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# Reliability Assessment of a Multi-State HVDC System by Combining Markov and Matrix-Based Methods

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**Abstract:** The purpose of this paper is to highlight that, in order to assess the availability of different HVDC cable transmission systems, a more detailed characterization of the cable management significantly affects the availability estimation since the cable represents one of the most critical elements of such systems. The analyzed case study consists of a multi-terminal direct current system based on both line commutated converter and voltage source converter technologies in different configurations, whose availability is computed for different transmitted power capacities. For these analyses, the matrix-based reliability estimation method is exploited together with the Monte Carlo approach and the Markov state space one. This paper shows how reliability analysis requires a deep knowledge of the real installation conditions. The impact of these conditions on the reliability evaluation and the involved benefits are also presented.

**Keywords:** HVDC-LCC; HVDC-VSC; MTDC comparison; system reliability; transmittable capacity of HVDC systems

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## 1. Introduction

High Voltage Direct Current (HVDC) systems represent a key technology for strengthening the electrical network, as it is confirmed by several contributions in scientific literature. They are able to connect grids that operate at different frequencies and allow installing very long interties by involving fewer power losses than HVAC systems. In the energy transition scenario, characterized by the increasing penetration of renewable energy sources in the electrical network, HVDC interconnections are an effective support for the grid to counteract the stability problems that a massive installation of RESs implies, thereby making the electrical grid more reliable and safer [1–5]. It is also worth noting that the fewer power cables required for the DC transmission lines compared with the AC ones and the negligible electromagnetic field emission make the HVDC systems fully compatible with the installation in railway/highway infrastructures [6].

However, a significant penetration of HVDC links in the worldwide networks implies that the current scenario of electrical power systems is becoming more and more complex due to the number of components that need to work together, and their availability and reliability requirements are becoming very stringent.

There are two types of HVDC technologies, Line Commutated Converter (LCC) based and Voltage Source Converters (VSC) based, exhaustively described in [7–11]. Regarding the VSC systems, the modular multi-level converter (MMC) configuration is the most used. In particular, the VSC-based HVDC links currently are living a continuous boost due to their key features: in combination with cross-linked-polyethylene-extruded (XLPE) cables, VSC-HVDC technologies are able to provide vital services for the electrical grids, such as the frequency or the voltage regulation ones [12–15]. The use of overhead lines or submarine/underground cables, or a combination of them, generates different issues and have pros and cons depending on the type of application [16–18]. Effective reliability and availability assessment tools [19–30] are of paramount importance in order to safely manage a whole HVDC-VSC link and to minimize the system outage risk.

The availability of an HVDC link can be associated with its transmittable power capacity. In fact, the failure of a single component does not necessarily lead the whole system to fail, but this event certainly reduces the transmitted power capacity. This is particularly meaningful in the case of multi-terminal HVDC systems due to the huge amount of components connected together.

A reliability computation method that fits well with HVDC multi-terminal connections is the multi-state matrix approach (MSR) [31–34] which, starting from the availabilities of the HVDC system components, allows correlating the reliability of the system with the transmitted power capacity.

The authors applied the MSR technique to compare the reliabilities of different HVDC multi-terminal systems based on both HVDC-LCC and VSC-MMC technologies in the conference paper [34]. Since the MSR approach foresees the component availabilities of the whole HVDC system as input data, the present paper is an extended and enriched version of [34], where different techniques are adopted to estimate the availability of the cable systems.

The aim of the paper is to evaluate how different availability computation methods can affect the overall availability estimation of an HVDC system by applying the MSR and Markov approaches. Typically, the use of the MSR method does not take into account the real management of the cable system. Differently, in this paper, the reliability assessment is addressed by combining the matrix-based reliability method with the Markov state diagram approach. In particular, the Markov models are exploited in order to analyze the impact of the cable spare management on the overall availability of the MTDC systems, thus a much more realistic approach to the reliability evaluation problem.

## 2. Materials and Methods

### *2.1. Matrix-Based System Reliability Approach*

The MSR method allows computing the failure probability of a system by using matrix-based procedures.

Starting from the estimated availability of each component, the basic principle of the MSR approach is that a given system can be characterized by means of $m$ Mutually Exclusive and Collective Events (MECE) $e_j$, $j = 1, \ldots,$ m. Each event represents a specific fault condition of the system, which is related to a specific transmitted power capacity. Hence, by exploiting the MSR method [31,32], it is possible to evaluate the probability that the system falls in a particular fault condition and transmits the related specific power capacity.

Let $p_j = Pe(j), j = 1, \ldots\ m$ denote the probability of $e_j$.

A system constituted of $i$ components can be represented by means of an event matrix $\boldsymbol{C}_i$ and a probability vector $\boldsymbol{p}_i$.

