Development of Asset Health Indices based on Dynamic Condition Parameters in Smart Grids: An Application to High Voltage Gas Insulated Switchgears

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ABTRACT

Defining asset condition is a key aspect in effectively managing smart grid assets. With the development of recent advanced technologies on monitoring and diagnostics systems for electrical assets, several data can be collected from grids simultaneously regarding condition of individual assets. However, making decisions out of the collected condition data requires a certain methodology combined with system overview and product knowledge which can then be applied to all assets types and classes. This paper introduces a methodology in order to construct health indices for electrical assets based on dynamic condition parameters, being applied to high voltage gas insulated switchgears.

ÖZETÇE

Akıllı Şebeke Varlıklarının verimli yönetimi için bu varlıkların durumlarını belirlemek kilit rol üstlenir. Son zamanlarda, elektriksel verlıkların izleme ve tanı sistemlerindeki ileri teknoloji gelişmeleri ile her bir varlıkın anlık durumu hakkında bir çok veri toplanabilmektedir. Fakat, bu toplanan durum verilerinden yararlanarak karar verilmesi gerektiğinde, tüm varlık sınıf ve tiplerine uygulanabilen, sistem ve ürün bilgisi ile harmanlıanmış güvenilir bir metodolojiye ihtiyaç duyulur. Bu makale, yüksek gerilim gaz izole sistemler için uygulanan, dinamik durum parametrelerine dayanıp elektriksel varlık için sağlık göstergerleri oluşturmaya yarayan bir metodolojyi sunmaktadır.

I. Introduction

Electrical utilities often use risk management tools based on pure probabilistic analysis and basic financial asset valuation (e.g. depreciated book-values). Traditional risk management practices in electrical utilities have several weaknesses.

Firstly, the risk modeling is usually based on high level asset data decreasing the accuracy of the results. Secondly, actual condition of individual assets is not considered. Thus, the risk analysis is not capable to provide time based risk mitigation and optimization measures such as shortened or extended maintenance intervals, retrofit, refurbishment and replacement based on individual assets. Thirdly, there is no or very limited risk classification which reduces the transparency of the results. Lastly, the risk forecast is usually is in the form a trend analysis which also reduces the future risk accuracy usually leading to various over-forecasting issues.

The proposed methodology uses dynamic asset condition parameters in order to calculate an Asset Health Index (AHI) for each and every asset within the electrical grid. In order to manage different input data, a hierarchical system has been applied. The model, which is described in this methodology, is configured in the asset group level. An asset type is where type specific data like nominal values are stored and maintained. The asset level is where asset data like identifiers and also asset-specific condition values are managed.

The asset health index (AHI) is calculated monthly by looking into four sub-health indices which belong to the major components of the switchgear and a fourth health index composed of others factors. These are insulation system health index (HI_{IS}), drive mechanism health index (HI_{DM}), breaking capacity health index HI_{BC} and other factors health index (HI_{OF}).

Four sets of smart parameters have been used in order to construct each of the four health indices.
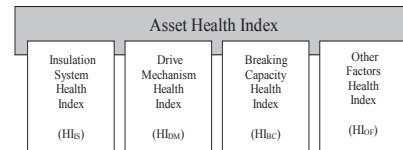

Figure 1. Dimensions of Health Index

II. Construction of Asset Health Indices

Four dimensions have been constructed for High Voltage Gas Insulated Switchgears (HV GIS). Total number of events for has been assigned to chosen condition parameters in order to derive weight factors

[1]. Thus, the severity which is given by the number of failure causes per asset components is weighted adequately. Any other approach then always considering the full event count, may distort the grading scheme as the number of affected condition parameters varies significantly at the different condition parameters.

