

HVDC grids protection strategies comparison method

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ABSTRACT – The protection of Multi Terminal high voltage Direct Current grids (MTDC) is one of the key issues to address to ensure the recourse to this technology for the transmission of power over large distances. This paper presents a method to compare protection strategies that can or could be used for such grids. This method is based on the use of dedicated key performance indicators (KPI) that are defined to evaluate the various protection strategies on the DC side. The method is described and applied on benchmark grid to compare three envisioned protection strategies.

Mots-clés—HVDC, MTDC, Protection, KPI.

1. INTRODUCTION

The projected construction of onshore and offshore wind farms and their use in very large grids will require dedicated solutions to overcome the problem linked to their intermittent power to ensure the stability of the frequency for instance. One envisioned solution is to connect the sources over long distances to take profit of the seasonality of each source and location. This bulk power transmission, mainly based on high voltage AC links, reaches technical barriers for long distances. Therefore high voltage DC links and grids become an interesting solution to overcome the faced problems but have also some challenges to solve. Among them, their protection stands out as an acute issue.

One of the remaining challenges towards the safe and reliable operation of MTDC grids is their protection. Several proposals on how to perform the fault clearing and grid restoration in a MTDC grid have been made last decades. The proposals found in literature are diverse; they cover a wide range of possible options for protection philosophy, components required and other aspects that can greatly impact performance and cost of the protection. They are based on various sets of components, sequences and protection philosophies (how to cope with a DC grid in short circuit?). Therefore, a method to evaluate and compare the strategies appears to be of great importance to find the most fitted one for a given DC grid structure.

The paper has the following structure. Section 2 will describe some protection strategies. The choice of the considered strategies will cover a wide range of possibilities. In this paper, we will focus only on the primary sequence of the selected protection strategies. Section 3 will define the Key Performance Indicators used for the evaluation of the strategies. The proposed

indicators are only effectiveness indicators in order to measure the DC performance of the strategies. Section 4 will introduce the benchmark grid used in section 5 to produce the KPI and to compare the strategies.

2. PROTECTION STRATEGIES FOR HVDC GRIDS

2.1. What is a protection strategy for HVDC grids?

An HVDC grid protection strategy can be considered as a collection of choices about how the fault occurrence will be managed. The fault considered is a short-circuit in a line of the DC grid. These choices can be classified into three main categories as shown in Fig. 1: system architecture, technology and protection sequence and algorithms [1].

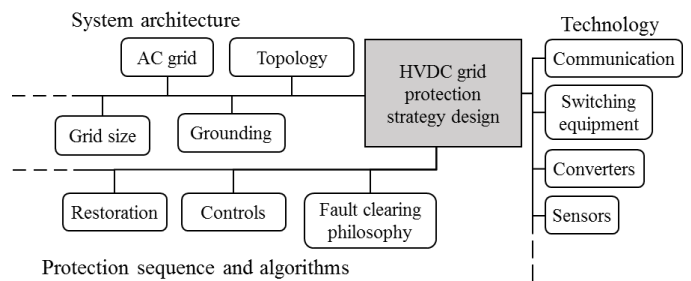


Fig. 1. Main elements in the HVDC grid protection strategy design.

The technology choices consist of decisions about the protection equipment that will be used to perform the different stages of the protection strategies. The actions to be launched and their sequencing during the protection strategy are defined in the axis protection sequence and algorithms. A protection strategy can be mainly divided into two stages: the fault clearing and DC grid restoration as shown in Fig. 2. A protection strategy can have several protection sequences (one primary sequence and many backup sequences). In this paper, we will focus only on the primary sequence for the sake of clarity.

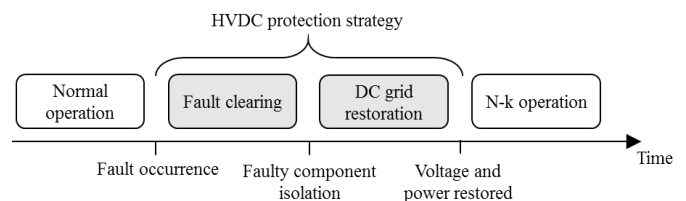


Fig. 2. HVDC protection strategy steps.

