of available diagnostics for GIS components

Diagnostic	***Used at component***	***Used at sub-component***	***Goal of diagnostic***	***Diagnostic input***	***Diagnostic output***	***Reference***
Visual inspection	All components		To reveal any mechanical damages, deformation, or abnormalities of expansion devices (bellows in case of oil type, or rupture disc for gas type), traces of dampness or moisture, such as rust or corrosive metal parts. Checks for loose connection, presence of fuses, etc., oil level for traces of oil leakage (oil type), pressure of gas for possible gas leakage (gas type)			[28]
SF_6 leak detection	CB, DE	Components at service voltage, i.e., main	To reveal any decrease in gas pressure	Gas pressure	Indicate the gas value	[28]
SF_6 gas moisture			To evaluate gas quality	Gas samples	Moisture content	
SF_6 contamination			To evaluate gas quality	Gas samples	Type/ amount of SF_6 by-products	
Partial discharge (PD)			To detect discharging GIS defects	Electromagnetic signals, acoustic signals, light signals and SF_6 by-products	Various kinds of data, graphs, and patterns that can reveal defects in GIS	
Main contact position			To reveal incorrect insulation distance caused by an incorrect end position of moving contacts	optical, mechanical, and electronic signals	Indicate the end position of the moving contacts	
Contact travel characteristics			To indicate abnormalities and failures of the contact mechanical operations	Electrical signals collected by the travel sensor	Position of the primary contacts as a function of time during a switching operation	
Contact resistance			To assess the current carrying ability	Voltage and current	Contact resistance value	

Table C-1 Continued: A summary of available diagnostics for GIS components

Diagnostic	***Used at component***	***Used at sub-component***	***Goal of diagnostic***	***Diagnostic input***	***Diagnostic output***	***Reference***
Contact temperature	CB, DE	Components at service voltage, i.e., main	To measure overheating results from poor contact	Making images (camera and infrared measurements) and gas pressure (SF_6 gas pressure is measured and compensated for the effect of load and ambient temperature)	Temperature value	[28]
Operation time			To indicate the overall condition of the circuit breaker	Voltage and time	The operating time is determined by measuring the time the voltage needs to change its value across the switching device from zero to the applied value or vice versa	
Pole discrepancy			To reveal pole disagreement that results in unsymmetrical primary current	Voltage and time	The operating time is determined by the three poles of CB	
Contact velocity (Refer to contact travel characteristics)			To reveal incorrect insulation distance and operating mechanism conditions	the contact velocity is the derivative of the contact position as a function of time	Contact velocity	
Contact wear (I^2t)			To indicate the arcing contact wear	The load current for opening and closing operations and the accumulated arc time	The contact wear is determined by the integral of the I^2t	

Table C-1 Continued: A summary of available diagnostics for GIS components

Diagnostic	*Used at component*	*Used at sub-component*	*Goal of diagnostic*	*Diagnostic input*	*Diagnostic output*	*Reference*
Arcing time	CB, DE	Components at service voltage, i.e., main	To indicate excessive arcing time. A long arcing time may be harmful to the switching device since it is associated with huge temperature and pressure rises, as well as contact erosion	Contact position, velocity and acceleration, switching timing data, and current waveform are combined to determine arcing time	Arcing time	
Stored energy (spring position, pressure)	CB, DE	Operating mechanism, i.e., mechanical transmission components, motors, pumps, actuator and damping devices, and energy storage elements	To reveal a large diversity of deviations and mechanical faults in the operating mechanism	Nitrogen pressure value (in hydraulic operating mechanism). Position monitoring of pistons, springs, and valve indicators	Amount of stored energy	[28]
Number of operations			To indicate the general condition of the switching device	Register the number of operations	Indicate the number of operations	
State of mechanism State of motor/ pump (current, voltage, running time per start, accumulated running time and number of starts) charging current/time (motor protection)			To indicate wear, deviations, and fault in the operating mechanism. Briefly it indicates the overall condition	Number of operations, current, time, etc.	Give data that can be used to reveal deviations and failures in operating mechanisms	

Table C-1 Continued: A summary of available diagnostics for GIS components

Diagnostic	***Used at component***	***Used at sub-component***	***Goal of diagnostic***	***Diagnostic input***	***Diagnostic output***	***Reference***
Vibration signature	CB, DE	Operating mechanism, i.e., mechanical transmission components, motors, pumps, actuator and damping devices, and energy storage elements	To focus on mechanical type of failures	Electrical signals collected by accelerometers	Vibration signature (plot of vibration amplitude vs. time)	
Contact travel characteristic			To indicate abnormalities and failures of the contacts mechanical operation	Electrical signals collected by travel sensor	Position of the primary contacts as a function of time during a switching operation	
Voltages	CB, DE	Control and auxiliary circuits, i.e., command coils, auxiliary switches and relays, thermostats, heaters, lockout devices, gas density supervision, and other monitoring devices	To reveal open and short circuits in the control and auxiliary circuit	Voltage value	Defective heating elements or some short- circuited windings in a coil or a motor can be detected	[28]
Coils current profile			To indicate the change in shape of the coil current and identify various types of malfunctions and failures	Measure the current and the operating time of the coil	Coil current plot. Deviation in the plot indicates problems in the release mechanism	
Status of auxiliary switches (position, operating sequence, timing			To indicate different failures in the control circuitry by knowing the status, sequence, and the of switching of the auxiliary switches	Observing the auxiliary switches status (open, closed), sequence and their timing	Failures and deviations in the auxiliary switches, their status (open, closed), sequence, and their timing is identified	
Circuit continuity			To verify the integrity of the control circuit	Current pulses	Measure any interruption in the current pulses	

Table C-1 Continued: A summary of available diagnostics for GIS components

Diagnostic	*Used at component*	*Used at sub-component*	*Goal of diagnostic*	*Diagnostic input*	*Diagnostic output*	*Reference*
Environment in control cabinet is important for outdoor installations (heating elements)	CB, DE	Control and auxiliary circuits, i.e. command coils, auxiliary switches and relays, thermostats, heaters, lockout devices, gas density supervision, and other monitoring devices	To reveal failures in the heating elements	Measure the temperature inside the cabinet	Temperature value	
SF_6 leak detection	Busbar and busduct system		To reveal decrease in gas pressure	Gas pressure	Indicate gas value	[28]
SF_6 gas moisture			To evaluate gas quality	Gas samples	Moisture value	
SF_6 contamination			To evaluate gas quality	Gas samples	Type/ value of SF_6 by-products	
Partial discharge (PD)			To detect discharging GIS defects	Electromagnetic signals, acoustic signals, light signals and SF_6 by-products	Various kinds of data, graphs, and patterns that can reveal defects in GIS	
Contact resistance			To assess current carrying ability	Voltage and current	The contact resistance value	

