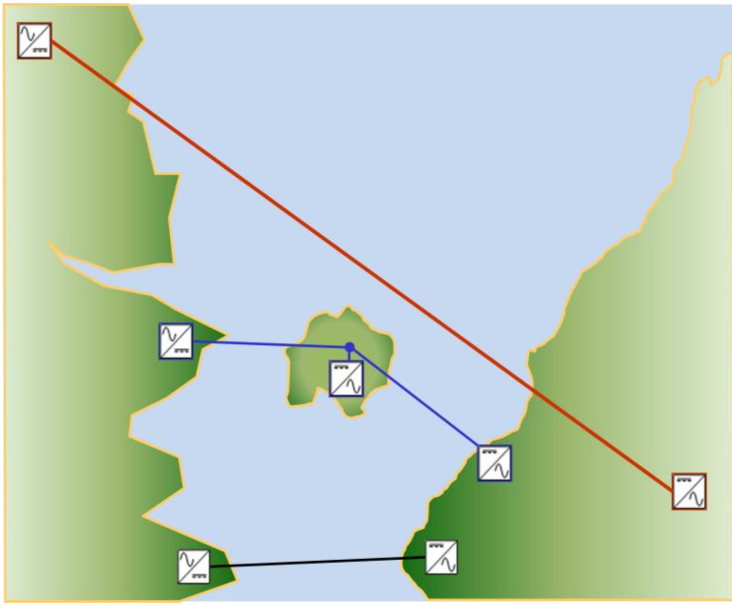
Calculating Target Availability Figures for HVDC Interconnectors



Final Report

- 21st December 2012

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1. Executive Summary

In the UK, a new regulatory framework for electricity interconnector investment, the cap and floor regime, is being developed. This framework is being developed for the pilot project, NEMO (the proposed interconnector between Great Britain and Belgium), for the regime by Ofgem and the Belgian regulator, CREG.

SKM were commissioned to develop a methodology for calculating the baseline case (target) of interconnector link availability for projects built using high voltage direct current (HVDC) technology under this regime.

The results presented in section 9 of this report show that there are significant variations between projects in expected availability. The most significant single factor in the variations between the projects is the cable length. Two projects which are identical apart from cable length could have very different calculated availabilities simply due to the length of cable. This can be demonstrated by simply changing cable route length in the model and for a model project (Project 2 defined in the report) with an alternative subsea cable distance of 350 km rather than 700 km, the calculated availability would change from 95.92% to 97.66%.

Even within a single two-stage project the variation in availability can be significant as demonstrated by the results obtained for an example project in this report (Project 3 stage 1 and Project 3 stage 2). This is due to the addition of a mid-point converter which has only a relatively small effect on the number of outages, but a significant effect on the available capacity during these outages.

A simple approach to the setting of availability targets cannot be justified considering the wide variation of availability figures calculated in this study. Calculating target availability figures on a project by project basis will result in targets which are much more closely matched to the expected availability of the connections based on the approach used in this study. Project factors include not only the configuration of the system but also the lengths of cable involved, risks of cable damage and possible protection measures and the mean time to repair (MTTR) following any fault. This latter aspect will be strongly influenced by the climatic conditions of the areas through which the interconnector passes.

Factors such as planned maintenance are strongly influenced by the approach taken by the operator of the interconnector as well as the design of the technologies utilised, hence are more appropriate for the setting of targets which can be applied across the regulatory regime.

Interconnector experience, particularly with Voltage Source Converter (VSC) technologies, of more recently developed cable technologies, cable installation and protection techniques is still limited. Therefore, consideration needs to be given to the regular review of certain aspects of reliability and availability data sources.

The following recommendations are concluded from the study:

a) Based on the approach taken it is suggested that for Project 1, which is similar to that envisaged for Project NEMO, that the target level of availability would be in the range of 97.1% to 97.8% considering the HVDC converters and HVDC cables. These figures would be reduced to 97.0% and 97.7% if the HVDC converter transformers were also considered. A further refinement of the model would be o also include AC switchgear into the calculations.

b) Given the scarcity of substantiated data generally for offshore transmission systems, and VSC technology in particular, it has been necessary for SKM to make assumptions as part of this work. As more experience is gained the models can be updated and sensitivity analyses performed to understand the key elements which impact on availability and those that can best be influenced at the design, construction and operational phases of any project. Hence, the assumed data for VSC converters and HVDC cables should be considered for review more frequently than for HVAC components such as transformers and switchgear. Initially it is recommended that VSC converter and HVDC switchgear and cable data should be reviewed at intervals of 6 months and the model refreshed. Data for HVAC switchgear, transformers etc. should not need to be reviewed more frequently than every two years.

c) The calculated availability for HVDC schemes is very dependent on the assumptions made concerning converter reliability and MTTR, particularly for offshore components. Sensitivity studies within this report demonstrate the potential impact that converter reliability assumptions may have, however it needs to be recognised that the approach taken to improve converter availability (HVDC module redundancy, configuration design redundancy, location of O&M teams etc.) will in part be reflected by the design of the cap and floor approach. This of course then reflects back to what is economically justifiable comparing the cost of achieving improved availability compared to the benefit for the project stakeholders and of course the consumer. Further study combining economic aspects and availability "options" is likely to be necessary.

d) HVDC converter configurations and technologies over the next 5 to 8 years are likely to be strongly influenced by project specific requirements. Whilst it is expected that there will be a significant number of VSC based symmetrical monopole schemes, particularly where multi-purpose projects are required, it is also likely that LCC technology will continue to be used in specific project applications.

e) Agreement on planned maintenance is likely to be difficult to agree due to the project specific nature of the scheduling of outages and the approaches taken by different vendors and interconnector operators. The co-ordination of outages to minimise downtime, whilst also providing sufficient maintenance to prevent an increase in unplanned outages requires detailed studies on an individual project basis. It may therefore be necessary to study this area in more detail when determining target availability figures for scheduled maintenance.

2. Aims

In the UK, a new regulatory framework for electricity interconnector investment, the cap and floor regime, is being developed. This framework is being developed for the pilot project, NEMO (the proposed interconnector between Great Britain and Belgium), for the regime by Ofgem and the Belgian regulator, CREG. In 2011, the national regulatory authorities (NRAs) set out their preliminary conclusions on the high level principles and the basic cap and floor design for NEMO as well as on the development of an enduring regulated regime for electricity interconnector investment in the UK.[1] The NRAs are now finalising the design of the cap and floor regime. They are proposing an availability incentive which would shift the level of the cap up or down based on actual availability of the link relative to target availability.

SKM were commissioned to develop a methodology for calculating the baseline case (target) of interconnector link availability for projects built using high voltage direct current (HVDC) technology under this regime. Informed by their findings, outlined in this report and demonstrated in the Excel model with accompanying user guide, SKM were asked to propose and comment on:

- whether target link availability should be set on a project by project basis, and if so, how this should be done
- what the target level of availability should be for NEMO
- the robustness of their findings, including the applicability of the data sources and how frequently the data sources should be reviewed in the future

[1] http://www.ofgem.gov.uk/Pages/MoreInformation.aspx?docid=67&refer=Europe

3. HVDC Vs HVAC

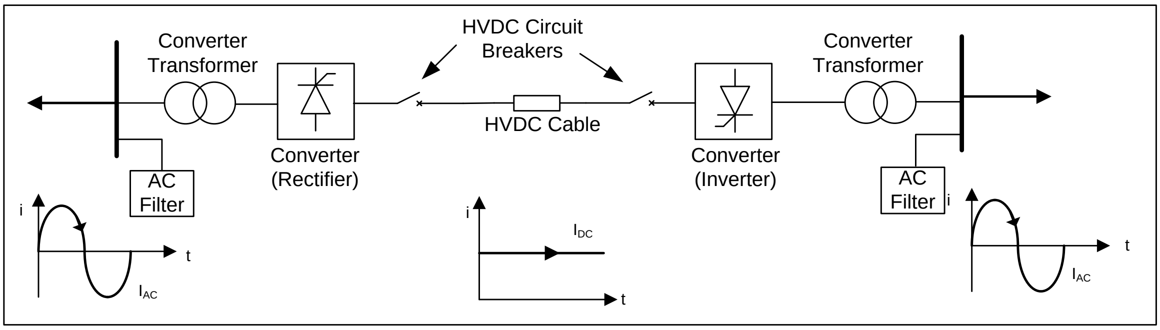
It is well known that significant reactive power (MVAr) compensation is required for HVAC cable connected systems due to the capacitive charging current of the cable. For long HVAC cables the reactive charging current requirements can be of the same magnitude as the active power rating. Given that interconnector projects require submarine cables it follows that for given cable electrical characteristics there becomes a distance beyond which the operation of an HVAC cable becomes impractical due to the dominance of the cable charging current.

