A Review on VSC-HVDC Reliability Modeling and Evaluation Techniques

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Abstract. With the fast development of power electronics, voltage-source converter (VSC) HVDC technology presents cost-effective ways for bulk power transmission. An increasing number of VSC-HVDC projects has been installed worldwide. Their reliability affects the profitability of the system and therefore has a major impact on the potential investors. In this paper, an overview of the recent advances in the area of reliability evaluation for VSC-HVDC systems is provided. Taken into account the latest multi-level converter topology, the VSC-HVDC system is categorized into several sub-systems and the reliability data for the key components is discussed based on sources with academic and industrial backgrounds. The development of reliability evaluation methodologies is reviewed and the issues surrounding the different computation approaches are briefly analysed. A general VSC-HVDC reliability evaluation procedure is illustrated in this paper.

1. Introduction

VSC-HVDC has been widely used for the integration of renewable generations as well as the interconnection of different systems [1]. The reliability evaluation of VSC-HVDC attracts more and more attention during recent years due to its major impact on the profitability of the system and thus the potential investors. The latest development of modular multilevel converter (MMC) based HVDC requires a large amount of power electronic devices with sophisticated control systems. This to some extent makes the reliability of the system even important in determining if these projects are technically and economically viable. However, despite the many efforts been made on the development of VSC technology [2, 3], the techniques for its reliability assessment and the accumulation of the associated reliability data has not gone yet far enough. This paper contributes to provide an overview of the reliability evaluation procedures for VSC-HVDC considering its latest development.

The process of reliability assessment normally consists of component reliability modeling, system state determination and reliability indices calculation [4]. In order to assess the reliability of VSC-HVDC, the key components which significantly affect the reliability of the system need to be modeled. State space techniques based on Markov process are effective ways for system reliability modeling [5, 6]. The model requires the collection of the corresponding reliability statistics for the key components. The reliability figures depend largely on the topology of the converters and also the configurations of the systems. Cigré has analyzed the HVDC transmission projects throughout the world and recommended some statistics for reliability studies [7], including energy availability/utilization,
forced/scheduled outage rates, mean time to first failure (MTTFF) [8] and mean time to repair (MTTR).

The energy availability defines the percentage of time that the system is expected to be operational, which has a great impact on revenue [9]. It is different from reliability as a fast repairable system can have high availability but low reliability. However, for some systems having a certain level of redundancy, repair may improve both reliability and availability [10]. The forced/scheduled outage rates as well as the MTTR and MTTF are statistics that are normally obtained from the existing projects [11-14]. These data reflects the performance of each component in the system and will be used as inputs for system reliability calculations.

Based on the developed reliability model, the system reliability indices are normally evaluated by analytical [6, 12, 14, 15] or Monte Carlo simulation methods [11, 16, 17]. Many of the state space concepts are effective for both methods as the main difference between them lies in the process of generating the system states. Analytical methods require the system to be represented by mathematical models and various mathematical approaches are developed to evaluate the system reliability, whereas Monte Carlo simulation techniques estimate the reliability indices by simulating the process and random behavior of the system model. A general problem is the requirement of large computation time due to the large number of possible system states associated with a practical composite system. However, analytical approaches can provide accurate adequacy indices with less computation time when suitable mathematical models are developed while simulation techniques are employed in cases where the required availability indices cannot be readily obtained using analytical techniques.

Many techniques have been proposed for analytical evaluations. A widely used technique is known as the Capacity Outage Probability Table (COPT), which is an array of different system capacity levels and their corresponding probability of existence [4]. This is a relatively straightforward manner and to be applied for analyzing HVDC system energy availability [9, 12]. Alternatively, the system operational behavior can be represented by an event tree, based on failure modes and effect analysis to deduce the expected system failure modes [18]. Considering the latest MMC and CTL converter topology, the k-out-of-n method is proposed to be used in the state space technique for the inclusion of converter power modules [15]. A method based on the Bayesian Network can also take the availability data of MMC sub-modules into account in the developed reliability model [19].

Monte Carlo simulation techniques are seen to be applied to make comparisons of the reliability of different multi-terminal DC (MTDC) network configurations in [20] where the effect of weather conditions and the availability of maintenance have been addressed. The results of the reliability analysis are claimed to be extremely sensitive to the input assumptions used. Combined utilization of both analytical and simulation methods are seen in [21] for evaluating the system reliability including protection failures. A method combing pseudo-deterministic and Monte Carlo simulation was also proposed to develop the COPT with reduced computation time [22].

