Reliability and Economic Evaluation of High Voltage Direct Current interconnectors for large-scale renewable energy integration and transmission

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Abstract

This paper outlines a methodology for assessing the reliability and cost of operating multi-terminal High-Voltage Direct Current (HVDC) transmission interconnectors with a comparison being drawn on the benefits of using modular multilevel converters (MMC). The MMCs random failure/repair processes are modelled as either a two-state or three-state Markov processes. A time-sequential Monte Carlo simulation is used to simulate the operation of the modified IEEE Reliability Test System (RTS) with the MMC-HVDC interconnectors, over a one-year period. The RTS accommodates variable wind generation, and the results confirm the use of HVDC as tie lines provide geographical aggregation, allowing for much greater penetration of variable generation in the connected systems. The three-state MMC model, in addition to the binary up and down states, consists of a derated state in which the converter voltage is reduced to 57.7 % of its nominal voltage. The additional state was found to reduce the downtime of the link by 89.6 %, increasing the available flow capacity by 458 GWh/year. The increase flow capacity leads to an increase in arbitrage revenue of €3.17m per year and a reduction in project payback time of 1.5 years.

1 Introduction

Integration of variable generation into the world's electrical systems presents a major challenge for system operators (SOs) when it comes to balancing supply and demand. In 2017, 55% of installed generation capacity within the EU was in the form of wind power [1] and overall renewable energy now accounts for 28% of total energy production within the EU surpassing other forms of energy production such as coal and natural gas [2]. This trend in renewable integration is set to continue, in order for nations to meet their climate agreements.

The increased level of offshore wind development in the North Sea along with policy and regulatory change, which includes the need to continue to drive down costs, will see greater project collaboration and sharing of electrical infrastructure leading to regional grid developments in areas such as the North Sea to facilitate connections between mainland GB and the Nordic region [3]. Meanwhile, to help balance the variable generation across Europe and maintain system security, SOs, through the European Network of Transmission System Operators for Electricity (ENTSO-E), are looking to increase the current level of interconnection [3]. The European Parliament has set a target for member states to achieve an interconnection capacity of 10% of their generation capacity by 2020 [4] with the aim to moving towards a European Super grid [5].

High-Voltage Direct Current (HVDC) interconnectors not only reduce the amount of unserved energy in a system but also allow the SOs to take advantage of arbitrage opportunities, which can result in high utilisation of the interconnector. For example, Skagerrak 4, the VSC-HVDC interconnector between Norway and Denmark, had a 93% of its available capacity in 2016 [6]. The use of the line in this manner aids in the reduction of wholesale energy prices as well as increasing system security by providing benefits through [7]: (i) deferral of investment in generation to meet peak demand; (ii) reduction in fuel and operating costs by substituting expensive generation units for cheaper generation; and (iii) reduced frequency control costs, leading to a reduction in energy prices for the consumer. As such, the reliability of the line is of great importance to its stakeholders.

There are two main types of HVDC converter technology, Line-commutated Converters (LCC) and Voltage-source Converters (VSC). VSC is currently the favoured technology due to its ability to be used in the connection of passive systems. The half-bridge based Modular Multilevel Converter (MMC) has become the favoured VSC topology and has come to dominate the HVDC market, in both tie lines and the connection offshore wind, due to its superior power losses, power quality, and failure management in severe fault conditions [8]. A schematic of the half-bridge MMC is given in Figure 1. Each phase of the three-phase input is divided into two arms (a positive arm and a negative arm), each composed of a series connection of submodules (SMs). Each SM is comprised of a half-bridge arrangement, the switching of the SMs are precisely coordinated to produce a sinusoidal output voltage, removing the need for AC filters. The current method to increase the reliability of the MMC is to add redundant SMs, in terms of standby SMs, into each arm of the converter.

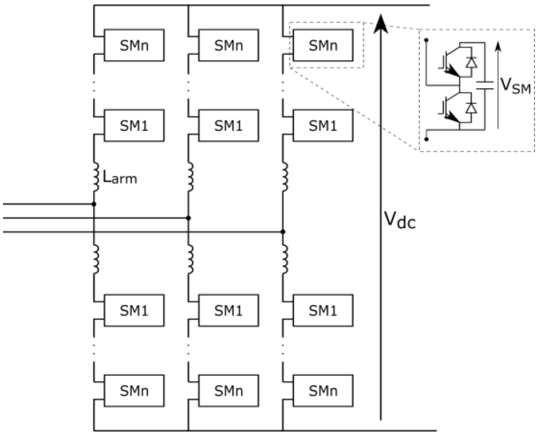


Figure 1: The Modular Multi-level Converter with a half-bridge submodule – Adopted from [8].

