Faults between AC and DC lines

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Energy Technology, EPSH-831, 2021-05

Master's semester Project

STUDENT REPORT

AALBORG UNIVERSITY

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Abstract:

HVDC is becoming more appealing when it comes to the transmission of power through long distances. An option when implementing new lines is for HVDC lines to share the same transmission tower than HVAC lines. However, some technical issues must be analysed like how the hybrid AC-DC network reacts under a fault. This project studies the behavior of the system under hybrid fault topologies which involve both systems so a suitable protection system can be implemented. Different fault locations are considered for each model. The faults in the AC-DC system are compared to individual AC and DC systems in order to assess the difference. Hence, three models are simulated: a pure AC system, a pure DC system and a AC-DC system under different fault conditions. Then the results are evaluated for each of the systems as a first step for choosing the best suited protection system.

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Contents

Chapter 1

Introduction

The development of technology and the way it eases some humans' tasks is leading to an increment of energy demand. Nowadays, 6.5 billion people have access to electricity while 20 years ago only 4,76 billion had [1]. This results in an increase of electricity demand since 2000 of 85%, from 13000 TWh to 24000 TWh as shown in Figure 1.1, due to private and industry consumption. Moreover, it is predicted that in 20 years the demand could increase another 54%, also represented in Figure 1.1. Therefore, more energy has to be transmitted from its generation sites to where it is consumed.

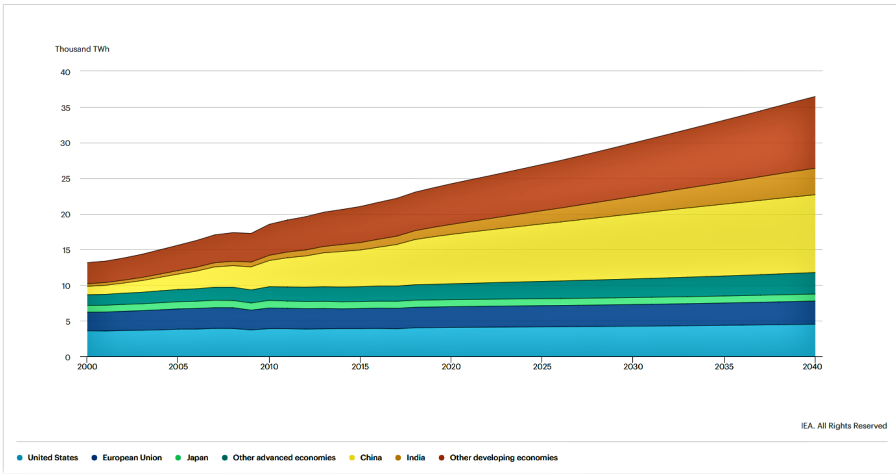


Figure 1.1: Global electricity demand by region [2]

Great part of the new electricity generation is, and will be, in regards to renewable energy production, which may result on remote generation due to its production restrictions. Exploring efficient power transmission at higher power levels is the direct result of this, besides intersystem connections. [3]

After the "war of currents" between Edison and Tesla, the AC (alternative current) stated as the preferred way of transmitting electrical energy because of the low voltages concerning DC (direct current). As transformers could not be used to increase the voltage in DC cases, more current would flow through the conductors increasing the power losses. However, when the voltage could be risen due to the evolve of power electronics, HVDC (high voltage direct current) was developed for transmission lines. Moreover, HVDC turn out to have some advantages when compared to AC for longer distances as it will be further explained.

Thus, HVDC lines would go across long distances. New OHL (overhead lines) are not received well by the population whereas underground lines are more expensive and entail other challenges. One possibility is to make the AC and DC lines share transmission towers also avoiding the expenses of building twice the amount of towers. Nonetheless, this entails a new challenge since AC and DC lines would share a path few meters apart. Possible faults between the different lines have to be studied and its repercussions on the electrical system.

1.1 Hybrid systems and faults

As mentioned before, HVDC transmission lines can share the same line length as the HVAC lines. This results in a hybrid model which entails several advantages: increase the power transfer without having to build double transmission towers and minor environmental impact [4].