A general "rule of thumb" used within the industry is that for HVAC, distances up to 60-70 km and for transmission capacities up to 1000 MW can be realised. For longer distances and/or higher capacities HVDC becomes the normally accepted solution. In practise a detailed technical/economic study is required to determine the least cost technically acceptable (LCTA) arrangement taking into account ongoing technology developments, including:

- 3-core HVAC cables are now available up to 220 kV which could extend the crossover or tipping point between HVAC and HVDC to at least 90 km.
- The concept of intermediate reactive compensation offshore platforms which could be used to potentially extend the range of HVAC systems
- Wider application of VSC HVDC and availability of extruded HVDC cables at higher voltages suggest that HVDC can be the LCTA solution for relatively short distances.

The use of HVDC technology for international interconnectors also facilitates the independent operation of the two connected networks. The distances and capacities associated with the interconnectors assumed in this report are such that they are beyond the point where HVAC can be considered.

4. HVDC Technologies



- **Figure 1 - HVDC Scheme**

Figure 1 shows the fundamental elements of a HVDC scheme, generally international interconnectors require a converter station at each end of the connection and both onshore and subsea cables. The system is generally comprised of the following electrical equipment:

- **Converter:** This is required for the conversion of the AC voltage to DC via a rectifier and the DC voltage back to AC via an inverter, using either Line Commutated Converter (LCC) or Voltage Source Converter (VSC) technology. Both converters can act as either an inverter or rectifier depending on the direction of power flow
- **Converter transformer:** This is the connection point between the AC and DC systems at the onshore grid connection point substation and at the offshore AC collector platform in the case of a connection to an offshore wind farm.
- **HVDC cable:** Offshore applications rely on cables as a transmission medium, rather than overhead lines.
- **HVDC switchgear:** This refers to all circuit breakers, disconnectors and all associated equipment to protect, isolate and monitor electrical equipment and systems on the DC side of the connection. HVDC switchgear exists today to a certain extent, but relies on the capability of the converters or AC circuit breakers to extinguish fault currents. The availability of a DC circuit breaker with DC fault current breaking capability is required to fully realise multi-terminal schemes.
- **AC filters:** These may be required on the AC side in order to remove any harmonics and to ensure that the resulting ac waveform is acceptable before it is fed in to the grid.

There are two basic types of HVDC convertor technology, LCC which have been used commercially since the 1950s and VSC which emerged more recently in the late 1990s.

The principal concept of both technologies relies on the use of power electronic switching devices to convert AC power into DC power, transferring the power over cables or overhead lines and converting the DC back to AC at the other end. LCC converter technology utilises silicon controlled rectifiers (SCRs or thyristors) switching devices, without gate turn-off capability and require an AC current zero to turn off, whereas VSCs being self-commutating converter technology employ IGBTs (insulated-gate bipolar transistors) as the switching device with both gate turn-on as well as turn-off capabilities that can turn-off at any AC point on wave.

In both technologies the converter is typically arranged as a number of full three-phase 6-pulse bridges. In each of the phases commutating valves are built with a number of modules connected in series comprising arrangements of either Thyristors or IGBTs. A single sub-module of a VSC converter arrangement will typically include two IGBT based switching devices hence with both gate turn-on and turn-off capabilities as well as anti-parallel diodes which serve a number of functions such as charging up the system and withstanding fault currents.

The main differences between LCCs and VSCs are outlined in Table 1 below:

- **Table 1 Comparison of LCC and VSC technology**

LCC-HVDC	VSC-HVDC
Switching process and “commutation” relies on connecting network	Switching process and “commutation” is controlled independently of connecting network
Energy stored inductively	Energy stored capacitively
LCCs require active network connection	VSCs can operate into passive networks with an independent clock to control firing pulses to the VSC valves, which also defines the AC frequency
LCCs require a typical AC network with a short circuit ratio (SCR) of >3	VSCs can feed into or out of weak AC systems. However, the AC system must be capable of delivering or receiving the transmitted power which will set a minimum limit to how comparatively weak the AC system can be in practice
LCCs cannot provide AC voltage control	VSCs can provide substantial AC voltage control at the AC interconnection busbars, even black start capability
LCC achieves reverse power flow though polarity reversal therefore cables must be capable of withstanding increased dielectric stresses.	VSCs can use lighter, solid insulated extruded DC cables which enables the effective use of undersea and underground cable transmission as polarity reversal not required.
Multi-terminal schemes require more complicated control schemes	VSCs are considered more appropriate for multi-terminal schemes
AC system faults lead to commutation failures	VSC valves are self-commutating and commutation failures due to ac system fault or ac voltage disturbances do not occur
LCC transmission has minimum DC current limits which would be a problem during periods of minimal wind generation.	VSCs Transmission has no minimum dc current limits
LCC schemes require separate reactive power control	VSCs can control reactive power, either capacitive or inductive, independently of the active power within the rating of the equipment
Extensive harmonic filters required leading to a larger converter station footprint.	Only minimal harmonic filters are needed

LCC-HVDC	VSC-HVDC
Converter transformers need to be able to withstand DC stresses.	Transformers do not have to be specially-designed HVDC converter transformers – conventional ac transformers may be used
LCC cannot be used for separate compensation and grid support.	The VSC stations can be operated as STATCOMs, even if the VSC is not connected to the dc line
Converter losses typically 0.7%.	Converter losses higher, typically 1.2 to 1.4% although expected to reduce to 1% over the next 5 to 10 years.
Lower cost per installed MW.	As a guide, currently onshore VSC converters might be approximately 25% more expensive than LCC of an equivalent rating

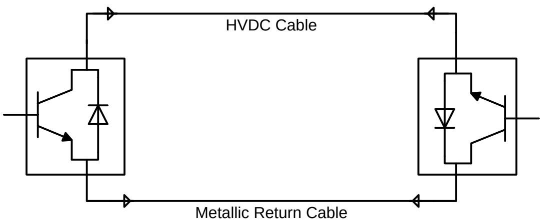
Based on the above brief summary it can be seen that there are many factors to be considered when the choice of HVDC converter technology is made for any particular interconnector arrangement. Key issues are likely to be the need for HVAC network support and network reinforcement together with converter station footprint. LCC cannot be used for separate compensation and grid support whereas VSC installations can be operated as a (Static Synchronous Compensator (STATCOM) to support electricity networks that have a poor power factor or provide voltage regulation., even if the VSC is not connected to the DC line. Electrical losses are likely to become less of a determining factor in the future.

LCC stations require a greater footprint due to filter equipment and layout, however are generally cheaper on the market due to the proven technology. VSC currently is more expensive for straightforward interconnectors but as volumes increase then costs are likely to reduce. The total cost comparison between a VSC and LCC will be specific to the application and needs to consider the reactive compensation and filtering requirements needed to implement each technology..So whilst VSC technology may dominate in applications for the connection of offshore wind farms for straightforward interconnectors the application of LCC technology is likely to continue for the 5 to 8 year time horizon being considered.