A number of areas affecting the reliability of MMCs have been analysed in the literature, including two half-bridge MMC topologies [8], and benefits of preventative maintenance [9]. Both papers refer to a two-state MMC, with the ability at any given time to be in a fully working (up) state or failed (down) state. There has been little work in the development of a derated state MMC, with the ability to operate somewhere in the middle of the up and down states. One way to operate an MMC with a faulty leg while still producing a three-phase output is presented in [10], this provides a fault ride through solution, rather than simply adding redundancy into the MMC, providing a very cost efficient solution. However, no work discusses the operational benefits of adding a derated state to the MMC. This paper will look to address this issue by analysing the benefits of operating the MMC in a derated fashion on the downtime, availability, and flow capacity of the HVDC interconnector. This paper will denote the converter with the ability to operate in a derated state, or third state, as MMC_3 and the original two-state converter as MMC_2. A bipolar MMC-HVDC transmission link is then used as an interconnector for balancing inter-area power flows between the three areas of the IEEE Reliability Test System [11]. The system security (i.e. the ability to balance generation and demand at all times) is measured by a suite of indices for both MMC models. To justify investment opportunities, a revenue generation stream is devised based on an arbitrage scheme between two markets namely, GB [12], and France [13].

The rest of the paper is organised as follows: Section 2 will present a formal description of the mathematical models; Section 3 will compare the use of MMC_3 and MMC_2 within an HVDC interconnector along with the resulting financial differences. Section 4 is the conclusion.

2 Model Description

2.1 System Exemplar

The IEEE-RTS consists of three areas with the total load and generation values given in Table 1. The system exemplar used in this paper modifies the IEEE RTS system by replacing the AC tie lines with bipolar MMC-HVDC links to connect the three areas. To demonstrate the benefits of interconnection and different MMC models as the level of renewable integration increases, the standard RTS is also be modified by replacing generation units in the three areas with Wind Turbine Generators (WTGs) in varying proportions from 0-100 % of generation capacity.

Quantity	*Value (GW)*
Total Generation Capacity	3
Variable Generation	0
Peak Load	2.85

Table 1: IEEE RTS data (per area)

2.2 Model Assumptions

In this paper, it is assumed that the failure/repair processes for all components, including the MMCs, are modelled as time-continuous Markov processes [14]. It follows that for a two-state time-continuous Markov process, the transition time to jump from the *up* state to the *down* state follows an exponential distribution, $f(t) = \lambda e^{-\lambda t}$, in which λ is the rate of transition (i.e. failure rate). The *mean* (expected) transition time is therefore $1/\lambda$ (i.e. Mean Time to Failure or MTTF). Following a similar argument, one can define a Mean Time to Repair (MTTR) and a repair rate μ for state transitions from the *down* state to the *up* state. In this paper, all components are modelled as two-state time-continuous Markov processes with the exception of the MMC which has two distinct models namely, a two-state MMC_2 and a more expansive three-state MMC_3. The relevant data for the components used in the case studies are given in Table 2 taken from [11], [15]-[16].

Component	***MTTF (y)***	***MTTR (h)***
230 kV GIS Switchbay	250	120
Transformer	95	1008
Submodule (SM)	64.744	60
Control System	1.6	3
MI Cable per 100 km	10	1440
WTG (Siemens SWT 3.6)	4.5625	80

Table 2: Data for the System Exemplar

2.3 The MMC-HVDC Interconnector

The simulated MMC-HVDC interconnector consists of two 500MW, 230kV, 200 km transmission lines to create a 1GW bipolar arrangement as shown in Figure 2. The use of a bipolar arrangement is generally favoured due to its ability to operate at half-capacity in the case of faults in one of the two lines. The state space diagram for the simulation of the link using MMC_2 is presented in Figure 3a. The use of MMC_3 allows an additional three system states as seen in Figure 3b with the converter voltage in the derated state being 57.7% of its nominal voltage, as determined in [10]. The MMC consists of 20 submodules (SM) in each of the six arms [17] with no redundant SMs, to allow for comparison of the proposed MMC_3 to the current industry standard.

