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EVALUATING THE AVAILABILITY OF VSC-HVDC CONNECTIONS USING MONTE CARLO SIMULATION

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The power transmission technology based on Voltage Source Converter High Voltage Direct Current (VSC-HVDC) plays a crucial role in modern power systems by enabling flexible and efficient long-distance electrical power transmission, integrating renewable energy sources, and supporting grid stability. However, to guarantee steady performance and reduce downtime, VSC-HVDC systems must be reliable. This paper highlights how crucial it is to assess the dependability of VSC-HVDC systems at the converter substation and DC link levels, where each component is subject to different stresses and possible failure scenarios. Monte Carlo simulations are an effective tool for this study because they allow for thorough probabilistic evaluations of failure scenarios, maintenance needs, and system recovery timeframes. This paper proposes a non-sequential Monte Carlo algorithm for the VSC-HVDC link implemented using Python programming language, capable of evaluating the main reliability indicators Loss of Load Expectation (LOLE), Loss of Load Probability (LOLP), Expected Energy Not Served (EENS).

Keywords: Availability, HVDC, Monte Carlo simulation, Python, VSC

1. Introduction

In the last decades, the reliability analysis of electricity networks, in particular of high voltage transmission networks, has been applied, considering reliability data related to constituent equipment such as overhead or underground transmission lines, switchgear equipment at substation level (circuit breakers, disconnector switchers), power transformers, and unavailability at power generator level. This type of reliability analysis is usually performed specifically to determine the reliability of both the power generation and transmission network in classical AC power systems, but with the increasing level of integration of HVDC links, reliability analysis of different types of DC links is becoming an essential aspect of ensuring the best possible continuity of supply [1-3].

In areas where hydropower [4] resources are situated distant from centers of consumption, HVDC technology has proven very useful for transferring electricity produced by these facilities across long distances. Similar to this, HVDC connections make it easier to integrate solar power [5], [6] effectively. By

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connecting large-scale solar farms in isolated locations to the main grid, they increase the resilience and dependability of the supply from renewable sources. Reliability analysis is therefore essential to guarantee continuous and stable energy supply as hydropower and solar power generation become more significant and are integrated with HVDC networks [7].

So far, over the years, several reliability analyses of HVDC links have been performed, and different methods have been used for reliability assessment, such as sequential and non-sequential Monte Carlo type analyses [8],[9], respectively, techniques based on Failure Mode and Effects Analysis (FMEA) [10],[11], or analytical techniques, such as those based on Capacity Outage Probability Table (COPT) [12]. In the FMEA method, the event tree and minimum cut set approach are used to represent the operational behavior of the system and infer the appropriate failure modes of the system.

The statistics show that the availability of HVDC systems in operation is over 90%, according to the average availability data of VSC - HVDC Murraylink and Cross Sound Cable [13].

This paper focuses on a proposed algorithm based on Monte Carlo non-sequential analysis developed in Python, which can be used for the availability evaluation of VSC-HVDC connection. The current paper is structured as follows: **Section 2** presents the main availability evaluation techniques used for HVDC systems; **Section 3** presents the theoretical aspects related to non-sequential Monte-Carlo simulation, **Section 4** presents the Monte-Carlo simulation algorithm developed using Python, and **Section 5** presents the simulation results for a VSC-HVDC bipolar connection with a total length of 611 km, and **Section 6** presents the main conclusions of the Monte Carlo Simulations done considering the study case VSC-HVDC connection.

2. Availability evaluation techniques for HVDC connections

There are several ways in which the availability of HVDC connections can be evaluated, including:

- **FMEA Analysis.** Through the identification and evaluation of probable failure modes in crucial components such as power transformers and converters, this technique improves the availability and dependability of HVDC systems. A Risk Priority Number (RPN), which identifies high-priority risks, is produced by rating each failure mode according to its severity, incidence, and likelihood of discovery. Operators can limit unexpected downtime by using preventative measures like redundancy and early problem detection by concentrating maintenance and monitoring on components with high RPNs. In addition to providing proactive maintenance for increased HVDC availability and adherence to reliability requirements, regular updates to the FMEA also aid in maintaining dependability as system circumstances change [10],[11].