Cost-benefit aspects are another area of importance for HVDC systems and the analysis for conventional HVDC is seen in [23]. Similar studies have been carried out also for VSC-HVDC in [24] for offshore windfarm connections where the impacts of transmission capacity constraints and the MTDC grid configuration have been addressed.

In this paper, an overview of the reliability assessment for VSC-HVDC is provided. The analysis of the key components and recent contributions on the calculation techniques are given in section II and III respectively. The emerging applications of reliability evaluation on VSC-HVDC and the effect of DC circuit breakers on MTDC grids are discussed.

2. Reliability of Key Components
The collection of reliability data need to be carried out first for model construction and calculations in the later stages. Fig.1 shows a general configuration of a VSC-HVDC terminal. An average energy availability of 96.5% and 96.9% has been published for the Murraylink and the Cross Sound Cable VSC-HVDC schemes [13].
In order to analyze the various reasons that will lead to system outage, the system can be divided into sub-systems based on the different sources of failure. This will help to identify the weakness of system reliability. Cigré has recommended to classify the system into six categories based on the data of forced outages for the reliability evaluation of conventional HVDC systems (LCC-HVDC) [7]. However, as the system configuration of a LCC-HVDC is very different from VSC-HVDC, it is suggested to break down the system into the sub-systems shown in Table 1 considering the latest VSC technology.

Table 1. Sub-systems for VSC-HVDC.

| No. | Component                              | Abbreviations |
|-----|----------------------------------------|---------------|
| 1   | Gas-insulated Switchgear and Transformer | GIS& TF       |
| 2   | Converter Reactor                      | CR            |
| 3   | Modular Multi-level Converter          | MMC           |
| 4   | Cooling and Ventilation System         | C&V system    |
| 5   | Control and Protection Systems         | C&P system    |
| 6   | DC Switchyard and DC Breakers          | DCS & DCCB    |
| 7   | Transmission Over-head Line or Cable   | TL            |

Unlike the LCC-HVDC, MMC-HVDC utilizes sub-modules comprised by controllable IGBTs and has no commutation failure. The schemes enhanced the quality of the converter output voltage waveform, allowing harmonic filtering equipment to be reduced or even eliminated [25]. DC filters are also unlikely to be included. Reactive power compensation devices are not necessary as most VSC schemes do not require reactive power support from the AC system. Limb reactors, which are connected in series with converter arms for the suppression of circulating/fault currents, are normally located outside of the valve hall and thus can be treated as separate components. On the DC side, DC breakers are crucial for the operation of future MTDC grids. According to the design published by ABB [26], the breakers have complicated topologies including a large amount of power electronics (e.g. IGBT stacks, diodes, surge arrester) and it is therefore necessary to assess its reliability carefully.

Based on the reliability recordings of HVDC throughout the world, the importance of components in LCC HVDC has been advised [7, 19, 27]. The transmission lines and the converter transformers are seen to be the most dominant components. Similar statistics are given in [28]. However, for windfarm connections using VSC-HVDC, the DC cable has the greatest effect on the availability of offshore windfarm connection schemes as claimed in [29]. Details are provided in Table 2.

The reliability data for each key component given in Table 1 is analyzed below:

2.1. GIS and Transformer
AC circuit breakers are the main components of a GIS switch bay. Their failure statistics can give an indication of the failure rates for the GIS [11, 12, 14]. The international survey on the reliability of gas-insulated substations has been published in the 1996 Cigré GIS survey [30]. About 70% of repairs could be carried out on-site and required a spare part or enclosure which requires extra transportation time. Both GIS and converter transformers’ failure statistics can be categorized based on the voltage rating of the equipment.
Table 2. Data for HVDC component importance

| Component               | LCC HVDC Importance | VSC-HVDC Component | Importance |
|-------------------------|---------------------|--------------------|------------|
| Converter transformer   | 52%                 | Converter reactor  | 9%         |
| Converter valve         | 6%                  | MMC                | 10%        |
| C&P system              | 3%                  | Onshore equipment  | 10%        |
| DC equipment            | 3%                  | DC switchyard      | 8%         |
| AC auxiliaries          | 7%                  | Other offshore equipment | 9% |
| Transmission line       | 28%                 | DC cable           | 54%        |
| other                   | 1%                  |                    |            |