The general iterative matrix procedures obtaining $C_i$ and $P_i$ for a generic system of n components are summarized as follows:

$$\mathbf{C}_{[i]} = \begin{bmatrix} \boldsymbol{C}_{[i-1]} & 1 & 0 & . & 0 & 0 \\ \boldsymbol{C}_{[i-1]} & 0 & 1 & . & 0 & 0 \\ . & . & . & . & . & . \\ \boldsymbol{C}_{[i-1]} & 0 & 0 & . & 1 & 0 \\ \boldsymbol{C}_{[i-1]} & 0 & 0 & . & 0 & 1 \end{bmatrix} \boldsymbol{P}_{[i]} = \begin{bmatrix} p_{[i-1]} \cdot p_1 \\ p_{[i-1]} \cdot p_2 \\ \cdot \\ p_{[i-1]} \cdot p_j \\ \cdot \\ p_{[i-1]} \cdot p_{si} \end{bmatrix} \tag{1}$$

where $\boldsymbol{C_{i-1}}$ is placed $s_i$ times, so $C_i$ has a total of $\sum\limits_{i=1}^{n} s_i$ column vectors, which are identified as the event vectors for the component events $C^{\mathrm{E1(1)}}$, $C^{\mathrm{E1(2)}}$, …, $C^{\mathrm{E1(sn)}}$, $C^{\mathrm{E2(1)}}$, $C^{\mathrm{E2(2)}}$, …,

$C^{E2(sn)}$; $\boldsymbol{P_i(j)}$ denotes the probability that the $i_{th}$ component takes the $j_{th}$ state, for $i = 1, \ldots, n$, and $j = 1, \ldots, s_i$.

Due to the property of MECE, the probabilities of a system event $E_{sys}$ are the sum of the probabilities of the event that belong to the specific system event, so:

$$\boldsymbol{P}(E_{sys}) = \sum_{i=1}^{s_i} p_j = \boldsymbol{c}^{E_{sys}} \cdot \boldsymbol{p} \tag{2}$$

Hence, starting from the vector P(Esys), it is possible to infer the probability that a specific fault condition of the system occurs and, consequently, to assess the transmitted power capacity related to this specific condition.

### 2.2. Case Studies and Availability Estimation Methods

The availability analysis of different Multi-Terminal DC (MTDC) configurations is performed for different transferred power capacities. The data used as input for the availability estimations are reported in Table 1 and they are taken from the technical literature [31,34]. In particular, for the cable system failure rates and mean time to repairs (MTTRs), the Cigrè TB [35] is considered whereas, for the other components of the system, the input data are based on the paper [31].

**Table 1.** Reliability data of the HVDC configuration components.

| Component | Failure Rate (occ/year) | Mean Time to Repair (h) | Mean Time to Reinstall (h) | Availability Monte Carlo |
|---|---|---|---|---|
| ***ACF*** | 0.54 | 6 | 0 | 0.999630274 |
| ***CAP*** | 0.002 | 6 | 0 | 0.999998630 |
| ***VSC CAP*** | 0.0015 | 10 | 0 | 0.999998288 |
| ***DCF*** | 0.4 | 12 | 0 | 0.999452355 |
| ***VSC DCF*** | 0.001 | 5 | 0 | 0.999999429 |
| ***SR*** | 0.05 | 300 | 0 | 0.998290598 |
| ***PR*** | 0.14 | 24 | 0 | 0.999616585 |
| ***LCC CONVERTER*** | 1 | 5 | 0 | 0.999429549 |
| ***VSC CONVERTER*** | 0.5 | 4 | 0 | 0.999771742 |
| ***AC BREAKER*** | 0.015 | 50 | 0 | 0.999914391 |
| ***VSC AC BREAKER*** | 0.001 | 40 | 0 | 0.999995434 |
| ***DC BREAKER*** | 0.033 | 50 | 0 | 0.999811679 |
| ***DC SWITCH*** | 1 | 4 | 0 | 0.999543587 |
| ***DC CABLE (250 km)*** | 0.2495 | 720 | 0 | *by considering only the cable failure rate: 0.979905231*<br>*by considering the failure rates of cable spans, terminations, and joints and their management: 0.960061242* |
| ***DC CABLE (200 km)*** | 0.1996 | 720 | 0 | *by considering only the cable failure rate: 0.983859316*<br>*by considering the failure rates of cable spans, terminations, and joints, and their management: 0.967727545* |
| ***LCC TRANSFORMER*** | 0.07 | 1200 | 72 | 0.999424988 |
| ***VSC TRANSFORMER*** | 0.05 | 1000 | 48 | 0.999726102 |
| ***CENTRAL BUS*** | 0.11 | 50 | 0 | 0.999372540 |
| ***PROTECTION DEVICES*** | 0.003 | 20 | 0 | 0.999993151 |

The different MTDC configurations considered in this study are summarized in Table 2. The connection between terminals 1 and 2 consists of a 250 km long double-circuit submarine cable, whereas terminal 3 is connected by means of a 200 km long submarine cable.