The MMC-HVDC link is used as an interconnector (i.e. tie line) for balancing inter-area power flows between the three areas in the system exemplar. Two case studies are considered namely, a PtP case to connect two areas and an MTDC case to connect all three areas. It is assumed that the input and output nodes of the system, that is the transmission and distribution systems within each area, are 100% reliable.

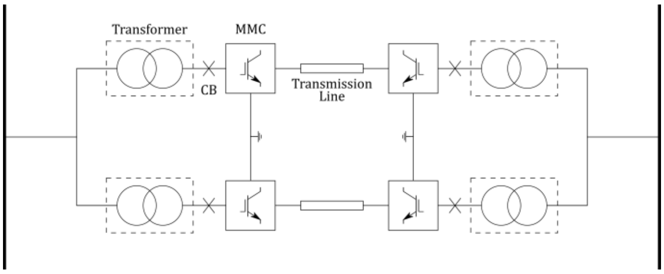


Figure 2: Bipolar MMC-HVDC arrangement, MMC- Modular Multilevel Converter; CB – GIS Switchbay

For the analysis replacing conventional generation units with WTGs, wind data is taken from [18], which provides a realistic time series for the output of a number of WTGs in a user defined geographical location. The data gathered for areas one, two and three, used in this simulation are from typical offshore sites in the UK, Denmark and Germany respectively, employing a Siemens SWT 3.6 107 in all cases.

2.4 Underlying Monte Carlo Simulation

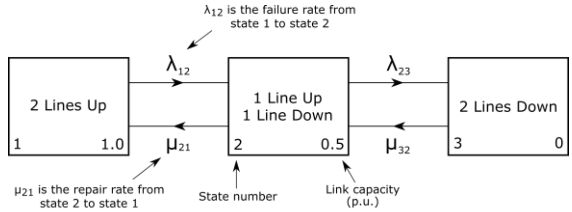
The operation of the MMC-HVDC considering the state space diagrams in Figure 3 is simulated using a time-sequential Monte Carlo Simulation (SMC). The key benefit of time-sequential simulation is the ability to simulate realistic phenomena such as weather dependent generation, where the current time step is dependent on the preceding step. Following the Markovian process assumption, one can simulate the operation of the system over a specific chronological time span (e.g. one year) by sampling state transition durations as given in Equation (1).

$$\begin{cases} TTF = -\dfrac{1}{\lambda}\ln(U) \\ TTR = -\dfrac{1}{\mu}\ln(U) \end{cases} \tag{1}$$

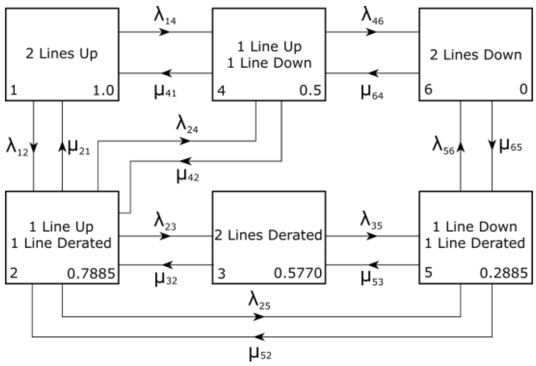
In Equation (1), U is a uniformly distributed random number between 0 and 1. The sequence of TTR and TTF values produce a time-trace for the components' state transitions. For the MMC the state transitions follow the state space models given in Figure 3. The time resolution of the load data, provided in the IEEE RTS, is one hour and as such, the time step used for the simulation is one hour. The rated capacity of generation units within each area is given in [11]. Within each area of the RTS the load and generation were aggregated to form a single supply and demand for each time step and area.
The Energy Deficit (ED) for a system is then calculated at each time step as,

$$ED_t = D_t - GC_t - IP_t \tag{2}$$

In Equation (2), D_t is the system demand at time, t, GC_t is the generation capacity at time, t and IP_t is the interconnection import (or export) power flow to the system. It should be noted that, IP_t is a positive (or negative) dependent on whether the area is importing (or exporting) electricity.



(a) MMC-HVDC Link State Space Diagram for MMC_2



(b) MMC-HVDC Link State Space Diagram for MMC_3.