Reliability of HVDC converter transformers is of paramount importance, especially for LCC-HVDC systems [6]. Reliability surveys (Table 2) point to transformers as the dominant contributors to failure statistics. However, there has been significant improvement in recent years thanks to the improved standards and designs. Transformers used in the MMC-HVDC schemes are less complex than the transformers used in the LCC-HVDC schemes and therefore have better reliability statistics. Cigré 1983 report [31] provides reliability statistics for auto-transformers and substation station transformers. Since auto-transformers with on-load tap-changer are not normally used in HVDC schemes, the statistic for substation transformer may be used as representative of a transformer used in a HVDC scheme. A general data is that the MTTF for a 100-300kV substation transformer with an on-load tap-changer and a 300-700kV transformer is 62.5 years and 50.85 years respectively. It is reasonable to assume that these figures can be improved for a modern transformer. The mean downtime for a 100-300kV transformer with an on-load tap-changer was reported as being between 46 and 76 days. This may also be longer in cases where the location of the transformer is difficult to access (e.g. offshore or high attitude area)

2.2. Converter Reactor
The converter reactor reliability statistics for VSC-HVDC are given by Det Norske Veritas (DNV) in [11] and also in [17]. An outage of Murray link caused by a fault in the converter reactor is mentioned in [13]. Based on the description, the converter reactor are normally replaced rather than repaired in case of a failure and therefore the converter site needs to be designed to accommodate such a replacement.

2.3. Converter
The converter reliability statistics for HVDC published so far are mainly for LCC or two-level VSC schemes as the MMC-HVDC projects have only been constructed in recent years. MMC has more complex topology and control systems. This is likely to slightly reduce its reliability. For accurate reliability analysis, it is suggested to treat the converter IGBT system, the converter C&P system, and the C&V system separately [11]. However, for system level reliability studies, the MMC would be an appropriate component to include the C&V system during calculations. Redundant power modules are normally readily available in an MMC in case of a failure since they are crucial for converter operation and takes very small storage space. Duplication is also normally made for the C&P and C&V systems. This will need to be taken into consideration when calculating their reliability indices. The actual forced outage statistics collected for LCC-HVDC schemes in [14] provide a credible basis for estimating the reliability indices for the controls used in MMC schemes as the hardware for the controls is similar in both schemes.

2.4. DC Switchyard and DC Circuit Breakers
The major components in the DC switchyard are quite similar in LCC and lower level VSC schemes. Both contain measurement transducers and switchgear. VSC schemes have HV capacitor banks and line reactors while LCC schemes have DC filters and smoothing reactors. Therefore, the reliability statistics data for LCC schemes [11, 14] would give a good indication for the estimation of DC
switchyard failure statistics used for VSC schemes. However, when it comes to MMCs, HV capacitor banks are not necessarily required.

The trend of MTDC grid has accelerated the development of DCCBs. DC faults can be isolated by DCCBs to avoid complete shutdown of the whole DC grid, hence enhancing the reliability of power supply. The failure of DCCB occurs either when it opens with no faults or it fails to open on demand [32]. A latest design by ABB utilizes IGBT valves for the main DC breaker. The device is expected to achieve a current breaking capability of 9kA in less than 2ms from fault inception but with relatively high losses [26]. DCCB is more complex than AC breakers which means it has low reliability and high cost. They are likely to be placed at the ends of DC transmission lines connecting to DC bus bars. Due to the high complexity of DCCBs, it is suggested to treat them separately when constructing the system reliability model. Estimated DCCB reliability data and the analysis of DCCB reliability using Monte Carlo simulation is given in [14] and [32] respectively. An investigation into the need case for DCCBs is given in [20].

2.5 Overhead Lines and Cables
The reliability of HVDC Overhead Lines (OHL) is very similar to HVAC OHLs, only the probability of temporary monopolar fault may be higher due to the higher risk of back flashovers across the insulators [14]. It is suggested in [14] to increase the annual average fault rate of 0.3 failures/100km for HVAC OHLs to 0.4 failures/100km for HVDC OHLs and consider the ratio of 10% between permanent and temporary faults. For VSC-HVDC schemes, XLPE cable is also widely adopted. Operation experience of a 180km cable system for the Murraylink is given in [13] which had only a single cable fault shortly after commissioning. Cable failures are heavily influenced by surrounding factors which is better to be analyzed on a case by case basis. The majority of the known cable failures were due to external damage, which is likely to be independent of cable type and voltage rating. However, sensitivity studies have been carried out in [9] which show different DC cable failure rates have a strong effect on the availability of the VSC-HVDC link.