**Table 2.** Analyzed cases.

| *Case* | *1st Terminal* | *2nd Terminal* | *3rd Terminal* |
|---|---|---|---|
| *1* | *(HVDC)-LCC* | *(HVDC)-LCC* | *(HVDC)-LCC* |
| *2* | *(HVDC)-VSC* | *(HVDC)-VSC* | *(HVDC)-VSC* |
| *3* | *(HVDC)-LCC* | *(HVDC)-LCC* | *(HVDC)-VSC* |
| *4* | *(HVDC)-MMC* | *(HVDC)-MMC* | *(HVDC)-MMC* |

In order to cover the typical HVDC configurations that are installed nowadays, four case studies are analyzed by taking into account the LCC configuration for two terminals with a derived VSC tapping station.

Table 3 shows the difference in the availability estimation of the cable systems by considering different spare quantities and times to resupply $\tau_x$ for a given failure rate, $\lambda_x$, in order to have an idea of their impact on the cable availability. It is possible to note that a more detailed characterization of the cable systems performed by means of the Markov chains significantly affects the availability estimation of the overall HVDC multi-terminal interconnection. For each case study, the availability analysis is carried out by exploiting the MSR method for different fault conditions [31,34], which determines different power transmission capacities (capacity states) which are summarized in Table 4.

At first, the availability of the cable systems, which is necessary as input for MSR, is computed by means of the Monte Carlo approach, with and without considering the influence of joints and terminations. Subsequently, the cable system availability is estimated by means of the Markov chains by exploiting the state space diagram of Figure 1 as an example of management for the cable system by assuming one spare available for each component (10 states required) and time to resupply the cable spare of 5 months. Hence, the overall availability of the HVDC system has been assessed once again. The cable spans are supposed 20 km long [36]. Regarding the mathematical steps to pass from the Markov diagram of a given system to its availability and to characterize different spare quantities with the Markov chain, refer to [19]. The significant digits used in the simulations are kept at nine in order to achieve greater computational accuracy.

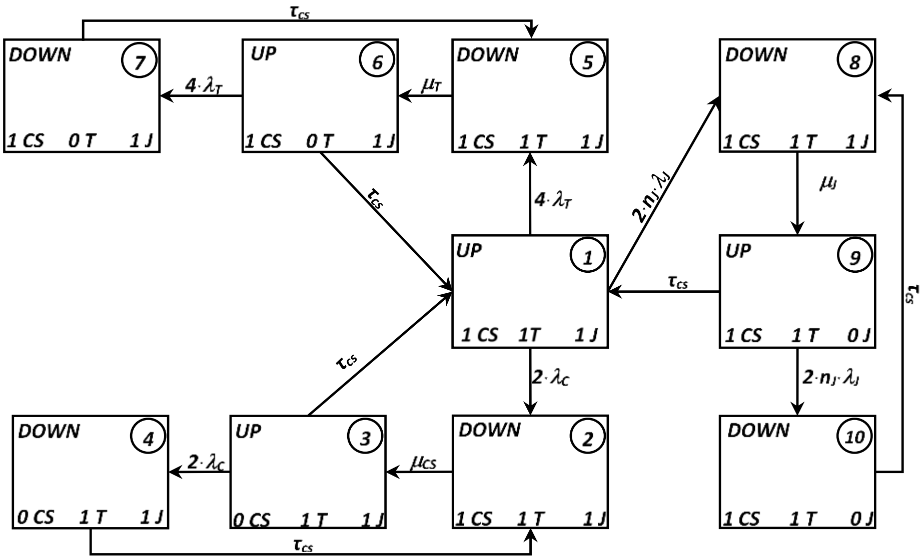

**Figure 1.** Markov state space diagram of the cable subsystem.

**Table 3.** Sensitive Analysis of the 250 km cable system.

| | *Monte Carlo (By Considering Joints and Terminations)* | *Markov (1 Spare) $\tau_{cs}$ = 5 Months* | *Markov (3 Spares) $\tau_{cs}$ = 5 Months* | *Markov (1 Spare) $\tau_{cs}$ = 3 Months* | *Markov (3 Spares) $\tau_{cs}$ = 3 Months* | *Markov (1 Spare) $\tau_{cs}$ = 7 Months* | *Markov (3 Spares) $\tau_{cs}$ = 7 Months* |
|---|---|---|---|---|---|---|---|
| ***Availability*** | *0.960169250* | *0.929307760* | *0.959131820* | *0.948094450* | *0.960220020* | *0.904892290* | *0.955983320* |
| ***Unavailability (h/year)*** | *348.9* | *619.2* | *358* | *454.7* | *348.5* | *833.1* | *385.6* |