Four dimensions so called the sub-health indices (sub-HIs) have been identified in order to define an overall Health Index (HI) for high voltage switchgears. Each of the dimensions contributes to overall HI as follows [1]:

HEALTH INDEX DIMENSIONS		Weight (w)
HI_{IS}	Insulation System	51.9 %
HI_{DM}	Drive Mechanism	22.1 %
HI_{BC}	Breaking Capacity	7.7 %
HI_{OF}	Other Factors	18.3 %
	Total	100.0%

Table 1. HV GIS Health Index Dimensions
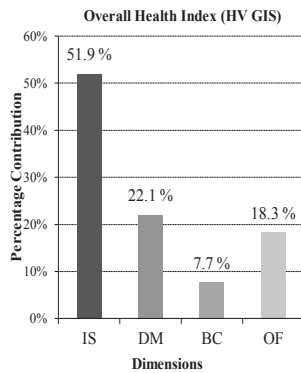
Graph 1. HV GIS Health Index Dimensions

Insulation system is the group of components which are responsible for isolating the high voltage from ground level and it includes:

Insulation System	51.9 %
Components at high voltage	18.3 %
Metallically earthed components	0.9 %
Gas insulation	12.5 %
Solid insulation within GIS	15.4 %
SF6 gas sealing	3.8 %
SF6 gas density supervision	1.0 %

Table 2. Insulation System Components

Insulation system dimension contributes to overall health index calculation by 51.9 % (w_{IS}).

Drive Mechanism	22.1 %
Operating mechanism-compressor, motors, pumps and pipe-work fittings	6.7 %
Operating mechanism-energy storage, mechanical transmission, actuator and damper	15.4 %

Table 3. Drive Mechanism Components

Drive mechanism dimension contributes to overall health index calculation by 22.1 % (w_{DM}).

Breaking capacity is the result of inter-operation of the making - breaking units and it includes:

Breaking Capacity	7.7 %
Making and breaking units (e.g. CB chamber, switch or interrupter assemblies)	4.8 %
Other main contact assemblies (e.g. drive rods)	2.9 %

Table 4. Breaking Capacity Components

Breaking capacity dimension contributes to overall health index calculation by 7.7 % (w_{BC}).

Other factors influencing the health index of an HV GIS are age, inspection compliance, maintenance compliance, inspection results and maintenance results. Coming from [1], remaining asset components which do not (yet) have an own condition parameter have logically to be assigned to here.

Other factors dimension contributes to overall health index calculation by 18.3 % (w_{OF}).

Inter-relations among the dimensions have been defined as follows (R is a relation, NR is no relation and N/A is not applicable.) [2]:
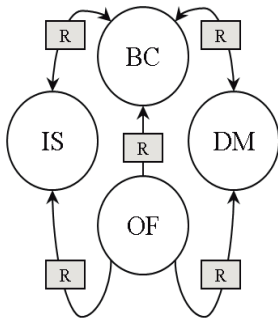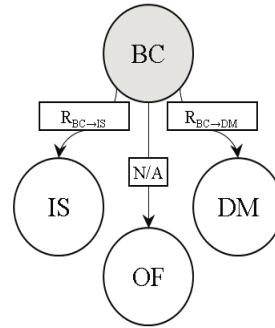
Figure 2. Relations between Dimensions

Figure 5. Influence of Breaking Capacity on Others
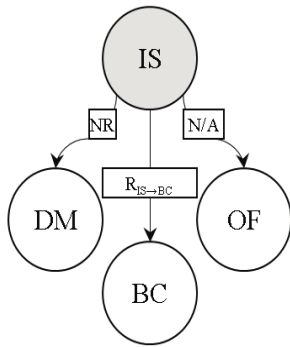
$$R_{BC \to IS} = Medium$$
$$R_{BC \to DM} = Low$$