- **COPT Simulations**. By estimating the likelihood of different system states based on component breakdowns, this method is utilized in HVDC systems to evaluate and improve availability. COPT measures the possibility that certain capacity levels will remain accessible despite outages by simulating possible failures across components, such as converters and transformers. By directing resource allocation and redundancy techniques to preserve operational capacity, this probabilistic approach assists operators in understanding how outages affect system dependability. By offering a thorough understanding of availability concerns in HVDC systems, COPT analysis enables focused enhancements and guarantees that the system can consistently satisfy demand in a range of scenarios [12].
- **Monte-Carlo Simulations (sequential and non-sequential).** In HVDC systems, this philosophy is an effective tool for modeling how component failures affect availability and dependability. To capture the chronological sequence of events and provide a realistic perspective of system performance across time, sequential Monte Carlo analysis analyses the time-dependent behavior of each component failure and repair. Non-sequential Monte Carlo, in contrast, focuses on the total failure probability without regard to precise time, treating each failure event separately. By using these techniques, operators may assess different outage situations and repair dynamics, which helps them optimize redundancy plans, schedule maintenance, and increase the overall dependability of HVDC systems [8],[9].

The availability of HVDC links depends primarily on the failure intensity and mean time to repair (MTTR) of equipment associated with HVDC systems. The reliability of an HVDC system also depends on its design and the investments made in it. Aspects related to cost-benefit analysis (CBA analysis) have been included in the reliability analysis of HVDC systems [14].

In contrast to Line Commutated Converter High Voltage Direct Current (LCC-HVDC) links, VSC-HVDC links, especially modern Modular Multi-Level Converter High Voltage Direct Current (MMC-HVDC) technologies, utilize controllable IGBT sub-modules, which do not exhibit switching-induced failures in operation. Also, equipment such as DC filters are often optional and not mandatory. Reactive power compensation devices at VSC-HVDC converter stations are not required.

Based on HVDC reliability records worldwide, the importance of components in HVDC LCC has been presented in various publications, which resulted in transmission lines and converter transformers being considered to be the most dominant components. However, for wind farms utilizing VSC-HVDC connections, the transmission DC cable/line has the largest effect on offshore power availability [15].

3. Theoretical aspects for non-sequential Monte Carlo simulation

In comparison with the analytical approach to network element reliability assessment, where a fixed set of values for the failure and repair rates of substation components (busbars, transformers, breakers, etc.) are considered, Monte-Carlo simulation allows the random generation of the operating states (unavailability or availability) of network elements, i.e. equipment and subsystems within a VSC-HVDC connection.

The basic principle of the State Sampling Approach is described in this chapter. A system state depends on the combination of all component states, and each state of a component can be determined by sampling the probability of that component to occur in that state. The behavior of each component can be described by a uniform distribution between [0,1]. This type of distribution is specific to the state sampling approach and is in direct correlation with the methods described in academic work on the subject [16].

Assume that each component has two possible states of operation: the unavailability state ("failure state") and the normal operation state ("success state") and that the unavailability states of the components are independent events.

The state of operation for the "ith" component is extracted following the logic in equation (1) [16]:

$$S_i = \begin{cases} 0\ (succes\ state),\ if\ U_i \geq\ PF_i \\ 1\ (failure\ state),\ if\ 0 \leq U_i\ \leq\ PF_i \end{cases} \tag{1}$$

where: S_i - represents the state of the ith component; U_i - randomly generated number Ui distributed between [0, 1] for component "i"; PF_i - represents the probability of component unavailability.

Therefore, each random number corresponds to one trial of the component state. This form of sampling is called direct Monte Carlo sampling.

After a system state is selected from the sampling, system analysis is performed to judge whether or not it is a failure state, and if it is, a risk index function is evaluated for that state. When the number of samples is sufficiently large, the sampling frequency of the system state "s" can be used as an unbiased estimate of its probability [16]. A necessary step is to generate a sequence of random numbers for each component.

The random numbers must fulfill the three basic requirements: uniformity, independence, and a long repetition cycle. Monte Carlo simulation is a fluctuating process.

