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# Feasibility and Reliability Analysis of LCC DC Grids and LCC/VSC Hybrid DC Grids

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**ABSTRACT** Power system interconnections using high-voltage direct-current (HVDC) technologies between different areas can be an effective solution to enhance system efficiency and reliability. Particularly, the multi-terminal dc grids that could balance and ensure resource adequacy increase asset utilization and reduce costs. In this paper, the technical feasibility of building dc grids using the line-commutated converter-based (LCC) and voltage source converter-based (VSC) HVDC technologies is discussed. Apart from presenting the technical challenges of building LCC dc grids and LCC/VSC hybrid dc grids, the reliability modeling and analysis of these DC grids are also presented. First, the detailed reliability model of the modular multi-level converters (MMCs) with series-connected high-voltage and low-voltage bridges is developed. The active mode of redundancy design is considered for the reliability model. To this end, a comprehensive whole system reliability model of the studied systems is developed. The reliability model of each subsystem is modeled in detail. Various reliability indices are calculated using this whole system reliability model. The impacts of the redundancy design of the MMCs on these indices are presented. The studies of this paper provide useful guidance for dc grid design and reliability analysis.

**INDEX TERMS** LCC-HVDC, VSC-HVDC, MMC, multi-terminal dc grid, reliability analysis, k-out-of-n.

## I. INTRODUCTION

High-voltage direct-current (HVDC) technology which has been used for more than 70 years [1]–[3], is suited to transport large amounts of power over long distances with minimum losses. Thyristor-based line commutated converter (LCC) HVDC is used for transferring bulk power (over several GW) over long distances due to its mature technology that is efficient, reliable and cost-effective [1]–[3]. However, LCC-HVDC brings some inherent problems, such as commutation failure, difficulty in connecting weak AC systems, and the need for DC voltage polarity reversal during power flow reversal [4]–[6]. These obstacles make this technology difficult when considering large-scale DC grids.

Over the last two decades, the voltage source converter (VSC) based HVDC technology has become more attractive compared to the LCC-HVDC for building multi-terminal DC (MTDC) grids [7], [8]. The features of VSC-HVDC technology include [9]–[11]:

1) compact and flexible station layouts, low space requirements, and a scalable system design;
2) fast dynamic performance and stable operation with AC networks;
3) capability to supply passive networks and of black-start;
4) independent control of active and reactive power;

Even though VSC technology is foreseen to dominate the future HVDC market, it is still facing challenges in the voltage level, converter power losses, transmission capacity and capital costs. The LCC systems have the self-healing capability against DC overhead line faults, while the VSC systems

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would depend on DC circuit breakers (DCCBs) or converters with fault blocking capability. Moreover, compared to LCC systems, it is difficult to achieve an overload operation in VSC systems. These limitations are slowing their wide spread applications. However, the gaps between LCCs and VSCs are narrowing on all counts.

Deployment of HVDC is leading to an increasing number of point-to-point connections in different parts of the world. The logical next step is to interconnect the links to form MTDC networks which can improve the reliability of power supply, reduce power losses, integrate and optimize the use of renewable energy sources from different regions [12].

As there are and will be many point-to-point LCC HVDC and ultra HVDC (UHVDC) links in operation, under construction or at the planning stage, one of the solutions to form MTDC grids is to interconnect the existing LCC-HVDC links so as to provide more flexible operations [13]–[16]. Two existing links can be directly interconnected through additional transmission lines if their DC voltages are the same. Otherwise DC/DC transformers may be needed if the two links are at different DC voltages. However, the risk of commutation failure is an important factor that limits the number of LCC terminals connected in an MTDC grid [13].

In the foreseeable future, the capacity and voltage level matching of LCCs and VSCs may not be a problem because of the continuing development of VSCs [17]. Therefore, the LCC/VSC hybrid DC grid can be a possible and effective solution to combine the merits of both technologies. Hybrid DC grids will improve the flexibility and reliability of power supply and reduce power losses and capital costs [17]–[22].

The technical feasibility, operation and control strategies of VSC-based DC grids have been studied widely [7], [13], [22]–[26]. However, the technical feasibility and reliability analysis of LCC DC grids and LCC/VSC hybrid DC grids are still under-researched and are also very important aspects in future MTDC transmission system design, construction and operation [27].

Considerable research has been carried out in the area of reliability analysis of HVDC transmission systems [27]–[33]. In [28] and [29], state-space models of mercury arc valve-based converter and the whole HVDC transmission system have been proposed based on the Markov process. A reliability evaluation method based on failure modes and effects analysis has been proposed in [30] and [31]. This method uses the event tree and minimal cut-set approach to describe the system operational behavior and failure modes. References [32] and [33] develop the reliability block diagrams of HVDC transmission systems with the consideration of the effects of different components on the overall reliability of HVDC systems. However, only point-to-point HVDC links are studied in these published literatures. With an increasing demand for MTDC systems, the reliability evaluation of MTDC systems becomes essential.

The reliability and outage cost evaluation of a five-terminal modular multi-level converter (MMC) based HVDC network has been conducted through Monte Carlo simulation method in [34]. However, it does not consider the detail reliability modeling of MMCs and the whole HVDC system. References [35]–[37] investigate the reliability modeling and redundancy design of MMCs. However, the reliability of MMCs with series connected high-voltage and low-voltage bridges are not studied in these references.

In [38], the reliability of a hybrid LCC/VSC HVDC transmission system is studied. The LCC HVDC transmission system is tapped by a VSC station. The reliability model and indices of the hybrid system are presented based on reliability block diagrams. However, the test system is not a DC grid in which each converter has more than two connections with other converters. Moreover, the noted literature does not consider the effect of LCC's commutation failure on the system reliability.