Table C-1 Continued: A summary of available diagnostics for GIS components

Diagnostic	*Used at component*	*Used at sub-component*	*Goal of diagnostic*	*Diagnostic input*	*Diagnostic output*	*Reference*
PD measurements	Bushing		To detect discharging GIS defects	Electromagnetic signals, acoustic signals, light signals and SF_6 by-products	Various kind of data, graphs and patterns that can reveal defects in GIS	
SF_6 leak detection			To reveal decrease in the gas pressure	Gas pressure	Indicate the gas value	
Infrared measurements			To reveal hot spots and loose contacts	Making infrared images	Indicate failures based on the images	
leakage current	Surge arrester		To verify arrester condition during operation	Current	Indicate the value of the leakage current	[29]
Infrared measurements			To reveal hot spots and loose contacts	Making infrared images	Indicate failures based on the images	
SF_6 leak detection			To reveal decreases in gas pressure	Gas pressure	Indicate the gas value	
SF_6 leak detection	IT		To reveal decreases in gas pressure	Gas pressure	Indicate the gas value	[33]
SF_6 gas moisture			To evaluate gas quality	Gas samples	Moisture value	
SF_6 contamination			To evaluate gas quality	Gas samples	Type/ value of SF_6 by-products	
Partial discharge (PD)			To detect discharging GIS defects	Electromagnetic signals, acoustic signals, light signals and SF_6 by-products	Various kind of data, graphs and patterns that can reveal defects in GIS	
Ratio check			To reveal deviations in the transformation ratio	Voltage, current	Turn ratio	

Appendix D Voltage and overvoltage stresses in GIS

GIS is continuously operated under AC power-frequency voltage during its lifetime [37][38]. In addition to the continuous AC power-frequency voltage stress, GIS may experience internal and external overvoltage stress. Internal overvoltage stress originate from switching components installed inside GIS. External overvoltage stress is related to grid operations and environmental causes.

DC voltage stress in GIS is caused by trapped charges left after a switching operation on parts of GIS. Depending on the discharge time, these trapped charges can persist for several days and can have a maximum amplitude of 1.2 pu [37].

Besides AC and DC voltage stress, temporary overvoltage (TOV) occurs as a result of a ferro-resonance or a single line to ground fault through impedance in a three-phase system. TOV has a frequency close to 50 Hz and can have amplitudes of up to 1.7 pu.

Slow front transient overvoltage (SFO) occurs due to fault clearing [39]. The SFO is usually limited to the protection level of the surge arrester, particularly when a surge arrester is installed at the line entrance of the GIS [37]. For test purposes, SFO has been standardised through an impulse voltage with a front time of 250µs and time to half-value of 2500 µs [39]. SFO can have an amplitude (depending on the protection level of the arrester) of up to 3.5 pu [37].

Fast front overvoltage (FFO) originates mainly from lightning strikes. The amplitude and the front time has been standardised through an impulse voltage having a front time of 1.2 µs, a time to half-value of 50 µs, and an amplitude of up to 6 pu [37]. Usually, a surge arrester would reduce the FFO amplitude to about 3.5 pu.

Very vast front transient overvoltage (VFTO) occurs whenever an instantaneous change in the voltage takes place [45]. The majority of the instantaneous voltage changes in GIS are caused by operating the GIS switching devices.

During the operation of a disconnector, for instance, pre- and re-strikes might occur between the disconnector electrodes. The number of such strikes depends on their time duration and the disconnector speed. During the pre- and re-strikes, voltage surges are generated which propagate into the GIS. At impedance discontinuities, these voltage surges experience reflection and refraction, and therefore complex waveforms result.

Simulations have shown that the voltage peak value of a VFTO can reach 3.3 pu for a 20-m-long busbar [45]. Measurements in a 380 kV GIS substation have shown that VFTO can have a peak amplitude of up to 2.7 pu [45]. The rise time of a VFTO waveform generated by a disconnector in GIS is in the order of few up to some tens of nanoseconds [45].

The different types of the overvoltage stresses and their time durations and amplitudes in GIS have been summarised in Figure D-1.

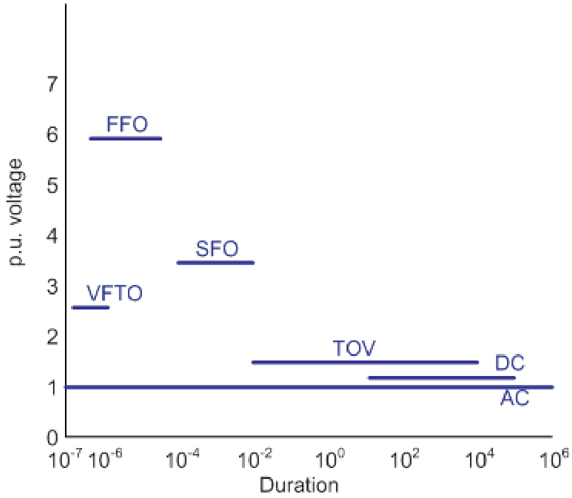

Figure D-1: Types of overvoltage stresses and their durations and amplitudes [37]

Appendix E Experimental results of particle motion in GIS

A particle laying on the inner side of the GIS enclosure can lift off and start moving towards the high-voltage electrode under the influence of the electric field. A particle starts moving when the electrostatic force (F_e) exceeds the gravity force (F_g) and the drag force (F_d). Hence, the motion of a particle is calculated by [43][44]:

$$m\,.\ddot{y}\,(t) = F_e - F_g - F_d \qquad \text{……... E-1}$$

By including F_e, F_g, and F_d in equation E-1, the particle motion is expressed as

$$m\,.\ddot{y}\,(t) = \underbrace{\frac{\pi\,\varepsilon_0\,l^2\,E\,(t)}{\ln(\frac{2\,l}{r}-1)}\left(\frac{\hat{V}\ sin(wt)}{[r_o - y\,(t)]\ \ln(\frac{r_o}{r_i})}\right)}_{F_e} - \underbrace{m\,g}_{F_g}$$

$$- \underbrace{\dot{y}\,(t)\pi r(\,6\mu\,k_d(y) + 2.65\,[\mu\,\rho_g\,l\,\dot{y}\,(t)]^{0.5}}_{F_d} \qquad \text{……... E-2}$$