**Table 4.** Availability assessment for different fault conditions for Case 1 [31].

| *State* | *Component Out* | *Capacity (p.u.)* |
|---|---|---|
| 1 | All components are considered | 1.0 |
| 2 | Only one cap is considered | 0.9 |
| 3 | Only one DCF could be combined or not when the failure of one Cap is considered | 0.75 |
| 4 | Only one ACF is considered, which could be combined or not with the failure of one DCF | 0.65 |
| 5 | Two Caps are considered, which could be combined or not with the failure of one DCF | 0.62 |
| 6 | One Cap and one ACF are considered, which could be combined or not with the failure of one DCF | 0.6 |
| 7 | One or more components affecting a branch formed by AC-Brk, Trn, Vlvs, and/or a Cable line which could be combined or not with the failure of one Cap and/or the failure of One Cap and one ACF are considered | 0.5 |
| 8 | Two Caps and one ACF are considered, which could be combined or not with the failure of one DCF and/or with the failure of one or more components affecting a branch formed by AC-Brk, Trn, Vlvs, and/or Cable line | 0.3 |
| 9 | Other combinations are considered | 0 |

## 3. Results

### *3.1. LCC-MTDC Analysis (Case Study One)*

With reference to Figure 2, the LCC-MTDC configuration consists of a bipolar LCC for the first and second terminal, whereas the third terminal, which is derived from the middle of the cable line, consists of an LCC monopolar system.

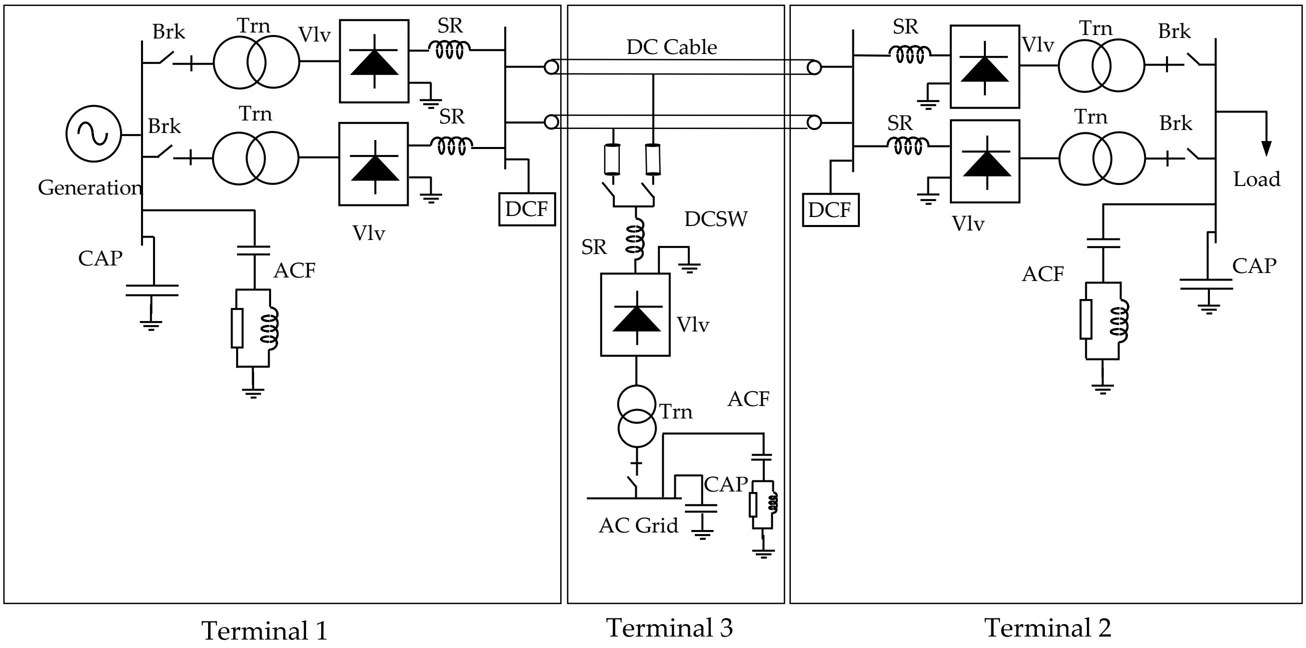

**Figure 2.** Electrical scheme of the HVDC-LCC multi-terminal link.

By using the MSR approach, the estimated reliability for different power transmitted capacities are shown in Table 5. It can be noted how the capacity states for the whole system are more than the capacity states of Table 4. This effect is due to the combination of the three terminals, which determines 15 possible fault conditions for the overall system.