Figure 3: State space diagrams for a bipolar MMC-HVDC Link

Due to the random nature of a SMC simulation, the error in the simulated values reduces to zero as the number of iterations approaches infinity. To decide the number of iteration needed to produce a result within an acceptable error, a stopping criterion is needed. In this simulation, the relative uncertainty, U_r, in the Loss of Load Expectation (LOLE), is used as the stopping criterion as outlined in [14] and is given by,

$$U_r = \frac{\sigma}{m\sqrt{N}} \leq \alpha = 0.05 \tag{3}$$

Where α is relative uncertainty limit (set to 5% in this case), σ is the standard deviation, m is the mean value of the LOLE index and N is the total number of iterations.

2.5 System Security Indices

The indices relating to system security used in this study look to quantify the ED over the simulation period. A positive ED, as given by Equation (2), is known as a shortfall in supply. The system security is then measured by the indices given in Equations (4) – (8). In all equations T is the total number of time steps (i.e. 8760 for a 1-year simulation), and N is the total number of iterations. Duration of Shortfall (DS) is defined in Equations (4) and measured in hours per year. Equations (5) and (6) define the Loss of Load Expectation (LOLE) - as the mean number of hours per year in which the system is in an energy deficient state - and Loss of Load

Duration (LOLD), which is the mean duration of load curtailment period in hours. Equation (7) gives the Expected Energy Not Served (EENS) in MWh of electricity demand not met over the year. EENS combines both the frequency and the size of any shortfall. Finally, Equation (8) calculates the Total Flow Capacity (TC) of the MMC-HVDC interconnector over the simulation period.

$$DS = \sum_{i=1}^{T} x_i \quad \& \quad x_i = \begin{cases} \Delta t, & ED_t > 0 \\ 0, & ED_t \leq 0 \end{cases} \tag{4}$$

$$LOLE = E(DS) = \frac{1}{N}\sum_{j=1}^{N} DS_j \tag{5}$$

$$LOLD = \frac{1}{N}\sum_{j=1}^{N} \frac{DS_j}{NSE} \tag{6}$$

$$EENS = \frac{1}{N}\sum_{j=1}^{N}\left(\sum_{i=1}^{T} \max\{ED_i, 0\}.\Delta t\right)_j \tag{7}$$

$$TC = \frac{1}{N}\sum_{j=1}^{N}\left(\sum_{i=1}^{T} C_i\right)_j \tag{8}$$

Meanwhile, as a standard measure for estimating the WTG penetration levels, in this paper, the Equivalent Firm Capacity (EFC) [19] is used. The EFC essentially measures the percentage of conventional generation, with 100% availability, which would be required to replace the entire WTG capacity for a given system security level. In this paper, the standard level of system security is taken to be LOLE of three hours as per the standard requirements, which are in force in the UK.

3 Results and Discussion

The immediate effect of using MMC_3 when compared to MMC_2 in the bipolar PtP MMC-HVDC interconnector is a reduction of downtime by 89.6% where downtime is taken as the time when the flow capacity of the link equals zero. Nevertheless, the additional flow capacity of allowing the converter to operate in a derated fashion accounts for only a 6% rise over MMC_2.

3.1 MMC-HVDC Interconnector: Reliability

In this section, the two case studies mentioned in Section 2.3, are simulated and the system security is measured using indices introduced in Equations (4) – (7). In all cases, the results of system indices are compared to an island case (as the control case) with no interconnection. The two distinct models introduced in Figure 3 are used to model the MMCs in order to compare the impact of operating the converters in a derated fashion. The resulting system indices for area one, in the three cases, are presented in Tables 3 for 9% wind penetration level. The EFC used in the simulation was 0.23 [17] which translates to 268MW (9%) of generation capacity replaced with 1165MW of WTGs (i.e. 268/0.23). As expected the best case for all system indices is that with the greatest level of interconnection between areas. The use of MMC_3 is shown to further increase the benefit of interconnection reducing the LOLE, LOLF (Loss of Load Frequency), and the EENS, in both the PtP and MTDC cases. However, the actual benefit provided by MMC_3 is small in this case. In the simulation, the link was clearly underutilised (11.6% of its total flow capacity) and it is suggested that the use of MMC_3 will be more beneficial when the power flow through the link regularly exceeds 50% of flow capacity, as it is here where the benefit of the derated state will be more apparent.

Meanwhile, Table 4 gives the results of the simulation repeated with 41.3% of the generation capacity of the RTS replaced with WTGs. The average power transfer through the link in this case increased to 294MW (29.4% of flow capacity). This increase in the average power transfer through the link is an indication of the increase in the variability of system generation capacity. The use of MMC_3, in this case, provides a greater percentage reduction in LOLE, LOLF and EENS than the reduction provided in Table 3 where the utilisation of the link was also lower.