In this paper, the reliability model for MMCs employed for UHVDC systems is studied using a hierarchical reliability model which can clearly illustrate the series-parallel structure of the studied systems. The active mode of submodules is considered for the MMC redundancy design. The obtained reliability results of the MMCs will be applied in the models of the LCC/MMC hybrid DC grids. The hierarchical reliability model and reliability block diagrams will be used to analyze the reliability of the LCC DC grids and LCC/MMC hybrid DC grids. First, the studied systems will be divided into several subsystems. In each subsystem, series-parallel reliability principle is used to construct the reliability model. The effect of LCC's commutation failure will be considered in the reliability model of LCCs operating as inverters. Then the reliability models of all subsystems are combined to obtain the whole system reliability model. The reliability indices of the studied systems are calculated and compared.

## II. TECHNICAL FEASIBILITY ANALYSIS OF LCC DC GRIDS AND LCC/VSC HYBRID DC GRIDS

The existing point-to-point HVDC connections contribute to bringing power to the customers efficiently and in line with demand. The next move is to interconnect the links to form MTDC grids in which multiple (more than two) converters are interconnected through DC transmission lines and/or DC/DC transformers in meshed configurations. In this section, the technical feasibility of LCC DC grids and LCC/VSC hybrid DC grids are presented.

### A. TECHNICAL FEASIBILITY OF LCC DC GRIDS

The successful applications of the existing LCC HVDC links and networks pave the way for LCC DC grids. An LCC DC grid may reduce the number of converter stations and transmission lines compared to point-to-point links. An LCC DC grid can also reduce the impact of losing a DC line or a converter on system operation and therefore, improve the reliability of power supply. Additionally, the flexible controllability for integrating multiple power sources and loads makes the MTDC grid a highly competitive solution to achieve exchange of electricity among different areas.

An LCC DC grid can be realized by connecting the converter stations in parallel or series configurations or through DC/DC transformers, as described below.

#### 1) PARALLEL ARCHITECTURE

In the parallel schemes, the converters are connected in parallel and operate at the same DC voltage. The DC network can be either radial or meshed. A meshed connected MTDC grid is shown in Figure 1.

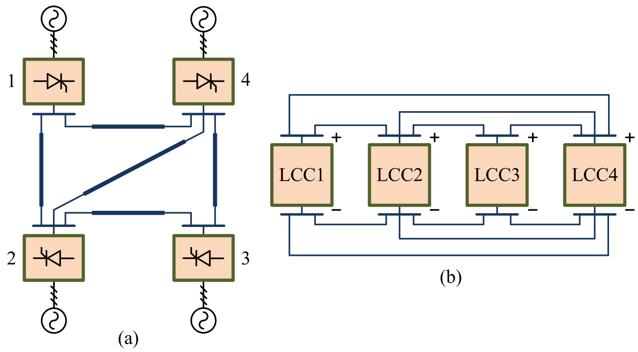


**FIGURE 1. Parallel LCC DC grid with a meshed configuration. (a) Meshed MTDC network; (b) Converter stations' connection.**

The converters in the parallel schemes work with different operation modes. To achieve the stable operation of the whole system, the operational characteristics of the converter control need to intersect at a common point [1], [23]. To achieve this, one of the converters needs to control the operating voltage of the DC circuit and the remaining converters operate on constant current (power) control mode. For a large DC grid, more sophistication, such as droop control, is needed as the use of a single converter controlling the DC voltage may not be effective, due to power limitations. Either a rectifier or an inverter can operate in the DC voltage control mode. However, for LCCs, it is always more beneficial if a rectifier station with a large capacity maintains the DC voltage while the rest of the stations control the currents. This makes the system more stable and less dependent on fast communication [23].

It should be mentioned that there are some drawbacks of parallel-connected LCC MTDC systems:

- Power reversal at any LCC converter station requires additional fast switches on the DC side;
- Blocking of a single bridge in a converter consisting of two or more series-connected bridges requires either operation of the whole system at reduced voltage or disconnection of the affected converter station;
- Commutation failure at an inverter can draw large currents from other terminals and this may affect the system recovery process.

#### 2) SERIES ARCHITECTURE

Figure 2 shows the series architecture of an LCC DC grid. The converter stations are connected in series to form a loop.

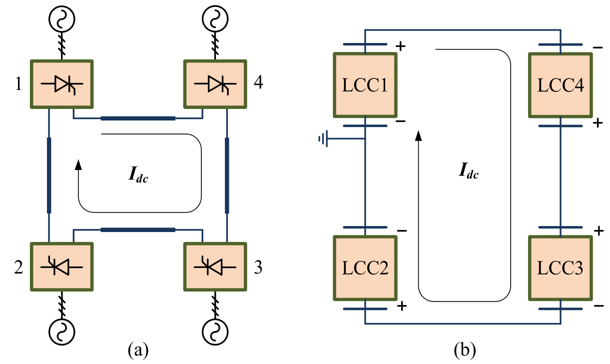


**FIGURE 2. Series LCC DC grid with a meshed configuration. (a) Meshed MTDC network; (b) Converter stations' connection.**

The common DC current flows through all the terminals in the loop. The converter voltage ratings are proportional to their individual power ratings. The DC network is grounded at one converter station. However, the insulation of the converter transformer must be rated for the full DC network voltage [1].

For series-connected systems, the DC current is controlled by one station, and all other stations either operate at constant-angle ($\alpha$ or $\gamma$) control or DC voltage control. The voltage references of the converters must be balanced in series-connected systems while the current references must be coordinated for parallel-connected systems. The protection methods for a serial LCC DC grid have been investigated in [39].

The series connected systems allow power reversal at a converter without the switching operations in the DC network. Converter bridges or the whole converter can be out of service without affecting the rest of the network. Communication among terminals is needed for controlling DC currents to minimize losses [1].

It should be mentioned that the series-connected LCC MTDC systems also suffer from certain limitations:

- As the converter-to-ground voltages are different for all terminals, different stations require different levels of insulation, which makes the insulation coordination very challenging;
- A permanent DC fault leads to the outage of the entire system;
- Flexibility for future expansion is highly limited as it needs a complete redesign of insulation coordination.