**Table 5.** Availability Assessment for Case 1.

| **Transferred Power Capacity [pu]** | **Availability MSR *(By Not Considering Joints and Terminations)*** | **Availability MSR *(By Considering Joints and Terminations)*** | **Availability MSR & Markov *(1 Spare)* $\tau_{cs}$ *= 5 Months*** |
|---|---|---|---|
| ***1*** | *0.838431777* | *0.836921414* | *0.734398449* |
| ***0.95*** | *0.000885806351* | *0.000883893503* | *0.000758777026* |
| ***0.9*** | *0.00000238229892* | *0.00000237879947* | *0.00000212945309* |
| ***0.85*** | *0.000598574247* | *0.000597281661* | *0.000512735529* |
| ***0.82*** | $1.51876215 \times 10^{-12}$ | $1.51548247 \times 10^{-12}$ | $1.30096361 \times 10^{-12}$ |
| ***0.8*** | *0.00000000164009568* | *0.00000000163655399* | *0.00000000140489727* |
| ***0.75*** | *0.000953517617* | *0.000952116848* | *0.000852309524* |
| ***0.7*** | *0.0716220665* | *0.0722307951* | *0.11030195* |
| ***0.65*** | *0.000697349156* | *0.000696853214* | *0.000657587622* |
| ***0.62*** | $1.76942560 \times 10^{-12}$ | $1.76816758 \times 10^{-12}$ | $1.66855522 \times 10^{-12}$ |
| ***0.6*** | *0.00000000191078458* | *0.00000000190942606* | *0.00000000180185568* |
| ***0.5*** | *0.0835876285* | *0.0844250210* | *0.142377211* |
| ***0.3*** | $1.43267368 \times 10^{-15}$ | $1.43305281 \times 10^{-15}$ | $1.45197815 \times 10^{-15}$ |
| ***0.2*** | *0.00155131567* | *0.00158412007* | *0.00476723031* |
| ***0*** | *0.00166957954* | *0.00170612214* | *0.00537161837* |

### 3.2. *VSC-MTDC Analysis (Case Study Two)*

With reference to Figure 3, the VSC-MTDC topology is based on a bipolar configuration for terminals 1 and 2, while for terminal 3, a VSC monopolar tapping station has been included. Since VSC converters at terminals 1 and 2 are not MMC type, it is not possible to avoid the use of AC filters. A phase reactor is required for voltage source HVDC schemes in order to allow the control of the active and reactive powers from the VSC.