3.2 Effects of Wind Penetration on System Security Levels

Figure 4 presents the EFC value needed to maintain system security in the simulation as the percentage of the original generation capacity is replaced with WTGs. It can be seen that for a certain level of WTG penetration the EFC is increased with added interconnection. The increase in EFC means that less renewable generation will be needed to meet climate change agreements due to better resource sharing through the interconnector.

Topology	*LOLE (h/y)*	*LOLD (h)*	*LOLF (occ/y)*	*EENS (GWh/y)*
Island	53.55	5.19	10.31	8.117
PtP MMC_2	10.11	2.75	3.82	1.541
PtP MMC_3	9.48	2.46	3.65	1.428
MTDC MMC_2	3.49	1.40	2.44	0.704
MTDC MMC_3	3.46	1.41	2.42	0.702

Table 3: System security indices for area one with 9% renewable generation

Topology	*LOLE (h/y)*	*LOLD (h)*	*LOLF (occ/y)*	*EENS (GWh/y)*
Island	407.3	6.48	62.86	129.7
PtP MMC_2	131.2	7.15	18.38	46.2
PtP MMC_3	121.3	7.47	16.18	42.2
MTDC MMC_2	78.6	6.81	11.58	33.8
MTDC MMC_3	76.3	7.17	10.63	33.2

Table 4: System security indices for area one with 41.3% renewable generation

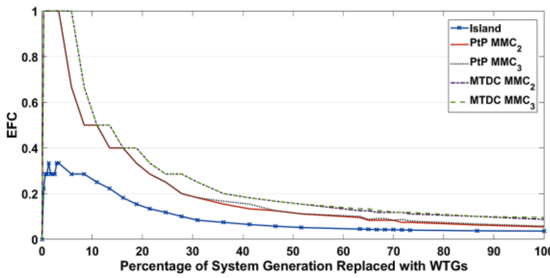


Figure 4: Changes in EFC as wind penetration increase for LOLE 3 hours/year

3.3 MMC-HVDC Link: Revenue Generation

Financial transmission rights is another complex area that will determine the profitability of an interconnector and the final investment decision. There is therefore a need for regulation to aid investment in interconnectors (especially crucial, as with added interconnector capacity market prices will smooth out thus decreasing revenues). The UK Ofgem Cap and Floor mechanism is one such mechanism that guarantees a minimum revenue for 25 years. Ultimately, there are three main income streams from an interconnector namely, market arbitrage; capacity market payments; and ancillary services, such as frequency response. This paper will only take into account the arbitrage revenue, *R*, of the interconnector due to the lack of available data on other income streams. Over a year, *R* is given by,

$$R = \sum_{i=1}^{T} (P_B - P_A)_i P_{act,i} \tag{9}$$

where $(P_B - P_A)$ gives the price difference between the two interconnected markets A and B, $P_{act,i}$ is the actual power flow through the link during the contract block *i*, and *T* is the number of contract blocks within the year. Forecasting the price of one market a year ahead is difficult but forecasting the price difference between two markets, for 25 years, is even more uncertain. In addition, the actual power flow through the line, similar to the power output of generation units, will only be determined by the outcome of auctions such as the day-ahead auction and spot markets, providing contracts for as little as 15 minutes.

The wholesale electricity prices for GB [12] and France [13] for the period from January to October 2016 are given in Table 5. Based on these values the mean arbitrage value would be €6.91/MWh, which is used as the value between the two connected markets A and B for this analysis. MMC_3 provides an additional arbitrage revenue over the year of €3.17m, see Table 6. This is a relatively small increase in revenue, taking into account the project CAPEX (€600m). Figure 5 shows the cumulative cash flow forecast for the three-year construction phase and the following 25-year operational life. A discount rate of 2.5%; yearly maintenance costs of €8.24m [20]; and a link utilisation of 90% were assumed. The cumulative cash flow, with MMC_3 shows a payback time of 21 years from year 0 of the project, 1.5 years less than MMC_2. However, both provide a similar Net Present Value (NPV) of €53.5m and €99.0m for MMC_2 and MMC_3 respectively. The small NPV reflects the risk of the investment. Further analysis shows that a reduction in arbitrage revenue to €6/MWh, based on the assumptions stated, would be enough to result in negative NPV and demonstrates the need for frameworks like the Cap and floor mechanism to guarantee revenue.