The fault clearing starts with the fault occurrence and finishes with the faulty component isolation. The fault clearing itself can also be divided into fault current suppression and faulty component isolation.

The DC grid restoration is also part of the protection strategy since it is intrinsically related to the actions of the protection components. For instance, in [2], the grid restoration can only be performed when converter DCCBs are closed whereas in [3], a progressive fault restoration is performed by using switching equipment to gradually restore healthy parts of the system.

Several classifications for fault clearing philosophies have been proposed in literature [4], [5], [6]. For instance, using the classification proposed in [6], the philosophies for fault clearing can be listed as it follows:

- Fully-selective fault clearing: the fault current is interrupted at the terminals of faulty line or bus.
- Non-selective fault clearing: the fault current is suppressed by interrupting, or at least intentionally limiting, the fault current contribution of the converter stations.
- Partially-selective fault clearing: the DC grid is separated into zones by means of firewalls confining the fault within a zone and isolating it from the healthy zones.

In this paper, we will study three different protection strategies.

2.2. ACCB protection strategy

This non-selective strategy is based on the recourse to AC circuit breakers (ACCB). Despite their relatively long operation time compared to DC circuit breakers (DCCB), ACCB are a mature technology and a possible solution for MTDC grids protection. Such a protection strategy is very close to what is already in use to protect almost the totality of today point-to-point DC links based on VSC converters.

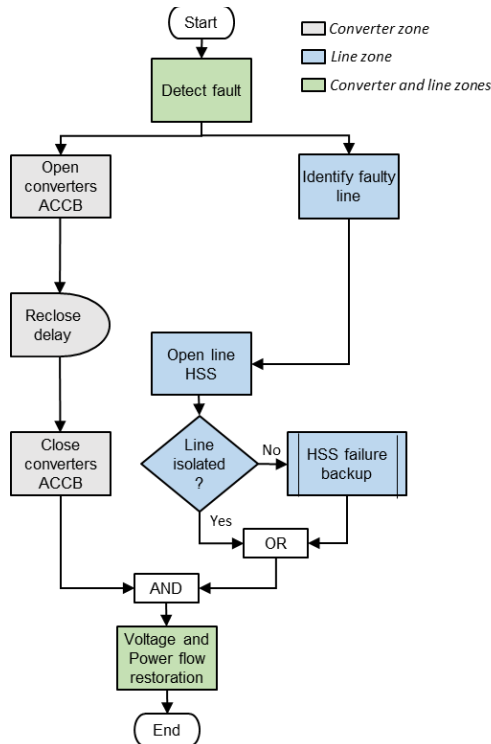


Fig. 3. Primary sequence of the ACCB protection strategy.

The breakers at the AC side of converters are used to eliminate the current flow from the AC system into the DC fault. High-speed switches (HSS) are located at all lines ends to

perform faulty line isolation. In this paper the HSS technology is supposed to be based on AC circuit breaker chamber with a DC breaking capability of few A (e.g. 10A) and an opening time of 10ms. As it can be seen in Fig. 3, it is during the decay of the fault current that the fault identification is performed using a communication based algorithm. The ACCB are reclosed after a reclosing delay and the grid is restored (voltage and thereafter power).

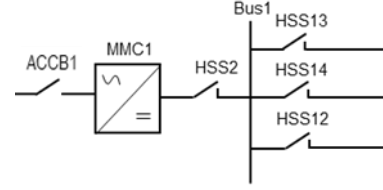


Fig. 4. Protection devices for ACCB protection strategy (at a DC node).