In a HVAC (high voltage alternative current) system, different faults may take place: one-phase to ground (70-80% of failures), phase to phase, two-phase to ground and three-phase to ground. On the other hand, short circuits may also occur in the DC lines such as pole-to-ground or pole-to-pole. In all cases, the system will react to the fault in a specific way which has being studied and has result on appropriate protections to avoid a large damage.

However, in a hybrid system, the HVAC and HVDC will be linked, so the possible faults that may occur in each would affect the other. The behavior of the interrelated system would be different than when they are separated. Furthermore, faults between both systems may happen too (e.g. one-phase AC to pole DC).

Given this new situation, protections might not act as they were intended to. Moreover, the converters which rectify and invert the current from DC to AC, may be affected as the current protections may not be fast enough and they are fragile devices. [5]

1.2 Outline of project work

Motivation of the project

The motivation behind this project is the utilization of HVDC to connect remoted places due to the limitations renewable energy come with. Apart from economic reasons, there is an environmental reason behind locating the DC and AC transmission lines in the same tower. Accordingly, issues regarding AC and DC faults must be studied to make the sharing path feasible and assure no damage in the power network.

Problem statement

To increase power capacity of the transmission corridors or to connect remote locations for generating energy, HVDC lines may share transmission towers with HVAC lines. Therefore, they would be nearby, and different faults may happen. The scope of this project is to study the effect these faults have on the AC and DC lines in order to protect the system properly.

Project objectives

The purpose of the project is to evaluate different fault scenarios between AC and DC lines using a simulation model for it. Investigating the different waveforms (i.e. currents and voltages) when a fault occurs is key for designing or selecting proper protections for the system. These faults will be assessed and compared to the ones that might happen a pure AC and DC system respectively, to discern the differences, so as to decide the most suitable protections in the future. Therefore, faults in the individual AC and DC systems will be initially analysed in order to make the comparison with the hybrid system.

When finalizing the project, several objectives should have been accomplished:

- Comprehend literature on transmission lines (HVDC, HVAC) and faults behavior. Study different protection systems which can be utilised.
- Design different models: pure DC, pure AC and an hybrid AC-DC system for further faults studies.
- Analyse the different fault scenarios: Faults in AC system to ground and between phases, faults in DC system between poles and to ground, and faults between AC and DC lines. Steady state and transients analysis should be conducted.
- Assess the differences between the pure and hybrid system faults.

Methodology

To accomplish the aim of the project, several steps are executed:

- Study literature and State of the Art
- Build a model on PSCAD
- Simulate different fault scenarios
- Analyse the models results

Limitations

Some limitations have to be considered for the project. The simulation program, PSCAD, there is a limitation when implementing ideal transposition. It does not allowed to group together a number of conductors which is not multiple of three in parallel lines so they can be transposed. Therefore, since a HVAC line, with three conductors, and a HVDC line, with two conductors, are located in parallel when sharing the same transmission line, ideal transposition cannot be considered in the simulation program.

Development of the project

Chapter 2 includes the possible fault topologies as well as the State of the Art for protection systems for AC and DC lines. Chapter 3 describes the main characteristics of the model which is going to be evaluated. In Chapter 4 and 5, the main assessments are conducted. Three systems are analysed: pure AC system, pure DC system and hybrid AC-DC system. The respective simulation models are presented and then, the results obtained are discussed. Specifically, Chapter 4 evaluates the pure systems while Chapter 5 analyses the hybrid AC-DC system. Finally in Chapter 6, a conclusion regarding all the results obtained is presented along with future work.

Chapter 2

State-of-the-Art

2.1 HVAC

The reliability of the power system is affected by the faults that take place in the transmission lines and how they are treated. It is essential to try to maintain a continuous service for costumers. When a fault happens the least part of the network should be affected. After the actuation of the protection system only the fault section should be isolated while it should be done as quick as possible. [6]

The correct selectivity and speed of the protection systems should be chosen to attenuate fault´s consequences. Therefore, the first step for choosing the best fitting protective devices is to study the behavior of the system while facing a fault. Hence, the values that can be reached and how long the these values will endure are obtained.