Therefore, the estimated risk indices always assume consideration of a confidence band (confidence interval). There is no guarantee that a larger number of samples will certainly lead to a smaller error. However, the confidence interval indeed decreases with increasing number of samples.

In the assessment of the risk of failure at the level of a power system, different risk indices have different speeds of convergence. The coefficient of variation of the EENS index has been found to have the lowest convergence speed and should therefore be used as a convergence criterion in a multiple index study.

An alternative is to use a predetermined maximum number of samples as a stopping rule (10^6 samples). This number of samples is considered sufficient to generate accurate results in the domain of expertise of the reliability of power substations, i.e. subsystems in the HVDC link component, according to academic works [16].

Failure intensity (λ) and repair rate (μ). In the case of VSC-HVDC links an overview of failure rates, i.e. average repair rates derived from several Monte Carlo studies, is presented in [17]. In other words, the failure intensity, often denoted by the symbol λ (lambda), is a key parameter used in reliability assessment to quantify the frequency with which failures occur over time at the system or component level. It represents the failure occurrence rate and is usually expressed as the number of failures per unit of time. Mathematically, the failure intensity can be defined according to equation (2):

$$\lambda = \frac{Total\ number\ of\ failures}{Total\ operating\ time} \quad (2)$$

Thus, the repair rate, denoted by μ, is the average time taken to repair a faulty system or component once a fault occurs. It is calculated as the total number of repair events in a specified period divided by the total downtime. Mathematically, the repair rate can be defined according to equation (3):

$$\mu = \frac{Total\ number\ of\ repair\ events}{Total\ downtime} \quad (3)$$

Mean Time to Repair (MTTR). According to the Romanian Technical Standard NTE 005/06/00 used to calculate the reliability of National Power System(NPS) equipment, the definition of Mean Time to Repair (MTTR) is given as follows: "*The average value of the time included in the restoration time, exclusively assigned to the actual repair or replacement actions*." [18].

$$MTTR = \frac{1}{\mu} \quad (4)$$

This relationship demonstrates that the average repair time is the reciprocal of the repair rate. In other words, the MTTR is the average time taken to complete a repair and the repair rate is the frequency of repairs occurring in a given period.

Mean Time Between Failures (MTBF). According to the Romanian Technical Standard NTE 005/06/00 used to calculate the reliability of National Power System (NPS) equipment, the definition of the Mean Time Between Failures (MTBF) is given as follows: "*The average value of the operating time between two consecutive failures (unsuccessful states) of an element, device (installation).*" [18].

$$MTBF = \frac{1}{\lambda} \tag{5}$$

Thus MTBF is the mean time between consecutive failures of a system or component. A higher MTBF indicates that the system or component is more reliable, which means that it is less likely to fail within a given period. Systems with higher MTBF values experience less frequent failures [16].

4. Monte Carlo simulation algorithm implementation for VSC-HVDC

The main steps associated with the Monte Carlo simulation are the following:

STEP 1. ***Provide the input data associated with the elements of the converter station and DC link.*** The input data: failure intensity (λ_i), respectively repair rate (μ_i), for the Direct Current Underground Cable (DC UGC) the length is also provided.

STEP 2. ***Analytical calculation of the failure probability of each element within the VSC-HVDC link.*** The probability of failure is calculated for each equipment:

$$PF_i = q_i = \frac{\lambda_i}{\lambda_i + \mu_i} \tag{6}$$

STEP 3. ***Generating random states using the Monte Carlo method ("State Sampling Approach") and determining the probability of failure based on them.*** Assume that a component (equipment) has a probability of failure (q_i) and assume that each component (equipment) has two states: failure (not functioning) and success (properly functioning) and that component (equipment) failures are independent events. Generate numbers between [0,1] with uniform distribution, if the generated number (U_i) is greater than the probability of failure (q_i), the component state is considered a "success state", otherwise the component state is considered a "failed state".

STEP 4. ***Determining the failure probability for the subsystems within the VSC-HVDC connection, respectively calculating the total failure probability***

Series elements: $$q_e = q_1 + q_2 \tag{7}$$

Parallel elements: $$q_e = q_1 \times q_2 \tag{8}$$

According to the Monte-Carlo simulation, a final probability of failure of the equivalent subsystem, and finally of the total VSC-HVDC link, is obtained.

