Ofgem

Calculating Target Availability Figures for HVDC Interconnectors – Update

August 2016

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Executive Summary

Availability targets for the Ofgem Cap and Floor regulatory assessment framework have been based on an agreed methodology and model, developed in 2013 for the Nemo interconnector by Sinclair Knight Merz (SKM).

The SKM report made a recommendation to regularly update the model to ensure developments in VSC converter and HVDC cable technologies are captured.

GHD were engaged by Ofgem to review and update the existing SKM model and to:

- include in the model any new information that has become available since 2013;
- ensure that the model is able to capture the specific design factors of NSL and other current projects; and
- ensure that the availability target set for NSL is as accurate and appropriate as possible.

The GHD review concludes that adjustments can be made to the original SKM model taking into account:

- Additional up to date information concerning the reliability of HVDC schemes based on a CIGRE survey. This results in a marginal improvement in the expected unavailability of HVDC converters due to forced outages
- A reduced HVDC circuit breaker reliability figure
- Improved HVDC converter transformer reliability
- The least frequent scheduled maintenance time of 24 hours per converter per annum in the SKM model was deemed to be too ambitious, hence this was increased to 36 hours
- The cable data is predominantly unchanged, with the exception of the external failure rate of subsea cables which is anticipated to reduce due to improvements in cable burial risk assessment methodologies.

The basic functionality of the SKM model is considered by GHD as appropriate with some small adjustments to enhance user defined project features which take into account a wider range of potential project characteristics.

Using the updated model, it is suggested that the target level availability for the NSL project (utilising the project characteristics provided) would be in the range of 90.5% to 93.01% with a proposed base target level of 92.86%. As a comparison, using the original SKM model would provide a target level availability of the NSL project in the range of 90.1% to 92.8% with a base target level of 92.68%.

These differences are a result of the improved HVDC converter reliability figures included and the assumed marginally reduced external failure rates for subsea cables.

1. Aims

The Ofgem Cap and Floor assessment framework[1] for new electricity interconnectors includes three major stages, i.e. the Initial Project Assessment, Final Project Assessment and Post-Construction Review.

Ofgem are currently undertaking the Final Project Assessment (FPA) stage for the North Sea Link (NSL) project to Norway, which was approved in 2015. The NSL FPA is a high-profile project; a first-of-a-kind assessment for what will be the longest subsea interconnector in the world. It is imperative for all stakeholders that all aspects of the regime are robust and well-justified, in order to protect consumers and to ensure developer confidence in the Ofgem administration of the regime.

One of the main deliverables of the FPA stage is a target for the availability incentive, which can increase or decrease the level of the cap on revenues.

The availability target is set based on an agreed methodology and model, developed in 2013 for the Nemo interconnector by SKM. This methodology[2] and spreadsheet tool[3] was made publically available by Ofgem so that the process for setting of targets was completely transparent.

The SKM report made a recommendation to regularly update the model to ensure developments in VSC converter and HVDC cable technologies are captured.

GHD were engaged by Ofgem to review and update the existing SKM model and to:

- include in the model any new information that has become available since 2013 and ensure that the model continues to be otherwise fit for purpose
- ensure that the model is able to capture the specific design factors of NSL and other current projects, and
- ensure that the availability target set for NSL is as accurate and appropriate as possible.

This updated methodology, along with a new Excel model, will allow developers and other stakeholders interested in interconnector projects regulated under the cap and floor regime to calculate target availability for their project, as well as provide the basis for the target for the specific NSL project.

[1] https://www.ofgem.gov.uk/electricity/transmission-networks/electricity-interconnectors
[2] https://www.ofgem.gov.uk/ofgem-publications/59247/skm-report-calculating-target-availability-figures-hvdc-interconnectors.pdf
[3] https://www.ofgem.gov.uk/ofgem-publications/59248/skm-model-target-availability-model-hvdc-interconnectors.xlsx

2. HVDC Technology and Configuration

The 2013 SKM report included information on:

- Main components of an HVDC scheme
- Description and comparison of main types of HVDC technology:
  - LCC (Line Commutated Converter)
  - VSC (Voltage Source Converter)
- Main types of HVDC configuration:
  - Monopole
  - Symmetrical Monopole
  - Bipole

The assumptions made by SKM were that:

- for Monopole configurations only metallic return would be considered (no earth/sea return)
- for Bipole configurations that only metallic return or no return would be considered (no earth/sea return)

GHD considers that the assumptions made in 2013 by SKM concerning HVDC technology and configurations are still valid, but we note that the model has sufficient flexibility such that if for example, a project with earth/sea return were to be considered, then the model could be adapted accordingly.

3. Availability Data

GHD have reviewed the availability data used within the existing SKM model, and any updates to reliability data or assumptions are detailed within this section.

3.1 Methodology

Technical brochures and papers published by CIGRE[4] (International Council on Large Electric Systems) provided the majority of equipment reliability data used within the SKM model as they were deemed to be the most reliable source of information due to the large sample sizes recorded globally.

GHD considers that CIGRE remains the best source of available data across a wide range of technologies and our review of other potential sources of data has not changed the approach in the updated model. Whilst some project specific information is available in the public domain, this tends to supplement rather than undermine the CIGRE information.

CIGRE regularly updates information within technical brochures to ensure any new developments within technology are captured. CIGRE has also been used to source updated reliability information since the model was prepared by SKM in 2013.

[4] http://uk.cigre.org/

The Mean Time Between Failure (MTBF) figures assumed are based on average figures collected for equipment populations over various lengths of time and do not take into account any consideration of the age of the particular asset.

The failure rates used within the model were applied independently of asset age due to the 25 year requirement of the cap and floor regime.

The MTBF information extracted from CIGRE sources was applied to the estimated or recorded Mean Time To Repair (MTTR) together with planned maintenance assumptions to calculate the future availability for an individual asset or system.

3.2 HVDC Converter Unplanned Availability Data

The CIGRE advisory group B4-04 collects data annually on the reliability performance of HVDC systems in operation throughout the world. The reports published by this group provide a continuous record of reliability performance for the majority of HVDC systems in the world since they first went into operation. This now constitutes over 800 system-years of data on thyristor (LCC) and IGBT (VSC) valve systems.

At the time of the SKM report, reliability data for VSC converters was limited, hence the reliability of LCC and VSC converter technologies were assumed to be equivalent by SKM.

The SKM model used an HVDC scheme forced unavailability figure of 0.65% which was published by CIGRE in 2012[5]. This equated to a system unavailability time of 57 hours with an equivalent MTBF of 1 year. This unavailability figure excluded any transformer failures which were considered separately. An HVDC interconnector will comprise two converters, hence the unavailability for a single converter was assumed to be 0.325%.

Two further reports on HVDC reliability have been published by B4-04 since the SKM model was created[6,7]. The CIGRE paper B4-131[7] is the first to report on the reliability of VSC systems, which refers to the Caprivi and EstLink 1 projects; however reliability data for VSC projects is still limited.