Figure 3. Influence of Insulation System on Others

$$R_{IS \to BC} = Low$$
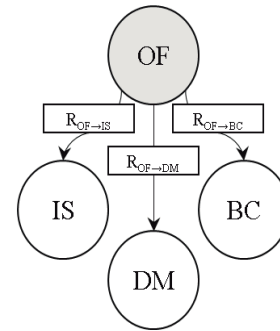
Figure 6. Influence of Other Factors on Others

$$R_{OF \to IS} = High$$
$$R_{OF \to DM} = Medium$$
$$R_{OF \to BC} = Low$$
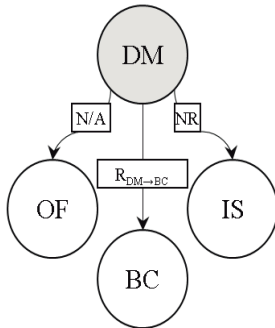
Figure 4. Influence of Drive Mechanism on Others

$$R_{DM \to BC} = High$$

D	Relation	Level	R
IS	$R_{IS \to BC}$	Low	0.08
DM	$R_{DM \to BC}$	High	0.42
BC	$R_{BC \to IS}$	Medium	0.24
	$R_{BC \to DM}$	Low	0.04
OF	$R_{OF \to IS}$	Medium	0.34
	$R_{OF \to DM}$	Medium	0.26
	$R_{OF \to BC}$	Low	0.06

Table 5. Relations between IS, DM, BC and OF

R_{Low}	R_{Medium}	R_{High}
$0 < R \leq 0.15$	$0.15 < R \leq 0.35$	$0.35 < R \leq 0.50$

Table 6. Classification of Correlation Co-efficients

The factor R is added to the weighting value w (in balanced cases) or w* (in imbalanced cases); when the respective dimension is significantly at a higher value (i.e. poorer health) then at least two of others.

$R_{IS \rightarrow BC} = 0.08$ means:

HI_{IS}	HI_{DM}	HI_{BC}	HI_{OF}
8.10	5.20	5.30	5.10
$w*_{IS} \rightarrow 1.3 \cdot w_{IS} = 1.3 \cdot 51.9\% = 67.5\%$			
$w*_{DM} \rightarrow 0.9 \cdot w_{DM} = 0.9 \cdot 22.1\% = 19.7\%$			
$w*_{BC} \rightarrow (0.9 + R) \cdot w_{BC} = (0.9 + 0.08) \cdot 7.5\% = 21.5\%$			
$w*_{OT} \rightarrow 0.9 \cdot w_{OT} = 0.9 \cdot 18.3\% = 16.2\%$			
$HI*_{HV} = w*_{IS} \cdot HI_{IS} + w*_{DM} \cdot HI_{DM} + w*_{BC} \cdot HI_{BC} + w*_{OF} \cdot HI_{OF}$			
$HI*_{HV\ GIS} = 5.47 + 1.02 + 1.14 + 0.83 = 8.46$			

Table 7. A Typical Imbalanced Case

III. Selection of Input Parameters

Input/condition parameters need nominal values to enable a meaningful grading systems as well as a sound ageing pattern parameterization. In most times the data given by the Original Equipment Manufacturer (OEM) are used. But at least in one case the experience of the Condition Monitoring Manufacturer (CMM) has to be used as a start-up value until asset-type specific experience can be implemented into the parameterization.

The following set of parameters will be taken into consideration [3]:

INSULATION SYSTEM		
IS-GP	Gas Purity	OEM
IS-DP	Gas Dew Point	OEM
IS-PD	Partial Discharge	CMM
DRIVE MECHANISM		
DM-OT	Open Time	OEM
DM-CT	Close Time	OEM
DM-OC	Open Coil Current	OEM
DM-CC	Close Coil Current	OEM
DM-MR	Spring/Comp. Mot. Runtime	OEM
DM-MC	Spring/Comp. Mot. Current	OEM
DM-NO	Number of Operations	OEM
DM-NF	No of Fail to Close/Trip	OEM
BREAKING CAPACITY		
BC-NB	Number of Break Faults	OEM

BC-LC	Load Current	OEM
BC-IT	i^2t	OEM
OTHER FACTORS		
OF-AG	Age	---
OF-IC	Inspection Compliance	---
OF-MC	Maintenance Compliance	---
OF-IR	Inspection Results	---
OF-MR	Maintenance Results	---

Table 8. Condition Parameters

IV. Condition Data

Condition parameters need input from different data sources. Some parameters (e.g. partial discharge alarms) get inputs from more than one sensor. The resulting value shall be the yield of all sensor data.