2.1.1 AC Faults

Faults in AC-OHL can be classified as in Table 2.1 [7].

Table 2.1: Faults in AC transmission lines (*l:line , G:ground)

Series Faults:	1 conductor is open	2 conductors are open
Shunt Faults:	Asymmetrical Faults	Symmetrical Faults
	l-G ; l-l ; l-l-G	l-l-l ; l-l-l-G

Shunt faults are more usual than series ones. In the series faults one or two lines will be open while the third one remains closed. They may be caused by a wrong joint or broken conductor, due to a malfunction of a relay or a failure while closing operations. On the other hand, the main reason behind shunt faults are weather conditions (e.g., lighting strikes, heavy rain, pollution) and isolation failure. However, vandalism and external object such as trees can also lead to this kind of faults [8]. Shunt faults occur because two points with different voltage get in contact. One phase to ground are the most common ones involving 70-80% of overall faults.[9]

Faults can also be classified regarding its time scale, in temporary or permanent faults. Temporary faults do not affect the supply permanently as they tend to be self-cleared. They may be caused by a momentary flashover across an insulator. They are more typical than permanent faults.

Moreover, permanent faults entail the de-energization of a line´s section that may limit the service at some ends of the network. Also, by trying to maintain the service, other parts of the network may get overloaded which may lead to a casade effect causing other failures [10]. Permanent faults might be caused by a broken insulator or an external object like a tree. Therefore, it is essential that faults are located, classified, and cleared.

When a fault occurs, a transient period takes place before the steady state is reached. The transient is characterized by the following expression in case of 1^{st} order systems [9]:

$$i(t) = i_{ss}(t) + [i(0^+) - i_{ss}(0^+)] \cdot e^{-t/\tau} \tag{2.1}$$

As the OHL are mainly inductive, for a first approximation, this equation may be considered. The transient is composed of an AC component and a DC component which decreases exponentially, Figure 2.1. The figure represents a case in which the fault occurs farther from the generating point. If the fault occurred closer to a generator, the reactance is initially lower during the subtrancient period and therefore, the AC component is affected. [9]

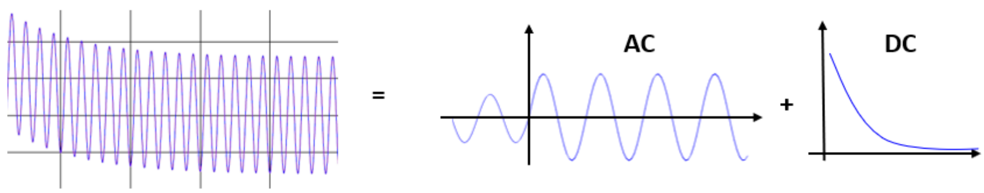


Figure 2.1: 1^{st} order system - transient current behaviour

The maximum value of the DC component which leads to the maximum value the currents reach, is characterized by the prefault conditions of the system. Two conditions are considered: inductances cannot change their current instantly and capacitances cannot change their voltage instantly either.

The DC component decreases exponentially by a time constant. The time constant value depends on the impedance of the system. When the steady state is reached, the DC component is extinguish.

However, if a capacitance on the system is included for the analysis, a 2^{nd} order system will result. The system will be also characterized by its natural frequency and damping factor which vary depending on the configuration of the system. Transformation to Laplace domain is one approach to solve the second order differential equation.

2.1.2 AC Protective Relays

A relaying system for transmission lines includes at least an instrument transformer, a relay and a circuit breaker. The transformer lowers the energy levels to protect the relay which is connected to its secondary winding. The relays may have different topologies but generally they compare the input measurements to their defined boundaries which may lead to open the circuit breaker. When the circuit breaker is tripped, the current flow is interrupted. [11]

Power systems commonly may include overcurrent, distance and differential protections as protective relays. If the system includes differential relays, the system will also include communication channels so the relays at both ends of the line can exchange information. Moreover, the communication channels can also be included to increase the selectivity and accuracy of the protection system for other kind of relays. This might be the the case if overcurrent and distance relays include directionality as a facet. However, communication channels would increase the cost of the protection system. [11]

The protection system might consist of a combination of the mentioned types of relays. The system may include differential relays despite them being more expensive and have overcurrent relays as a backup. Others may have the distance relays as their main protection and do not include differential relays. It will vary from one company to another.