Due to above limitations, till date, only LCC MTDC networks with parallel architecture exist in practice [40]: Sardinia-Corsica-Italy project (200 kV), Hydro–Québec–New England (Canada) project (± 450 kV) and North-East Agra UHVDC project (± 800 kV).

#### 3) LCC DC GRIDS USING DC/DC TRANSFORMERS

The above section does not consider the employment of DC/DC transformers to interconnect LCC HVDC links with different DC voltage levels. References [14]–[16] use an MMC based DC/DC transformer to connect two existing LCC-HVDC links to form an MTDC network, as shown in Figure 3.

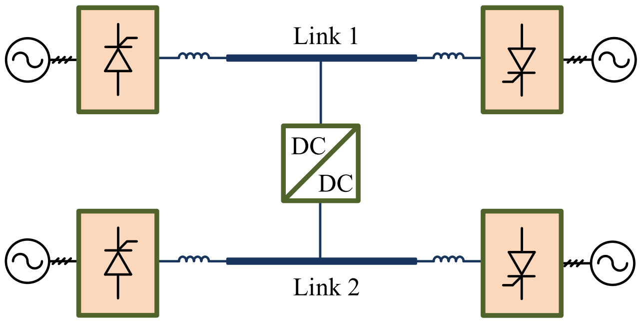


**FIGURE 3.** Connecting two LCC HVDC links using a DC/DC transformer.

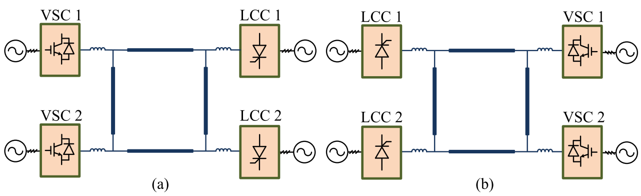


**FIGURE 4.** LCC/VSC hybrid DC grids. (a) VSCs as rectifiers and LCCs as inverters; (b) VSCs as inverters and LCCs as rectifiers.

The interconnected system using DC/DC transformer enables the interconnection of existing HVDC links with different voltage levels. Moreover, the flexible power exchange within the network can be used to mitigate commutation failure. The DC/DC transformer can limit DC fault current using its inherent control capability and prevent the propagation of DC faults. Therefore, the impact of losing an LCC terminal or DC faults on system operation can be mitigated. The proposed methods in the references [14]–[16] are suitable for the LCC-HVDC links whose geographic locations are close to each other.

It should be mentioned that, until now, the design and manufacturing of DC/DC transformers with large capacity, large voltage ratio, low losses and fault isolating capability are still under development. In addition, the high capital cost of the construction for interconnecting the existing links, is another key fact limits their potential application.

### B. TECHNICAL FEASIBILITY OF HYBRID LCC/VSC DC GRIDS

The DC voltage, power rating and transmission distance of VSC HVDC technology have been continuously increasing since it emerged in the 1990s. There are now more than 40 operational VSC HVDC projects worldwide [42]. The DC voltage ratings of the MMC is likely to reach up to ±800 kV with a power rating of 5000MW [43]. To this end, the developments in the VSC technology is going to approach the same level as the LCC technology, thereby enabling the combination of LCCs and VSCs in both HVDC and UHVDC applications.

Figure 4 shows two examples of LCC/VSC hybrid DC grids. In Figure 4(a), the VSCs operate as rectifiers and the LCCs as inverters. Bidirectional power transfer can be achieved in this architecture. However, it may be suitable for offshore wind power integration wherein MMCs can be employed as the offshore converter. It is because that the offshore converter station has strict requirements for space. Therefore, the devices in the offshore converter platform need to be designed compactly. MMCs can be employed due to their compact design and absence of AC filters. Moreover, the MMCs have the capabilities of black start and controlling the active and reactive power independently for the offshore AC networks. As for the onshore converters, the LCCs have higher power rating, auto-extinguishing capability for DC line faults and can minimize the power losses and capital costs compared to MMCs. Although this architecture still has the risk of commutation failure, proper control strategies can be designed to mitigate commutation failure [44]. It should be mentioned that these strategies can only reduce the probability of commutation failure but cannot fully solve it. If commutation failure occurs in the inverters, for example caused by a severe AC fault, the inverters will be blocked and the wind farms in sending ends will have to be tripped.

Figure 4(b) shows an LCC/VSC HVDC grid where the LCCs are rectifiers and the VSCs are inverters. This architecture utilizes the advantages of LCCs in terms of its technical maturity, high power rating, low manufacture cost, and low power losses. It also eliminates the risks of commutation failure as the VSCs operate as the inverters.

The operation, control and protection of LCC/VSC hybrid DC networks have been studied in [17]–[20]. In real applications, the Kun-Liu-Long three-terminal LCC/VSC project is the first multi-terminal UHVDC network using LCC/VSC hybrid technology in the world [45]. The topology of the network is shown in Figure 5.

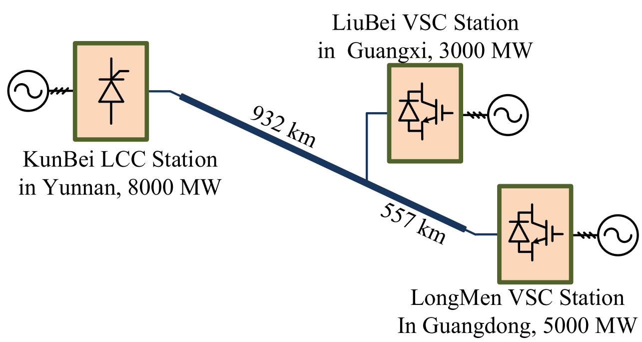


**FIGURE 5.** The Kun-Liu-Long hybrid multi-terminal UHVDC project.

In this three-terminal system, the DC voltage is ± 800 kV. The capacity of the LCC in Wudongde, Yunnan province is 8000 MW. It will operate as the rectifier and send the hydropower to the Guangxi (3000 MW) and Guangdong (5000 MW) provinces. The two receiving converters are MMCs which use hybrid full-bridge and half-bridge submodules. The system is bipolar configuration. The converter uses double-series connected high-voltage and low-voltage converters to achieve 800 kV [46]. The overhead transmission line between Yunnan and Guangdong provinces is over 1489 km.