Where

ε_0	*Free space permittivity*	*8.85×10^{-12} F.m^{-1}*
l	*Particle length*	*5, 10, 15, 20 and 30 mm*
r	*Particle radius*	*0.25 mm*
$\hat{V}$	*Peak voltage*	*80-140 kV (increased in steps of 20 kV)*
r_o	*Outer radius*	*150 mm*
r_i	*Inner radius*	*35 mm*
$y\,(t)$	*Height of the particle measured from the outer electrode*	
$\dot{y}\,(t)$	*Particle velocity*	
$\ddot{y}\,(t)$	*Particle acceleration*	
m	*Particle mass*	$\pi\,r^2 l\,\rho$
ρ	*Particle density*	*2700 kg/m^3 (Aluminium)*
g	*Gravitational acceleration*	*9.81 m/s^2 or N/kg*
$k_d(y)$	*Drag coefficient*	*1 (vertical position)*
μ	*SF6 viscosity*	*15.5e^{-6} kg/ms*
ρ_g	*Gas density*	*4 bar (Absolute)*

The detailed derivative of the equation is discussed in [43] and [44]. Figure E-1 shows an example of the simulated particles' motion.

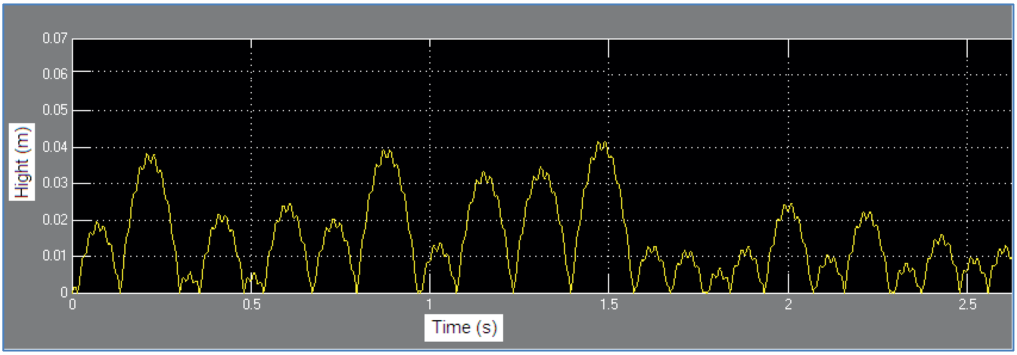

Figure E-1: Simulated motion of aluminium particle 15 mm in length with 0.25-mm radius at 120 kV$_{rms}$

During the computer simulation, the simulation time was set to 30 seconds to be in line with the experimental part. The simulation results of various aluminium particles under 120 kV$_{rms}$* AC voltage are summarised in Table E-3.

Table E-3: Particles' simulated maximum jump altitude under 120 kV$_{rms}$ AC voltage

Particle size (mm)	***Maximum altitude (as percentage of the gap distance between the high and the low electrodes)***
2	0%
5	5–14%
10	14–35%
15	22–57%
20	35–69%
30	55–100%

*120kV$_{rms}$ AC voltage is used to achieve an actual electric field as in one of the 380 kV GIS substations located Meeden in the Netherlands.

Confirmation of the simulation results by acoustic measurements

The computer simulations described in the previous section aimed to determine the particles' maximum jump altitude. To confirm the simulation results, the maximum time a particle could fly under AC voltage was measured by means of the acoustic method. Thereafter, the maximum jump altitude was calculated [43].

The AC test circuit shown in Section 5.2.1 and depicted in Figure E-2 was used to perform the acoustic measurements.

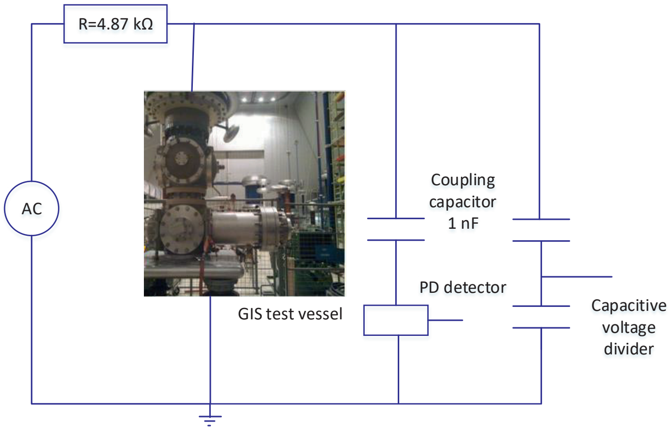

Figure E-2: Circuit diagram of AC test setup

The acoustic method is based on measuring the acoustic waves transmitted during the particles' impact on the inner side of the GIS enclosure. Acoustic waves result from two phenomena. The first is the mechanical impact of the particle onto the enclosure, and the second is the partial discharge between the particle and the enclosure. Acoustic waves resulting from partial discharges have a very small amplitude compared to those resulting from the mechanical impact [43].

The acoustic signals are received by a piezoelectric sensor attached to the outer side of the enclosure. The signals are converted then into electrical signals and pre-amplified before they are analysed by the Acoustic Insulation Analyser (AIA). The complete measuring setup is shown in Figure E-3.

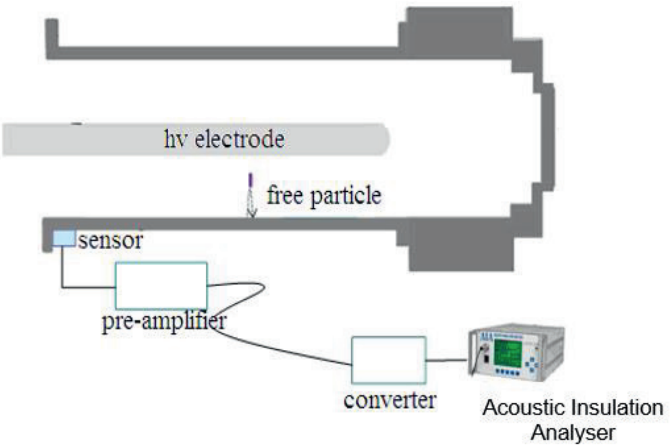

Figure E-3: Acoustic measurement system

An example of the measurement results is shown in Figure E-4. Peaks in the figure indicate moments of impacts of the particle on the inner side of the enclosure. Time of flight is the time between two consecutive signals. The maximum time of flight can be extracted from such figures.