STEP 5. ***Calculation of reliability indices*****:** LOLP (Loss of Load Probability), LOLE (Loss of Load Expectation), and EENS (Expected Energy Not Served).

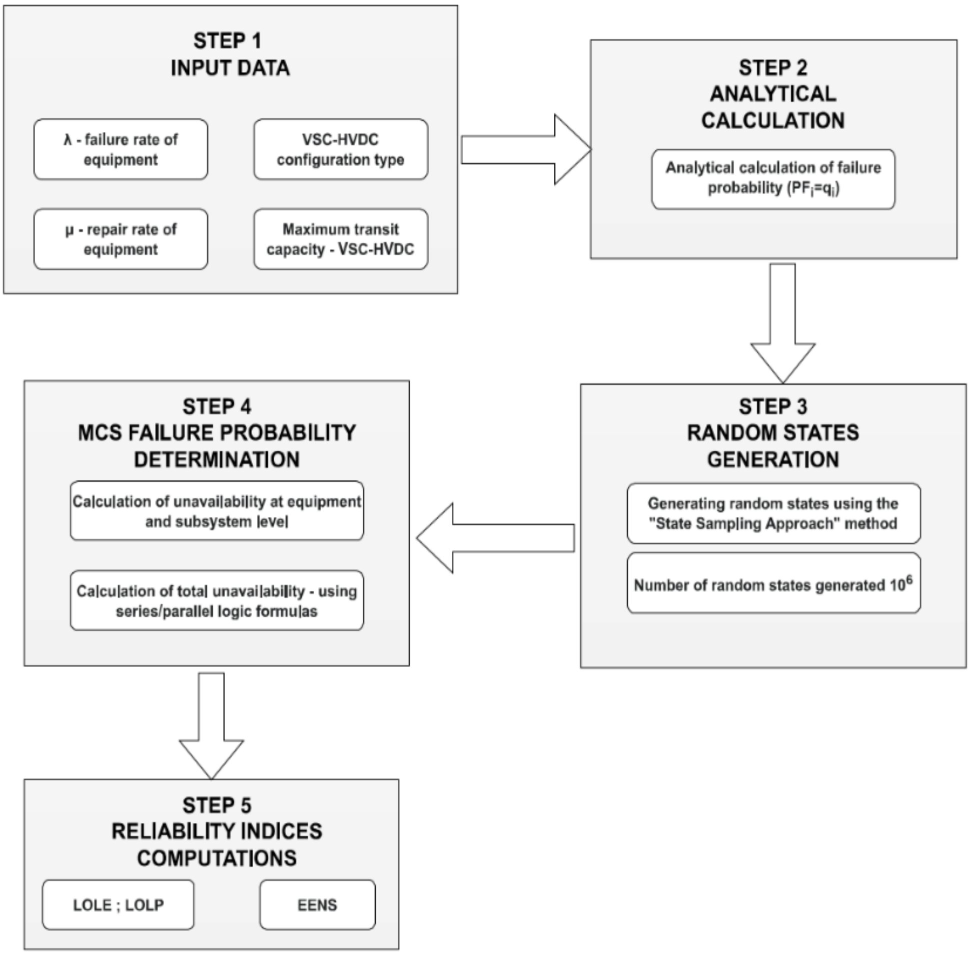

Fig. 1 – Monte – Carlo – Algorithm main steps

VSC-HVDC bipolar connection – Main subsystems

Using the code written with the Python programming language, the reliability of a VSC-HVDC Bipolar link with a capacity of 2000 MW, considering a non-sequential Monte Carlo simulation algorithm with a number of 10^6 samples. Fig. 2 shows the simplified diagram containing the main subsystems and the main elements of the bipolar VSC-HVDC connection.