Several information has to be taken into account when considering a relay. It includes the time dial, the trigger value for each relay location, and extreme short circuit values for fault currents. In addition, it must exist some coordination between the different relays so not the entire network is affected by a fault in one section of the line. It can be done by the already mentioned communication channels, or by implementing an algorithm which will determine the trigger priorities. [11]

Overcurrent relays

Overcurrent protection is based on tripping a signal when the current goes over a certain value. Figure 2.2 represents overcurrent protection in different segments of the line. When a fault happens, the current reaches higher values the closer the fault happens to the source. This is useful for choosing the trigger priority since the trip signal is associated to the current amplitude. Moreover, time delay is typically inversely proportional to the magnitude: the higher the value is, the shorter the relay operation time is. This ensures a higher selectivity. [6, 11]

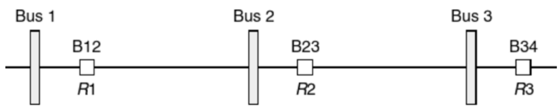


Figure 2.2: Overcurrent relays [12]

This protection system is very reliable for stiff networks where not large fluctuations take place. They are often used in HV (high voltage) transmission lines, mostly as a backup. They can include a directional facet to increase the selectivity, as it may be needed in parallel lines. [11]

Directionality of a relay is important for implementing the relays schemes, not only in overcurrent relays but also in distance ones. The direction of the fault is determined by the angle between the voltage of the line and the fault current, which determines the direction of the power flow. [11]

Distance protecion for transmission lines

Distance relaying is extensively used in transmission lines as their main protection relay. They work better than overcurrent relays under certain conditions. When the current increases and the direction of the power flow changes at the same time, overcurrent protection may fail whereas distance will not. The principle behind distance relaying, represented in Figure2.3, is a comparison between the instantaneously voltage-current ratio and another predefined value which characterizes the line under normal conditions. [11]

The voltage-current ratio is defined as apparent impedance. If the difference between the apparent impedance of the line and the predefined value reaches a certain level, the relay would trip. The apparent impedance is proportional to the line´s length and therefore it can also be useful for locating where the fault takes place, as well as setting different zones for protection. They may include directionality facet as overcurrent relays. [11]

Nevertheless, there are some limitations regarding this kind of protection being

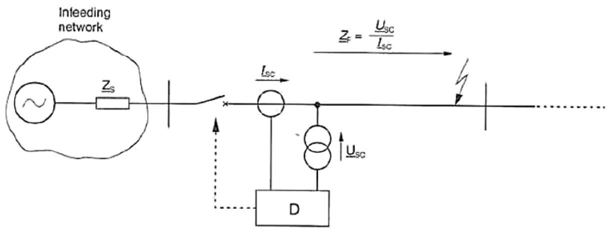


Figure 2.3: Distance protection principle [13]

the infeed effect the most relevant one. It will cause that the relay sees a larger impedance that the one expected. They might also fail due to the fault resistance as it depends on the nature of the fault and it may be difficult to forecast it. Another reason for their failure is a possible coupling between phases or different transmission lines as may happen in parallel lines which would entail an error when calculating the impedance. Even though all this issues can be minimize, their reliability can be reduced. [11]

Differential relays

The last widely used devices for protection are current differential relays, in Figure 2.4. They consider that if there is no fault along the line, the current entering and leaving the power system must be almost equal and therefore, the circuit breaker does not have to act. Otherwise, if the difference is noticeable, the breaker would trip. They usually compare the values on their sequence form.[6, 11]

They are often use when directional relays are not sufficient. They provide full protection to the transmission lines affecting so little to the rest of the system. However, as a communication system is needed, the cost of their implementation may be expensive. [11]