## III. RELIABILITY MODEL OF MMCS FOR UHVDC APPLICATIONS

Many researches have been carried out for HVDC reliability study [28]–[33]. However, few of them focuses on the reliability analysis of the MMCs for UHVDC systems. In this section, the reliability of MMCs with high-voltage and low-voltage bridges is studied.

Reliability is defined as the probability of a device working for a time interval under a specified operating condition [41]. Let $\lambda(t)$ be the failure rate of a component:

$$\lambda(t) = \lim_{\Delta t \to 0} \frac{R(t) - R(t+\Delta t)}{R(t)\Delta t} = -\frac{1}{R(t)}\frac{d[R(t)]}{dt} \quad (1)$$

where $R(t)$ is the reliability function of the component, that is the probability of a device not failing during an interval $[0, t]$ with $R(0) = 1$, $R(\infty) = 0$.

From (1), the reliability function of the component is derived:

$$R(t) = e^{-\int_0^t \lambda(t)dt} \quad (2)$$

The mean time to failure (MTTF) is the mean expected value of lifetime $t$. Based on the probability theory:

$$MTTF = \int_0^\infty R(t)dt \quad (3)$$

It should be noted that electronic equipment's failure pattern is typically a Bathtub curve [36], [47], in which the normal operating period is characterized by a constant failure rate. The reliability function of a component is calculated by:

$$R(t) = e^{-\lambda t} \quad (4)$$

where $\lambda$ is the failure rate of the component.

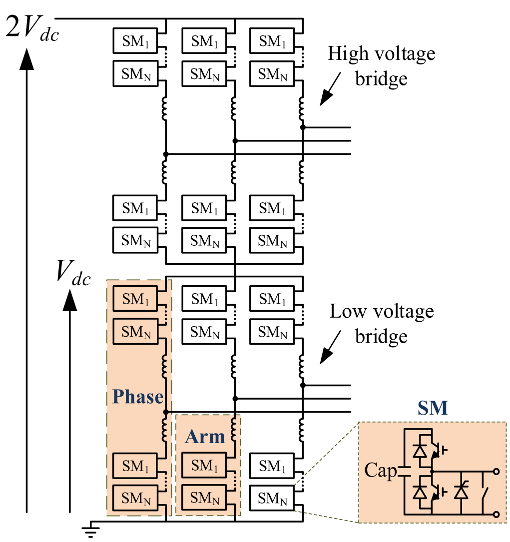


**FIGURE 6.** Schematic diagrams of an HB-MMC for UHVDC applications.

Similar to LCC-UHVDC systems, MMCs can be connected in series on the DC side to achieve an ultra-high DC voltage. Figure 6 shows the schematic diagram of an asymmetrical monopole half-bridge (HB) MMC with two series connected bridges, a high-voltage and a low-voltage bridge. Each phase consists of one upper and one lower arm. Each arm has $N$ series-connected submodules (SMs) and one inductor. Each SM contains two IGBTs, two diodes, one capacitor, one thyristor and one bypass switch.

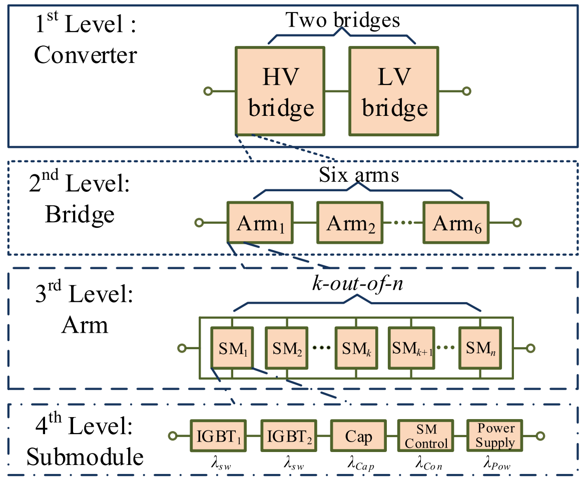


**FIGURE 7.** Hierarchical reliability model of the HB-MMC for UHVDC applications.

To calculate the reliability of the converter, it is subdivided into four hierarchical levels, as shown in Figure 7. In each hierarchical level, a reliability block diagram is used to represent the reliability relationship of MMC components.

In normal operation, the sum of the voltages of all SM capacitors in each arm equals the DC side voltage $V_{dc}$. Then, the minimum number of SMs can be calculated as follows:

$$N = \left\lfloor \frac{V_{dc}}{V_{SM}} \right\rfloor \quad (5)$$

where $V_{dc}$ is the DC side voltage of each bridge and $V_{SM}$ is the voltage of each SM.

As the high-voltage and low-voltage bridges are in series, both need to be in good states for normal operation. Therefore, the two bridges are in series in the first level. The reliability function of a converter is given by:

$$R_C(t) = R_{B-HV}(t) \times R_{B-LV}(t) \quad (6)$$

where $R_{B-HV}(t)$ and $R_{B-LV}(t)$ are the reliability functions of the high-voltage bridge and low-voltage bridge, respectively.

In the second level, each arm is regarded as one combined reliability block. All six arms are required to be in a good state for normal operation. Hence, they are connected in series. The reliability function of a bridge is:

$$R_B(t) = [R_{Arm}(t)]^6 \quad (7)$$

where $R_{Arm}(t)$ is the reliability function of an arm.

The third level shows the reliability model of one arm. The *k-out-of-n* system model is suitable for MMC redundancy analysis [35]–[37], [41]. A *k-out-of-n* system is a system that continues to operate if and only if at least $k$ out of $n$ components are in good states. In the third level, the $SM_1$ to $SM_k$ are the $k$ basic SMs required for a normal operation of the MMC. The $SM_{k+1}$ to $SM_n$ are the redundant cells in each arm.