GHD has considered the additional survey data and calculated an average system unavailability figure. Although the reliability data recorded for 1983 to 2006 represents a larger sample size, it has not been given a higher weighting than the annual data for 2007 to 2014 as the reliability figures for these years are anticipated to be more representative of future performance of HVDC technology. Hence, the HVDC converter unavailability has been calculated as 0.63% using an average of the annual CIGRE data collected between 2007 to 2014 and a single annual figure for the period 1983 to 2006.

The system forced unavailability figures (excluding transformer faults) published by CIGRE are provided in Table 1. The average figure is 0.63% between 1983 to 2014 which is slightly lower than the unavailability figure of 0.65% quoted in the SKM model. The average unavailability figure of 0.63% corresponds to 55 hours of system unavailability per year, or 27.5 hours per year for each converter.

More widespread utilisation of VSC converter technology in HVDC interconnector projects should improve the average system availability on projects; hence the reduction of unavailability from 0.65% to 0.63% correlates with this prediction.

[5] CIGRE Paris 2012 paper B4-113 A Survey Of The Reliability Of HVDC Systems Throughout The World During 2009 – 2010. Paris 2012.
[6] CIGRE Paris 2012 paper B4-117 A Survey Of The Reliability Of HVDC Systems Throughout The World During 2011– 2012. Paris 2014.
[7] CIGRE Paris 2012 paper B4-131 A Survey Of The Reliability Of HVDC Systems Throughout The World During 2013 – 2014. Paris 2016.

Experience suggests that the number of forced outages per year will be higher than 1, with a reduced time to repair. We anticipate VSC technology will improve availability due to the:

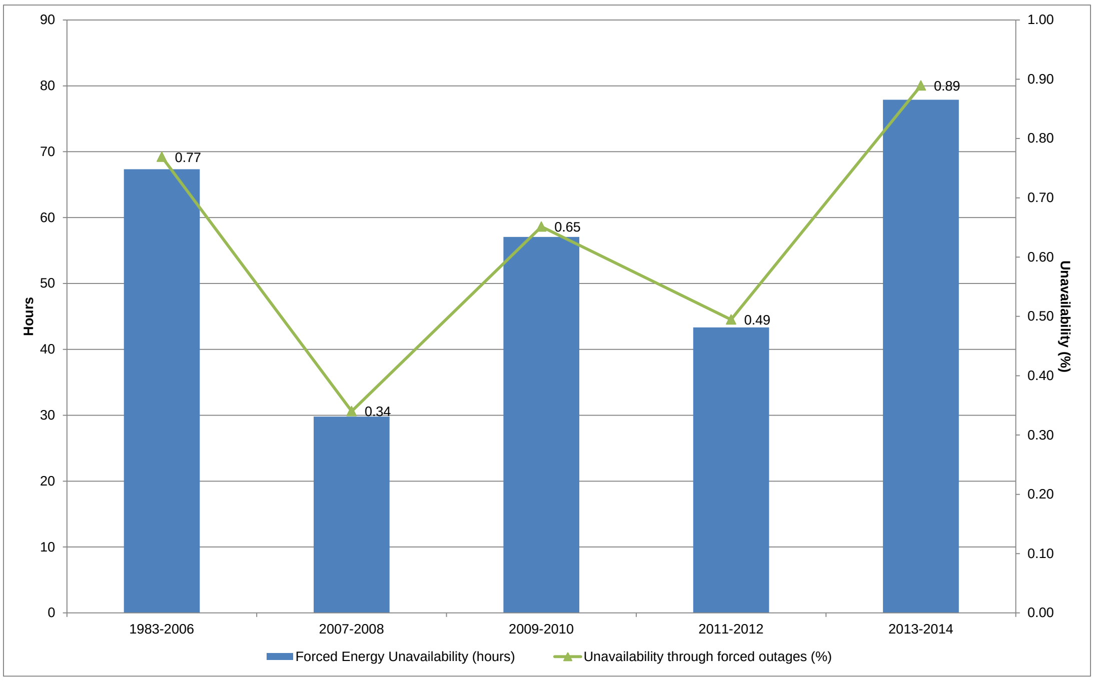
- Growing maturity of IGBT technology
- Ability to more easily build redundancy into VSC schemes
- Modular design of VSC converters and ease of module changes.

Table 1: HVDC Converter Unavailability Published by CIGRE [5,6,7,8]

Reference	Year	System Unavailability (%)	Hours	Unavailability per Converter (hours)
CIGRE B4-209	1983-2006	0.77*	67	33.7
CIGRE B4-209	2007-2008	0.34	30	14.9
CIGRE B4-133	2009-2010	0.65	57	28.5
CIGRE B4-117	2011-2012	0.49	43	21.7
CIGRE B4-131	2013-2014	0.89	78	38.9
Average	**1983-2014**	**0.63**	**55**	**27.5**

*assuming 95% of AC & auxiliary equipment failures were caused by transformers

Figure 1: HVDC Converter Unavailability



The level of redundancy and impact of a failure of converters is considered within the SKM model. The base case of MTBF was chosen as 2 per annum, with a best case of 1 fault per year and a worst case assumption of 3 faults per years.

We consider the assumptions made by SKM on MTBF tolerance are reasonable, hence they are applied within the updated model, as referenced in Table 2. Also, as with the SKM model the MTTR will be based on an assumed two forced outages per year, giving a MTTR of 13.8 hours.

Table 2: Unplanned Unavailability Range for HVDC Converters in GHD Model

Scenario/Range for MTBF	MTBF (Faults/Year)	MTTR (hours)	Total Annual Outage (hours)	Total Annual Outage (days)	Unavailability %
Base Case	2	13.8	27.5	1.146	0.314
Best Case	1	13.8	13.8	0.575	0.158
Worst Case	3	13.8	41.3	1.721	0.471

3.3 HVDC Circuit Breakers Unplanned Availability

At the time of the SKM model there were no applications of modern HVDC breakers in service, hence reliability had to be derived from assumptions. HVDC circuit breakers have now been demonstrated by at least two manufacturers; however commercial experience of these devices is limited which consequently limits available reliability data.

The SKM report suggested that HVDC circuit breakers would be a combination of conventional mechanical switches and power electronic components; the hybrid breaker reliability was quoted to be 0.015 failures per year with a MTTR of 8 days.

It was discovered there was an inconsistency between the circuit breaker reliability data quoted in the report and the data quoted within the SKM model. The model utilised an HVAC circuit breaker failure rate of 0.0091 which was extracted from CIGRE TB 150[8], and the MTTR figure within the model was 25 days. An MTTR figure of 8 days is more realistic and will be used in the updated model.

ABB and STRI[9] predict the reliability characteristics of HVDC circuit breakers in the future will be comparable to existing technology for VSC converters, so they suggest reliability should be based upon the failure rate of one IGBT switch, i.e. 0.075 per year.

It is also worth noting however that there are currently no planned interconnector projects identified in the public domain which envisage utilising HVDC circuit breakers.

Given the above; the approach adopted by GHD is to consider a MTBF figure which is between the original SKM figure of 0.015[2] and the higher figure suggested by ABB and STRI[9], therefore an average figure of 0.045 as indicated in Table 3 is proposed.