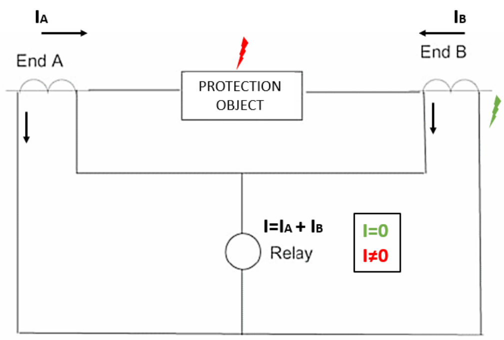


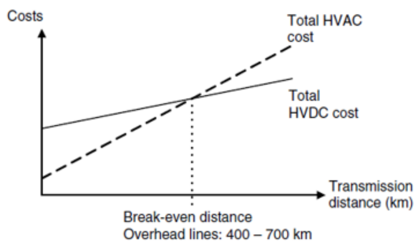
Figure 2.4: Differential relay [14]

2.2 HVDC

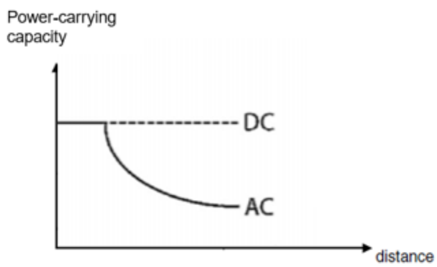
As the energy demand is increasing, new and more efficient transmission lines are needed. In this search of rising the efficiency for long distances, HVDC turned out to be better than the current HVAC lines. [15]

Economic motivations is the main reason for choosing DC instead of AC for long distances transmission lines. They have higher power capacity as well as higher reliability and stability which will impact not only the economic feasibility but also the technical one. [16]

Despite being the initial cost of HVDC higher than HVAC due to more expenses related to the converter stations needed in the DC terminals, after a break-even distance, the HVDC is cheaper, Figure 2.5a. Fewer conductors causing less losses, unnecessary inductance compensation and reduced corona effect are among some reasons for their lower prize. [3, 16]



(a) Transmission lines cost



(b) Power capacity transmission lines

Figure 2.5: [15]

Length is not only a key factor regarding its economic feasibility, but also its technology performance. Figure 2.5b shows that the power capacity is not affected by the length of DC lines while it does decrease in case of AC lines. The reason behind it is the increase of inductance reactance for OHL entailing issues associated with the angle stability. For cables, with higher capacitance, the issue lies in the reactive power increasing with the distance. [3]

Another significant motivation for DC lines is the possibility of connecting asynchronous systems. The connection of two systems with different frequencies could not be done with AC. They can also improve the control power flow between different parts of the system stabilizing it. [16, 17]

However, HVDC also comes with some disadvantages. As already mentioned, the substations are more expensive due to the need of converters which will increase the harmonics and filters may be needed. In addition, the control system is relatively more complex and good protection solutions are still under development. Lastly, the use of HVDC is quite recent, thus it exist less experience in this field when comparing with HVAC. [17]

HVDC configuration may be monopolar or bipolar. In the monopolar configuration, the transmission is made by a single conductor which can have either positive or negative polarity. On the other hand, the bipolar configuration consists of two conductors with opposite polarities in parallel and it is a frequent configuration for OHL. [16]

2.2.1 HVDC faults

The different DC shunt fault topologies are collected in Table 2.2.

Table 2.2: Faults in HVDC transmission lines

HVDC configuration	Bipolar	Monopolar
	Pole-to-pole Pole-to-ground Pole-to-pole-to-ground	Pole-to-ground

The transient analysis explained for AC faults is also applicable for the DC system, being equation 2.1 also valid. However, the DC nature of the current has to be considered. Also, if there is DC and AC current simultaneously in the system, superposition must be applied.

2.2.2 HVDC protection system

The protection system regarding HVDC is generally more complex than for HVAC systems. There are a few facets which make their protection more complex. First, it is the time scale. The peak values reached after a fault in HVDC systems are reached in shorter periods of time than in HVAC systems. Second, DC faults currents do not have zero crossing as AC do. Finally, HVDC transmission systems include converters. It has to be considered that power electronics does not stand high current values caused by faults, they are not as resilient as other devices. Therefore, the fault must be cleared faster. Moreover, the current and voltage values in the system after the fault may affect the converter components like IGBTs switching them off. [17].