Three different sources of data have been considered:

- M_S: Manual static (one-time) data (e.g. manufacturer)
- M_D: Manual dynamic (regular) data (e.g. gas purity)
- O_{CMS}: Continuous on-line condition monitoring system data (e.g. PD alarms)

Data regular retrieval interval for high voltage parameters will be as follows [4]:

INSULATION SYSTEM		
Annually	Gas Purity	M_D
Annually	Gas Dew Point	M_D
Hourly	Partial Discharge	O_{CMS}
DRIVE MECHANISM		
Hourly	Open Time	O_{CMS}
Hourly	Close Time	O_{CMS}
Hourly	Open Coil Current	O_{CMS}
Hourly	Close Coil Current	O_{CMS}
Hourly	Spring/Comp. Mot. Runtime	O_{CMS}
Hourly	Spring/Comp. Mot. Current	O_{CMS}
Hourly	Number of Operations	M_D / O_{CMS}
Annually	No of Fail to Close/Trip	M_D
BREAKING CAPACITY		
Hourly	Number of Break Faults*	M_D / O_{CMS}
Hourly	Load Current	O_{CMS}
Hourly	i^2t	O_{CMS}
OTHER FACTORS		
---	Age	A
Annually	Inspection Compliance	M_D
Annually	Maintenance Compliance	M_D
Annually	Inspection Results	M_D
Annually	Maintenance Results	M_D

* Number of break faults will be calculated, initial manual upload is required.

Table 9. Retrieval Frequencies

Data measuring/look-back period for health index calculation for high voltage parameters will be as follows [4]:

INSULATION SYSTEM	
Most Recent	Gas Purity
Most Recent	Gas Dew Point
Last 30 days	Partial Discharge
DRIVE MECHANISM	
Most Recent	Open Time
Most Recent	Close Time
Most Recent	Open Coil Current
Most Recent	Close Coil Current
Last 30 days	Spring/Comp. Mot. Runtime
Most Recent	Spring/Comp. Mot. Current
Over lifecycle *OR* since last revision	Number of Operations
Over lifecycle *OR* since last revision	No of Fail to Close/Trip
BREAKING CAPACITY	
Over lifecycle *OR* since last revision	Number of Break Faults
Last 30 days	Load Current
Over lifecycle *OR* since last revision	i^2t
OTHER FACTORS	
Over Lifecycle	Age
Most Recent	Inspection Compliance
Most Recent	Maintenance Compliance
Most Recent	Inspection Results
Most Recent	Maintenance Results

Table 10. Look-back Periods for Health Index Calculation

V. Health Index Calculation

The overall health index (HI_{HV}) consists of four dimensions so called the sub-health indices (sub-HIs) [5]:

These are:

1. HI_{IS}: Insulation System sub-Health Index
2. HI_{DM}: Drive Mechanism sub-Health Index
3. HI_{BC}: Breaking Capacity sub-Health Index
4. HI_{OF}: Other Factors sub-Health Index

$HI_{HV} = w_{IS} \cdot HI_{IS} + w_{DM} \cdot HI_{DM} + w_{BC} \cdot HI_{BC} + w_{OF} \cdot HI_{OF}$

Subject to:

$w_{IS} + w_{DM} + w_{BC} + w_{OF} = 100\ \%$

- $0 \leq HI_{IS} \leq 10$
- $0 \leq HI_{DM} \leq 10$
- $0 \leq HI_{BC} \leq 10$
- $0 \leq HI_{OF} \leq 10$

Thus, $0 \leq HI_{HV} \leq 10$

Nineteen parameters for HV GIS are used to calculate the respective sub-HIs and the resulting overall health index of assets. The most recent value of each parameter (stored via time-stamps within the system) is used for the calculation [6]. Ordinary maintenances triggered by 'poor condition' alarms, will improve the monitored/updated values and thus lower the respective health index over time.