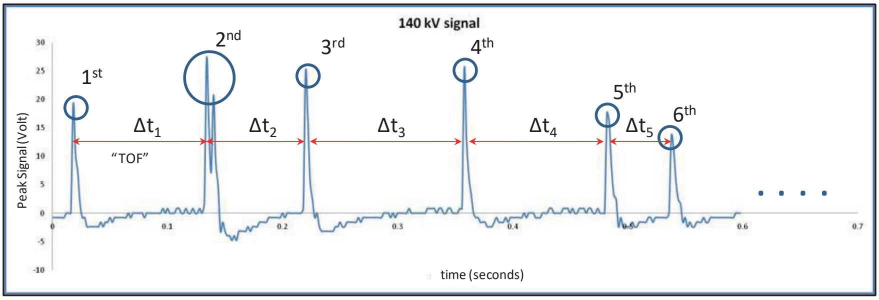

Figure E-4: An example of acoustic signals resulting from particles 15 mm in length with 0.25-mm radii moving at 140 kV_{rms}

The particle motion is assumed to follow a parabolic trajectory. The highest point in the particle motion is determined by [43][42]:

$$h_{max} = \frac{1}{2} g \left(\frac{\Delta t_{max}}{2}\right)^2 \qquad \text{……... E-4}$$

Where

g = the gravitational acceleration= 9.81 m/s^2

t_{max} = the maximum time of flight in seconds

The calculation results are listed in Figure E-5 for the aluminium particles 10–30 mm in length. It was not possible to measure the jump height of shorter particles (i.e. particles 5 mm in length and shorter) since they were not moving sufficiently under the applied AC voltage stress.

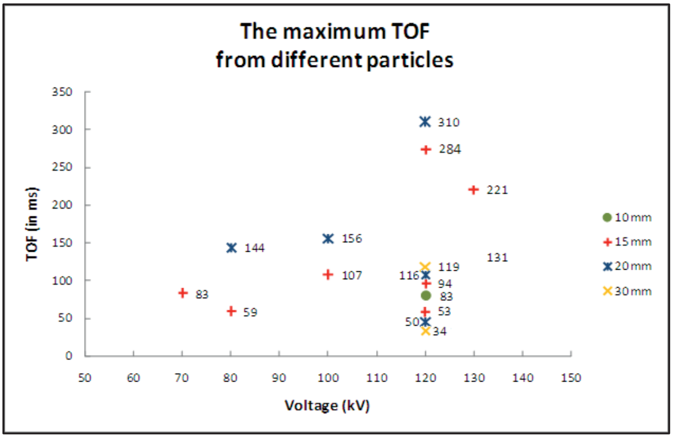

Figure E-5: Time of flight (TOF) calculated based on the acoustic measurements

Figure E-5 shows that the maximum jump height increases in general with the voltage applied and the particle length.

The acoustic measurement results of Figure E-5 have been plotted on the same graph as the simulation results as shown in Figure E-6. Two different restitution coefficient (CR) values were used during the simulations. CR was used to simulate the effect of the particles impact with the inner surface of the enclosure. CR is equal to the ratio between the particle velocity before and after impact.

The CR of wire-shaped aluminium and copper particles was approximately 0.5 and tended to decrease below 0.4 when the mass of the particle was less than 2 mg [43].

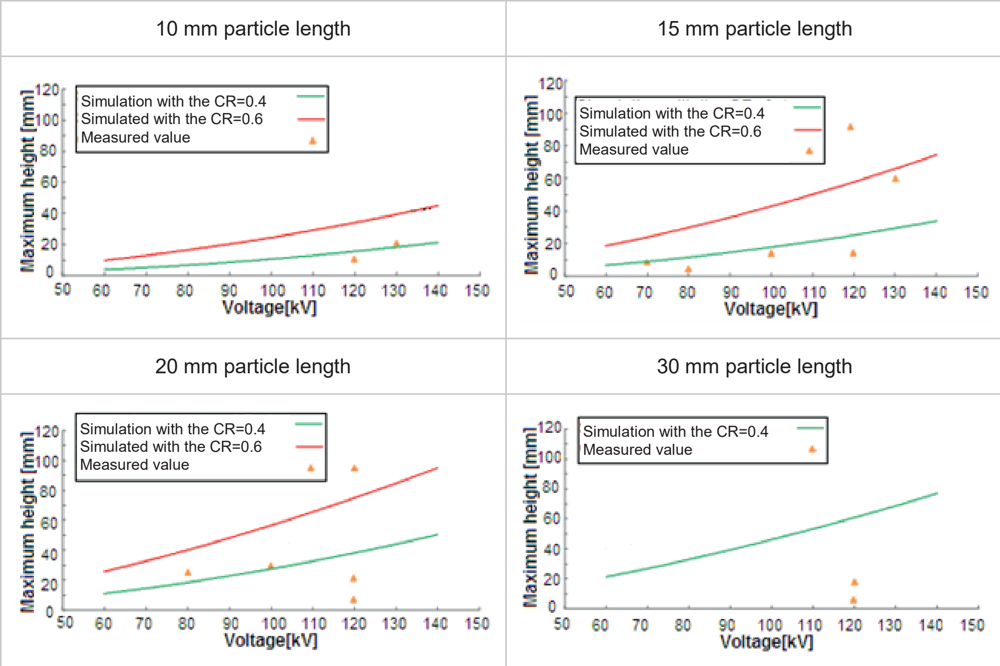

Figure E-6: The particles' jump height, measured values vs. simulation results

It can be observed that the maximum jump height calculated based on the acoustic measurements deviates from the maximum jump height based on the computer simulations. This deviation can be related to the following factors which were not taken into account during the simulations:

- Charges at the lift-off: In equation E-2, the charges at the lift-off were determined by the following equation:

$$Q = \frac{\pi \, \varepsilon_0 \, l^2 \, E\,(t)}{ln(\frac{2\,l}{r} - 1)} \qquad \text{……... E-5}$$

  It has been found that the actual charges are approximately 20% higher than the value obtained by this equation. This is because the exact shape of the particle should be more accurately considered in the equation [44].