3. Reliability Modeling and Study Methodology for VSC-HVDC
VSC-HVDC system reliability indices are evaluated by either analytical or simulation method. The procedure for assessing the overall performance of the HVDC grid generally followed the approach where the system is firstly broken down into sub-systems which are composed of key components. Each component is assigned a failure rate and repair time should a failure occur. Then reliability models are developed for each sub-system based on the reliability data and the sub-systems will be further combined to calculate the whole system reliability indices.

3.1. General Indices and Reliability Modelling
The probability of a components being in a particular state is given in equation (1), where \(n\) is the number of occurrences of the state, \(D\) and \(TD\) are the duration of a particular state and the total duration of all system states respectively.

\[
P_{state} = \frac{\sum D_{state}}{TD_{state}}
\]

Another commonly used expression is the components failure rate (\(\lambda\)) which is given as:

\[
\lambda = \frac{1}{MTTF}
\]

A general method for calculating the reliability indices of different system states is to categorize the system states into discrete levels (e.g. 0%, 50%, 100%). The probability \(P\) of the system being at a certain level (x%) can be estimated as:
where $\sum P_{\text{states}}$ is the probability function summing the probability of all system states which results in the system performance level $x\%$. For simple systems, where the different system configurations are of limited quantity, the availability can be calculated directly using this method. Alternatively, the probability of a system state can be expressed using the unavailability of the components where the performance level is given by different combinations of component failures [14].

Based on the calculated results, the array of capacity levels and their associated probabilities of existence can be summarized in a COPT [9, 12]. During actual calculations, the table can be truncated by omitting all capacity outages for which the cumulative probability is extremely small, e.g. $<10^{-6}$, for simplicity without affecting the calculated results. The components availability is given by:

$$\text{Availability} = \frac{MTTF}{MTTF + MTTR}$$

The location of the component can significantly affect the time it takes to repair the component as some locations are not easily accessed (e.g. offshore platforms). Factors like the method of transport, weather conditions, location of maintenance as well as the availability of required personnel could all affect the MTTR [9]. Also, some components in a VSC-HVDC system, especially the C&P and C&V systems, are normally duplicated to increase availability of the system. Most VSC projects adopt symmetrical monopole structures, as shown in Fig.1. Considering only one terminal, a general reliability model for a VSC terminal sub-system is developed as given in Fig.2.

![Reliability model of a VSC-HVDC terminal.](image)

The system has series dependency. Failure of any one sub-system from the reliability model will result in the failure of the transmission scheme. However, there may be one or more converter transformers in sub-system 1 depending on the capacity of the DC link as well as the size of each transformer. Failing one or more transformers will lead to the system operating at reduced capacity. Similarly, based on the key components on the DC side of the system, A point-to-point VSC-HVDC link reliability model is presented in Fig.3.

![Reliability model of a VSC HVDC-link sub-system.](image)

### 3.2. Reliability Calculation Method

Many methods have been proposed for the evaluation of power system reliability. Some basic and commonly used techniques are given in this section.

#### 3.2.1. State Space Techniques

The state space techniques are based on the Markov process which has generally been applied in engineering reliability assessment [4, 5]. A detailed procedure for establishing a Markov model for power systems is illustrated in [21]. Depending on the categorization of sub-systems, the state space model can be developed. It provides the discrete or identifiable states where the system and its components can reside, as well as the transition rates between the states. The
model assumes that the system event processes have no memory — the future states for the system are only reliant on the current state. Also, the probability of making a transition between two specific states is constant at all times. A Markov model for a system behavior that varies continuously is referred to as Markov process which is developed from the Markov chain for discrete models. Fig.4 shows a basic example of a Markov process in a state space transition diagram.

**Figure 4. Two-state state space transition diagram.**

A VSC-HVDC system can be considered as having discrete system states with constant transition rates between them. After establishing the state space model for the system, the system state probabilities can be calculated. The transitional probabilities can be defined as $A = [a_{ij}]$ which is an $n$ by $n$ matrix where $a_{ij}$ is the transition rate from state $i$ to state $j$ and $a_{ii}$ is the departure rate from state $i$. Since the system will always be in some state with probability 1, we have

$$p_1(t) + p_2(t) + \cdots + p_n(t) = 1$$  \hspace{1cm} (5)

where $p_n(t)$ is the probability of the system state $n$ at time $t$. As the steady state probabilities are constant values, whose derivatives with respect to time are zero. The linear equation used to obtain the steady state probability is expressed as:

$$\begin{bmatrix}
PA &= 0 \\
p_1 + p_2 + \cdots + p_n &= 1
\end{bmatrix}$$  \hspace{1cm} (6)

where vector $P$ is defined as $P = [p_1, p_2, \ldots, p_n]$. Taking the VSC terminal sub-system in Fig.2 as an example, the system is broken down into 4 key components as shown in Fig.5. Two converter transformers in parallel are assumed.