[8] CIGRE Technical Brochure 150 – Report on the second international survey on high voltage gas insulated substations (GIS) service experience 2000

[9] CIGRE B4-108, 2010, Reliability study methodology for HVDC grids

Table 3: HVDC Circuit Breaker Reliability Data in GHD Model

Component	Source	Failure Rate	Average MTTR (days)
HVDC Circuit Breaker	Average figure used within GHD model	0.045	8

3.4 Converter Transformers Unplanned Availability

Due to differences in design requirements for VSC HVDC converter transformers and those for LCC converter transformers, it is recognised that transformer reliability is dependent upon the chosen converter technology.

3.4.1 VSC Converter Transformer Reliability

The SKM model uses an annual converter transformer failure rate of 0.03267 per annum[10] derived from CIGRE data.

CIGRE formed the working group A2.37 to review all existing transformer reliability information and to propose a uniform way of collecting and presenting data for future surveys. An international survey on transformer failures was published by WG A2.37 in 2015[11]. The paper compared the results from the pre-1978 and post-1978 CIGRE surveys on transformer reliability, refer to Table 35 in CIGRE Brochure 642.

It was assumed by SKM that 70% of failures could be resolved on-site, whilst failures which require the transformer to be removed from site to be repaired in a factory represent the remaining 30%. SKM also assumed that the MTTR for an on-site transformer repair would be 7.5 days, whilst the transformer faults which would require a “back to workshop” repair would result in a MTTR of 90 days.

The most recent survey suggests that the location of failures has not changed; therefore we consider it is reasonable to continue to use the above assumption within the updated model regarding MTTR.

The updated model will use the most up to date HVAC transformer failure rate of 0.4% as shown in Table 4 for VSC converter transformers[11].

The average MTTR repair figure of 32.25 days has been calculated using the 70/30% ratio and MTTR figures for on-site and “back to workshop repairs”.

3.4.2 LCC Converter Transformer Reliability

CIGRE investigated HVDC LCC converter transformer failures in 2010[12] after it was identified that converter transformer failures were the most significant contributor to unavailability of HVDC systems.[13]

The recorded failure rates for LCC converter transformer failures are significantly higher than standard HVAC transformer failure rates. The average failure rate was confirmed as 1.5% for the reporting period 1972 to 2008. The failure rate of 1.5% for LCC converter transformers[12]

[10] A. Bossi, 1983, “An International Survey on Failures in Large Power Transformers in Service” – Final report of CIGRE Working Group 12.05, Electra, No.88.
[11] CIGRE 642, Transformer Reliability Survey, Working Group A2.37
[12] CIGRE 406 HVDC Converter Transformers Design Review, Test Procedures, Ageing Evaluation and Reliability in Service
[13] Joint Task Force B4.04/A2-1, Analysis of HVDC Thyristor Converter Transformer Performance, (CIGRE Publication 240, February 2004)

has been applied within the GHD model, see Table 4. It is assumed that the MTTR for VSC and LCC transformers would be equivalent.

3.4.3 Transformer Reliability Data in GHD Model

The capability of the availability model has been expanded to include the reliability data for both LCC and VSC transformer technologies.

The data used within the model is shown in Table 4.

Table 4: VSC and LCC Converter Transformer Reliability Data

Transformer Technology	Failure Rate (%)	Average MTTR (days)	In Situ Failure (70%)	In Situ MTTR (days)	Back to Workshop Failure (30%)	Back to Workshop MTTR (days)
LCC	1.5	32.25	1.05	7.5	0.45	90
VSC	0.4	32.25	0.28	7.5	0.12	90

3.5 HVDC Cables Unplanned Availability

The SKM model utilised CIGRE cable reliability data[14] for HVAC and HVDC XLPE cables and MIND cables, as this source was deemed to be the most comprehensive source of service experience for both underground and submarine high voltage cable systems, primarily from European respondents. It is anticipated the survey will be updated by the working group B1.10 in 2018 however new information has not been published since the SKM model hence the base reliability data used to populate the updated model has not changed. Any new assumptions applied to the cable reliability data are detailed within this section.

It should be noted that the cable reliability data extracted from the CIGRE survey is based on an annual failure rate per kilometre of cable circuit.

3.5.1 Underground Cable Failure Rates and Repair Times

Underground cable failure rates were recorded for a sample size of 18,000 km of XLPE AC cable[14], the average internal and external cable failure rates across all voltages were used within the model and are presented in Table 5.

Table 5: Underground Cable Failure Rates[14]

Failure	All Voltages (fail./yr/cct.km)
Internal	0.0003
External	0.00058
All	**0.00088**

It should be noted that the cables included within the survey are classified within the voltage range of 60-500 kV. The available cable ratings have now increased such that 600 kV MIND

[14] CIGRE Brochure 379 Update on Service Experience for HV Underground and Submarine Cable Systems

cables and 525 kV XLPE cables and even higher[15] are now available. Whilst it could be proposed that the cable failure rates may be higher for higher rated cables, it could also be similarly argued that differences may occur between specific designs of cable or suppliers. Hence, it is suggested that the base failure rates are common and (if required) then the failure weighting functionality incorporated into the model could be utilised..

The SKM report detailed the underground repair times for cables buried directly and within ducts/troughs and tunnels for the voltage ranges of 60-219 kV and 220-500kV, see Table 6. Although the repair times varied depending on the rated voltage of the cable, an average MTTR value was used within the model.

The form of underground cable installation has a direct effect upon repair times. Cables which are directly buried are more easily accessed whilst cables installed within ducts, troughs and tunnels may pose a complex repair process hence increasing the MTTR.

CIGRE survey information provides an average repair time for directly buried XLPE cables of 20 days whilst the MTTR for cables within ducts, troughs or tunnels is 30 days as included in Table 6. It has been assumed the cable repair times for AC and HVDC XLPE cables would be the same.

The repair process of MIND cables is more complex and time consuming than for XLPE cable repairs hence the MTTR is slightly higher; SKM assumed an MTTR of 40 days for a directly buried MIND cable installation. The repair time for a MIND cable installed within ducts, troughs or tunnels was included in the SKM model as 65 days. GHD agree this is a reasonable assumption and have applied it within the updated model.

The repair times quoted within the SKM model are considered reasonable and will be used within the GHD model as provided in Table 6 and Table 7.

Table 6: Underground XLPE Cable Repair Times[14]

Voltage Range	Direct Burial Repair Time (Days)	Ducts/Troughs/Tunnel Repair Times (Days)
60-219 kV	14	15
220-500 kV	25	45
All Voltages	**20**	**30**

Table 7: Underground MIND Cable Repair Times

Voltage Range	Direct Burial Repair Time (Days)	Ducts/Troughs/Tunnel Repair Times (Days)
All Voltages	**40**	**65**

The underground cable data used within the updated model is provided in Table 8.

The SKM model offers the functionality to choose high or low cable failure rates depending on the cable installation factors which may determine the risk of failure; these high and low values have been calculated using a basic multiplier which can be amended as required.