- Discharges during flight: During its flight, a particle can have an in-flight corona. This depends on the particle charge, particle position, and value of the electric field [44]. An in-flight corona results in a change in the net charges that the particle has, and therefore the computer simulations determine a different height.

A threshold level for discharges during flight has been estimated to be 3×10^6 V/m [44]. To estimate if discharges occurred during flight in the laboratory experiments, the electric field was simulated at the upper tip of particles 10 mm, 15 mm, 20 mm, and 30 mm in length at 25% of the gap distance. The results are shown in Figure E-7.

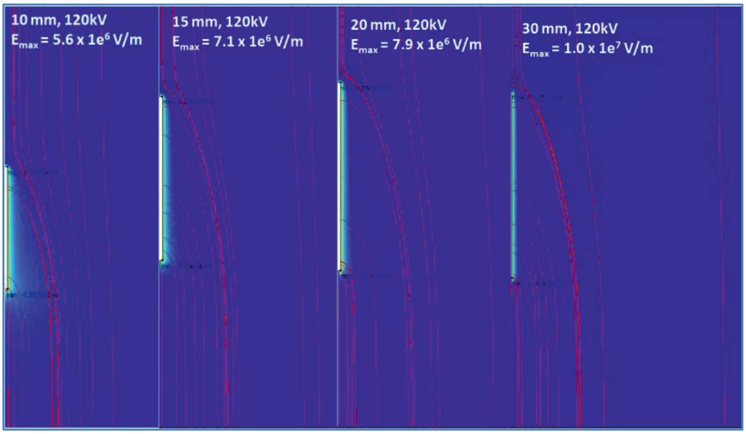

Figure E-7: Electric field distribution at the tip of different particles

The figure shows that, for example, a particle of 30 mm experiences an electric field which is about 3.3 times higher than the threshold level. This finding implies that discharges during flight have probably occurred. Therefore the net charge of the particle is reducing, and the electrical force and jump height reduce as well. This explains the lower measured jumping height with the acoustic method. Without such discharges, the 30-mm particle would reach a higher altitude. In such situations, the computer simulation results represent the worst case, i.e. the maximum height jump a particle can reach in the case that no in-flight corona has occurred.

Despite the deviation between the simulation and experimental results, the jump height measurements obtained from the simulations and measurements were used during the breakdown experiments.

The simulation and the experimental results of aluminium particles with various lengths under AC voltage stress are summarised in Figure E-8 [43].

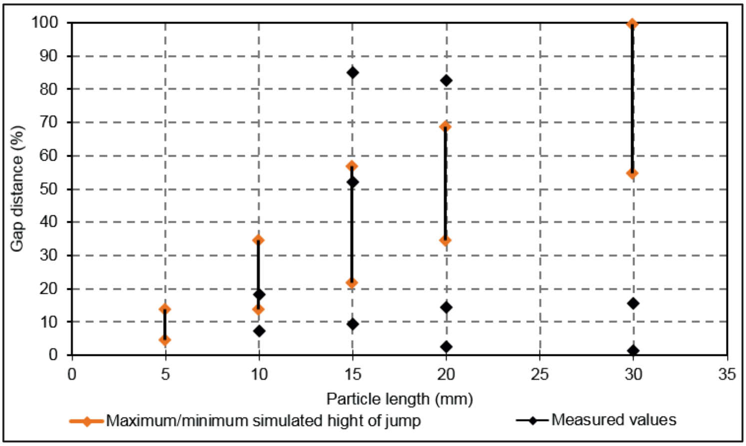

Figure E-8: The jump height of aluminium particles of r = 0.25 mm under 1 pu + 8% AC voltage stress in GIS

Appendix F Knowledge Rules for GIS

Appendix F.1 Knowledge Rules Overview

An overview of the GIS knowledge rules is listed in Table F-1. Rules for partial discharge measurements, which are excluded in the first table, are summarised in Appendix F.2.

Table F-1: Overview of the GIS diagnostics’ knowledge rules

Diagnostic method	***Diagnostic outcome***	***Rules***	***Remarks***
Quantity of insulation medium (Switching components)	The outcome of this method is the value of the gas pressure (P)	**P ≥ x** $x = \left(1 + \frac{maximum\ pressure - nominal\ pressure}{nominal\ pressure}\right) \times 100\%$ Where x is the gas pressure in the percentage at which the status deviation is distinguished	Technical status is “*Deviated*”. The rupture discs would be released in the case that the gas pressure equals or is larger than the relief gas pressure due to an internal breakdown.
		y < P < x $y = \left(1 + \frac{alarm\ pressure - nominal\ pressure}{nominal\ pressure}\right) \times 100\%$ Where y is the pressure in the percentage at which an alarm signal is generated	Technical status is “*Normal*”. The gas pressure lies within the specified limits.
		z < P ≤ y $z = \left(1 + \frac{minimum\ allowable\ pressure - nominal\ pressure}{nominal\ pressure}\right) \times 100\%$ Where z is the gas pressure in the percentage at which the status failure is distinguished	Technical status is “*Deviated*”. Alarm signal is generated. Gas pressure is equal to or less than the alarm level due to leakage.
		P ≤ z	Technical status is “*Failed*”. Circuit breaker operation is locked out. Gas pressure decreases such that the gas pressure is equal to or less than the lockout level due to leakage.

Table F-1 Continued: Overview of the GIS diagnostics' knowledge rules

Diagnostic method	***Diagnostic outcome***	***Rules***	***Remarks***
Control Voltages (V)	The outcome of this method is the value of the control circuit (V)	**V ≥ x** $x = \left(1 + \frac{maximum\ voltage - nominal\ voltage}{nominal\ voltage}\right) \times 100\%$ Where x is the maximum allowable voltage in a percentage (with respect to the nominal voltage)	V≥ max. voltage An alarm is ignited followed by a visual inspection and check.
		y < V< x $y = \left(1 + \frac{minimum\ voltage - nominal\ voltage}{nominal\ voltage}\right) \times 100\%$ Where y is the minimum allowable voltage in a percentage (with respect to the nominal voltage)	Technical status is "*Normal*". The control voltage lies within the specified limits.
		V≤ y	Under voltage-trip would be activated. The cause of the low voltage is either problems in the operating mechanism or problems in the voltage supply itself.