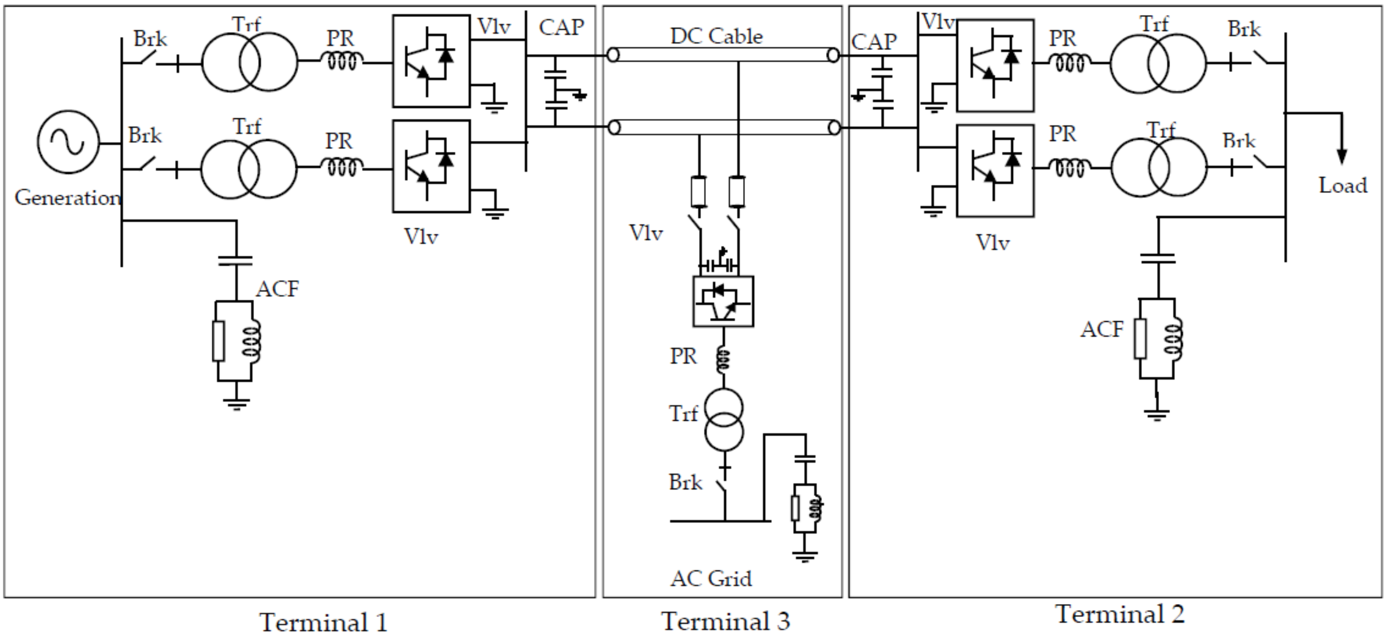

**Figure 3.** Electrical scheme of the HVDC-VSC multi-terminal link.

Moreover, the phase reactor reduces the high-frequency harmonic content and limits AC side short circuit currents.

By combining the MSR method with different availability estimation approaches for the cable system as described in Section 4, the estimated reliability for different power transmitted capacities are shown in Table 6. It is interesting to note that the capacity states that case study two can assume is less compared to the ones of case study one. This is due to the lower number of components.

**Table 6.** Availability Assessment for Case 2.

| **Transferred Power Capacity [pu]** | **Availability MSR** *(By Not Considering Joints and Terminations)* | **Availability MSR** *(By Considering Joints and Terminations)* | **Availability MSR & Markov** *(1 Spare)* $\tau_{cs}$ *= 5 months* |
|---|---|---|---|
| **1** | *0.847195666* | *0.845669511* | *0.742074892* |
| **0.9** | *0.00000299777836* | *0.00000299338197* | *0.00000267999401* |
| **0.85** | *0.000605741633* | *0.000604433569* | *0.000518875073* |
| **0.82** | $2.40008070 \times 10^{-12}$ | $2.39489786 \times 10^{-12}$ | $2.05589641 \times 10^{-12}$ |
| **0.8** | *0.00000000207406290* | *0.00000000206958408* | *0.00000000177663129* |
| **0.7** | *0.0687501958* | *0.0693701595* | *0.108161849* |
| **0.65** | *0.000698962649* | *0.000698470616* | *0.000659404429* |
| **0.62** | $2.76950414 \times 10^{-12}$ | $2.76755512 \times 10^{-12}$ | $2.61279252 \times 10^{-12}$ |
| **0.6** | *0.00000000239330527* | *0.00000000239162100* | *0.00000000225788076* |

**Table 6.** *Cont.*

| Transferred Power Capacity [pu] | Availability MSR *(By Not Considering Joints and Terminations)* | Availability MSR *(By Considering Joints and Terminations)* | Availability MSR & Markov *(1 Spare)* $\tau_{cs}$ = *5 months* |
|---|---|---|---|
| ***0.5*** | *0.0795319491* | *0.08037035862* | *0.138426587* |
| ***0.3*** | $2.23184555 \times 10^{-15}$ | $2.23243965 \times 10^{-15}$ | $2.26212113 \times 10^{-15}$ |
| ***0.2*** | *0.00155226264* | *0.00158526662* | *0.00478756778* |
| ***0*** | *0.00166222565* | *0.00169880291* | *0.00536814065* |

### *3.3. MIXED-MTDC Analysis (Case Study Three)*

With reference to Figure 4, it is proposed a mixed HVDC-MTDC configuration. In this case, terminal 1 and 2 are based on LCC technology and terminal 3 on the VSC one. The estimated reliability for different power transmitted capacities are shown in Table 7.