This capability allows the flexibility to model project specifics, however it is anticipated that most projects will use average cable failure rates.

[15] Prysmian, "Latest HVDC cable technologies from the Group up to 700 kV on display", http://www.prysmiangroup.com/en/corporate/press-releases/Prysmian-at-CIGRE-2016

Table 8: Underground Cable Data in GHD Model

Cable Type	External Failures (fail./yr/cct.km)			Internal Failures (fail./yr/cct.km)			MTTR (days)	
	High	Low	Average	High	Low	Average	Average	High
AC Onshore XLPE Cable	0.00087	0.000435	0.00058	0.00045	0.000225	0.0003	20	30
HVDC Onshore XLPE Cable	0.00087	0.000435	0.00058	0.00045	0.000225	0.0003	20	30
HVDC Onshore MIND Cable	0.00087	0.000435	0.00058	0.00045	0.000225	0.0003	40	65

3.5.2 Submarine Cable Failure Rates and Repair Times

The submarine cable failure rates used within the SKM model are representative of HVAC XLPE cables and HVDC MIND cables. The CIGRE paper[14] used to extract submarine cable data has not been updated since the SKM model. The GHD model therefore contains the same base cable data as the SKM model with an exception to the external failure rate.

The SKM report suggests a standard cable burial depth of 1.5 m which would be applied using a common practice of a uniform burial depth for the length of cable. SKM assumed the external failure rate of subsea cables was 35% of the CIGRE failure rate of 0.000705, i.e. 0.00025 failures/yr/cct.km due to most of the cables in the CIGRE report being unprotected.

A new submarine cable installation method[16] has emerged since the SKM model was developed, whereby a risk assessment of the full cable route is undertaken to inform the suitable burial depth to mitigate damage by third parties. This would suggest that the failure rate would improve further as the submarine cable should be appropriately protected for the full route length. It has been assumed by GHD that the external failure rate will reduce from 0.00025 to 0.00021 failures/yr/cct.km to reflect the reduced risk of submarine cable installations as a result of the employment of the “cable risk assessment” method.

The submarine cable repair times assumed within the SKM report are shown in Table 9; these figures are representative for a cable repair in water depths of 30 m where the cable and suitable vessels are available.

The submarine cable repair time is sensitive to equipment/vessel availability and weather; hence the SKM model offers the functionality to modify the cable repair times if required. We consider the cable repair times suggested by SKM are still valid and have therefore been applied within the GHD model.

Table 9: Submarine Cable Repair Times[2]

Activity	Duration Days
Mobilisation of repair vessel to site	15
Surveying, de-trenching and recovery of cable	10

[16] Carbon Trust, Cable Burial Risk Assessment Methodology, Guidance for the Preparation of Cable Burial Depth of Lowering Specification CTC835, February 2015, https://www.carbontrust.com/media/622265/cable-burial-risk-assessment-guidance.pdf

Repair and testing of cable	15
Lay-down, reburial and surveying	10
Weather contingency	15
Total	65

The submarine cable data used within GHD model is provided in Table 10. The high and low failure rates have been calculated using a basic multiplier which can be amended as required.

Table 10: Submarine Cable Data in GHD Model

Cable Type	External Failures (fail./yr/cct.km)			Internal Failures (fail./yr/cct.km)			MTTR (days)	
	High	Low	Average	High	Low	Average	Average	High
AC subsea XLPE Cable	0.000315	0.0001575	0.00021	0.000405	0.0002025	0.00027	65	90
HVDC subsea XLPE Cable	0.000315	0.0001575	0.00021	0.000405	0.0002025	0.00027	65	90
HVDC subsea MIND Cable	0.000315	0.0001575	0.00021	0.000405	0.0002025	0.00027	65	90

3.5.3 User Defined Cable Repair Time

It is recognised that future interconnector projects may require unusual and more complex cable installation scenarios which would consequently increase the complexity of the cable repair process. For example, this could be a result of cables installed in very deep waters/within existing infrastructure with associated access constraints. If the MTTR for a specific length of cable deviates from the norm, the user should insert the cable as a user defined type where they may define a different MTTR specific to the project.

3.6 Planned Unavailability Due to Maintenance

The SKM model provides the capability to account for system unavailability due to planned maintenance of the HVDC converter equipment.

A planned maintenance scheme would be tailored to each specific project based upon the availability of spares and maintenance team to complete the planned outage. As with the MTBF figures the MTTR figures do not take into account any consideration of the age of the particular asset.

It was assumed that any planned unavailability would be influenced by maintenance of HVDC converters and the associated equipment, so the proposed outage period within the SKM report was 1 to 3 days per converter.

We consider that the least frequent maintenance scenario proposed by SKM of 24 hours per converter per year is too optimistic and should be increased to 36 hours. The other assumptions are considered to be still valid and will be applied to the updated model; the resultant unavailability is provided in Table 11.

Table 11: System Unavailability Due To Planned Maintenance in GHD Model

Maintenance Scenario	Total Annual Outage (hours)	Unavailability %
Least Frequent Maintenance	36	0.411
Base Case Maintenance	48	0.548
Most Frequent Case Maintenance	72	0.822

4. Availability Model

The functionality of the SKM model has been reviewed by GHD and is deemed fit for purpose to simulate the reliability performance of a wide range of interconnector schemes including HVAC and HVDC arrangements. The changes to reliability data which have been made within the model are detailed in Appendix A

The updated model uses the same basic approach as the SKM model; the functionality within the model is almost identical hence the original user manual provided by SKM remains valid and only minor changes are necessary. The updated user manual is provided in Appendix B.

The GHD model has been updated to offer the capability to simulate the reliability of both VSC and LCC converter transformers which was not possible in the SKM model.

It is worth noting that the user should enter a new data set if the there are any project specific details which may deviate from the norm offered in the model; refer to section 5.1 for an example of a project specific cable data requirement.

5. Modelling Results

The updated model includes the target availability calculations for two interconnector projects as agreed with Ofgem. The first example project is ‘Project 1’ from the 2013 SKM report which is similar to that envisaged for the Nemo project.

The second example is representative of the NSL (North Sea Link) interconnector project[17] due for completion in 2021 which will provide a link between Norway and the UK.

The project specific details for the NSL interconnector scheme are provided in section 5.1.

5.1 NSL

The NSL interconnector project was modelled with the details provided in Table 12.

The offshore cable is 714 km of HVDC subsea MIND cable. It was indicated that there was a further 4.9 km of HVDC subsea MIND cable which would be installed within a constrained tunnel and a lake feature with deep waters at the Norwegian side of the interconnector. The risk of external failures would be low for this length of cable; however the cable MTTR could be significantly longer. It was assumed that the average MTTR for this section of cable, “Project 4 (High Cable MTTR) Section” was 120 days.

[17] http://nsninterconnector.com/about/what-is-nsn-link/

The onshore cables of the NSL project are 4 km of HVDC onshore MIND cable and 0.5 km of HVAC onshore XLPE cable. Further details on the HVAC cable connection are not known; hence we have used the same approach as SKM and have not included this HVAC connection within the model. It should be noted however that the unavailability due to these HVAC connections is very small.