5. HVDC Configurations

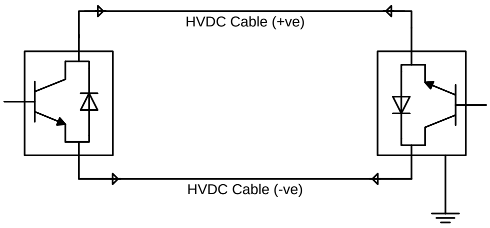
5.1. Converter Topology

Both LCC and VSC converters can be assembled into various configurations as shown in Figure 2 and Figure 3 below. For long distance transmission, the bipolar arrangements shown in Figure 3 are generally considered to be more suitable; the poles are designed to be independent of each other. During an outage of a transmission line or station for one pole, the second pole should still be capable of monopolar operation, with the metallic return providing the return current path for the dc current.



Monopole, metallic return

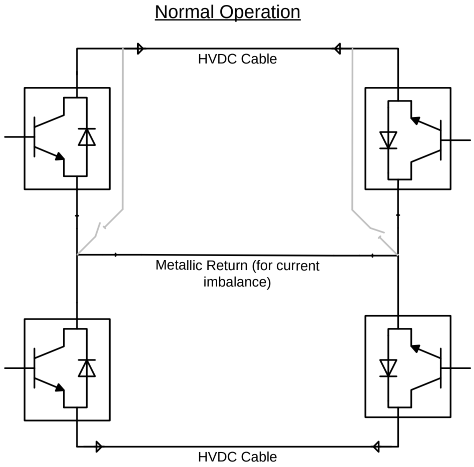
If there are constraints against using earth electrodes (there are issues with corrosion of pipelines, production of chlorine and ship navigation) then such a metallic cable can be installed instead



Symmetrical Monopole

If a fully rated HVDC cable is installed instead of a return conductor, then two converters per pole can be utilised to double the power transferred using opposing voltage polarities. However, if a cable or converter is faulted then the whole transfer capability is lost.

- **Figure 2 - Monopole Converter Arrangements**



Bipole, metallic return

The bipole arrangement utilises a single return path for two poles. An equal and opposing voltage from each pole means that the return path will carry only minor current due to any imbalance between the two poles. The return path can be provided by either a metallic conductor or sea/earth electrodes if consent can be gained for their use.

- **Figure 3 - Bipole Converter Arrangements**
- **Table 2 Summary of Converter Arrangements**

Arrangement	Converter Requirements	Cable Requirements	Availability
Monopole Metallic Return	1 x Rectifier, 1 x Inverter	1 x HVDC 1 x LVDC	Zero output during cable or pole outages. Increased losses.
Symmetric Monopole	2 x Rectifier, 2 x Inverter	2 x HVDC	Zero output during cable or pole outages
Bipole Metallic Return	2 x Rectifier 2 x Inverter	2 x HVDC 1 x LVDC	Half capacity during cable or pole outages.
Bipole without Earth Return	2 x Rectifier 2 x Inverter	2 x HVDC	Half capacity during pole outages. Zero output during cable outages

Table 2 provides a summary of the main converter arrangements and a high level indication of availability during a cable or pole outage.

The options identified in Table 2 could be increased if it is considered that a system reliant on ground return through the earth or sea could be viable on an environmental basis. Whilst such schemes are operating successfully in Scandinavia and New Zealand the assumption made here is not to consider a ground-return system making use of earth or sea return.

6. Availability Data

This section describes the general approach used in collating availability data and provides the details of the data used in the modelling of the example projects.

6.1. Availability Data – General Approach

Sources of equipment reliability information are generally used as the starting point for any availability assessment. For VSC HVDC assets this restricts the potential sources due to the very limited experience with such transmission systems.

CIGRE (International Council on Large Electric Systems) is generally recognised as being the definitive source of information for transmission and distribution systems based on the access to large sample populations given that CIGRE is a global organisation. CIGRE being an excellent source for submarine cables and switchgear in particular, however it is appreciated that some caution must be exercised when applying any such data and these issues are discussed further in the appropriate part of this section of the report.

Mean Time Between Failure (MTBF) information from CIGRE and other various sources, can then be applied with estimated/recorded Mean Time To Repair (MTTR) together with maintenance assumptions to enable the future availability for an individual asset or system to be estimated.

The 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 asset.

It is recognised that traditional transmission and distribution assets can suffer from an initial higher failure rate after commissioning due to initial failures. Such failure rates then tend to diminish over the lifetime of the asset until any equipment deterioration mechanism starts to cause a reduction in performance. Many transmission and distribution assets show this initial increase in failure rate (which could be an order of magnitude higher than the average failure rate during the first 12 months of operational service) but do not show any upturn in failure rate as end of life approaches, end of life often being determined by other factors such as the cost and frequency of maintenance. For VSC converters equipment is more likely to be provided with a factory “burn-in” having been performed, particularly for control systems.

Given that the first regime for regulated interconnector assets under the cap and floor regime will be for a maximum of 25 years it is not appropriate to consider any adjustments of failure rates due to age and the average figures are used throughout the study. This means any availability target proposed will likely be conservative as the period after 25 years is not being taken into consideration.

In addition to unplanned availability due to failures it is also necessary to include planned unavailability due to maintenance

Planned maintenance is determined considering the frequency of the required activity, duration of the maintenance and the connection capacity that may remain during any maintenance activity.

Of course any assessment of asset availability based on the average interruption rate method will result in calculated availability probabilities which can only ever be considered as average based on a significant period of time for each project and taking an average across a large number of projects. Hence, these average figures will only be realised in practice because one or two projects will suffer from major events, thus having very poor availability, whilst most projects will actually achieve better than “average” availability.

6.2. HVDC Converter Availability Data

A number of CIGRE reliability surveys have established data for LCC converter reliability however determination of VSC availability based on direct reference to reliability surveys is not possible due to the limited experience of VSC systems and in particular the almost total absence of experience with HVDC systems operating offshore. A number of Cigre Working Groups have been set up in this area and in particular B4-60: “Designing HVDC Grids for Optimal Reliability and Availability Performance” will provide information in the future, currently however the information collected and published is limited. Hence, the derivation of VSC availability requires assessments including the comparison of;

- VSC HVDC with LCC HVDC onshore, where experience exists.
- HVDC with HVAC offshore on an equivalent basis.
- Bottom up assumptions as to what will be achieved with VSC technology

As with LCC schemes there is scope to determine overall converter availability through the selection of redundancy in components or systems, based on the specified level of availability required. This approach has been well proven in LCC HVDC projects and will continue on VSC schemes; hence consideration of failure rates of sub-components within the HVDC converter module is not necessary and will be addressed by the VSC vendors depending on the detail of their respective design approaches. The basic assumption made here is for similar MTBF rates for VSC converter modules as achieved for onshore LCC converters.

Similar engineering design approaches will be made for LCC and VSC technologies and of course lessons learnt in some of the earlier LCC schemes will be applied in VSC schemes. It is also recognised that whilst VSC has a higher number of individual components the more extensive application of self-diagnostics will assist when assessing reliability.

The most comprehensive LCC HVDC reliability data is that published by Cigre in 2012[2] where the average energy unavailability through forced outages was 0.65% with a system unavailability time of 57 hours with an equivalent MTBF of 1 year. This does not take into account any failures of converter transformers which are considered separately. This figure based on an HVDC system excluding cables and converter transformers, therefore the figures for an individual converter would be 50% of these values.

On the basis of 50% of 0.65% unavailability per annum this would be equivalent to 0.325% unavailability per converter or 28.5 hours per year.