There are usually two operation modes for the redundant SMs: active mode and standby mode [37], [41]. The active redundancy scheme is considered in this paper. In the active mode, all the $n$ SMs share the DC voltage. Each operating SM is subjected to a voltage that is lower than the nominal value. When there is a failure of an SM, the faulty SM is bypassed. Then the rest of the SMs are assigned a slightly higher voltage than the original value. The arm continues to operate after the short transient for setting down at a higher voltage for each SM [37]. The MMC needs to be shut down if the number of SMs in good states is less than $k$. Therefore, the reliability function of the arm is:

$$R_{Arm}(t) = \sum_{i=k}^{n} C_n^i [R_{SM}(t)]^i [1 - R_{SM}(t)]^{n-i} \tag{8}$$

where $R_{SM}(t)$ is the reliability function of a SM.

The fourth level is the reliability of SMs. The SM needs to quit operation if any failure occurs in any of the two IGBTs, the capacitor, the SM control system or the SM power supply system. The failed SM will be bypassed by its bypass switch. Therefore, these three components are in series in the reliability block diagram and their reliability model is:

$$R_{SM}(t) = [R_{sw}(t)]^2 \times R_{Cap}(t) \times R_{Con}(t) \times R_{Pow}(t) \tag{9}$$

where $R_{sw}(t)$, $R_{Cap}(t)$, $R_{Con}(t)$ and $R_{Pow}(t)$ are the reliability functions of the IGBT, capacitor, SM control system and SM power supply system of the SM.

Let the failure rates of the IGBT, capacitor, SM control system and power supply system be $\lambda_{sw}$, $\lambda_{Cap}$, $\lambda_{Con}$ and $\lambda_{Pow}$ respectively. According to equation (4), the reliability functions of them are:

$$R_{sw}(t) = e^{-\lambda_{sw} t} \tag{10}$$

$$R_{Cap}(t) = e^{-\lambda_{Cap} t} \tag{11}$$

$$R_{Con}(t) = e^{-\lambda_{Con} t} \tag{12}$$

$$R_{Pow}(t) = e^{-\lambda_{Pow} t} \tag{13}$$

According to equation (3), the MTTF of the converter is calculated by:

$$MTTF = \int_0^{+\infty} R_C(t)dt \tag{14}$$

According to equation (1), the failure rate of the converter is given by:

$$\lambda_C(t) = -\frac{1}{R_C(t)} \frac{dR_C(t)}{dt} \tag{15}$$

In a ± 800 kV HVDC system, the bipolar configuration is used. The voltage of each pole is 800 kV, thus the voltage of each bridge is 400 kV. IGBT modules with a withstand voltage of 4.5 kV were considered and a de-rating factor of 56% for the voltage of IGBT modules was applied in the SMs. This is to make sure that the IGBT modules have a long lifetime and have the capability to withstand overvoltage. Therefore, the nominal voltage of one single IGBT module in each SM is 2.52 kV. According to equation (5), each arm needs to contain at least 159 SMs to meet the requirement of the DC voltage. To make sure enough redundancy for normal operation, 8 more (5%) redundant SMs are added in each bridge. There are 167 × 2 = 334 IGBT modules in each arm. The failure rate of the IGBT module was assumed to be 0.004 occ/year based on statistical data in practical projects [48]. The failure rates of the capacitor, SM control system and power supply system were assumed to be 0.001752 occ/year, 0.03 occ/year and 0.03504 occ/year [37].

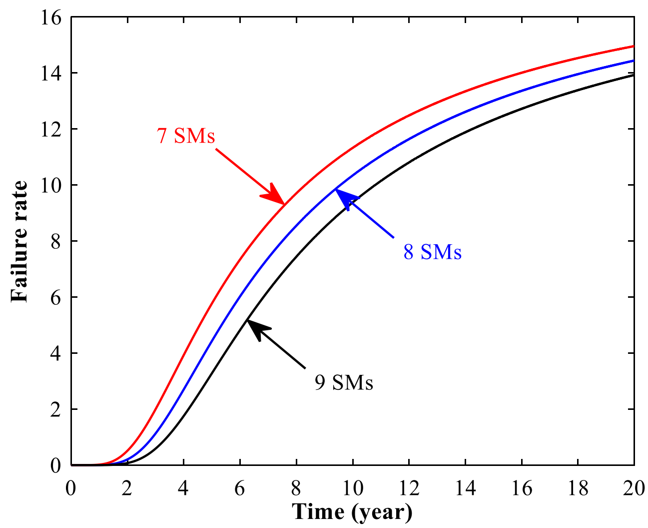


**FIGURE 8. Failure rate of the studied MMC with different redundancy design.**

The reliability indices of the MMC, the MTTF and failure rate, are calculated using (14) and (15) respectively. The calculated MTTF is 3.03 year. The failure rates with different numbers of redundant SMs are illustrated in Figure 8. The failure rate in the first 2 years is very low. Then it increases rapidly over time in the first few years and grows slightly after 15 years. The results also show that the failure rate will reduce if more redundant SMs are used. However, the capital cost and power losses will be increased if more redundant SMs are used. It should be mentioned that Figure 8 just reveals the theoretical results of the converter reliability. The converter will be scheduled shut-down for maintenance every one or two years in real applications. The failed components will be replaced during the maintenance period.

## IV. RELIABILITY ANALYSIS OF LCC DC GRIDS AND LCC/VSC HYBRID DC GRIDS

In this section, the system reliability of LCC DC grids and LCC/VSC hybrid DC grids will be investigated. The studied systems are illustrated in Figure 9. The LCC DC grid in Figure 9(a) is the base system. The receiving ends and sending ends are replaced by MMCs in Figure 9(b) and Figure 9(c), respectively. The capacity of the converters and lines are shown in the figure as well.