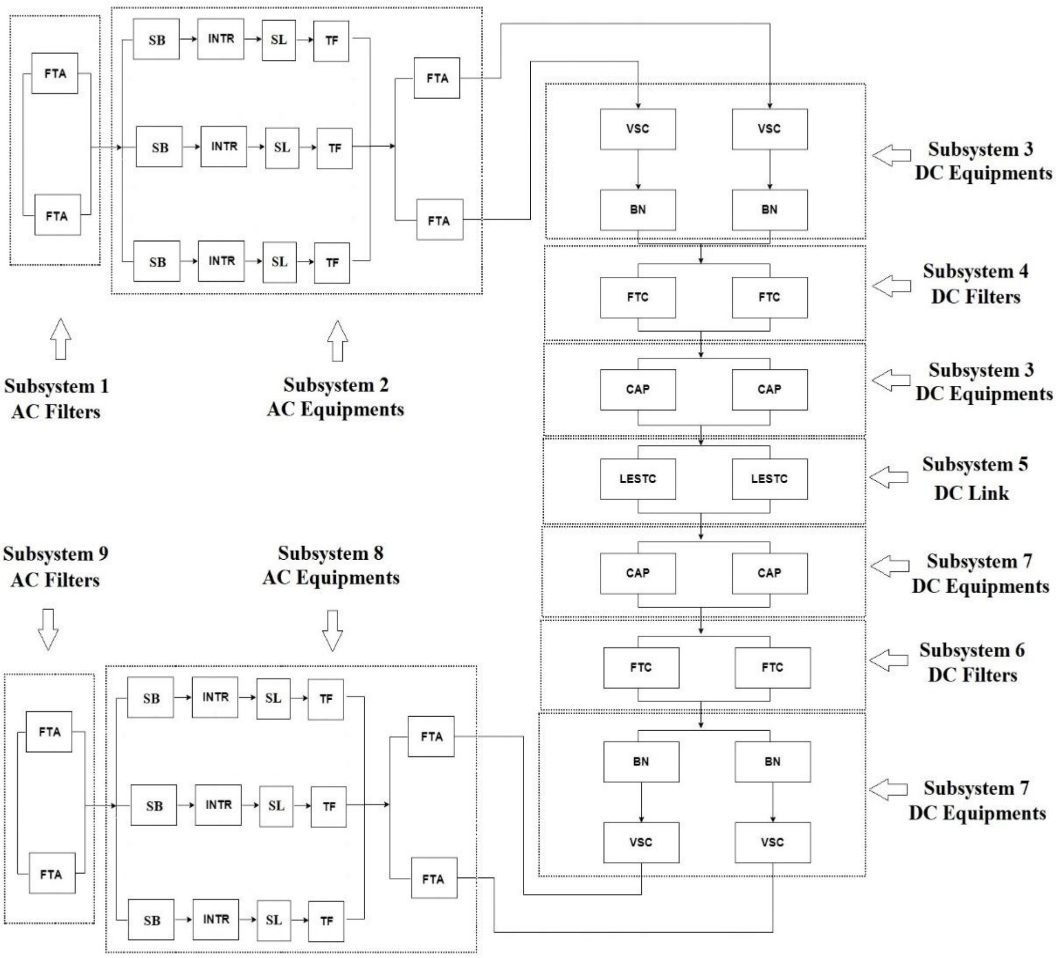

Fig. 2 – VSC-HVDC – Main Subsystems

From the perspective of the electrical equipment within the VSC – HVDC link, the elements were modeled individually, considering failure rate (λ) and repair rate (μ). Later, to more effectively track the impact of the various categories of equipment and to make the calculation easier, they were divided into a series of subsystems, namely:

Subsystem 1 – AC Filters. It contains the AC filters from within the conversion stations, from the Rectifier Converter Station level (within the code written in Python they have the name FTA) – similarly for the inverter converter station **Subsystem 9** is associated;

Subsystem 2 – AC Equipment. It contains the busbar disconnectors, circuit breakers, line disconnectors, respectively the converter transformers, and the phase reactor associated with the rectifier converter station (in the code written in Python they are named SB, INTR, SL, TF, RF) – similarly for the inverter converter station **Subsystem 8** is associated;

Subsystem 3 – DC Equipment. It contains the VSC-HVDC converters, and the smoothing reactors, respectively DC capacitors, associated with the rectifier converter station (in the code written in Python they are named VSC, BN, CAP) – similarly for the converter station inverters are associated with **Subsystem 7**;

Subsystem 4 – DC filters. It contains the DC filters, within the conversion station, at the level of the rectifier converter station (within the code written in Python they have the name FTA) – similarly for the inverter converter station **Subsystem 6** is associated;

Subsystem 5 – DC link. It contains the DC underground cable within the link VSC-HVDC bipolar rectifiers (within the code written in Python they have the name LESTC).