Experience suggests that the number of forced outages per year will be higher than 1, with a reduced time to repair.

This aligns with the characteristics that vendors can guarantee and therefore provide warranties for – a LCC symmetrical monopole with the transformers arranged with three single phase units and the provision of one spare transformer at each end would be expected to have an unavailability due to forced outages that will not exceed 0.5%. Also, the unavailability due to scheduled outages will not exceed 0.5%. In relation to the pole forced outage rate guarantees would be expected to be given that the fault incidence will not exceed 4 per year (i.e. 2 per year per converter). This implies an 11 hour MTTR for each forced outage. Such guarantees would not cover the cable and hence align with the above assumptions. Manufacturer warranties are of course negotiated on a project by project basis depending on the project characteristics and the commercial arrangements.

Also, the impact of a failure of converters needs to be considered and the level of redundancy provided in the design. The combination of these is illustrated in Table 3 which is provided to illustrate potential approaches rather than defining specific arrangements applied to particular projects. Conceptually further scenarios could be developed where MTBF was improved beyond the values outlined in Table 3 or potentially even with considered MTBF values worse than those outlined in Table 3.

It is recognised that there is some uncertainty in the MTBF and MTTR figures for HVDC converters due to the lack of historical data. To account for such uncertainties, a best case and worst case have been considered as well as the base case for MTBF figures.

[2] Cigre Paris 2012 paper B4-113 A Survey Of The Reliability Of Hvdc Systems Throughout The World During 2009 – 2010. Paris 2012.

- **Table 3 Unplanned Unavailability Range for HVDC Converters**

Scenario/Range for MTBF	MTBF (Faults/Year)	MTTR (hours)	Total Annual Outage (hours)	Unavailability %
Base Case	2	14.25	28.5	0.325
Best Case	1	14.25	14.25	0.1625
Worst Case	3	14.25	42.75	0.488

6.3. HVDC Circuit Breakers Unplanned Unavailability

The interconnectors developed under the regime may include multi-terminal designs with a common HVDC node. These nodes may need to utilise HVDC switchgear to ensure the maximum availability is achieved during outages of equipment.

The specific devices envisaged are not yet fully developed and therefore the representation of component availability can only be estimated at this stage. Devices are likely to be a combination of conventional mechanical switches and power electronic components. Hence, for the purposes of the availability model the following approach has been taken as shown in Table 4.

- **Table 4 HVDC Circuit Breaker Failure Rates and Repair Times**

	Failure Rate (failures/yr)	Mean Time to Repair (Days)	Basis for assumptions
Mechanical Circuit breaker	0.010	4	Based on Cigre reliability studies
Power electronic components	0.005	4	Whilst switching devices should be extremely reliable a conservative approach is taken that failure rate will only be 50% of mechanical component given the new application of HVDC circuit breakers.
Hybrid DC circuit breaker	**0.015**	**8**	Composite of above

6.4. Converter Transformers Unplanned Unavailability

CIGRE surveys[2] indicate that the most significant element causing unavailability in HVDC schemes are converter transformers and separate surveys have been published presenting these findings[3].

The most recent survey[4] suggests a marked improvement in converter transformer reliability since previous surveys in 2004. The reduction in failures being attributed to a number of factors including:

- Modern transformers are now more closely monitored (e.g. on-line gas monitoring)
- Most of the systems are designed with spare transformers being readily available
- Implementation of the modified IEC Standard (61378-2) issued in 2001

This has significantly impacted upon the unplanned unavailability experienced and reported which indicated an unavailability of some 2.5% across the entire population of HVDC schemes. Based on this improvement this unavailability figure would reduce to less than 1%.

Additionally, it needs to be considered that the converter transformers reported upon are mainly associated with LCC HVDC systems and for VSC technology the transformers will be equivalent to standard HVAC transformers and therefore the availability figures for VSC converter transformers will be assumed as being common to HVAC transformers.

6.5. HVDC Cables Unplanned Unavailability

For the HVDC interconnectors being considered there is clearly a need for HVDC submarine and underground cable information.

This scope also includes cable joints and the transition joint made between the onshore and offshore cables. The impact of joints and terminations on failure rate are minimal when comparing cable lengths of many kilometres such as those expected in the VSC HVDC projects. Anticipated cable joint failures based on experience are very low and for this reason the failure rates of this equipment is incorporated into the overall cable failure rate and not considered separately.

CIGRE brochure 379 builds upon the earlier CIGRE studies and provides the most comprehensive source of service experiences for both underground and submarine high voltage cable systems, primarily from European respondents.[5,6] This document is based on responses from utilities as well as cable suppliers from the global market with land cable data acquired from the five year

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[3] Joint Task Force B4.04/A2-1, Analysis of HVDC Thyristor Converter Transformer Performance, (CIGRE Publication 240, February 2004)

[4] Cigre Brochure 406 HVDC Converter Transformers Design Review, Test Procedures, Ageing Evaluation and Reliability in Service

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

[6] CIGRE ELECTRA No 137 1991Survey on the Service Performance of HVAC Cable Systems

period 2001-2005 and submarine cable data from 1990-2005. The population of cables represented is 33,000 km and 7,000 km for underground and submarine cables respectively. Information is provided for both AC and DC cable technologies. Cable data for both HVDC and HVAC being equally useful when considering external failures such as; mechanical damage due to anchors, trawler fishing gear etc. for submarine cables or diggers and excavator damage for underground cables. In addition, CIGRE Brochure 398 provides further detail as to the causes of failures, particularly those attributable to third parties, of both underground and submarine cables.[7]

Within CIGRE Brochure 379 failure rates are defined by insulation technology, operating voltage level (60-219 kV and 220-500 kV) and external/internal failures for both underground and submarine cables.[8,9,10] This source provides an overview of failure and repair rates with a large survey sample which allows benchmark figures to be taken following some analysis. Although highly relevant in terms of submarine and underground cabling, the sample covers worldwide failures and repair times and is not specific to the UK. The benchmark figures derived here can be manipulated based on project specific factors to give a more representative view of any specific project circumstances.

CIGRE brochure 379 is the primary source of cable reliability data used as it provides an extensive sample of data. This is supported by CIGRE brochure 398 for further detail on external, third-party, impacts on cable failure rates. In addition, data of current UK interconnectors is considered to allow specific consideration of subsea cable installations off UK shores.

The growing experience of installed and operational offshore transmission projects in the UK and throughout Europe is recognised but cannot be referenced in this study due to lack of published sources. Additionally, direct offshore transmission experience is limited in the UK to the extent that, as at present (as of September 2012), there is only around 550 km of 132 kV and above HVAC cable installed and operational, with a limited number (approximately 600 km years) of service experience estimated.[11] Nevertheless, the only transmission cable failures are believed to have been associated with installation and commissioning rather than in-service operation which bodes well for expected future operational performance.

Operational performance on European and global wind farm projects is believed to be comparable with projects such as Horns Rev, Nysted, Egmond aan Zee, Lilgrund, Princess Amelia, Alpha Ventus and Donghai in service but definitive cable reliability and connection availability figures are not available. Hence, the emphasis placed in this study is on publically available relevant sources.

The MTBF and MTTR data associated with cables, as used in the studies is summarised in Table 5 to Table 9.

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[7] CIGRE Brochure 398 Third Party Damage to Underground and Submarine Cables
[8] Cross-Linked Polyethylene
[9] Self-Contained Oil Filled
[10] High Pressure Oil Filled
[11] SKM Database.