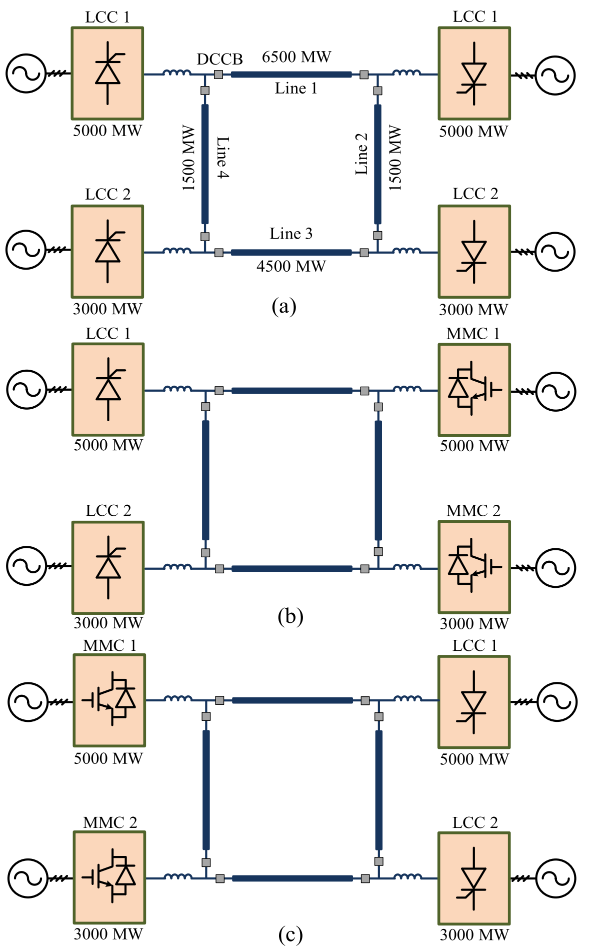


**FIGURE 9.** Test systems. (a) LCC DC grid; (b) LCC/MMC DC grid with two MMCs as inverters; (c) LCC/MMC DC grid with two MMCs as rectifiers.

## A. RELIABILITY MODELING OF LCC DC GRIDS AND LCC/VSC HYBRID DC GRIDS

The DC voltage of the DC grids is ± 800 kV. The system is bipolar configuration, with two series connected converters in each pole, both for the LCC and the VSC. The reliability parameters of the LCCs and DC lines are from the literature for ± 800 kV LCC UHVDC transmission system with slight changes [27]. It is assumed the lengths of lines 1 and 3 are the same. The lengths of lines 2 and 4 are the same and are half of lines 1 and 3. The reliability parameters of the MMCs are from the previous section. It is assumed that the DCCBs are available for this voltage level and are applied to the end terminals of each transmission line. However, in the open literature there is a lack of information on the reliability data for DCCBs. For the reliability study performed in this paper with DCCBs we modified the data from the Zhoushan five-terminal project considering the installations of DCCBs [34].

To establish the reliability models for the studied systems, the functions of the systems, the constraints that limit their operation, and the reasons that cause their failure should be clearly defined. Each element in the HVDC systems will affect the availability and reliability of the whole system. Therefore, an accurate reliability model needs a precise reliability analysis of the system with the consideration of all the components [38]. This section will establish accurate and comprehensive reliability models of the studied systems shown in Figure 9. The models are based on the configurations of the studied systems and their subsystems.

The systems in Figure 9 are complex and therefore, they are divided into different subsystems. As the circuit topologies of the studied systems are the same, one reliability model can be used to represent all of them, as shown in Figure 10. Each subsystem is divided into several hierarchical levels to facilitate the modeling process. The details of each subsystem will be described in the following sections.

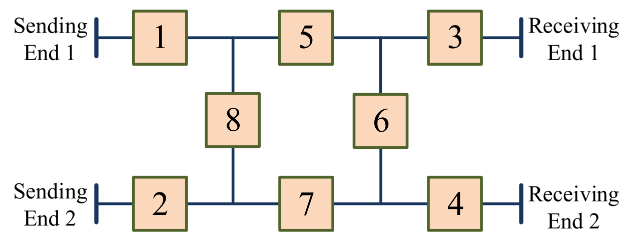


**FIGURE 10.** Whole system reliability model.

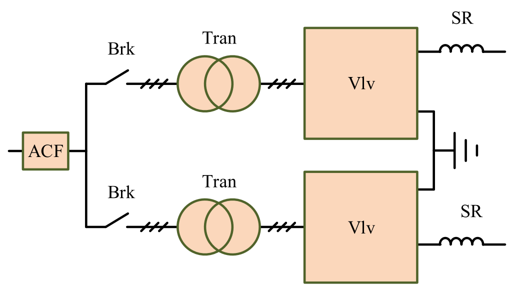


**FIGURE 11.** Whole system reliability model.

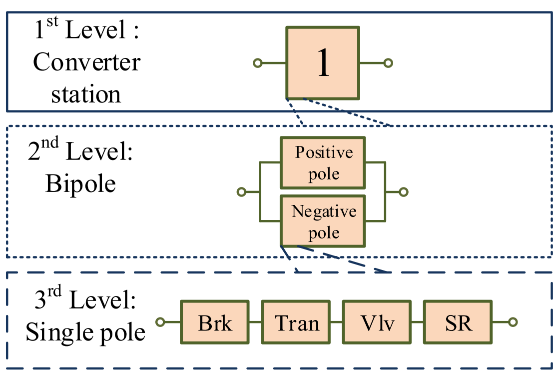


**FIGURE 12.** Reliability model of the converter station 1.

## B. RELIABILITY MODELING OF CONVERTER STATIONS

Figure 11 shows the main components of converter station 1 (Block 1 in Figure 10). The hierarchical reliability model of converter station 1 is shown in Figure 12. The converter has two poles. Each pole consists of four components: AC side filter (ACF), AC side breaker (Brk), converter transformer (Tran), valve (Vlv), DC side smoothing reactor (SR).

Each one of these components is represented by an equivalent reliability model with one or more de-rated states.