All cables proposed for the NSL project will be unbundled.

The unavailability of the VSC converter transformers was applied within the model

Table 12: NSL Project Model Details

Project Detail	Value	Unit
Rated Capacity	1400	MW
Converter Technology	Bipole VSC No Earth Return	
Cable Technology	HVDC MIND	
Rated Voltage	525	kV
Offshore Cable Properties	HVDC Subsea MIND, unbundled	
Offshore Cable Length	714	km
Cable (in Infrastructure) Properties	HVDC Subsea MIND, unbundled	
Cable (in Infrastructure) Length	4.9	km
Onshore HVDC Cable Properties	HVDC Onshore MIND	
Onshore HVDC Cable Length	4	km

5.2 Comparison of System Availability in SKM and GHD models

The system availability of the NSL project was calculated within the GHD and SKM model using the average sensitivities for weather, maintenance and converter outages. The comparison of results for the base case is provided in Table 13.

Table 13: Comparison of Base System Availability in SKM and GHD model

Project	Overall System Availability (%)	
	SKM Model	GHD Model
NSL	92.68	92.86

The NSL system base case target availability was calculated to be 92.68% within the SKM model which increased to 92.86% in the updated GHD model.

As a comparison, the system availability of the Nemo project would increase from 97.5 % in the SKM model to 97.6 % in the GHD model.

The improvements of system availability in the GHD model are as a result of an improved availability figure for the HVDC converters and a reduced external failure rate for subsea cables due to improvements of the subsea cable burial process.

The cable fault unavailability was found to dominate the overall system availability figures. The proposed cable length of the NSL project (723.4 km) will be the longest subsea interconnector in the world, hence the high level of cable fault unavailability is inevitable and results in system availability significantly lower than that of the Nemo and other projects.

The Bipole converter configuration for NSL project improves the system availability in comparison to the monopole topology used in the Nemo project.

5.3 Sensitivity Analysis

Sensitivity analysis was performed to determine how much the system unavailability of the NSL project would deviate from the base case of 92.86%, taking into account the range of MTBF and MTTR factors included within the model.

SKM suggested the reliability data associated with HVDC converters suffered from the most uncertainty due to limited data on reliability performance and new developments in technology.

A best and worst case assumption of 1 and 3 converter outages per year, Table 2, was included in the model; a sensitivity study was performed and the results are shown in Table 14.

An average MTTR figure for cable failures was assumed to be 65 days for offshore cables with a worst case assumption of 90 days due to weather conditions. The system availability figures whilst considering the worst case cable MTTR are provided in Table 14.

The planned unavailability due to scheduled maintenance could vary dependent upon the project maintenance plan and required outage time. The model allows the system availability to be calculated using a range of scheduled maintenance from more frequent (3 days per year) to less frequent (1.5 days per year).

Table 14: Sensitivity Analysis in GHD Availability Model

Project	Overall System Availability (%)				
	Worst Case Converter MTBF	Best Case Converter MTBF	Worst Case Cable MTTR	Most Frequent Maintenance	Least Frequent Maintenance
NSL	92.70	93.01	90.49	92.58	92.99

The equivalent sensitivity analysis was performed in the SKM model; the results are provided for comparison with the GHD model in Table 15.

Table 15: Sensitivity Analysis in SKM Availability Model

Project	Overall System Availability (%)				
	Worst Case Converter MTBF	Best Case Converter MTBF	Worst Case Cable MTTR	Most Frequent Maintenance	Least Frequent Maintenance
NSL	92.51	92.84	90.13	92.54	92.81

6. Conclusions

The GHD review concludes that there are some adjustments that can be made to the original SKM model taking into account:

- Additional up to date information concerning the reliability of HVDC schemes based on a CIGRE survey. This results in a marginal improvement in the expected unavailability of HVDC converters due to forced outages.
- A reduced HVDC circuit breaker reliability figure
- Improved HVDC converter transformer reliability
- The least frequent scheduled maintenance time of 24 hours per converter per annum in the SKM model was deemed to be too ambitious hence this was increased to 36 hours
- The cable data is predominantly unchanged, with the exception of the external failure rate of subsea cables which is anticipated to reduce due to improvements in cable burial risk assessment methodologies.

The basic functionality of the SKM model is considered to be appropriate with some small adjustments to enhance user defined project features which take into account a wider range of potential project characteristics.

Using the updated model, it is suggested that the target level availability for the NSL project utilising the project characteristics provided, would be in the range of 90.5% to 93.01.% with a proposed base target level of 92.86%. As a comparison, using the original SKM model would provide a target level availability of the NSL project in the range of 90.1% to 92.8 % with a base target level of 92.68%.

Using the updated model, it is suggested that the target level availability for the NSL project (utilising the project characteristics provided) would be in the range of 90.49% to 93.01% with a proposed target base level of 92.86%. As a comparison, using the original SKM model would provide a target level availability of the NSL project in the range of 90.13% to 92.84% with a base target level of 92.68%.

As a useful comparator, the target availability figure previously set for the NEMO interconnector project would increase from 97.5% as calculated in the SKM model to 97.6% within the updated model. This is likely to be as a result of the improved HVDC converter reliability figures and the marginally reduced external failure rates for subsea cables.

The length of the subsea cable for the NSL project could increase the difficulty for fault locating hence increasing the length and complexity of the repair process. Given the sensitivity of the calculated availability figure to submarine cable MTTR this will be a critical item for the design and operation of the NSL project.

Appendices

Appendix A – Data Changes in Availability Model

Component	Value in GHD Model	Value in SKM Model	Description
HVDC Converter Unavailability	0.63 %	0.65 %	The value of 0.65% within the SKM model was taken from CIGRE B4-133 2009-2010. The new figure of 0.63% considers new updated data published since the SKM model was created (2011-2012 and 2013-2014) in addition to reliability data from 1983-2006 and 2007-2008. This ensured the maximum sample size was used to determine a suitable figure. The reduced availability figure correlates with our predictions that VSC technology is improving.
HVDC Circuit Breaker Failure Rate	0.045	0.015 (although incorrect figure of 0.0091 in model)	The SKM report assumed the failure rate of a hybrid circuit breaker would be 0.015 per annum. There was an inconsistency between this figure and the figure of 0.0091 quoted in the model. ABB and STRI predicted the reliability of HVDC circuit breakers would be comparable to VSC converter technology and suggest a reliability figure the same as the failure rate of one IGBT switch i.e. 0.075 per year. GHD felt this figure was pessimistic hence the original SKM figure of 0.015 with the ABB/STRI figure of 0.075 was averaged to give a failure rate of 0.045 per annum.
VSC Transformer Failure Rate	0.4 %	N/A	The HVAC transformer failure rate of 3.267% used in the SKM model was extracted from CIGRE data published in 1983. A new survey was published in 2015 (CIGRE 642) which provides more up to data and clarification on the definition of a transformer failure. The paper quotes an updated failure rate of 0.4% in Table 35 hence this has been used within the GHD model.
LCC Converter transformer failure rate	1.5 %	3.267 %	CIGRE 406 provided failure rates for LCC converter transformers which have now been added to the GHD model
External Failure Rate for Subsea Cables	0.0021	0.0025	Although the CIGRE cable data has not been updated since the SKM model the external failure rate of subsea cables has reduced to 0.0021 within the GHD model to correlate with improvements in cable burial techniques.
Planned Unavailability due to maintenance (best case)	36 hours	24 hours	GHD considers that the least frequent maintenance scenario proposed by SKM of 24 hours per converter per year was too optimistic hence this was increased to 36 hours within the new model.