2.3. Converter Breaker protection strategy

This non-selective strategy is characterized by the use of DCCB at each converter output to suppress the fault current in a non-selective way. The recourse to DCCB makes it possible to suppress quickly the AC contribution to the fault current (all converter breakers are tripped with a maximum difference of a few milliseconds). A DCCB with current breaking capability of 20kA and breaker operation time of 15ms has been considered for this strategy. Since other sources for fault current – converter capacitors and cables discharge – do not last long, the fault current is suppressed few milliseconds after the converter breakers opening. A distinctive feature of the converter breaker strategy regarding the ACCB protection strategy is that right after a converter is disconnected and before faulty line isolation, it can be controlled to reestablish the reactive support to the AC system (as we will see in the results part).

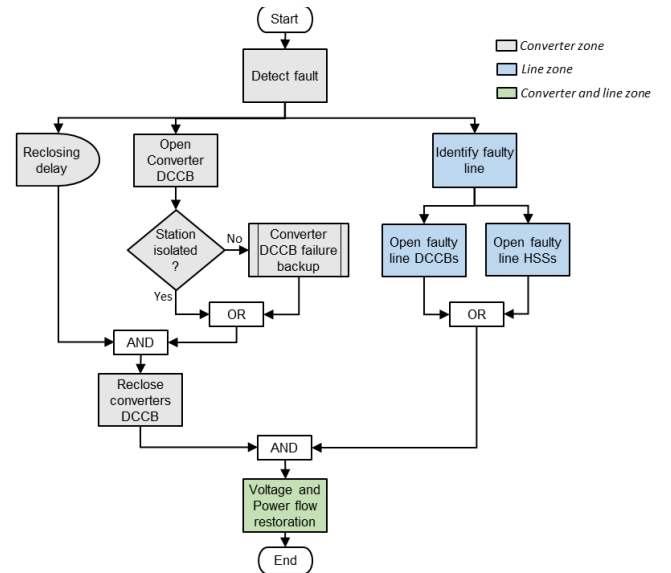


Fig. 5. Primary sequence of Converter Breaker strategy.

The faulty line isolation starts after the execution of the fault identification algorithm with the use of communication based algorithms; both line HSS and DCCB are tripped to isolate the line. Even if only the line HSS are sufficient to perform the faulty line isolation when the fault current is successfully suppressed by the converter DCCB, the line DCCB is needed in case of converter DCCB failure. The grid is restored by reclosing the converter DCCB through pre-insertion resistances (PIR) after a fixed delay, chosen to cope with the unsynchronized

reconnection of the converters as there is no communication coordinating these actions. The use of the PIR ensures that the converter will not block again due to in-rush currents. After voltage restoration, the power flow is re-established by the converter controllers.

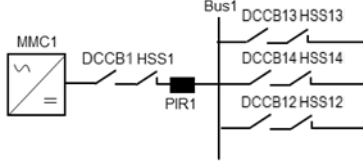


Fig. 6. Protection devices for Converter Breaker protection strategy (at a DC node)

2.4. Fully Selective protection strategy

The Fully-Selective HVDC protection strategy considered in this paper is based on the strategy described in (PROMOTioN WP4, 2018). This protection strategy starts with the identification of the fault. Thereafter DCCB are tripped to isolate the faulty line. A DCCB with current breaking capability of 16 kA and breaker operation time of 2ms in series with a DC limiting reactor of 50mH has been considered for this strategy.

The flowchart for the primary sequence is shown on Fig. 7. DCCB are also located at each converter terminal for backup purposes.

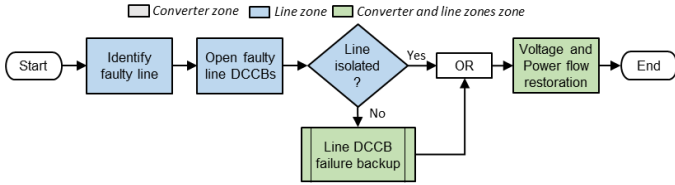


Fig. 7. Primary sequence of the Fully-Selective protection strategy.

If for some reason the DCCB fails to isolate the line, a backup sequence is triggered to isolate the fault with recourse to the DCCB located at converter terminals and at the adjacent lines.