5. Case study – input data, assumptions and results

In Table 1, the reliability parameters input data is presented regarding, failure intensity, respectively the repair rate, associated with the various components (equipments) within VSC – HVDC links, according to the information available in the academic literature.

MCS simulation analysis results

Following the simulations carried out using the calculation program developed with the Python programming language, starting from the input data according to Table 1, containing information from academic literature [18-21], which is usually based on statistical analysis of historical data [22], and using a number of 10^6 randomly generated states, the LOLP, LOLE, and EENS reliability indicator values resulted, according to Table 2.

The Monte Carlo simulation captures the VSC-HVDC operation as follows:

- **Partial unavailability**, possible to transfer up to 50% of the maximum load, up to 1000 MW (only one of the converter poles available, or only one of the DC UGC links available);
- **Total unavailability**, it is no longer possible to transfer power through the bipolar VSC-HVDC link (both converter poles are unavailable, or both the DC UGC links are unavailable).

Table 1

Reliability Parameters – VSC – HVDC connection

Component/equipment	VSC-HVDC connection – main reliability parameters				
	Lifetime	Failure rate	Repair rate	Mean Time to Repair	Mean Time Between Failures
	(years)	λ (outages /year)	μ (repairs /year)	MTTR (hours)	MTBF (years)
Converter valves (IGBT) [19]	30	0.5	2190	4	2
Converter transformer [19]	45	0.024	4	2160	41.7
Circuit breaker AC [19]	35	0.075	2920	3	13.3
Disconnector Switch AC [18]	35	0.01	0.057	18	100*
DC UGC [20]	22	0.133 /100km	15	600	7.5
Conversion station control systems [19]	25	0.0002	1752	1.5	5000*
Cooling systems [19]	15	0.27	5840	12	3.7
Smoothing reactor [19]	25	0.28	730	262.5	3.6
Phase Reactor [21]	25	0.05	33	300	20
AC Harmonic Filters [19]	40	0.54	29	6	1.9
DC Harmonic Filters [19]	20	0.001	1460	5	1000*
Auxilliary power source [19]	25	0.0002	1752	11	5000*
Earthing Electrode [19]	40	0.0042	796	10	238.1*

**free maintenance during lifetime*

Table 2

Global results – MCS analysis

Link configuration	Length DC UGC [km]	Load loss [MW]	LOLP [%]	LOLE [hours]	EENS** [GWh]
VSC-HVDC Bipolar	611	Partial (1000 MW)	5.1941	455	159.26
		Total (2000 MW)	0.29	25.1	17.66

***considering an average loading level of approximately 35% of the VSC-HVDC link, correlated with the yearly average power generation of the renewable wind power plants*

Fig. 3 shows the global results associated to the LOLP and EENS indicators computed in both failure scenarios, partial load loss and total load loss.