- **Table 5 Underground HVAC XLPE Cable Failure Rates**

Failure	60-219kV (fail./yr/cct.km)	220-500kV(fail./yr/cct.km)	All Voltages (fail./yr/cct.km)
Internal	0.00027	0.00067	0.00030
External	0.00057	0.00067	0.00058
All	0.00085	0.00133	0.00088*

- **Table 6 Underground Cable Repair Times**

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

- **Table 7 HVAC XLPE Submarine Cable Failure Rates**

Failure	60-219kV (fail./yr/cct.km)	220-500kV(fail./yr/cct.km)	All Voltages (fail./yr/cct.km)
Internal	0.000000	Not Available	0.000000
External	0.000705	Not Available	0.000705
All	0.000705	Not Available	0.000705

- **Table 8 HVDC MI Submarine Cable Failure Rates**

Failure	60-219kV (fail./yr/cct.km)	220-500kV(fail./yr/cct.km)	All Voltages (fail./yr/cct.km)
Internal	0.000000	0.00000	0.000000
External	0.001336	0.000998	0.001114
All	0.001336	0.000998	0.00114

- **Table 9 Assumed Submarine Cable Repair Times**

Activity	Duration Days
Mobilisation of repair vessel to site	15
Surveying, de-trenching and recovery of cable	10
Repair and testing of cable	15
Lay-down, reburial and surveying	10
Weather contingency	15
Total	65

The weather contingency in the above table is based on typical weather delays as experienced in waters around the UK and represents an average across the year. However, during extreme weather conditions such as storms and sea-ice, the overall repair time could increase significantly. As a result a 'worst case' average MTTR figure of 90 days has been considered as well which accounts for the loss of 40 days due to weather, clearly for some projects the worst case could be significantly longer than this during winter periods..

6.5.1. Cable Base Data Summary

The cable base data proposed is summarised in Table 10 both for HVAC and HVDC cables in submarine and underground applications.

- **Table 10 Summary of Proposed Submarine Cable Failure Rates and Repair Times**

<table>
<tr><th></th><th colspan="2">Failure Rate HVAC (failures/yr/cct.km)</th><th colspan="2">Failure Rate HVDC (failures/yr/cct.km)</th><th colspan="2">Mean Time to Repair (Days)</th></tr>
<tr><td rowspan="2">Underground</td><td>Electrical</td><td>0.000300</td><td>Electrical</td><td>0.000300</td><td>Directly Laid</td><td>20</td></tr>
<tr><td>Mechanical</td><td>0.000580</td><td>Mechanical</td><td>0.000580</td><td>Ducted</td><td>30</td></tr>
<tr><td rowspan="2">Submarine</td><td>Electrical</td><td>0.000270</td><td>Electrical</td><td>0.000270</td><td colspan="2" rowspan="2">65</td></tr>
<tr><td>Mechanical</td><td>0.000250</td><td>Mechanical</td><td>0.000250</td></tr>
</table>

6.6. Planned Unavailability Due to Maintenance

6.6.1. VSC HVDC Converter Modules Planned Unavailability

Based on publically available information and judgements made by SKM, data has been provided to enable assessments to be made of unplanned unavailability due to failures. This includes all main equipments required for the connection of a HVDC system.

When considering planned unavailability due to maintenance it is recognised that a complete maintenance programme would be required to assess the scheduling of outages, optimisation of maintenance teams and spares availability, which becomes particularly complex for an interconnected network. Where assets are installed offshore then additional factors associated with access and specialist equipment such as vessels can become a dominant factor.

Planned maintenance therefore needs to be considered on a project by project basis, taking into account not only project design factors but also aspects such as availability of resources, philosophy on spares holding and other factors which will be used by the operator to economically optimise availability levels across unplanned and planned events taking into account MTTR factors.

Hence, the simplifying assumption made here is that the planned unavailability due to maintenance is dominated by that of the HVDC converters and maintenance on associated equipment would be scheduled during the converter outages.

▪ **Table 11 Assumed HVDC Converter Unavailability Due to Scheduled Maintenance**

Maintenance Scenario	Total Annual Outage (hours)	Unavailability %
Base Case Maintenance	48	0.548
Best Case Maintenance	24	0.274

7. Availability Model Approach

A number of approaches exist for the calculation of unavailability of electrical networks. SKM utilised its extensive knowledge in the development of availability and economic tools to derive a tool with a high degree of flexibility that could be easily adapted to model not only HVDC elements but also associated HVAC elements so a complete interconnector set of assets could be represented. This flexibility allows meaningful comparison to be performed of not only different HVDC arrangements but also comparison between HVDC and HVAC schemes.

The purpose of the development of the tool for this project is to allow the target availability of a predefined technical configuration to be calculated. The fundamental basis of the tool is to follow an analytical technique for quantitative assessment of probabilities based on the average interruption rate method[12]. This allows reliability functions to be determined based on independent component failure rates, times to repair which determine forced outages and add scheduled maintenance durations to determine a probability of availability. Treatment of series and parallel assets is based on the same approach and allows the use of sub-systems to be combined to represent a complete system. This approach has been applied extensively in reliability and availability studies undertaken in HVAC and HVDC transmission. Alternative approaches of Frequency/Duration or a full Markov approach were not considered appropriate given the level of model complexity that would result as well as the need to consider not only VSC converters but also cables and HVAC components. Additionally, it is recognised that there is a scarcity of data which would be needed to follow such approaches.

The Excel based tool makes extensive use of drop down menus and pre-set “factors” to facilitate not only easy construction of different models but performance of sensitivity checks on different sets of assumptions. Such assumptions are necessary for some aspects of the technology where evidence of operating experience is not supported by data. Here qualitative engineering judgements are applied to derive values which can be utilised in the quantitative assessment.

The tool is based only on the consideration of absolute availability with no inclusion of generation load factors or other approaches to weight assessment of availability.

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[12] Reliability Assessment of Large Electric power Systems R. Billinton & R. Allan Plenium Press.

8. Availability Model Description

8.1. General Approach

The calculation of the overall availability of any connection configuration will be determined by the total availability of each item of equipment that makes up the connection. However, as each piece of equipment may have a different impact on the connection capacity available during any outage and also an individual MTTR associated with it, a simple summation of the availability figures is not sufficient to cover all of the potential converter arrangements as discussed in Section 5. SKM have therefore developed a spreadsheet availability tool which considers the component parts associated with the connection, grouping components together where appropriate, and calculates the overall availability of the connection.

The effect of unplanned outages associated with any component on the overall connection availability can be determined from three factors:

- Failure Rate - the average number of failures per year of the component
- Mean Time To Repair - the number of days required to repair the component after a fault
- Available Capacity - the percentage of the capacity of the connection which can still be used during the fault and associated MTTR.

Similarly, the effect of planned maintenance of the equipment can be determined by the following three factors:

- Maintenance Frequency - the number of times in a year that an outage is required on the component to undertake scheduled maintenance
- Maintenance Duration - the number of days required to undertake the scheduled maintenance
- Available Capacity (%) - the capacity of the connection which can still be used during the outage of the component due to the maintenance.

It is recognised that for a large transmission system the optimisation of maintenance schedules requires extensive planning based on the maintenance intervals for components, the duration of maintenance activities, number of maintenance teams available and the maintenance plans for interconnected networks. The approach taken here is simplistic and will tend to overstate unavailability due to scheduled outages, this could be refined by adjusting individual maintenance durations or grouping activities.

By identifying these factors for each component (or group of components where appropriate), SKM have built up availability models which consider all major items of equipment associated with VSC HVDC and associated HVAC connection designs.

8.2. Availability Model

The model is based on a database of MTBF, MTTR and Available Capacity % figures for each item of equipment associated with HVDC interconnectors. The MTBF and MTTR data is as described in section 6 with available capacity % data being dependent on the specific design of a project (converter arrangements will determine the available capacity figure).

The model allows a list of components to be input as well as specific parameters associated with them such as cable length, converter arrangements etc. Based on the input data the model will calculate the associated planned and unplanned availability figures for a specific project using the method outlined in section 7. The effect of redundancy within equipment or components in parallel is accounted for by setting the correct available capacity value for each component.