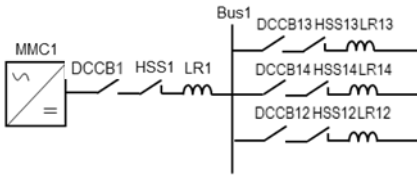


Fig. 8. Protection devices for Fully selective protection strategy (at a DC node).

Despite the speed of the DCCB, the converters in the fully-selective strategy could block before fault suppression due to their internal protection. The blocked converters will unblock when the current and voltage respect once again the normal operation conditions.

3. SOME KEY PERFORMANCE INDICATORS FOR THE COMPARISON OF PROTECTION STRATEGIES

In order to evaluate protection strategies performance and to establish thresholds of minimum performance some metrics must be defined. These metrics are referred as the Key Performance Indicators (KPI). The definition of KPIs is a broadly applied technique to collect, analyze and report information regarding the performance of a process [7]. The proposed KPIs are specific for DC protection strategies and must be based on metrics that are not dependent on the parameters or topology of the AC systems connected to the DC grid. The

proposed KPIs for HVDC protection strategy can be divided into various categories as shown in Fig. 9.

Effectiveness indicators are the KPIs related to how the protection strategy manages the fault clearing process and the grid restoration. Failure indicators are KPIs that assess features related to the malfunctioning of a protection strategy. The reliability indicators are divided into two categories the security and dependability indicators. In this paper, we will focus only on some effectiveness indicators. These latter are used to express the results of the protection strategies in achieving the protection objectives. They are useful to assess the stress of HVDC grid components during the fault. They can also, if needed, be used to estimate how much the AC grid is disturbed during the DC fault clearing and restoring process.

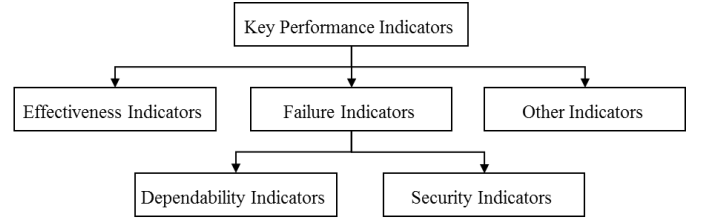


Fig. 9. Categories of KPIs for HVDC grid protection strategies.

3.1. Fault interruption time

As for the clearing time in AC systems, it is pertinent to define a protection strategy KPI linked to the fault suppression process duration. Regarding the event that starts the interruption time, there are two mainly used options as depicted in Fig. 10: when the fault event occurs (similarly to AC fault clearing time definition) or when the measuring equipment providing the fault information detects the presence of a fault in the DC grid. Another point to discuss is when it is considered that the fault has been suppressed. To indicate the fault is cleared, similarly to the last choice, there are two options; it can be considered cleared when the fault current is suppressed or when the faulty component is isolated. It is important to remind that these two events do not necessarily happen at the same time in DC protection. Non-selective protection strategies, for example, suppress the fault at the converter level by interrupting the AC contribution to the fault, and they isolate the faulty line only when the breaking capability of the switching equipment at line ends is attained. The time difference between the fault suppression and the faulty component isolation can be up to hundreds of milliseconds as in the strategy presented in (Dantas et al., 2018).

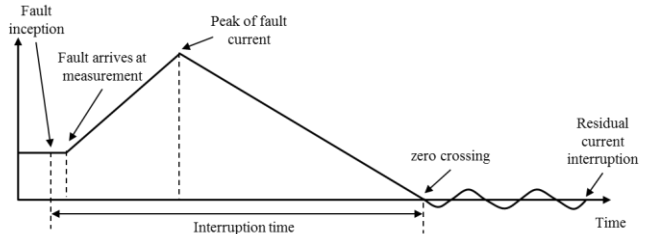


Fig. 10. Fault current interruption process of a DC mechanical breaker.