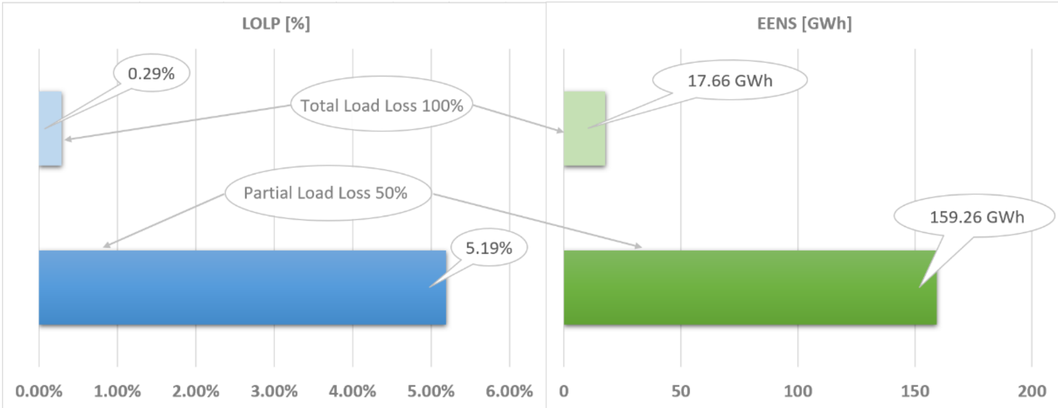

Fig. 3 – Global results – MCS analysis – left LOLP, right EENS

The failure probabilities for each subsystem resulting from the MCS simulations for the 2000 MW bipolar VSC-HVDC link (L=611 km) are presented in Table 3.

Table 3

Results – MCS Analysis – Subsystems

No.	**Subsystem**	**Associated failure probability [-]**
1	Subsystem 1 – AC Filters	1.3134E-07
2	Subsystem 2 – AC equipment	2.22133E-07
3	Subsystem 3 – DC equipment	0.000105935
4	Subsystem 4 – DC filters	0.00000000
5	Subsystem 5 – DC link	0.00265111
6	Subsystem 6 – DC filters	0.00000000
7	Subsystem 7 – DC equipment	0.0001072
8	Subsystem 8 – AC equipment	2.25088E-07
9	Subsystem 9 – AC Filters	1.42093E-07

6. Conclusions

This paper proposes a non-sequential Monte Carlo based algorithm developed using Python language which can be used to compute the main global reliability indicators LOLE, LOLP, EENS for a bipolar VSC-HVDC connections as well as the failure probability for each of the main subsystem.

The main availability evaluations techniques, like FMEA, COPT, sequential and non-sequential Monte Carlo simulations are presented in Section II.

In Section III theoretical aspects for non-sequential Monte Carlo simulations are presented, the logic behind the State Sampling Approach for random number generation is explained. Furthermore, the main reliability parameters, failure intensity (λ) and repair rate (μ), as well as MTTR and MTBF are defined.

Section IV presents the logic behind the proposed Monte Carlo algorithm, highlighting the main steps associated with availability evaluation as well as defining the main subsystems at the level of a VSC-HVDC bipolar link. To showcase the Monte-Carlo algorithm proposed in the current paper, a VSC-HVDC bipolar link with a total length of 611 km is considered for a case study. The main input data, considered for the electrical components of the VSC-HVDC link: the failure intensity, and repair rate are aligned with the academic available information.

An important note is that the input data on failure intensity and repair rate used in the case study (Table 1) are based on information available in the academic literature. Those values are usually determined by statistical analysis of historical failure recordings and are influenced by the quality of the data and hypothesis considered, therefore in some cases, high values of MTBF could result.

It is recommended that the input data provided by the manufacturers be used at a later stage when the provenance of the equipment within the VSC-HVDC installation and the technical design details are known. This approach will improve the accuracy of the results.

In Section V, the results of the case study (performed using Monte-Carlo algorithm developed using Python programming language) are shown.

Following the reliability analysis of the 2000 MW bipolar VSC-HVDC link, for the total load loss case (2000 MW), the Loss of Load Probability (LOLP) value resulted equal to approximately 0.29%, respectively a Loss of Load Expectation (LOLE) value equal to 25 hours and expected energy not served (EENS) value of 17.66 GWh, in the case of partial load loss (1000 MW) the LOLP value resulted equal to approximately 5.2%, respectively a LOLE value equal to 455 hours and an EENS value of 159.3 GWh.

In terms of subsystem impact, it can be observed that the element with the highest impact is the Direct Current Underground Cable (DC UGC), with a value associated with the probability of failure equal to approximately 0.265%.

VSC-HVDC connection availability must be assessed for dependable operation as the integration of renewable energy sources into contemporary power networks increases. Probabilistic evaluation of these DC links is made possible by Monte Carlo simulations, which aid grid operators in identifying weak points and strengthening defenses. In the face of shifting generation and demand, this strategy maintains long-term grid stability and guarantees constant electricity delivery

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