**Figure 5. Single-line diagram for a VSC terminal sub-system.**

For system level analysis, the MMC and the cooling and ventilation system can be treated together. Sub-system (1) can have three capacity levels: 100%, 50% and 0%. For the capacity level with more than one state (i.e. capacity level 50%), its transition rates between the other two levels can be combined as:

$$\lambda_{eq} = \frac{\sum \lambda_{ij}}{\sum p_i} \hspace{1cm} (7)$$

$$\nu_{eq} = \frac{\sum \nu_{ij}}{\sum p_j} \hspace{1cm} (8)$$

where $I$ is the set of all system states in capacity level $I$ while $J$ is the set of all system states in capacity level $J$. Applying the equation for the two transformers in parallel, the resulting reliability model can be expressed by Fig.6.
The transition rate matrix for the above state space model is given as:

\[
A = \begin{bmatrix}
\alpha_{11} & \alpha_{12} & \alpha_{13} \\
\alpha_{21} & \alpha_{22} & \alpha_{23} \\
\alpha_{31} & \alpha_{32} & \alpha_{33}
\end{bmatrix} = \begin{bmatrix}
-\left(\lambda_1 + \lambda_3\right) & \lambda_1 & \lambda_3 \\
\nu_1 & -(\nu_1 + \lambda_2) & \lambda_2 \\
\nu_3 & \nu_2 & -(\nu_1 + \nu_3)
\end{bmatrix}
\]  

(9)

Taking the transition rate into equation (6), the state probabilities: \(P_{100\%}\), \(P_{50\%}\), \(P_{0\%}\) can be solved. The state probabilities need to be calculated for all components in a sub-system if they are not readily available.

Except the transformers, all other components in this VSC terminal sub-system have only two states (up and down). However, due to the system’s series dependency, the terminal sub-system will still have three capacity levels. The state space diagram for the VSC terminal sub-system is expressed in Fig. 7.

\[P_{100\%} = P_1^{100\%} \times P_2^{100\%} \times P_3^{100\%} \times P_4^{100\%}\]

(10)

\[P_{50\%} = P_1^{50\%} \times P_2^{100\%} \times P_3^{100\%} \times P_4^{100\%}\]

(11)

\[P_{0\%} = 1 - P_{100\%} - P_{50\%}\]

(12)

where \(P_n^{x\%}\) is the probability of subsystem \(n\) at capacity \(x\%). The VSC terminal sub-system reliability model is the base of interconnected DC grids. To construct a reliability model for a MTDC system, the sub-system models for each terminal and DC transmission system need to be developed and then combined. The system may contain a large number of states with very small probabilities. Therefore, certain reduction in the insignificant states can effectively simplify the calculation process.

3.2.2 Monte Carlo simulation. The software for the application of Monte Carlo simulation in power system reliability analysis can be categorized into sequential and non-sequential methods. The simulation requires the generation of system states and the effect of each failure on the system performance. The performance indices calculated in the simulation process are normally the probability, frequency as given in section III-A. The calculated indices for different system performance levels are accumulated and the simulation process continues until the coefficient of variation tolerance level is reached. Normally, in order to estimate reliability indices with a very high
degree of confidence, the simulation requires to be run for very long time. Based on the developed system reliability model, the simulation generally has the procedures as given below [16].

Table 3

| Step | Detailed procedure |
|------|--------------------|
| 1    | Generate system states |
| 2    | Verify the effect of each state |
| 3    | Calculate performance indices of the states |
| 4    | Accumulate the calculated indices for each system performance level |
| 5    | Check whether the coefficient of variation tolerance level is reached or not |
| 6    | The process continues/stops depending on the result of step 5 |

4. Conclusions

The use of sections to divide the text of the paper is optional and left as a decision for the author. Whichever sources with academic and industrial backgrounds are provided for the collection of VSC-HVDC reliability data. However, there is a lack of data for new developed technologies such as MMC converter and DC circuit breakers which need to be estimated from similar components used in existing projects. The techniques of VSC-HVDC reliability modeling and evaluation based on both analytical and simulation methods are illustrated in this paper. It is suggested to break down the VSC system into seven sub-systems for reliability modelling and the DC circuit breakers need to be treated separately due to its high complexity.

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