Table F-1 Continued: Overview of the GIS diagnostics' knowledge rules

Diagnostic method	*Diagnostic outcome*	*Rules*	*Remarks*
Coil current profile	The outcome of this method is the profile of the coil current during an opening or closing operation, which is characterised by A, B, C, and D [28], where • A indicates the current energy required to move the armature from the starting position • B is the time period which indicates the swiftness of the release mechanism	**min x ≤ A ≤ max x** **min y ≤ B ≤ max y** **min z ≤ C ≤ max z** **min i ≤ D ≤ max i** Where x, i is the allowable tolerance in the current in percentage (with respect to the nominal value) y, z is the allowable tolerance in time in a percentage (with respect to the nominal value) $\pm x = \left(\frac{A\ \pm tolerance\ value\ in\ the\ current}{A}\right) \times 100\%$ $\pm y = \left(\frac{B\ \pm tolerance\ value\ in\ the\ time}{B}\right) \times 100\%$ $\pm z = \left(\frac{C\ \pm tolerance\ value\ in\ the\ total\ time}{C}\right) \times 100\%$ $\pm i = \left(\frac{D\ \pm tolerance\ value\ in\ current\ value}{D}\right) \times 100\%$ *+ indicates that x, y, z and i is maximum* *- indicates that x, y, z and i is minimum*	Technical status is "*Normal*". The coil current profile lies within the specified limits.
		A < min x OR **A > max x**	Technical status is "*Deviated*". Deviation in the energy required to move the armature from starting position is due to problems in the release mechanism.
		B < min y OR **B > max y**	Technical status is "*Deviated*". Deviation in the measured swiftness is due to problems in the release mechanism.
		C > max z	Total running time increases due to problems in the auxiliary switches.

Table F-1 Continued: Overview of the GIS diagnostics' knowledge rules

Diagnostic method	***Diagnostic outcome***	***Rules***	***Remarks***
Coil current profile	• C is the time period which indicates the total time for which the coil was energised • D is the current value which indicates the D.C. resistance of the coil	**D < min i**	Decrease in the coil current due to short circuit in the coil windings.
Status of auxiliary switches	The auxiliary switches' positions, operating sequences, timing, and mutual consistency during an operation	No deviation in the switches' status (open or closed), timing, and sequence during a breaker operation	The technical status of the auxiliary switches is "*Normal*".
		Deviation in the switches' position, operating sequence, timing, and mutual consistency during a breaker operation	Technical status is "*Deviated*". Deviation in the operating time of the auxiliary switch which supervises the operating time of the circuit breaker indicates a deviation in the operation time of a circuit-breaker.
			Technical status is "*Deviation*". Change in the status of the position auxiliary switches indicates a deviation in the position of the main contact.

Table F-1 Continued: Overview of the GIS diagnostics' knowledge rules

Diagnostic method	***Diagnostic outcome***	***Rules***	***Remarks***
Status of auxiliary switches	The auxiliary switches' position, operating sequence, timing, and mutual consistency during an operation	Deviation in the switches' position, operating sequence, timing, and mutual consistency during a breaker operation	Change in the sequence of the density monitor contacts, which are intended to provide a warning and to interlock operation when the SF_6 gas density reaches the lockout level, indicates defective blocking systems for breaker operation in case of too low gas density or insufficient spring charging. Refer to quantity of insulation medium.
Circuit continuity	The interruption in the received signals which are injected into an electric circuit	No interruption in the received current pulses	The continuity of the circuit is confirmed.
		Interruption in the received current pulses	Interruption in the received current pulses indicates problems such as *short-circuits and open circuits in the electrical circuit to which the current pulses are injected.*
Stored energy	The pressure value (P) of the compressed gas in the operating mechanism	**P ≥ x** $x = \left(1 + \frac{maximum\ pressure - nominal\ pressure}{nominal\ pressure}\right) \times 100\%$ Where x is the gas pressure in the percentage at which the status deviation is distinguished	Technical status is "*Deviated*". The pressure is equal to or exceeds the maximum pressure. An alarm is ignited followed by a visual inspection and check.

Table F-1 Continued: Overview of the GIS diagnostics' knowledge rules

Diagnostic method	***Diagnostic outcome***	***Rules***	***Remarks***
Stored energy	The pressure value (P) of the compressed gas in the operating mechanism	**y < P < x** $y = \left(1 + \frac{alarm\ pressure - nominal\ pressure}{nominal\ pressure}\right) \times 100\%$ Where y is the pressure in the percentage at which an alarm signal is ignited	Technical status is "*Normal*". The pressure value lies within the specified limits.
		z < P ≤ y $z = \left(1 + \frac{minimum\ allowable\ pressure - nominal\ pressure}{nominal\ pressure}\right) \times 100\%$ Where z is the gas pressure in the percentage at which the status failure is distinguished	Technical status is "*Deviated*". An alarm signal is ignited as a result of the pressure drop. In this case, the stored energy is equal to or less than the alarm level (but still higher than the lockout level). The reasons could be successive operations or leaks or clogging problems in the hydraulic circuit.
		P ≤ z	Technical status is "*Failed*". At this level, the circuit breaker is switched out. Possible reasons for the decrease in the energy stored are successive operations or leaks or clogging problems in the hydraulic circuit.

Table F-1 Continued: Overview of the GIS diagnostics' knowledge rules

Diagnostic method	***Diagnostic outcome***	***Rules***	***Remarks***
State of motor	Five parameters reflecting the state of the motor, where • A = the motor current • B = motor voltage • C = motor temperature, • D = motor starts number • E = running time per motor starts	**min x ≤ A ≤ max x** **min y ≤ B ≤ max y** **C < z** **D < i** **E < f** Where • x is the allowable tolerance in the motor current in a percentage (with respect to the nominal value) • y is the allowable tolerance in the motor voltage in a percentage (with respect to the nominal value) • z is the maximum allowable motor temperature in a percentage (with respect to the reference value) (e.g. room temperature) • i is the maximum allowable motor starts number • f is the maximum allowable motor running time per starts in a percentage (with respect to a reference value) $\pm x = \left(\frac{A \pm tolerance\ value\ in\ motor\ current}{A}\right) \times 100\%$ $\pm y = \left(\frac{B \pm tolerance\ value\ in\ motor\ voltage}{B}\right) \times 100\%$ *+ sign indicates that x, y, z, and i is maximum* *- sign indicates that x, y, z, and i is minimum* $z = \left(\frac{maximum\ allowable\ temperature - reference\ temperature}{\text{reference temperature}}\right) \times 100\%$ $f = \left(\frac{E + maximum\ tolerance\ value\ in\ the\ running\ time\ per\ motor\ start}{\text{E}}\right) \times 100\%$	Technical status is "*Normal* ". The state of the motor lies within specifications.