The KPI fault interruption time is defined here as the time span from the fault inception until the fault current interruption within the faulty component as depicted in Fig. 10.

3.2. DC Voltage restoration time

Concerning the operation of the grid under disturbance, a commonly found requirement in the AC grid codes is the fault ride through capability. In discussions about future HVDC grids code, several types of voltage requirements can be found. The

AC/DC converters shall withstand the AC voltage at the Point of Connection and continue stable operation without tripping, blocking during normal operation, symmetrical or asymmetrical faults. During steady state operation of the HVDC grid there is a band for acceptable nodes voltage compliant with maximum power to be transferred and foreseeable power flows within the DC grid. As far as transient and temporary DC voltage profiles are considered, when the voltage is not within the limits, the subsystem would be allowed to reduce its operational performance, to block or to disconnect safely from the DC system.

Given the importance of the voltage restoration, the KPI DC voltage restoration time is defined as the time from the fault occurrence until DC grid voltage is restored and remains within a 10% range of its nominal value as illustrated in Fig. 11.

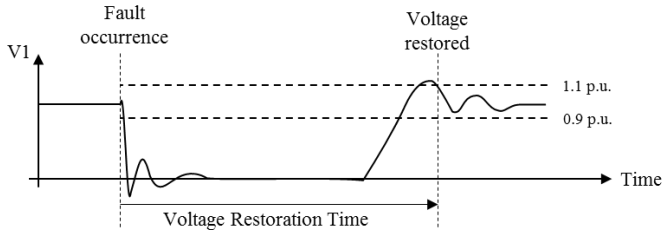


Fig. 11. Illustration of the voltage restoration time for a DC grid bus.

3.3. Active power restoration time

The KPI active power restoration time is defined as the time span from the fault occurrence until the power flow of all concerned converters is restored and remains within a range of $\pm 10\%$ of its nominal value around its post-fault value. Due to its insensitivity to AC system parameters and its direct link with relevant issues for the AC grid, it is considered that for the purpose of performance evaluation, the power measured at the AC side of the converter is more pertinent. The concerned converters are those that remain connected to the grid after the fault clearing.

The definition for active power restoration time uses the time when the power is restored on all converters in the DC grid. However, instead of using all converters in the grid (all zones without distinction), each active power restoration time would use only the power exchanged by converters connected to the respective associated AC zone.

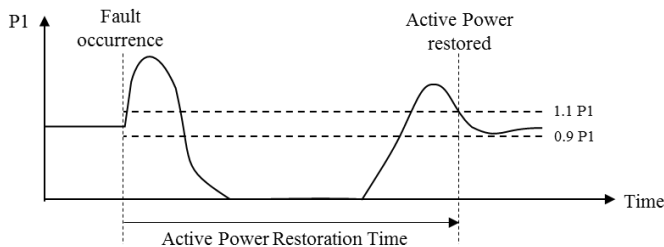


Fig. 12. Illustration of the active power restoration time for an AC zone.

3.4. Reactive power restoration time

Even when HVDC converters are not transmitting active power, they can provide reactive support by being operated in STATCOM mode. The fast reestablishment of reactive power has also been shown to impact not only voltage restoration at the AC side of the converter, but also to have an impact on the transient stability of the AC grid [8]. The KPI reactive power restoration time is defined as the time from the fault occurrence until the reactive power of an AC zone is restored and remains

within a range of $\pm 10\%$ of its post-fault level. Fig. 13 illustrates the reactive power restoration time for an AC zone.

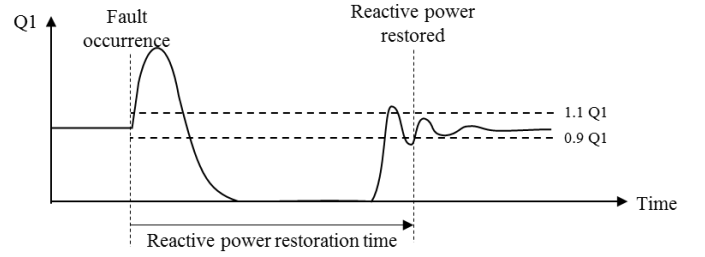


Fig. 13. Illustration of the ready to restore reactive power time for one AC zone.