However, if the elapsed time is more than half of the retrieval period (e.g. for annual data retrieval, older than six months); corresponding ageing function is used to calculate the current value of the parameter (data with hourly retrieval period are exempt from this rule).

Relative weights of sub-HIs are used to define two cases:

1. Balanced case, when/if all of the boundary value conditions are satisfied.

2. Imbalanced case, when/if one or more of the boundary value conditions are not satisfied.

The algorithm ensures that by looking into the value of each sub-HI and checking relative ratio (r) of each dimension defined as follows:

$$r_{IS/DM} = \frac{HI_{IS}}{HI_{DM}}$$

$$r_{IS/BC} = \frac{HI_{IS}}{HI_{BC}}$$

$$r_{IS/OT} = \frac{HI_{IS}}{HI_{OT}}$$

$$r_{DM/BC} = \frac{HI_{DM}}{HI_{BC}}$$

$$r_{\text{DM/OT}} = \frac{HI_{DM}}{HI_{OT}}$$

$$r_{\text{BC/OT}} = \frac{HI_{BC}}{HI_{OT}}$$

The boundary values of relative weights have been defined as follows:

$$0.8 \le r_{IS/DM} \le 1.25$$

$$0.8 \le r_{IS/BC} \le 1.25$$

$$0.8 \le r_{IS/OT} \le 1.25$$

$$0.8 \le r_{DM/BC} \le 1.25$$

$$0.8 \le r_{DM/OT} \le 1.25$$

$$0.8 \le r_{BC/OT} \le 1.25$$

V.1 Balanced Case

When all boundary conditions are satisfied, the regular percentage contributions are applied.

Example cases are demonstrated below:

$HI_{HV} = w_{IS} \cdot HI_{IS} + w_{DM} \cdot HI_{DM} + w_{BC} \cdot HI_{BC} + w_{OF} \cdot HI_{OF}$

HI_{IS} (50.6%)	HI_{DM} (23.4%)	HI_{BC} (12.3%)	HI_{OT} (13.6%)	HI (100%)
0.80	0.90	0.95	0.85	0.87
2.40	2.60	2.30	2.40	2.49
6.80	7.00	7.10	7.20	7.01
8.60	8.50	8.70	9.0	8.64
9.65	9.10	9.20	9.90	9.39

Table 11. Balanced Case Sample Outputs

V.2 Imbalanced Case

A special algorithm has been applied to the overall health index calculation so that if one or more of the sub-health indices are relatively at a very higher or very lower level then the other health indices, the algorithm detects the exceptions and provides a system warning about the unbalanced dimensions. When/if one or more of the boundary value conditions are not satisfied, the system will provide a warning and the logic will iterate further as the following:

if $r_{IS/DM}$ is not in range, all others are in range then:

if $r_{IS/DM} > 1.25$ then;

$w^*_{IS} \rightarrow 1.30 \cdot w_{IS}$
$w^*_{DM} \rightarrow 0.90 \cdot w_{DM}$
$w^*_{BC} \rightarrow 0.90 \cdot w_{BC}$
$w^*_{OF} \rightarrow 0.90 \cdot w_{OF}$

if $r_{IS/DM} < 0.8$ then;

$w^*_{DM} \rightarrow 1.30 \cdot w_{DM}$
$w^*_{IS} \rightarrow 0.90 \cdot w_{IS}$
$w^*_{BC} \rightarrow 0.90 \cdot w_{BC}$
$w^*_{OF} \rightarrow 0.90 \cdot w_{OF}$

where w* is the forced-weight and HI* is the forced-overall HI resulting from imbalance amongst the parameters.