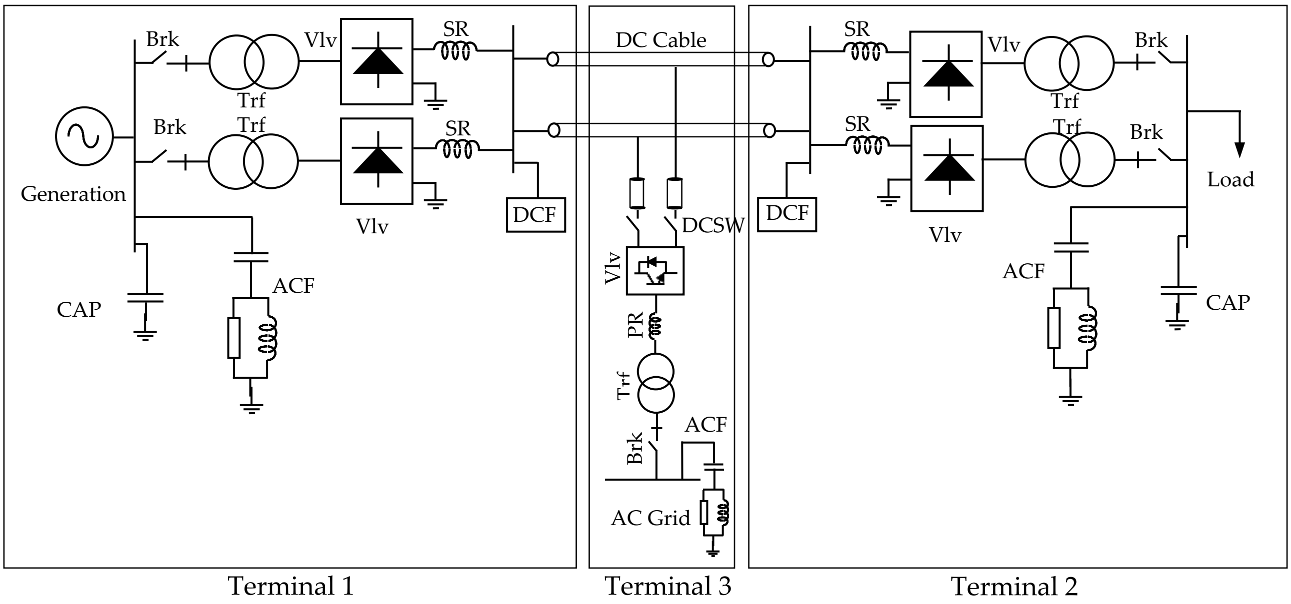

**Figure 4.** Electrical scheme of a mixed (VSC and LCC) HVDC multi-terminal link.

**Table 7.** Availability Assessment for Case 3.

| Transferred Power Capacity [pu] | Availability MSR *(By Not Considering Joints and Terminations)* | Availability MSR *(By Considering Joints and Terminations)* | Availability MSR & Markov *(1 Spare)* $\tau_{cs}$ = *5 Months* |
|---|---|---|---|
| ***1*** | *0.838431782* | *0.836921421* | *0.734398454* |
| ***0.95*** | $8.88112251 \times 10^{-4}$ | $8.86194492 \times 10^{-4}$ | $7.60752255 \times 10^{-4}$ |
| ***0.9*** | $2.37653982 \times 10^{-6}$ | $2.37305280 \times 10^{-6}$ | $2.12451990 \times 10^{-6}$ |
| ***0.85*** | $6.00132430 \times 10^{-4}$ | $5.98836481 \times 10^{-4}$ | $5.14070262 \times 10^{-4}$ |
| ***0.82*** | $1.5227151 \times 10^{-12}$ | $1.5194272 \times 10^{-12}$ | $1.3043501 \times 10^{-12}$ |
| ***0.8*** | $1.64436514 \times 10^{-9}$ | $1.64081428 \times 10^{-9}$ | $1.40855445 \times 10^{-9}$ |
| ***0.75*** | $9.51213417 \times 10^{-4}$ | $9.49817615 \times 10^{-4}$ | $8.50335757 \times 10^{-4}$ |
| ***0.7*** | *0.0718085110* | *0.0724188242* | *0.1105890851* |

**Table 7.** *Cont.*

| Transferred Power Capacity [pu] | Availability MSR *(By Not Considering Joints and Terminations)* | Availability MSR *(By Considering Joints and Terminations)* | Availability MSR & Markov *(1 Spare)* $\tau_{cs}$ *= 5 Months* |
|---|---|---|---|
| **0.65** | $6.95927172 \times 10^{-4}$ | $6.95435771 \times 10^{-4}$ | $6.56463821 \times 10^{-4}$ |
| **0.62** | $1.76581445 \times 10^{-12}$ | $1.76456873 \times 10^{-12}$ | $1.66570124 \times 10^{-12}$ |
| **0.6** | $1.906885143 \times 10^{-9}$ | $1.905539101 \times 10^{-9}$ | $1.798773712 \times 10^{-9}$ |
| **0.5** | 0.0834010460 | 0.0842368528 | 0.142089863 |
| **0.3** | $1.42920245 \times 10^{-15}$ | $1.42958323 \times 10^{-15}$ | $1.44860712 \times 10^{-15}$ |
| **0.2** | 0.0015553540 | 0.0015882438 | 0.00477964020 |
| **0** | 0.00166554121 | 0.00170199841 | 0.00535920841 |

### 3.4. MMC Effect (Case Study Four) and Summary of the Results

In this case study, the MMC technology is taken into account. If a high number of levels is assumed for the converters, it is possible to avoid the use of AC filters.