A full User Guide for the availability model is provided in Appendix A – User Guide.

9. Modelling Results

9.1. Converter Arrangement Availability

9.2. Example Projects

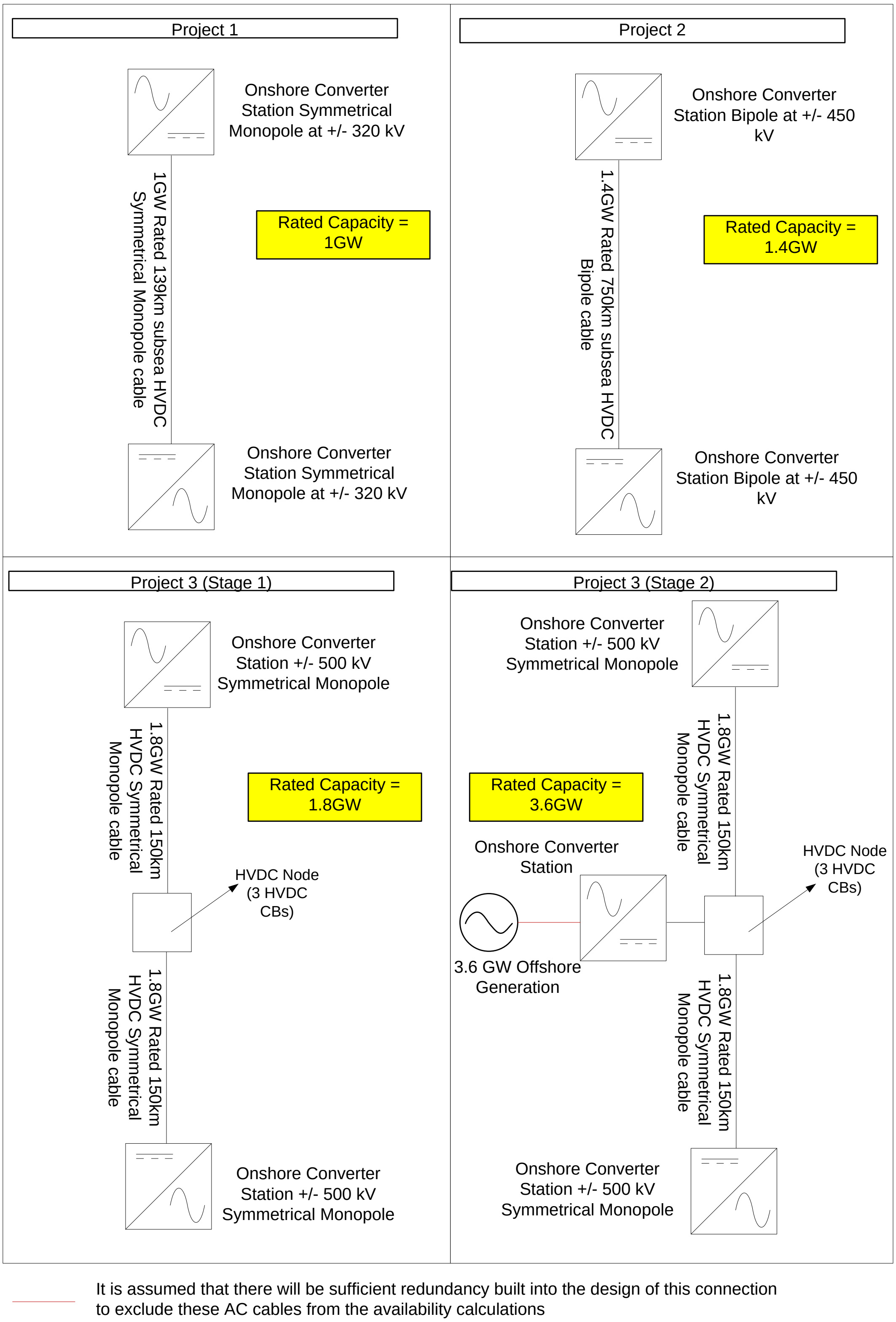
In order to determine appropriate target availability figures it is necessary to model example interconnectors which are representative of the planned interconnectors of the next 5 years. Three project examples were chosen in agreement with Ofgem and these are described below and shown in Figure 4. The converter types chosen (VSC or LCC) were based on what is deemed the most appropriate for each project. However as the unavailability figures used for each type of converter are the same (see section 6.2) at this stage, the converter technology will make no difference to the overall availability figures calculated.

Project 1 – 1000 MW Symmetrical Monopole (VSC), 139 km connection with 110km offshore and 29 km onshore. This is similar to that envisaged for the NEMO project.

Project 2 – 1400 MW Bipole (LCC), 750 km with 700 km of offshore cable and 50 km of onshore cable, a possible long interconnection.

Project 3 – This project considers a two stage multi-purpose development where:

- Stage 1 is a 1800 MW symmetrical monopole (VSC), 300km interconnector with an onshore HVDC node consisting of 3 HVDC circuit breakers (CBs) splitting the connection into two 150 km sections. Each 150 km section consists of 140 km offshore and 10 km onshore. At this first stage, the project will be considered as a point to point 1800 MW interconnector.
- Stage 2 will consider 3600 MW of generation is connected to the HVDC node via an HVDC converter forming a multi-terminal arrangement. The interconnector now has a capacity of 3600 MW during normal operation (with 1800 MW delivered to each side of the interconnector). During an outage of either of the 150 km sections, the capacity of the interconnector is restricted to 1800 MW.



- **Figure 4 - Example Projects**

9.3. Availability Results

9.3.1. Overall Availability Results

The expected availability of each of the example projects is shown below in Table 12. These results are based on the base case MTBF figures.

▪ **Table 12 – Calculated Base Case Availability Figures for Example Projects**

Example	Converter Fault Unavailability (%)	Cable Fault Unavailability (%)	Other Equipment Fault Unavailability (%)	Scheduled Maintenance Unavailability (%)	Overall Availability (%)
Project 1	0.65	1.30	N/A	0.55	97.50
Project 2	0.33	3.48	N/A	0.27	95.92
Project 3 (1)	0.65	2.79	0.19	0.55	95.83
Project 3 (2)	0.49	1.39	0.09	0.82	97.20

Projects 1, 2 and 3 (Stage 1) show the difference in the use of symmetrical monopole converters to bipoles with the bipole availability being double that of a monopole. The dominant component in the availability calculations in all cases is the cables, particularly in Project 2 which has very long cable length and the cable accounts for 85% of the total unavailability.

Another key point highlighted by the results is that the application of the interconnector will have a significant effect on the availability as demonstrated by Project 3. When the project is considered to be a symmetrical monopole point to point interconnector, the availability is 95.83%. However, this is increased when the mid-point converter is included in the connection, despite the additional components being included in the design. This is because an alternate running arrangement now exists during any fault (either cable or converter) which allows 50% of the interconnector capacity to be achieved.

9.3.2. Sensitivity to Converter MTBF

As discussed in Section 6 the MTBF associated with HVDC converters is the area with the most uncertainty. To determine the sensitivity of the overall availability figures to these assumptions, a worst case and best case has been calculated based on a range of MTBF for converters.

The results for each project are shown in Table 13 and Table 14.