Appendix B – User Manual

General

The HVDC Interconnector Availability tool consists of 7 interlinked Excel worksheets:

- 3 project example sheets (NSL, NEMO and Example Project)
- Converter Data
- Cable Data
- Other
- Converter Database

The Project example worksheets are the main worksheets where project specific data is defined. The Converter Data, Cable Data and Other worksheets contain the base availability data (e.g. failure rates and Mean Time To Repair data) and factors that can be applied to the base data to account for project specific details and to evaluate sensitivities to the data.

The Converter Data, Cable Data and Other Equipment worksheets contain all the data used in the studies as a database accessed by the project worksheets and also allows for any additional data to be input directly by the user as required. The converter database contains the availability data for each converter type for reference. The data in these worksheets is consistent with that utilised in the main report but can easily be changed by the user if required or additional equipment added.

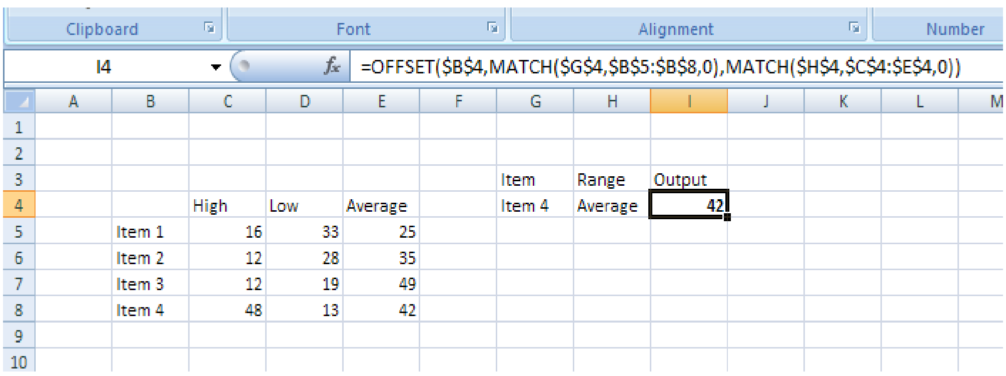
As a general rule, all data in the spreadsheet which is shown in *blue italics* is editable by the user. All other cells should not be edited. The functionality of the spreadsheet is described in more detail in the following sections:

B.1. Spreadsheet Functions

The tool calculates the total availability of a connection based on the average interruption availability figures for individual components, as input in the database worksheets (Converter Data, Cable Data and Other). The approach allows the appropriate data from the database worksheets to be taken into the project example worksheets when specific items of equipment are selected. To achieve this, the *OFFSET* and *MATCH* functions in Excel are utilised. These functions provide the required functionality without the need for extensive formulas and multiple *IF* statements in most cases and were therefore selected over the alternative *VLOOKUP* function.

The basic approach in the *OFFSET* and *MATCH* functions is shown below:

Figure 2: Offset & Match Functions



In the above example cell I4 is required to output the correct value from the table based on the row and column selections in cells G4 and H4. The cell B4 is therefore chosen as the initial cell to offset (the top left cell of the table is always chosen). The number of rows which the cell is offset is determined by the first *MATCH* function, which compares the cell G4 to the rows B5 to B8 (the '0' at the end of the formula ensures that an exact match is used). Cell B4 is therefore offset by 4 rows. The number of columns to offset by is determined by matching cell H4 to the range in C4 to E4. Cell B4 is therefore also offset by 3 columns. The result of the offset is therefore 4 rows and 3 columns which is equal to Item 4's average value.

The above method is used extensively throughout the spreadsheet to return data from the database worksheets depending on a user input. To ensure the user input matches the items in the database, drop down menus are used which are limited only to the range of items in the database.

B.2. Project Example Worksheets

These worksheets are the main spreadsheets where the project specific data is defined and where sensitivities to the data (e.g. cable MTTR, converter MTBF and maintenance assumptions) can be studied. The worksheet uses drop down menus to allow the input of each of the main items of equipment associated with the project, as shown on the Single Line Diagram (SLD). The examples included in the spreadsheet are based on the 2 projects detailed in the main report.

The availability data associated with each item of equipment selected is automatically input in the project example worksheet from the appropriate equipment worksheet where it has already been defined. If the user chooses to build a new project, and the equipment availability data already included by GHD is considered sufficient, then only this worksheet will need to be completed to determine the availability data. If additional equipment is required or if it is necessary to change the base availability figures outside of the sensitivities already included then this will need to be included in the appropriate equipment worksheet as detailed in sections B.3 to B.5 of this user guide.

B.2.1. Inputs

The inputs associated with this worksheet are described below:

This table in the spreadsheet is used to define all of the items of equipment associated with the interconnector which may be subject to unplanned outages (faults) and calculates the unavailability of the interconnector associated with unplanned outages. The user inputs in this table are:

Units – The number of the individual component being defined, enter any integer number. Note that if there are numerous components in parallel which all have the same availability data and the same effect on the capacity of the connection during an outage then these can all be entered in a single line in the table with the appropriate amount of units being defined. If, however the components do not have the same effect on the available capacity of the connection capacity then these must be entered separately.

An example of this is shown in Figure 2.

Circuit Length (km) – This only needs to be completed if the class of equipment (see below) is cable. The circuit length in km should be entered here so that the availability calculation can take this into account.

Class – Selects if the piece of equipment is associated with the VSC converter, a cable connection or any other equipment (e.g. transformers, switchgear etc.).