In addition, the shunt capacitor banks are not necessary for MMC installations. By using the MSR method, the estimated reliability for different power transmitted capacities are shown in Table 8. As above mentioned, the VSC technology requires a lower number of components compared to the LCC one. Hence, case study four presents the lower number of capacity states among the considered case studies since all the HVDC terminals are based on the VSC technology.

**Table 8.** Availability assessment for Case Study Four.

| Transferred Power Capacity [pu] | Availability MSR *(By Not Considering Joints and Terminations)* | Availability MSR *(By Considering Joints and Terminations)* | Availability MSR & Markov *(1 Spare)* *Tcs = 5 Months* |
|---|---|---|---|
| **1** | 0.848452743 | 0.846924329 | 0.743176049 |
| **0.7** | 0.0688777605 | 0.0694988746 | 0.108362541 |
| **0.5** | 0.0795699558 | 0.0804088501 | 0.138502406 |
| **0.2** | 0.00149735393 | 0.00152982457 | 0.00469681485 |

The summary of the estimated availabilities for the analyzed case studies is reported in Table 9. It is possible to see that different characterization of the cable systems determine very different values of unavailability for the HVDC link, up to 908 h/year. Hence, it is necessary to correctly represent the cable systems in order to have reliable availability estimations. Moreover, it must be observed that in [31] for 1 p.u. transferred power capacity state which corresponds to case study three of this paper, the computed availability value is equal to 0.9846596. By comparing this value with respect to the reliability assessment which takes into account the real installation conditions of the cable system (including joints and terminations), an availability decrease of about 15% arises. In addition, if also spare management is taken into account, the availability decreases by about 25%.

**Table 9.** Results of the availability assessment.

| Technology | Availability MSR *(By Not Considering Joints and Terminations)* | Availability MSR *(By Considering Joints and Terminations)* | Availability MSR & Markov *(1 Spare)* $\tau_{cs}$ *= 5 Months* | Unavailability MSR *(By Not Considering Joints and Terminations) (h/Year)* | Unavailability MSR *(By Considering Joints and Terminations) (h/Year)* | Unavailability MSR & Markov *(h/Year)* |
|---|---|---|---|---|---|---|
| ***HVDC LCC*** | *0.838431777* | *0.836921414* | *0.734398449* | *1415.3* | *1428.5* | *2326.6* |
| ***HVDC VSC*** | *0.847195666* | *0.845669511* | *0.742074892* | *1338.6* | *1351.9* | *2259.4* |
| ***HVDC MMC*** | *0.848452743* | *0.846924329* | *0.743176049* | *1327.5* | *1340.9* | *2249.8* |
| ***MIXED HVDC*** | *0.838431782* | *0.836921420* | *0.734398454* | *1415.3* | *1428.6* | *2326.7* |

## 4. Conclusions

In this paper, the availability assessment of MTDC configurations for different HVDC technologies is carried out by using the MSR approach. From the performed analyses, it emerges that the spare management of the cable systems strongly affects the availability estimation of the overall HVDC link. The paper demonstrates that the MSR approach combined with the Markov chain is an effective tool to support the planning and design phase of HVDC installations and to optimize the scheduled maintenance of the system. Moreover, the paper highlights that the joint of MSR and Markov's chains can be considered as a single and analytical tool: by means of it, it is possible to represent all the HVDC configurations and installation conditions. The analysis carried out in this paper allows concluding that the reliability of each installation depends not only on the performance of the components but also on how they are managed.

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## Abbreviations

| | |
|---|---|
| HVDC | High voltage direct current |
| MMC | Modular multilevel converters |
| MTDC | Multi-terminal direct current |
| VSC | Voltage-source converter |
| LCC | Line-commutated converter |
| SMs | Sub-modules |
| ACFs | AC filters |
| CAPs | Shunt capacitor banks |
| VSC CAPs | Shunt capacitor banks for VSC technology |
| Brks | AC breakers |
| Trns | Converter transformers |
| Vlvs | Valves |
| SRs | Smoothing reactors |
| PRs | Phase reactors |
| DCSWs | DC switches |
| DCFs | DC filters |
| VSC DCFs | DC filters for VSC technology |
| MSR | Matrix-based system reliability |
| $\tau_x$ | Time to resupply the component x [h/year] |
| $\lambda_x$ | Failure rate of the component x [h/year] |
| T | One spare cable termination |
| CS | One spare cable span |
| J | One spare joint |
| $\mu_x$ | Mean time to repair of component x [h/year] |
| n | Number of spans of 1 cable |
| L | Length Of Each Cable [km] |

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