For system warning,

if
$r_{IS/DM} > 1.25$ then "Please check IS"
$r_{IS/DM} < 0.8$ then "Please check DM"

And, so on so forth.

An imbalance-alarm be denoted with an (*), both for the respective dimensions and overall health index.

For example, when HI_{IS} significantly larger than HI_{DM}, HI_{BC} and HI_{OT}:

HI_{IS}	HI_{DM}	HI_{BC}	HI_{OF}
8.10	5.20	5.30	5.10
$w^*_{IS} \rightarrow 1.3 \cdot w_{IS} = 1.3 \cdot 51.9\% = 67.5\%$			
$w^*_{DM} \rightarrow 0.9 \cdot w_{DM} = 0.9 \cdot 22.1\% = 19.9\%$			
$w^*_{BC} \rightarrow 0.9 \cdot w_{BC} = 0.9 \cdot 7.7\% = 6.9\%$			
$w^*_{OT} \rightarrow 0.9 \cdot w_{OT} = 0.9 \cdot 18.3\% = 16.5\%$			
$HI^*_{HV} = w^*_{IS} \cdot HI_{IS} + w^*_{DM} \cdot HI_{DM} + w^*_{BC} \cdot HI_{BC} + w^*_{OF} \cdot HI_{OF}$			
$HI^*_{HV\ GIS} = 7.71$			

Table 12. Imbalanced Case with HI_{IS} very large
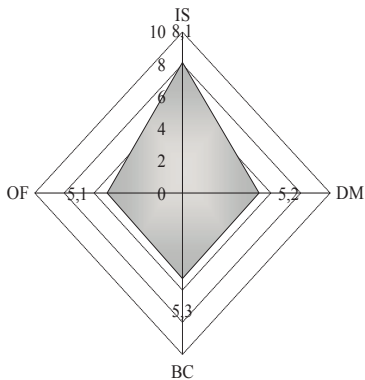
Graph 2. A typical Imbalanced Case

3.1	9.4*	2.7	9.3*	5.56*

Table 15. Imbalanced Case Sample Outputs

For example, when all of HI_{IS}, HI_{DM} and HI_{BC} are significantly larger than HI_{OT}:

HI_{IS}	HI_{DM}	HI_{BC}	HI_{OT}
9.1	**9.4**	**9.7**	3.3
$w^*_{IS} \rightarrow 1.1 \cdot w_{IS} = 1.1 \cdot 50.6\% = 55.7\%$			
$w^*_{DM} \rightarrow 1.1 \cdot w_{DM} = 1.1 \cdot 23.4\% = 25.6\%$			
$w^*_{BC} \rightarrow 1.1 \cdot w_{BC} = 1.1 \cdot 12.3\% = 13.5\%$			
$w^*_{OT} \rightarrow 0.7 \cdot w_{OT} = 0.7 \cdot 13.6\% = 9.5\%$			
$HI^*_{HV} = w^*_{IS} \cdot HI_{IS} + w^*_{DM} \cdot HI_{DM} + w^*_{BC} \cdot HI_{BC} + w^*_{OF} \cdot HI_{OF}$			
$HI^*_{HV\ GIS} = 9.10$			

Table 16. Imbalance Case with H_{IS}, HI_{DM} and HI_{BC} very large

Similarly, the results when any three of HI_{IS}, HI_{DM}, HI_{BC} and HI_{OT} is significantly larger than the fourth one have been tabulated as follows:

HI_{IS}	HI_{DM}	HI_{BC}	HI_{OF}	HI^*_{HV}
3.8	**9.4**	**9.7**	**8.9**	7.15
8.1	4.4	**8.7**	**8.3**	7.94
9.5	**9.4**	1.7	**9.3**	8.36

Table 17. Imbalanced Case Sample Outputs

Future health indices will be calculated based on the forecasted future values of parameters, through aging functions.

VI. Conclusion

The developed methodology may serve as a powerful tool in asset management with the following features:

Firstly, constructed health indices can be used to calculate current and future failures' probability pertaining to individual assets by making use of the aging patterns of the parameters.