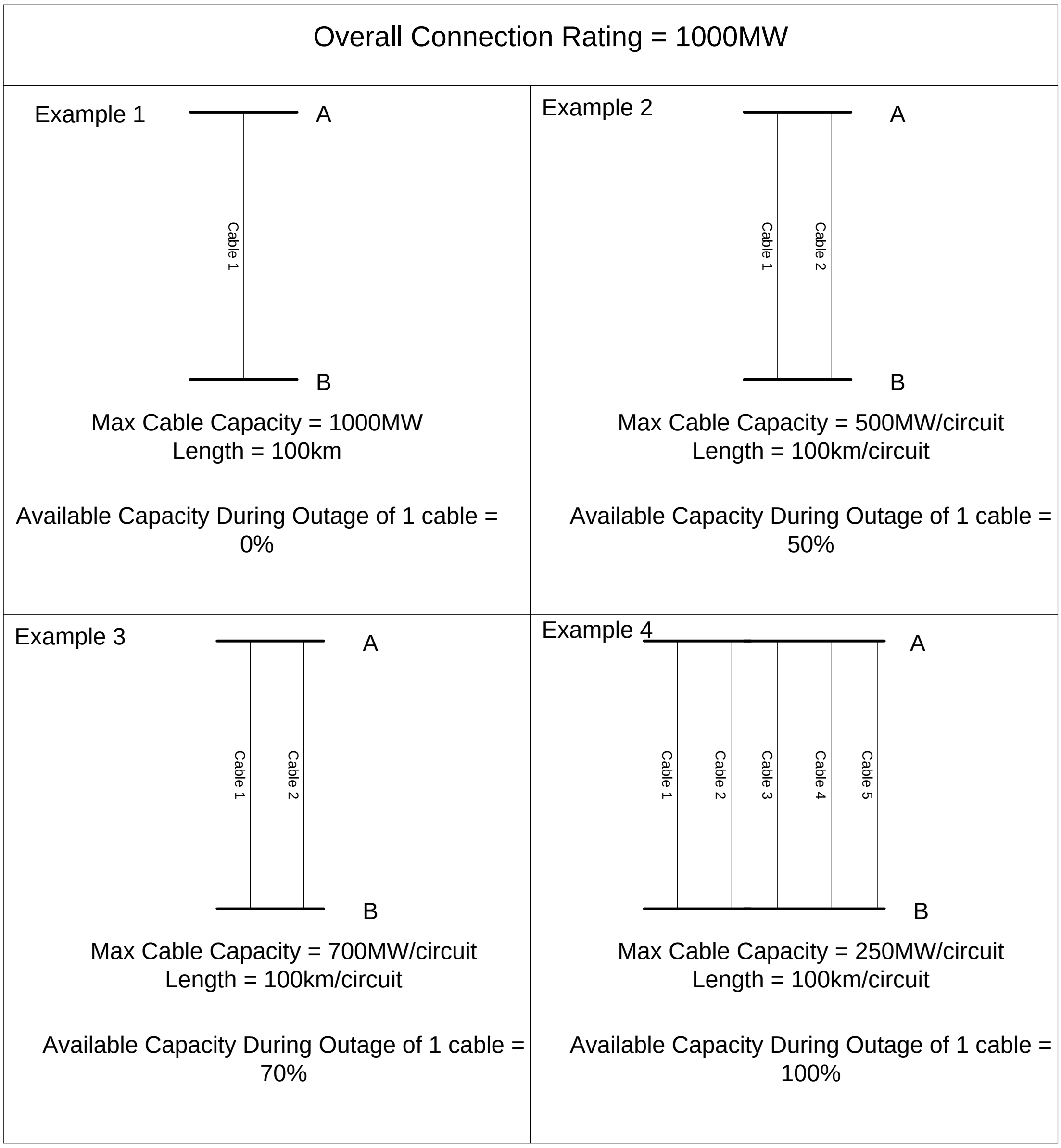
Equipment – The specific item of equipment considered. This is defined from a drop down menu. The choices of the menu are determined by the 'class' chosen (as described above) and the equipment defined in the associated worksheets. If the required piece of equipment is not shown in the drop down menu then it must be defined in that equipment worksheet.

If it is required to add converter transformers to a project then these can be selected from the Other asset class.

Available Capacity – Whilst this is not directly input in this worksheet, it is an important factor to consider when entering the connection design. The figures for available capacity are input into the appropriate worksheet depending on the asset class of the equipment. A description is provided here of available capacity which applies to all asset classes. An example of AC cable connections is used to highlight the importance.

Note that in the below example the base capacity figure is considered as 1000 MW. In some cases however the base interconnector capacity may be based on an MVA rating. An MVA rating can be used as the base capacity figure in the model providing that all resulting available capacity figures are calculated in MVA. The choice of whether to use MW or MVA as the base capacity figure is entirely up to the user providing that a consistent approach is taken throughout the input data into the model.

Figure 3: Available Capacity Examples



In example 1 it can be seen that if an outage occurs on the cable, there is no interconnector capacity available between A and B therefore the resulting available capacity figure is 0%.

In example 2, during an outage of either cable the total interconnector capacity is 500 MW and therefore has a 50% available capacity during outages. However in this scenario, in the calculation of overall availability, the figure would be the same as in example 1 as the total cable length has doubled and therefore the probability of a fault occurring doubles.

In example 3 the cables have spare capacity in normal operation as their total capacity is 1,400 MW for a 1000 MW interconnector. In the event of an outage of one of the cables the available capacity is therefore 70% (700/1000 MW). The probability of failure remains the same as in example 2 therefore the overall availability of this interconnector would be higher than in example 1 and example 2.

In example 4 there is again spare capacity in the design. In the event of an outage to one cable, the remaining capacity is 1000 MW therefore the available capacity figure is 100%. This arrangement represents full redundancy and therefore has full availability during single outage scenarios.

Therefore when determining the available capacity it is the capacity which is still provided without the element concerned which is populated into the spreadsheet.

B.2.2. Availability calculation – Scheduled Maintenance

Scheduled maintenance is discussed in more detail in the original SKM report. The total outage time due to scheduled maintenance cannot be determined as the sum of all the maintenance associated with each individual component in the way that it is for unplanned outages, as it is likely that overlapping outages will be scheduled where possible to minimise downtime. The approach used in the spreadsheet is to enter the frequency of maintenance and the time taken for the maintenance in the "Other" worksheet. The appropriate figures are automatically carried forward to the Project Example worksheets depending on the sensitivity chosen in the project example spreadsheet (Less Frequent, Average or More Frequent).

B.2.3. Sensitivities

As detailed in the main report there are three areas in which the sensitivity to the input data can be determined; cable MTTR (weather), scheduled maintenance frequency and converter unplanned outage frequency.

The appropriate sensitivity case is selected in the Sensitivities table with the data associated with these included in the appropriate equipment worksheet.

Weather and Maintenance sensitivities can be varied on a project by project basis (as these are project specific factors). The converter outage data applies equally to all projects (i.e. if the worst case is chosen it should be chosen for all projects to ensure a fair comparison) and therefore this is **varied on the NSL worksheet only** and automatically carried through to the remaining project worksheets.

B.2.4. Inserting/Deleting Rows

The layout of the worksheet has been designed to accommodate 22 individual items (or groups of items) of equipment, which it is envisaged will be sufficient for most connection designs studied. If however, it is required to insert more rows into the unplanned outages table this can be achieved with some modification to the spreadsheet as described below:

1) Right click on row 31 (i.e. the bottom row of the table), to highlight the entire row and insert a row above this row.
2) Select the entire row from the line above the new row and paste into the new row. This will be sufficient to update all of the formulas in the spreadsheet to accommodate the new row.

Rows can be deleted from these tables in the normal manner provided the entire row is deleted.

B.2.5. Outputs

This worksheet calculates the overall availability of the connection. The availability of the connection design, when considered in isolation, is shown beneath the scheduled maintenance table as the Overall availability.