Like the active power restoration, the reactive power restoration time can also be calculated separately for AC zones connected to the HVDC grid.

3.5. Transient energy imbalance

The KPI transient energy imbalance is defined as the difference between the energy that should be exchanged between the AC zone and the DC grid if the grid were healthy, and the actual energy exchanged by the zone under fault conditions of the DC grid. The considered time span for calculation of this KPI is the same as for the active power restoration time.

Fig. 14 illustrates the elements for the calculation of the energy imbalance. $P1$ is the active power exchanged between AC1 and the HVDC grid before the fault. $A0$ and $A1$ represent the energy exchanged between the AC system and the HVDC grid when the system is healthy and when it is in fault condition respectively. For the given example, the transient energy imbalance is calculated by subtracting $A1$ from $A0$.

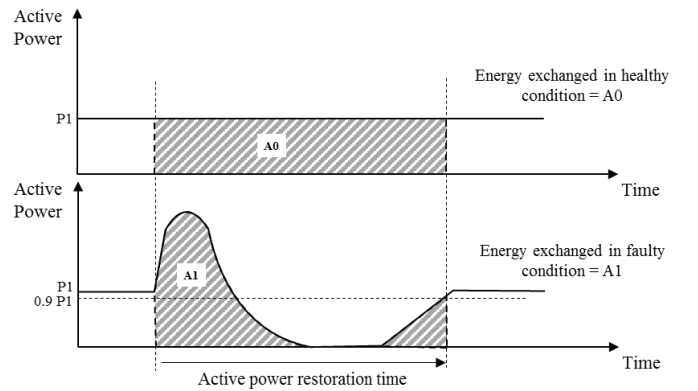


Fig. 14. Illustration of elements used in the calculation of energy imbalance for one AC zone.

Given the meaning of this indicator, similarly to the active and reactive power restoration time, it might be of interest to calculate the energy imbalance per AC zone, if needed.

4. AC/DC GRID BENCHMARK

To perform the simulations required for the comparison of the protection strategies, the benchmark grid presented in Fig. 15 is used.

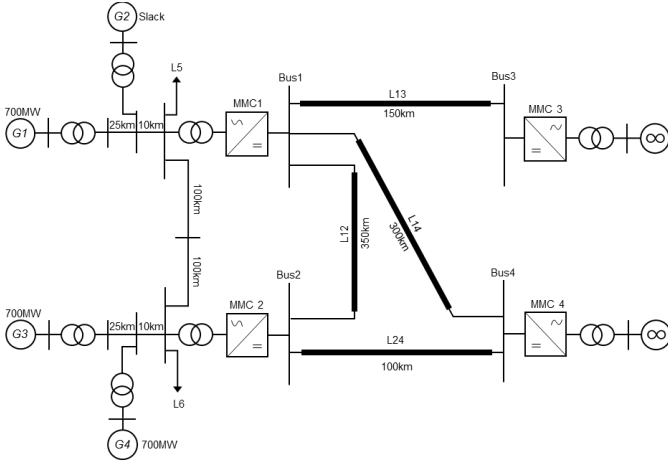


Fig. 15. AC/DC benchmark grid considered.

The MTDC grid has only cables, and it has a bipolar configuration operated at $\pm 320\text{kV}$ (only the positive pole is represented in the figure). The DC part of the above presented grid is similar to the network used by the PROMOTiON project to perform protection studies in [1] and [6]. The four terminals MTDC grid is partially embedded in the standard 2-zone 4-machine AC test system used in [9] for evaluating the impact of DC faults in the AC grid.

The converters considered in the MTDC grid are half-bridge Modular Multi-level Converters (MMC). In case of fault in the DC grid the MMCs are considered to work as shown in Fig. 16.