Table F-1 Continued: Overview of the GIS diagnostics' knowledge rules

Diagnostic method	***Diagnostic outcome***	***Rules***	***Remarks***
State of motor	Five parameters reflecting the state of the motor, where • A = the motor current • B = motor voltage • C = motor temperature • D = motor starts number • E = running time per motor starts	**A ≥ max x**	The measured motor current increases due to poor working lubricants in mechanical linkages or problems in the contact assemblies or compressors.
		B ≤ min y OR **B ≥ max y**	Deviation occurs in the measured motor voltage because of problems in the motor itself or in the supply voltage.
		C ≥ z	Motor temperature (thermal overload) increases due to problems in the mechanical linkages or compressors.
		D ≥ i	Measured motor starts number increases due to problems in the limit switches and contactors or leakage in the hydraulic system.
		E ≥ f	Measured running time per motor starts increases due to problems with the limit switches, contactors, pump, and compressor or leakage in the hydraulic system.

Table F-1 Continued: Overview of the GIS diagnostics' knowledge rules

Diagnostic method	***Diagnostic outcome***	***Rules***	***Remarks***
Vibration signatures	The operating mechanism vibration profile during an operation	The measured vibration signature is in line with the reference vibration signature.	Technical status is "*Normal*". No problems in the circuit breaker operating mechanism to be identified, or no problems could be identified based on the vibration signature.
		The measured vibration signature is not in line with the reference signature. The following problems can be identified based on the type of the analysis applied.	Broken parts, jamming elements, and cracks, or lubrication problems, incorrectly assembled crank, and incorrectly adjusted moving contact, or bush defect, damaged fix contact, cut rod, and removed rod, or shock absorber and eroded contacts.
Contact travel characteristics	The position of the primary contacts as a function of time during an opening or closing operation	The measured contact travel curve is in line with the reference contact travel curve.	Technical status is "*Normal*". No problems to be identified based on the contact travel curve.
		The travel curve has the same shape as the original curve, but the start and stop points are shifted to the right. See, for example, Figure 4.5 A in [28].	Indicate a delay in release mechanism, e.g. due to poorly lubricated release latches
		The travel curve has the same shape and the same starting point as the original curve, but the stop point is shifted to the right. See, for example, Figure 4.5 B in [28].	Indicate a low contact speed, e.g. due to reduced energy in the operating mechanism
		The oscillations in the measured contact travel curve increase. See, for example, Figure 4.5 C in [28].	Indicate a poor damping, e.g. due to defective dash pot
		The travel curve has the same shape as the original curve, but it is shifted upwards. See, for example, Figure 4.5 D in [28].	Indicate a low insulation distance in open position, e.g. due to incorrectly assembly

Table F-1 Continued: Overview of the GIS diagnostics' knowledge rules

Diagnostic method	***Diagnostic outcome***	***Rules***	***Remarks***
Quantity of insulation medium (non-switching components)	The value of the gas pressure (P)	**P ≥ x** $x = \left(1 + \frac{maximum\ pressure - nominal\ pressure}{nominal\ pressure}\right) \times 100\%$ Where x is the gas pressure in the percentage at which the status deviation is distinguished	Technical status is "*Failed*". The rupture discs would be released in the case that the gas pressure is equal to or larger than that the relief gas pressure due to an internal breakdown.
		y < P < x $y = \left(1 + \frac{alarm\ pressure - nominal\ pressure}{nominal\ pressure}\right) \times 100\%$ Where y is the pressure in the percentage at which an alarm signal is generated	Technical status is "*Normal*". The gas pressure lies within the limits.
		z < P ≤ y $z = \left(1 + \frac{minimum\ allowable\ pressure - nominal\ pressure}{nominal\ pressure}\right) \times 100\%$ Where z is the gas pressure in the percentage at which the status failure is distinguished	Technical status is "*Deviated*". Alarm signal is generated. Gas pressure is equal to or less than the alarm level due to gas leakage.
		P ≤ z	Technical status is "*Failed*". Alarm signal is ignited. Gas pressure seriously decreases due to gas leakage, creating possibility for dielectric breakdown.

Appendix F.2 Summary of the status of the insulation system in GIS in the presence of an insulating defect

Knowledge rules have been developed to assess the GIS insulation system in the presence of an insulation defect in GIS based on the partial discharge measurement results, as illustrated in Section 6.3. The knowledge rules developed for the GIS important defects are based on the amplitude and the shape of the PRPD pattern and the frequency spectrum. To give a complete overview of the status of the insulation system, the knowledge rules are summarised in Table F-2.

Table F-2: A summary of the technical status results for PD measurements*

			Voltage shape (voltage level in pu)					
			AC	TOV	LI	VFTO	DC	DC+LI
Type defect	Defect behaviour	PD activity/PD trend	Technical status	Technical status	Technical status	Technical status	Technical status	Technical status
[21] Free moving particle	Shuffling behaviour	PD spectrum has low amplitude and low selective intensity. PRPD pattern has low amplitude and high intensity. See Section 5.6.1.	Normal	Failed	Failed	Normal	Failed	Failed
	The particle tends to transition from the moving stage to the shuffling stage.	No gaps are observed in the frequency spectrum, and the PRPD pattern has decreasing amplitude and an increased intensity.	Normal	Failed	Failed	Normal	Failed	Failed
	The particle tends to stay at the moving stage or to transition to the jumping stage.	No gaps are observed in the frequency spectrum, and the PRPD pattern has stable or increasing amplitude and a low intensity.	Normal	Failed	Failed	Deviated	Failed	Failed
	The particle tends to transition from the jumping stage to the moving stage.	Gaps are observed in the frequency spectrum, and the PRPD pattern has decreasing amplitude and an increased intensity.	Normal	Failed	Failed	Deviated	Failed	Failed
	The particle tends to stay at the jumping stage and jumps higher.	Gaps are observed in the frequency spectrum, and the PRPD pattern has stable or increasing amplitude and a low intensity.	Normal	Failed	Failed	Deviated	Failed	Failed