B.3. Converter Data

This spreadsheet should only be used if the base availability data provided by GHD in the main report is being updated or if a new converter arrangement is being input into the spreadsheet.

There are two possible methods for entering the converter availability base data:

1) Enter overall unscheduled outage data for the converter arrangement which covers the whole equipment covered by the converter module (e.g. IGBT modules, filters, DC reactors etc.)

2) Enter the component parts associated with the converter arrangement and the spreadsheet will calculate the overall availability of the converter arrangement.

B.3.1. Project Converter Database

In this table the availability data associated with each converter type is calculated based on the sensitivity input on the Project Example worksheets. This table is used for calculating availability data only and does not need to be edited.

The table contains the four standard arrangements (monopole, symmetrical monopole, bipole with metallic earth return and bipole without metallic earth return) as covered in the main report. If an additional converter arrangement is desired, there are three 'user defined' arrangements which allow the input of the associated data. As most projects will only have a single converter arrangement associated with it, it is assumed that the potential converter arrangements included in this worksheet are sufficient for all projects likely to be studied therefore no arrangements have been made to include additional rows in this table.

B.3.2. Base Converter Component Availability Data

In this table the base availability figures of the components are entered. If the figures for the overall converter module are known then these should be entered here.

This table is also where data should be input when updating converter data as suggested should be done on a regular basis by editing the MTBF and MTTR figures next to the symmetrical monopole, bipole and the symmetrical monopole arrangement.

If it is desired to calculate the availability of the converter module from individual component figures, then all components included in the module should be defined here and their associated availability figures entered.

If the converter availability is being built up from component level, there is the potential to include a maximum of 21 components in the converter module design. It is recommended that these are included in the bottom of the table (as shown in the example spreadsheet) to avoid having to overwrite the data which has already been included for the standard arrangements. However the standard arrangements can be overwritten if required and the full table used for converter module components provided the standard arrangements are not required in the particular availability model being built.

If more than 21 components are required, rows can be inserted into this table as described below:

1) Right click on the bottom row of the table, to highlight the entire row and insert a row above this row.

2) Enter all data into the new row in the normal way

Rows can be deleted from these tables in the normal manner provided the entire row is deleted.

B.3.3. Converter Outage Factors

These factors allow the sensitivity of the overall connection design to the base converter availability figures to be studied easily. The factors which will be applied to the data depend on the sensitivity case chosen on the project specific worksheet. These factors can be adjusted if required although it is recommended to keep the medium case figures at 1 and adjust the base data in the ‘Converter Component Database’ if necessary.

B.3.4. Converter Design Database

These tables will be used to calculate the total availability of the converter arrangement from the components input into the ‘Converter Component Database’ table. The input method will be the same as used in the ‘Overall Availability’ worksheet to determine an overall availability for each the arrangement. The only additional column which needs to be completed for each of the converter arrangements is the ‘available capacity %’ column. This will be the percentage of the total connection capacity (1000 MW in the example) which remains when a single unit of the particular piece of equipment is lost. Therefore a piece of equipment, which does not have any redundancy and has the potential to cause an outage of the entire connection, would have an available capacity of 0%. If a fully dual/redundant arrangement is used on a piece of equipment then the available capacity will be 100%.

If an overall figure for the converter is being used, then the appropriate converter arrangement should be selected in the equipment column of the table. For the standard arrangements studied by GHD this has already been done.

If a converter availability figure being built up from component parts, then all the components should be selected in the equipment column and the number of units and available capacity figures also input here. The calculated data is carried forward to the Converter Design Database where factors can be applied if required. The adjusted overall availability of the converter module will then be carried forward to the ‘Overall Availability’ worksheet when the converter arrangement is selected there.

As the layout of these tables are similar to those on the Project Example worksheets, rows can be added or included into the scheduled maintenance and unplanned outage tables in the same manner as described in section B2.4, i.e. insert an entire new row and copy and paste the formula from the row above.

B.4. Cable Data

The details of all cables used on the connection are input into this worksheet.

The inputs associated with this worksheet are as follows:

B.4.1. Project Cable Database

As the installation methods and conditions will vary with each connection project, this table allows the individual characteristics of each cable associated with the project to be defined.

Cable Name – A unique name assigned to each cable (or group of cables if they are of identical design, installation method and installation conditions).

Technology – A drop down menu to select the cable technology type. If the required technology is not shown on the drop down menu then it must be defined in the 'Base Availability Data' table on this worksheet.

Failure Rate H/M/L – As the failure rate of cables is often provided as a range of failure rates, the option is available to use the lowest failure rate, the highest failure rate or the an average failure rate.

Burial Depth – The number of external failures is linked to the burial depth of the cable and shipping frequencies. This option allows a factor to be applied to the failure rate if the cable is unburied or has an especially deep burial depth. The standard burial depth is considered to be approximately 1.5 m.

MTTR – For offshore cables this is directly linked to the weather sensitivity chosen in the Project Example worksheets and should only be edited in the Project Example worksheets.

Converter Arrangement – For an HVDC connection, the percentage of the connection capacity lost will depend on the converter arrangement which must be selected here. If the cable is an AC cable associated with the connection, then the percentage of capacity lost when a single circuit fails must be defined manually in the 'Converter Arrangement' table of the Cable Factors (using the AC1, AC2 and AC 3 arrangements, or the user defined converter arrangements if more are required). This will depend on the number of circuits associated with the AC part connection and the capacity of each of these circuits.

Cable Configuration – For an HVDC connection, the percentage of lost capacity will also depend, in some cases, on whether the cables are bundled together before laying or whether a spaced arrangement is used.

The table allows up to 22 cables to be defined for the project. If more are required this should be done using the method described in section B2.4.

B.4.2. Base Cable Availability Data

In this section table the base failure rates (number per year) and MTTRs (in days) of the cable technologies are input. A range of data can be entered to determine the sensitivity of the connection design to the cable availability data. These are split between external failures and internal failures to be consistent with the way that cable availability data is usually reported. The overall figure is calculated from this data.

The table allows up to 17 cable technology types to be defined for the project. If more are required this should be done using the method described in section B2.4.

B.4.3. Cable Factors

These factors are applied to the base availability data of the technology, as defined in the above table. The selections made in the Project Cable Database determine which factors are applied. These factors can be edited if desired.

The connection arrangement table provides the available capacity figures for the standard converter arrangements.

If it is required to add more rows into the converter arrangement table this should be done using the method described in section B2.4.

It is not recommended to insert additional rows into the other cable factor tables, although the actual factors can be edited. If additional rows are required in these tables it is recommended to contact GHD.

B.5. Other

This worksheet is mainly used to define scheduled maintenance figures but is also used to define any other equipment associated with the interconnector such as HVDC circuit breakers.

Three sets of maintenance figures (frequency and maintenance time) are input for each project to allow the Best, Average and Worst case sensitivities to be studied easily. The maintenance figures associated with each project can be edited individually as it is recognised that scheduled maintenance is a project specific factor.

Other equipment is input directly into table and is then available for selection in the ‘Project Example worksheets.

If additional rows are required for other equipment this should be done using the method described in section B2.4.

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