- **Table 13 - Calculated Availability Figures for Example Projects with Worst Case Converter MTBF Assumptions**

Example	Converter Fault Unavailability (%)	Cable Fault Unavailability (%)	Other Equipment Fault Unavailability (%)	Scheduled Maintenance Unavailability (%)	Overall Availability (%)
Project 1	0.98	1.30	N/A	0.55	97.18
Project 2	0.49	3.48	N/A	0.27	95.76
Project 3 (1)	0.98	2.79	0.19	0.55	95.50
Project 3 (2)	0.73	1.39	0.09	0.82	96.96

- **Table 14 - Calculated Availability Figures for Example Projects with Best Case Converter MTBF Assumptions**

Example	Converter Fault Unavailability (%)	Cable Fault Unavailability (%)	Other Equipment Fault Unavailability (%)	Scheduled Maintenance Unavailability (%)	Overall Availability (%)
Project 1	0.33	1.30	N/A	0.55	97.83
Project 2	0.16	3.48	N/A	0.27	96.08
Project 3 (1)	0.33	2.79	0.19	0.55	96.15
Project 3 (2)	0.24	1.39	0.09	0.82	97.45

The most significant effect on availability is seen on the projects which use symmetrical monopoles as the converter arrangement. The maximum variation occurs on Project 3 (Stage 1) which has a 0.65% variation between best and worst case.

9.3.3. Sensitivity to Cable MTTR

As discussed in section 6.5.1 the MTTR for submarine cables could vary significantly depending on project location. To determine the sensitivity of the availability figures to this, a worst case assumption was made regarding average offshore cable MTTR of 90 days. The results are shown in Table 15.

- **Table 15 - Calculated Availability Figures for Example Projects with Worst Case Cable MTTR Assumptions**

Example	Converter Fault Unavailability (%)	Cable Fault Unavailability (%)	Other Equipment Fault Unavailability (%)	Scheduled Maintenance Unavailability (%)	Overall Availability (%)
Project 1	0.65	1.69	N/A	0.55	97.11
Project 2	0.33	4.73	N/A	0.27	94.67
Project 3 (1)	0.65	3.78	0.19	0.55	94.83
Project 3 (2)	0.49	1.89	0.09	0.82	96.71

It can be seen that an increase of average offshore cable MTTR to 90 days has a significant effect on the overall availability, particularly for Project 2 which has the longest cable length, here the availability is reduced from 96.06% to 94.67%.

9.3.4. Sensitivity to Maintenance

As discussed in section 6.6 the planned unavailability due to maintenance could vary significantly between projects dependent on the approach taken to the planning and execution of maintenance activities, particularly if offshore assets are utilised, all other factors being base case values.

- **Table 16 - Calculated Availability Figures for Example Projects with Best Case Maintenance Assumptions**

Example	Converter Fault Unavailability (%)	Cable Fault Unavailability (%)	Other Equipment Fault Unavailability (%)	Scheduled Maintenance Unavailability (%)	Overall Availability (%)
Project 1	0.65	1.30	N/A	0.27	97.77
Project 2	0.33	3.48	N/A	0.14	96.06
Project 3 (1)	0.65	2.79	0.19	0.27	96.10
Project 3 (2)	0.49	1.39	0.09	0.41	97.61

10. Conclusions

10.1. Main Conclusions

The results presented in section 9 show that there are significant variations between projects in expected availability. The most significant factor in the variations between the projects is the cable length. Two projects which are identical apart from cable length could have very different calculated availabilities simply due to the length of cable. This can be demonstrated by simply changing cable route length in the model and for example Project 2 with an alternative subsea cable distance of 350 km rather than 700 km, the calculated availability would change from 95.92% to 97.66%.

As a significant proportion of unplanned outages are associated with the cables, the MTTR of these cables will have a great effect on the overall availability. In international interconnectors where a large proportion of the cable route is offshore, the weather conditions will have a large impact on the MTTR. As weather conditions can vary significantly depending on project location the average MTTR is a project specific factor. It can be seen in section 9 that the overall availability of Project 2 is decreased from 95.92% (Table 12) to 94.67% (Table 15) when increasing the offshore cable MTTR by 33%. In some extreme conditions the average MTTR may be longer than this even.

Even within a single two-stage project the variation in availability can be significant as demonstrated by the results obtained for Project 3 Stage 1 and Project 3 Stage 2. This is due to the addition of a mid-point converter which has only a relatively small effect on the number of outages, but a significant effect on the available capacity during these outages.

A simple approach to setting availability targets cannot be justified considering the wide variation of availability figures calculated in this study. Within the projects considered and the potential range of project specific sensitivities (cable MTTR and planned maintenance) which could be applied to individual projects, the range of availability figures calculated is between 94.67% (Table 15) and 97.77% (Table 16), assuming the average converter MTBF in all cases. Calculating target availability figures on a project by project basis will result in targets which are much more closely matched to the expected availability of the connections based on the approach used in this study. Project factors include not only the configuration of the system but also the lengths of cable involved, methods of cable installation and protection and the MTTR following any fault which will be strongly influenced by the climatic conditions of the areas through which the interconnector passes.

Factors such as planned maintenance are strongly influenced by the approach taken by the operator of the interconnector as well as the design of the technologies utilised, hence are more appropriate for the setting of targets which can be applied across the regulatory regime. The actual approach adopted by the operator of an interconnector may in part be determined by the target availability figures that are set, although manufacturer's recommendations will also need to be considered. The scheduling of outages will be a significant factor in the overall availability and this will be a project specific factor as it depends on the arrangement of equipment. To demonstrate how scheduled maintenance can vary between projects the unavailability due to planned outage figures reported for existing HVDC projects vary between 0.14% to over 10% (with some extreme cases seen in particular years)[13,14]. It is therefore difficult to use average figures from existing projects to determine accurate planned maintenance unavailability figures for projects being installed or planned now.

Interconnector experience, particularly with VSC technologies, more recently developed cable technologies and cable installation and protection techniques is still limited. Therefore, consideration needs to be given to the regular review of certain aspects of reliability and availability data sources.

10.2. Recommendations

a) Based on the approach taken it is suggested that for example Project 1, which is similar to that envisaged for Project NEMO, that the target level of availability would be in the range of 97.1% to 97.8% considering the HVDC converters and HVDC cables. These figures would be reduced to 97.0% and 97.7% if the HVDC converter transformers were also included. A further refinement of the model would be o also include AC switchgear into the calculations.

b) Given the scarcity of substantiated data generally for offshore transmission systems, and VSC technology in particular, it has been necessary for SKM to make assumptions as part of this work. As more experience is gained the models can be updated and sensitivity analyses performed to understand the key elements which impact on availability and those that can best be influenced at the design, construction and operational phases of any project. Hence, the assumed data for VSC converters and HVDC cables should be considered for review more frequently than for HVAC components such as transformers and switchgear. Initially it is recommended that VSC converter and HVDC switchgear and cable data should be reviewed at intervals of 6 months and the model refreshed. Data for HVAC switchgear, transformers etc. should not need to be reviewed more frequently than every two years.

c) The calculated availability for HVDC schemes is very dependent on the assumptions made concerning converter reliability and MTTR, particularly for offshore components. Sensitivity studies within this report demonstrate the potential impact that converter reliability assumptions may have, however it needs to be recognised that the approach taken to improve converter availability (e.g. HVDC module redundancy, configuration design redundancy, location of O&M teams etc.) will in part be reflected by the design of the cap and floor approach. This of course then reflects back to what is economically justifiable comparing the cost of achieving improved availability compared to the benefit for the project stakeholders and of course the consumer. Further study combining economic aspects and availability “options” is likely to be necessary.

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[13] M.G. Bennett, e.a., "A SURVEY OF THE RELIABILITY OF HVDC SYSTEMS THROUGHOUT THE WORLD DURING 2007 – 2008", Cigré session 2010

[14] M.G. Bennett, e.a., "A SURVEY OF THE RELIABILITY OF HVDC SYSTEMS THROUGHOUT THE WORLD DURING 2009 – 2010", Cigré session 2012

d) HVDC converter configurations and technologies over the next 5 to 8 years are likely to be strongly influenced by project specific factors. Whilst it is expected that there will be a significant number of VSC based symmetrical monopole schemes, particularly where multi-purpose projects are required, it is also likely that LCC technology will continue to be used in specific project applications.

e) Planned maintenance is difficult to predict by using previous project data due to the project specific nature of the scheduling of outages. The co-ordination of outages to minimise downtime, whilst also providing sufficient maintenance to prevent an increase in unplanned outages requires detailed studies on an individual project basis. It may therefore be necessary to study this area in more detail when determining target availability figures for scheduled maintenance.