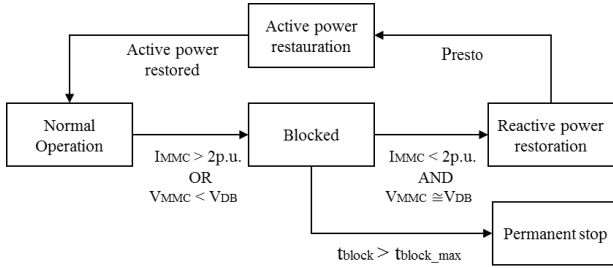


Fig. 16. MMCs operation in case of fault.

Details of the considered operating point of the system during simulations are found in Table 1 and Table 2. The operation point chosen for the benchmark grid is similar to the one presented in [6]. Negative values in Table 1 mean that the power is towards the AC grid.

Table 1. DC grid control strategy and power flow in pre-fault steady state operation. The values are for one pole.

Converter	Active Power (MW)	Reactive Power (MVAR)	Droop value (MW/kV)
MMC1	-500	-150	10
MMC2	-200	-150	10
MMC3	250	0	10
MMC4	450	0	10

Table 2. AC grid parameters in pre-fault steady state operation.

Parameter	Value
Slack bus power	719 MW
Load L5	2100MW -400MVAR
Load L6	2400MW 500MVAR

5.1. Methodology

DC short-circuits have been simulated on each of the cables L12, L14 and L24 at the extremities and in the middle of the line. Cases where the fault is located at a cable extremity are considered to be the worst cases to be protected due to the high level of current and the swift voltage variations observed at protection equipment near to the fault. Fault cases at the middle of cables are also simulated in order to cover more possible scenarios. Only faults on the meshed section of the grid have been considered. Indeed, a fault on L13 would lead to a loss of converter MMC3 and hence the calculation of power restoration time would depend mainly on the coordination of converter controls after a contingency (e.g. choice of droop parameters) and not only on the selected protection strategy. The following results have been computed only while considering the primary sequences as described in the previous sections.

5.2. ACCB protection strategy

Table 3 presents the values for the DC KPI when the primary protection sequence is considered. The average value of the Fault interruption time is around 940ms but the associated KPI value of 1100ms is considered as it is the longest fault interruption time found. This value can be explained by the fact that depending on the location of the fault with respect to the conversion station, the HSS reach their breaking capability at different moment.

Table 3. KPI for ACCB protection strategy (primary sequence).

KPI	Values
Fault interruption time (ms)	1100
DC voltage restoration time (ms)	1480
Reactive power restoration time (ms)	1507
Active power restoration time (ms)	1625
Transient energy imbalance (MJ)	$805 \cdot 10^3$

For the DC voltage restoration time, the average value is near to the highest value mentioned in the table. It can be explained by the protection sequence itself that leads to the tripping of all ACCB for each fault. The same remark is also valid for both active and reactive power restoration time. Therefore, the KPI transient energy imbalance will exhibit the highest value (compared to the respective values for the two other strategies).

5.3. Converter Breaker protection strategy

Table 4 presents the associated KPI for this protection strategy.

Table 4. KPI for Converter breaker protection strategy (primary sequence).

KPI	Values
Fault interruption time (ms)	25
DC voltage restoration time (ms)	80
Reactive power restoration time (ms)	27
Active power restoration time (ms)	140
Transient energy imbalance (MJ)	$65 \cdot 10^3$

Concerning the fault interruption time, the values found are in the range 23-25ms, showing that the behaviour of the grid is quite the same whatever the fault is. This small variation is linked to the very first instants of the protection strategy: all the DCCB trip quite simultaneously and quickly after the fault inception. The discrepancies may be explained by the time

requested for the tripping of the HSS, depending in the fault location and network power flow. As the AC part of the converter remains connected, it makes it possible to restore the status of the capacitors and to operate the voltage control more quickly than for the previous strategy.