Moreover, calculated probabilities can consequently be multiplied by consequence of failures (again, calculated for each individual asset) in order to calculate the risk associated with individual asset. In addition, all aggregated system risk can be calculated as the sum of individual asset risk.

Finally, based on the calculated risk projections, asset management related recommendations such as next maintenance due dates, intervention actions (e.g. refurbishment and retrofit) and replacement strategies can be derived.

Similarly, the results when any of HI_{DM}, HI_{BC} and HI_{OF} is significantly larger than the other have been tabulated as follows:

HI_{IS}	HI_{DM}	HI_{BC}	HI_{OF}	HI^*_{HV}
1.10	8.15*	1.05	1.15	2.88*
3.0	3.2	7.6*	3.4	4.37*
1.1	1.3	1.15	5.2*	2.03*

Table 13. Imbalanced Case Sample Outputs

For example, in HV 132 kV when both HI_{IS} and HI_{DM} are significantly larger than HI_{BC} and HI_{OT}:

HI_{IS}	HI_{DM}	HI_{BC}	HI_{OT}
8.1	**9.4**	2.7	3.1
$w^*_{IS} \rightarrow 1.15 \cdot w_{IS} = 1.15 \cdot 50.6\% = 58.2\%$			
$w^*_{DM} \rightarrow 1.15 \cdot w_{DM} = 1.15 \cdot 23.4\% = 26.9\%$			
$w^*_{BC} \rightarrow 0.85 \cdot w_{BC} = 0.85 \cdot 12.3\% = 10.5\%$			
$w^*_{OT} \rightarrow 0.85 \cdot w_{OT} = 0.85 \cdot 13.6\% = 11.6\%$			
$HI^*_{HV} = w^*_{IS} \cdot HI_{IS} + w^*_{DM} \cdot HI_{DM} + w^*_{BC} \cdot HI_{BC} + w^*_{OF} \cdot HI_{OF}$			
$HI^*_{HV\ GIS} = 7.86$			

Table 14. Imbalance Case with H_{IS} and HI_{DM} very large

Similarly, the results when any two of sub-HIs are significantly larger than the other two have been tabulated as follows:

HI_{IS}	HI_{DM}	HI_{BC}	HI_{OT}	HI^*_{HV}
3.1	9.4*	9.7*	3.3	6.14*
3.1	2.4	7.7*	7.3*	4.87*
9.1*	4.4	1.7	8.3*	7.01*
7.1*	1.4	7.7*	1.3	5.73*

References

1. Cheung, Heil, Kobayashi, Kopejtkova, Molony, O'Connell, Skyberg, Taillebois, Welch, CIGRÉ TB 150, Report On The Second International Survey on High Voltage Gas Insulated Substations (GIS) Service Experience, Issue 1, pg. 10-17-88, [2000]

2. FGH e.V. AiF/IGF-Vorhaben 16391N, Entwicklung Typspezifischer Prognose Modelle zur Beschreibung der Zuverlässigkeit von Betriebsmitteln im Rahmen des Asset Management in Elektrischen Verteilungsnetzen, Issue 1, pg. 44, [2013]

3. IEC 62271-100, High-voltage switchgear and controlgear – part 100: Alternating-current circuit breakers, Issue 2.0, pg. 188, [2008]

4. IEEE, Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems, Issue 97, pg. 40, [1997]

5. Janssen, Degen, Heising, Bruvik, Colombo, Lanz, Fletcher, Sanchis , CIGRÉ TB 083, Final Report of The Second International Enquiry On High Voltage Circuit-Breaker Failures And Defects In Service, Issue 1, pg. 31, [2000]

6. Siemens AG, PDM Installation, Operation and Maintenance Schedule For The i-Con^{PDM} – UHF Partial Discharge Monitoring & i-Con^{CBM} – Circuit Breaker Monitoring Ssystem, Issue 5, pg. 53, [2013]

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