The reliability of Blocks 2, 3 and 4 can be modeled in a similar way as Block 1. However, if the Blocks 3 and 4 are LCCs working as inverters, the effect of commutation failure needs to be considered. Reference [49] proposed a virtual device of commutation failure (VDoCF) which considers random factors of AC system faults, including the fault location, the fault type, the fault close angle, transition resistance. Therefore, the reliability models of the Blocks 3 and 4 become the structure as shown in Figure 13. The LCC will be out of service if a commutation failure occurs. Thus, the VDoCF is in series with the converters in the second level of the reliability model. The failure rate of the VDoCF can be calculated through the algorithm in [49] based on the data of the AC faults at the AC side of the converter. As the MMCs do not have the problem of commutation failure, the block of the VDoCF will be removed if the converters are MMCs.

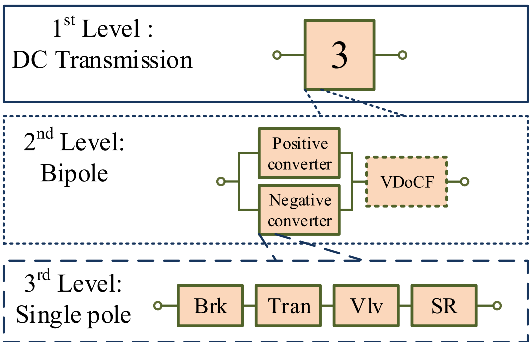


**FIGURE 13.** Reliability model of Block 3 with an LCC working as an inverter.

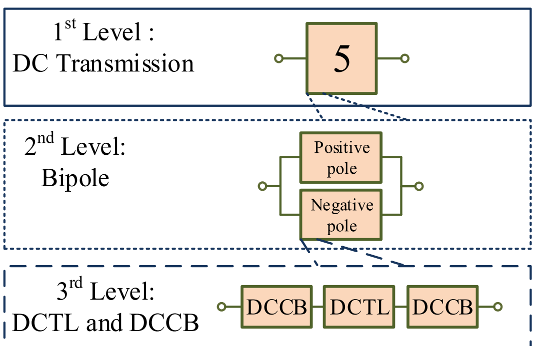


**FIGURE 14.** Reliability model of DC transmission lines.

### C. RELIABILITY MODELING OF DC TRANSMISSION LINES

The reliability model of the DC transmission lines is illustrated in Figure 14. The DCCBs and the DC transmission line (DCTL) are in series.

### D. CASE STUDY

The overall system reliability evaluation of the three systems in Figure 9 is quantified using the models developed in previous sections. To analyze the final reliability model, different methods, such as the capacity outage probability table (COPT) based risk model, network reduction, minimal cut sets, and Monte Carlo simulation can be used [38]. The COPT-based method is widely used for the reliability evaluation of an electric power system. An extension of this method is the equivalent assisting unit approach [50]. For instance, the generating potential of subsystem 1 is modeled as a multistate capacity table. This COPT has different capacity levels and probabilities (availabilities). Then the obtained COPT is combined with other subsystems' reliability models to calculate the reliability indices of the whole system.

The component reliability parameters are provided in Table 1. The reliability parameters are from [27], [38], and [49] with slight changes. As reliability data of the LCC in the literature is given for single bridge, the availability of the whole LCC valve is calculated considering the two bridges connected in series.

**TABLE 1.** Component reliability parameters.

| Component | Failure rate (occ/year) | Repair time (h) | Availability |
|---|---|---|---|
| AC circuit breaker (Brk) | 0.0028 | 48 | 0.9999847 |
| Converter transformer (Tran) | 0.015 | 2400 | 0.9959072 |
| LCC valve group (5000 MW) | 0.13 | 32 | 0.9995253 |
| LCC valve group (3000 MW) | 0.1 | 32 | 0.9996358 |
| LCC valve (Vlv_LCC, 5000 MW) | - | - | 0.9990508 |
| LCC valve (Vlv_LCC, 3000 MW) | - | - | 0.9992717 |
| MMC valve (Vlv_MMC, 5000 MW) | 0.33 | 40 | 0.9984954 |
| MMC valve (Vlv_MMC, 3000 MW) | 0.3 | 40 | 0.9986320 |
| Smoothing Reactor (SR_LCC) | 0.01 | 1400 | 0.9984044 |
| Smoothing Reactor(SR_MMC) | 0.015 | 5 | 0.9999914 |
| DC circuit breaker (DCCB) | 0.05 | 50 | 0.9997147 |
| DC transmission lines (DCTL) 1 & 3 | 0.22 | 8 | 0.9997991 |
| DC transmission lines (DCTL) 2 & 4 | 0.11 | 8 | 0.9998996 |
| VDoCF | 0.184 | 16.8 | 0.9996472 |

In the first stage, the reliability models of the subsystems 1 to 8 are calculated as shown in Tables 2 and 3.

It can be seen from Table 2 that the reliability of LCCs as rectifiers and inverters in the studied systems are different. The reliability of LCCs as inverters is lower than the ones as rectifiers because the factor of commutation failure is considered.

In the next stage, the final reliability models of the three systems in Figure 9 are calculated as shown in Tables 4, 5 and 6.

Table 7 unveils the reliability indices of the three systems with the consideration of the results in Tables 4-6. The load level of the two receiving ends are both at 0.8 p.u.