	GB (€/MWh)	FR (€/MWh)
High	56.03	79.92
Low	33.85	11.18
Mean	39.41	32.50

Table 5: GB [12], FR [13] mean baseload contracts Jan-Oct 2016

Converter Type	Capacity (GWh/y)	Revenue (m EUR)
MMC_2	7705	53.2
MMC_3	8163	56.4
Increase	458	3.17

Table 6: MMC-HVDC Interconnector capacity over a year for a link using MMC_2 and MMC_3 and the resulting arbitrage revenue

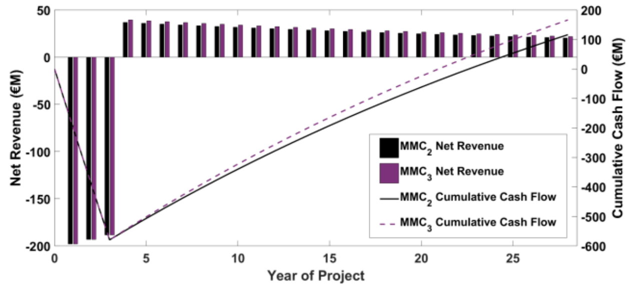
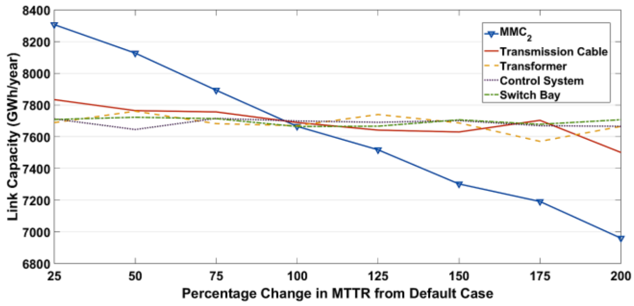
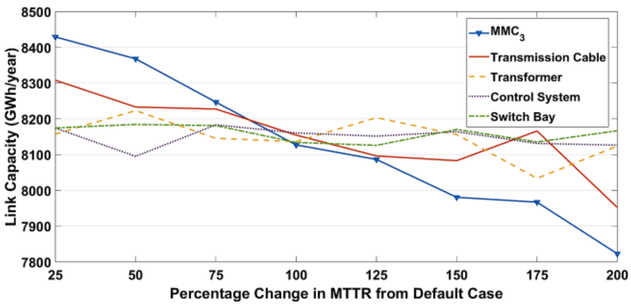


Figure 5: Cash flow diagram for the 25-year life of the interconnector, only including arbitrage revenues



(a) MMC-HVDC Link with MMC_2



(a) MMC-HVDC Link with MMC_3

Figure 6: Interconnector sensitivity to Component Repair Time

3.4 Sensitivity Analysis

In the section, a sensitivity analysis is conducted to better understand the component effects on the reliability of the HVDC interconnector. Figure 6 shows the effects of MTTR of the components on the flow capacity – see Equation (8). The use of TC provides a good measure of the link health throughout the year as it is a function of the flow capacity at each time interval. To perform the sensitivity analysis, the MTTR given in Table 2 for all components within the interconnector were varied from 25% to 200% of their nominal values in 25% increments. It can be seen from the figure that the flow capacity is strongly sensitive to variations in the MTTR in both MMC cases. The high sensitivity toward the converter's downtime clearly indicates the need for an improved maintenance regime for the converters (and the link as a whole). Having redundant SMs within the converter arms could also help greatly improve the sensitivity toward converter downtime. In this paper, however, the focus has been to compare the two distinct models for the MMC and therefore studying maintenance regimes however is out of the scope of this study.

4 Conclusions

This paper has presented a methodology for assessing the reliability of an HVDC link, and the associated effects of adding an additional, derated, state to the MMC. The benefit of adding this state was found to be beneficial on the reliability of the link, reducing downtime by 89.6%, but provided only a small benefit in terms of additional revenue of 3.17m per year. Reliability of the link is found to be highly sensitive to the repair rate of the MMC, modelled in this report, but the implementation of an additional state does reduce the sensitivity. Two case studies have been analysed to demonstrate the benefit of increased interconnection and the benefit of a derated operation of the MMC. A MTDC case was found to provide the greatest system security as the level of variable generation increased, while the benefit of a derated state MMC resulted in minimal additional benefit. Having outlined the benefits of MMC_3 it should now be compared to that of the current industry standard of adding redundancy into the arms of the converter, in terms of stand-by SMs.

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