Appendix A – User Guide

A.1 General

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

- 4 Project example sheets (Project , Project 2, Project 3 (1), Project 3 (2)
- Converter Data
- Cable Data
- Other

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.

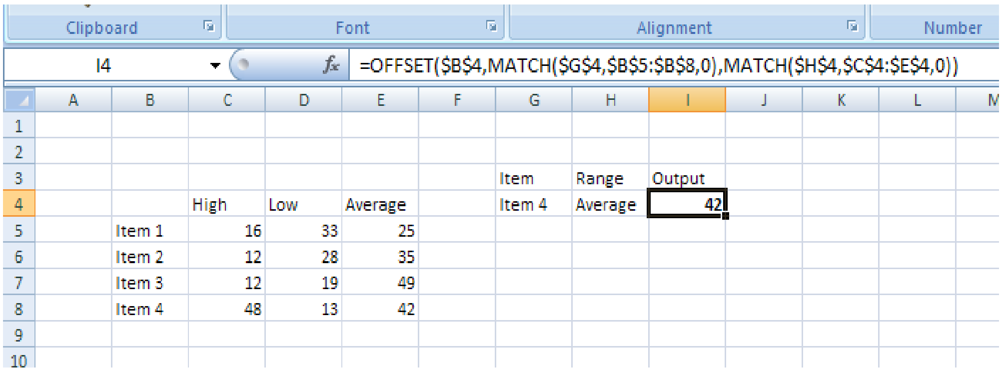
The Converter Data, Cable Data and Other Equipment worksheets contain all the data used in the studies as a database accessed by the project worksheets and also allows for any additional data to be input directly by the user as required. The data in these worksheets is consistent with that utilised in 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:

A.2 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:



	A	B	C	D	E	F	G	H	I
1									
2									
3							Item	Range	Output
4			High	Low	Average		Item 4	Average	42
5		Item 1	16	33	25				
6		Item 2	12	28	35				
7		Item 3	12	19	49				
8		Item 4	48	13	42				
9									
10									

- **Figure 5 - 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.

A.3 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 3 projects detailed in the main report.

The availability data associated with each item of equipment selected is automatically loaded into 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 SKM 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 0 to 5 of this user guide.

A.3.1 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 6.

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.

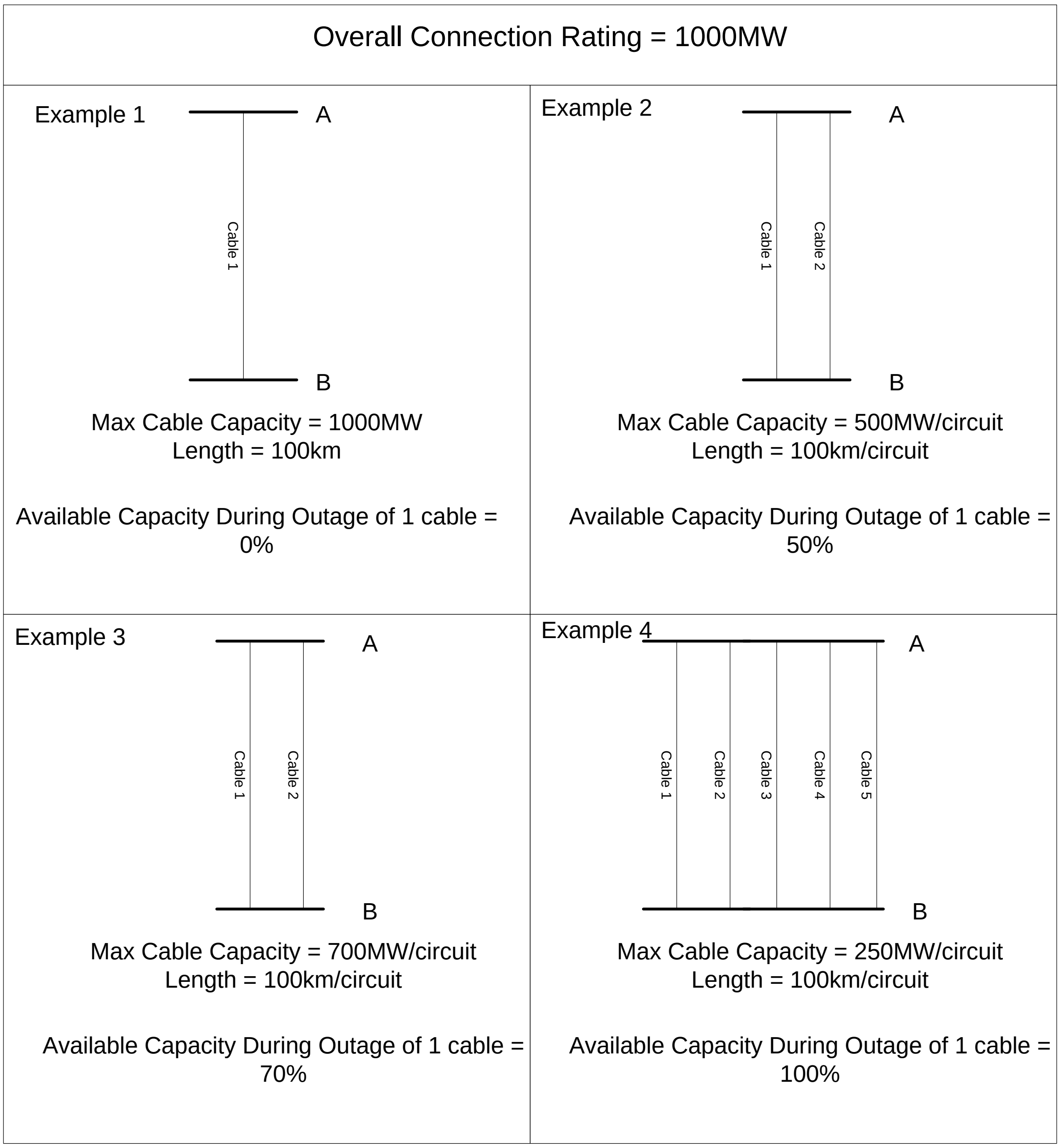
Class – Selects if the piece of equipment is associated with the VSC converter, a cable connection or any other equipment (e.g. transformers, switchgear etc).

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 form 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 6 - 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 500MW 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 1,400MW for a 1000MW interconnector. In the event of an outage of one of the cables the available capacity is therefore 70% (700/1000MW). 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 1000MW 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.

A.3.2 Availability calculation – Scheduled Maintenance

Scheduled maintenance is discussed in more detail in the main 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 (Best, Average or Worst).

A.3.3 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 project 1 worksheet only and automatically carried through to the remaining project worksheets.

A.3.4 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.

A.3.5 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.

A.4 Converter Data

This spreadsheet should only be used if the base availability data provided by SKM 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.

A.4.1 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.

A.4.2 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 specifically included for project 3-2.

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 row 54 (i.e. 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.

A.4.3 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.

A.4.4 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 (1000MW 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 SKM 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 A.3.4, i.e. insert an entire new row and copy and paste the formula from the row above.

A.5 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:

A.5.1 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 1.5m.

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 A.3.4.

A.5.2 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 A.3.4.

A.5.3 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 connnection 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 A.3.4.

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 SKM.

A.6 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 A.3.4.