The topologies of the DC circuits of the three systems are the same. Therefore, the impacts from the DC circuits on the overall system reliability of the three systems are

**TABLE 2.** Reliability models of the subsystems 1 to 4.

| Subsystems | Capacity in (p.u.) | Probability |
|---|---|---|
| Vlv_LCC, 5000MW as Subsystem 1 | 1 | **0.9867624** |
| | 0.5 | 0.0131935 |
| | 0 | 0.0000441 |
| Vlv_LCC, 5000MW as Subsystem 3 (considering commutation failure) | 1 | **0.9864142** |
| | 0.5 | 0.0131889 |
| | 0 | 0.0003969 |
| Vlv_LCC, 3000MW as Subsystem 2 | 1 | **0.9871988** |
| | 0.5 | 0.0127600 |
| | 0 | 0.0000412 |
| Vlv_LCC, 3000MW as Subsystem 4 (considering commutation failure) | 1 | **0.9868505** |
| | 0.5 | 0.0127555 |
| | 0 | 0.0003940 |
| Vlv_MMC, 5000MW as Subsystem 1 or 3 | 1 | **0.9888015** |
| | 0.5 | 0.0111670 |
| | 0 | 0.0000315 |
| Vlv_MMC, 3000MW as Subsystem 2 or 4 | 1 | **0.9890721** |
| | 0.5 | 0.0108979 |
| | 0 | 0.0000300 |

**TABLE 3.** Reliability models of the subsystems 5 to 8.

| Subsystems | Capacity in (p.u.) | Probability |
|---|---|---|
| 5 or 7 | 1 | **0.9984580** |
| | 0.5 | 0.0015426 |
| | 0 | 0.0000000 |
| 6 or 8 | 1 | **0.9986587** |
| | 0.5 | 0.0013417 |
| | 0 | 0.0000000 |

**TABLE 4.** Final reliability model of the system (a) in Figure 9.

| States | Capacity in (p.u.) | Probability |
|---|---|---|
| 1 | 1 | 0.9453387 |
| 2 | 0.91 | 0.0014566 |
| 3 | 0.81 | 0.0243749 |
| 4 | 0.78 | 0.0014566 |
| 5 | 0.69 | 0.0252174 |
| 6 | 0.63 | 0.0004158 |
| 7 | 0.56 | 0.0000000 |
| 8 | 0.38 | 0.0004215 |
| 9 | 0 | 0.0013178 |

*Note: the probability of 0.0000000 indicates the value is less than $10^{-7}$.

**TABLE 5.** Final reliability model of the system (b) in Figure 9.

| States | Capacity in (p.u.) | Probability |
|---|---|---|
| 1 | 1 | 0.9497599 |
| 2 | 0.91 | 0.0014634 |
| 3 | 0.81 | 0.0226824 |
| 4 | 0.78 | 0.0014634 |
| 5 | 0.69 | 0.0233680 |
| 6 | 0.63 | 0.0000683 |
| 7 | 0.56 | 0.0000000 |
| 8 | 0.38 | 0.0000725 |
| 9 | 0 | 0.0011215 |

the same. The differences come from the converters. As the MMCs in the studied system are more reliable than the LCCs, the reliability indices in Table 7 show that the system (a) is less reliable than the other two systems. The expected energy not supplied (EENS) [MWh/yr] and expected load curtailment (ELC) [MWh/yr] of the system (b) are slightly lower than system (c). This is because the reliability of the LCCs as inverters in the system (c) is lower than rectifiers in system (b).

**TABLE 6.** Final reliability model of the system (c) in Figure 9.

| States | Capacity in (p.u.) | Probability |
|---|---|---|
| 1 | 1 | 0.9490899 |
| 2 | 0.91 | 0.0014624 |
| 3 | 0.81 | 0.0226664 |
| 4 | 0.78 | 0.0014624 |
| 5 | 0.69 | 0.0233515 |
| 6 | 0.63 | 0.0004067 |
| 7 | 0.56 | 0.0000000 |
| 8 | 0.38 | 0.0004110 |
| 9 | 0 | 0.0011492 |

**TABLE 7.** Reliability indices of the three studied systems in Figure 9.

| Index | System (a) | System (b) | System (c) |
|---|---|---|---|
| Probability of failure | 0.0546613 | 0.0502401 | 0.0509101 |
| Expected energy not supplied (EENS) [MWh/yr] | 117.1468364 | 105.6433481 | 108.5050468 |
| Expected load curtailment (ELC) [MWh/yr] | 33.3644113 | 28.7713468 | 30.5585161 |

**TABLE 8.** Reliability indices of the three studied systems when 4 SMs are used as redundancy in the MMCs.

| Index | System (a) | System (b) | System (c) |
|---|---|---|---|
| Probability of failure | 0.0546613 | 0.0671127 | 0.0677708 |
| Expected energy not supplied (EENS) [MWh/yr] | 117.1468364 | 144.4724278 | 147.3548341 |
| Expected load curtailment (ELC) [MWh/yr] | 33.3644113 | 41.3865616 | 43.2129314 |

In order to test the impact of the converter reliability on the whole system reliability, the system reliability indices with 4 (2.5%) redundant SMs in the MMCs are calculated and shown in Table 8. In this case, the LCC DC grid becomes more reliable than the two LCC/VSC DC grids. The system (b) is still more reliable than the system (c) due to the impact of commutation failure on the LCCs.

## V. CONCLUSION

In this paper, the technical feasibility of building LCC DC grids and LCC/VSC hybrid DC grids was discussed. Then, the reliability analysis of LCC DC grids and LCC/VSC hybrid DC grids was conducted.

A hierarchical reliability model of MMCs with high-voltage and low-voltage bridges for UHVDC applications is developed in this paper. Impact of the redundant design of the MMCs on their reliability indices was presented. The study shows that the MMCs will be more reliable if more redundant SMs are employed. However, there is a level when the benefits become minimal, and the cost and power losses are affected.

A comprehensive whole system reliability model of the studied DC grids was developed. The reliability model of each subsystem of the whole system was modeled in detail. Various reliability indices were calculated using this whole system reliability model. The studies show that the consideration of commutation failure affects the reliability results of LCCs and the LCC/VSC hybrid DC grids. Moreover, the redundancy design of the MMCs affects reliability results of the LCC/VSC hybrid DC grids. More redundant SMs in the MMCs will improve the reliability of the whole system.

It should be mentioned that the reliability results may be changed when the DC grid configurations, voltage level and converter capacity are changed. An overall reliability analysis should be carried out case-by-case when the work is applied in real applications.

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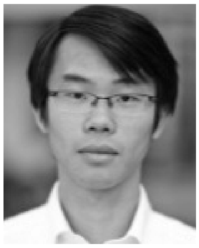

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