[21] See Section 5.6.1 for the description of the various stages of the movement of free particles

Table F-2 Continued: A summary of the technical status results for PD measurements*

			Voltage shape (voltage level in pu)					
			AC	TOV	LI	VFTO	DC	DC+LI
Type defect	***Defect behaviour***	***PD activity/PD trend***	***Technical status***	***Technical status***	***Technical status***	***Technical status***	***Technical status***	***Technical status***
Protrusion	Initial stage	-	Normal	Normal	Failed	-	Normal	Failed
	Intermediate stage	-	Deviated	Failed	Failed	-	Deviated	Failed
	Close-to-breakdown stage	-	Failed	Failed	Failed	-	Failed	Failed
Particle on insulation	-	Intermittent PD activity Decreasing PD amplitude	Normal	-	Failed	-	-	-
		Continuous/ Unknown PD activity Decreasing PD amplitude	Normal	-	Failed	-	-	-
		Intermittent PD activity Stable PD amplitude	Normal	-	Failed	-	-	-
		Continuous/ Unknown PD activity Stable PD amplitude	Normal	-	Failed	-	-	-
		Intermittent PD activity Increasing PD amplitude	Deviated	-	Failed	-	-	-
		Continuous/ Unknown PD activity Increasing PD amplitude	Failed	-	Failed	-	-	-

Table F-2 Continued: A summary of the technical status results for PD measurements*

			Voltage shape (voltage level in pu)					
			AC	***TOV***	***LI***	***VFTO***	***DC***	***DC+LI***
Type defect	***Defect behaviour***	***PD activity/PD trend***	***Technical status***	***Technical status***	***Technical status***	***Technical status***	***Technical status***	***Technical status***
Floating element	-	Intermittent PD activity Decreasing PD amplitude	Normal	-	-	-	-	-
		Continuous/ Unknown PD activity Decreasing PD amplitude	Failed	-	-	-	-	-
		Intermittent PD activity Stable PD amplitude	Normal	-	-	-	-	-
		Continuous/ Unknown PD activity Stable PD amplitude	Failed	-	-	-	-	-
		Intermittent PD activity Increasing PD amplitude	Deviated	-	-	-	-	-
		Continuous/ Unknown PD activity Increasing PD amplitude	Failed	-	-	-	-	-
Voids and cavities	Initial stage	Intermittent PD activity Decreasing PD magnitude	Normal	-	-	-	-	-
		Continuous/ Unknown PD activity Decreasing PD magnitude	Normal	-	-	-	-	-
		Intermittent PD activity Stable PD magnitude	Normal	-	-	-	-	-

Table F-2 Continued: A summary of the technical status results for PD measurements*

			Voltage shape (voltage level in pu)					
			AC	***TOV***	***LI***	***VFTO***	***DC***	***DC+LI***
Type defect	***Defect behaviour***	***PD activity/PD trend***	***Technical status***	***Technical status***	***Technical status***	***Technical status***	***Technical status***	***Technical status***
Voids and cavities	Initial stage	Continuous/ Unknown PD activity Decreasing PD magnitude	Normal	-	-	-	-	-
		Intermittent PD activity Increasing PD magnitude	Normal	-	-	-	-	-
		Continuous/ Unknown PD activity Increasing PD magnitude	Normal	-	-	-	-	-
	Conditioned stage	Intermittent PD activity Decreasing PD magnitude	Normal	-	-	-	-	-
		Continuous/ Unknown PD activity Decreasing PD magnitude	Deviated	-	-	-	-	-
		Intermittent PD activity Stable PD magnitude	Normal	-	-	-	-	-
		Continuous/ Unknown PD activity Decreasing PD magnitude	Normal	-	-	-	-	-
		Intermittent PD activity Increasing PD magnitude	Normal	-	-	-	-	-
		Continuous/ Unknown PD activity Increasing PD magnitude	Normal	-	-	-	-	-
	Final stage	Intermittent PD activity Decreasing PD magnitude	Deviated	-	-	-	-	-
		Continuous/ Unknown PD activity Decreasing PD magnitude	Failed	-	-	-	-	-
		Intermittent PD activity Stable PD magnitude	Normal	-	-	-	-	-
		Continuous/ Unknown PD activity Decreasing PD magnitude	Deviated	-	-	-	-	-

*The (-) sign in the table indicates unknown or a “not applicable” situation

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Curriculum Vitae

Muhannad Al-Suhaily born in 1975 in Iraq. He studied electrical engineering and received BSc degree from Baghdad University of Technology in 1997 and MSc degree from Delft University of Technology in 2008. At the same year he started his PhD research project at the department of DCE&S (former high voltage technology).

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List of publications

1. Muhannad Al-Suhaily, Sander Meijer and Johan Smit, “Selection of Preventive Diagnostics to Reduce Risk of Failure for Gas Insulated Switchgear”, ISH August 2017.
2. Muhannad Al-Suhaily, Sander Meijer and Johan Smit, “Knowledge Rules for the health status of GIS insulation systems using UHF Partial Discharge Measurements”, ISH August 2017.
3. Muhannad Al-Suhaily, Meijer, S.; Smit, J.J.; Sibbald, P., “Knowledge rules development for diagnostics outcomes in GIS”, IEEE Conference Publications.
4. Purnomoadi, A.P.; Muhannad Al-Suhaily; Meijer, S.; Smit, J.J.; Burow, S.; Tenbohlen, S., “The Influence of Free Moving Particles on the Breakdown Voltage of GIS under Different Electrical Stresses”, IEEE Conference Publications.
5. Muhannad Al-Suhaily, M.; Meijer, S.; Smit, J.J.; Sibbald, P.; Kanters, J., “Analysis of diagnostic methods to prevent failure of critical GIS components”, IEEE Conference.
6. Muhannad Al-Suhaily, M.; Meijer, S.; Smit, J.J.; Sibbald, P., “Two level on-line monitoring system to reduce GIS components failure”, CMD Conference.