5.4. Fully Selective protection strategy

As this strategy is selective, the time requested to suppress the faulty line is smaller than the associated time for the other strategies. This remark applies also for the other KPI considered in Table 5.

Table 5. KPI for Fully selective protection strategy (primary sequence).

KPI	Values
Fault interruption time (ms)	15
DC voltage restoration time (ms)	34
Reactive power restoration time (ms)	19
Active power restoration time (ms)	97
Transient energy imbalance (MJ)	$14 \cdot 10^3$

5.5. Some comparison elements

The radar plot presented in Fig. 17 show a synthesis of the various KPI for the three considered KPI. It leads to a very intuitive conclusion: the ACCB protection strategy is the worst considered strategy in terms of DC KPI. This bad performance can be explained by the time requested to open the AC circuit breakers and the associated consequences as far as voltage and power in the DC grids are concerned.

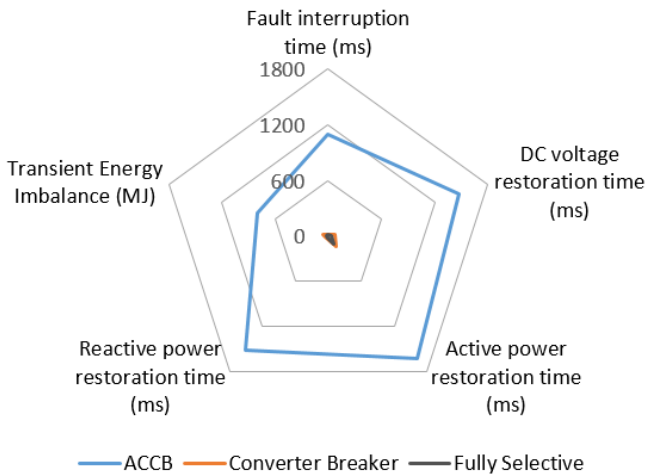


Fig. 17. KPI radar comparison.

A zoom on the two remaining strategies (the converter breaker and fully selective protection strategies) and their associated KPI makes it possible to highlight the differences between them. The major difference on KPI can be noticed for both active power restoration time and transient energy imbalance: the converter breaker strategy exhibits worse results. It is linked to the fact that the constraints on the converter are reduced in the case of the fully selective strategy compared to those for the converter breaker strategy: the active power restoration time is therefore reduced for the fully selective strategy. Results may change when considering the performance of the strategy during backup sequences.

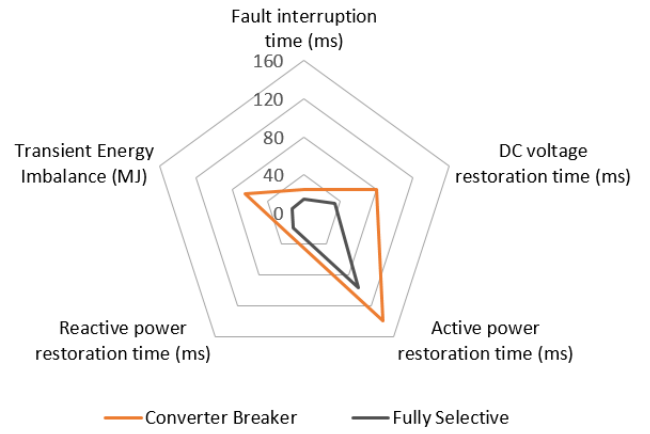


Fig. 18. Comparison between converter breaker and fully selective protection strategies.

6. CONCLUSIONS

This paper presented a methodology to compare HVDC grid protection strategies based on the recourse to effectiveness KPI defined on the DC side. These indicators have been used to measure the impact of the considered protection strategies on the fault clearing, voltage restoration and powers restoration processes. They have been computed for three various envisioned protection strategies.

The performance of a protection strategy must also be addressed and analysed by considering other KPI such as failure KPI and economic KPI. Furthermore the effect of the grid extensibility must be also included in the analysis.

7. ACKNOWLEDGEMENTS

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