Nevertheless, in HVDC systems, selectivity is a key aspect as in AC systems. The least part of the network must be affected by the disturbance and a failure cascade must be avoided.

There are three possibilities for clearing the fault in a HVDC system once it has been detected. The most common one is opening the breakers in the AC side. Despite being the most used one due to its higher reliability, it implies a large time delay since it involves communication. Another possibility is the implementation of blocking options in the converters. Even though, the clearing time is highly reduced since the fast operation time of the converter, the selectivity of the protection is reduced [17]. Lastly, HVDC circuit breakers are being developed. However, there are many challenges that have still to be solved as generally a large power has to be cut off. [18]

There are several protection methods for HVDC transmission lines.

Differential protection

This type of protection, which functionality has already been explained in AC protection system, is the most viable method nowadays. It is normally backed up with overcurrent protection. However, a fast communication between the relays at both ends of the line is critical. [18]

Overcurrent protection

It has also been explained in detail for AC protection system. Their low accuracy in selectivity makes them feasible for back up purposes only in HVDC.[18]

Other methods

There are other methods which are being studied and developed. The Transient/Derivative base methods might be very useful for future DC fault analysis. They consider the derivative of the current or the voltage. Research is still going on to identify the specific markers in order to choose proper selectivity, security and speed. [18]

On the other hand, frequency-based methods are also under development, mostly for hybrid systems. When a fault occurs in an AC-DC system, characteristic harmonics may materialize in the waveforms which may be a facet to detect them. [18]

Chapter 3

Modeling the system

Three systems will be model for a future analysis:

- Pure AC system
- Pure DC system
- Hybrid AC-DC system

The hybrid system is a combination of the first two individual systems. Their overall properties, which define each system, are collected in this chapter. More details regarding each specific case are explained in Chapter 4 when each system is analysed.

3.1 Transmission line model

Different models can be used for representing transmission lines: Pi-model, T-model, Bergeron’s model, frequecy dependent models,... . Different simplifications can be made depending on the level of accuracy and the complexity of the model.

For transient studies, Bergeron´s model and frequency dependent (phase) model are considered. Both models consider wave travelling time along the line. However, Bergeron´s model contemplates a constant frequency while the other one assesses several frequencies. Therefore, Bergeron´s is a simpler model but less accurate.

As a comparison is going to take place in this project, the accuracy level is a key factor. Despite the needed accuracy depending on the protection solution, as this is the first step for choosing that solution, high precision is required. Hence, frequency dependent (phase) model is chosen.

3.2 Transmission system

Two transmission lines with a length of 300km are considered. The nominal values of each system are abridged in Table 3.1. A bipolar configuration is considered for the HVDC transmission line.

Table 3.1: Rated values for HVAC/HVDC system

	HVAC	HVDC
Rated Voltage	380kV	$\pm$ 500kV
Rated Power	1000MW	1000MW
Frequency	50Hz	-

For the pure AC system, ideal transposition is considered. Hence, the system is balanced. However, as explained in the limitations in Chapter 1, ideal transposition cannot be applied in the simulation program for a hybrid model with 5 lines. Therefore, in the hybrid system, the AC phases are not transposed entailing an unbalanced system.

3.3 Transmission tower configuration

A configuration of the transmission tower has to be selected. The nature of the assessment does not have to be altered by the transmission tower configuration. Therefore, the pure AC and DC systems respectively must have the same configuration as their respective lines in the hybrid AC-DC system.

As discussed before, one possibility when implementing the HVDC lines is to set them in the already existing transmission towers even if some changes to the actual tower might have to be done, as well as changing the insulators.

Several configurations are considered. When the AC and DC lines are one above the other, the chances of a short circuit between them are higher. Finally, an DC system above the AC system is considered due to the future UltraNet project in Germany. In the project, one of the AC lines will be converted to DC. The new DC line will be be placed in existing pylons with the configuration represented in Figure 3.1 [19]. Only the right half of the transmission tower is considered, assessing only one AC system for simplification purposes.

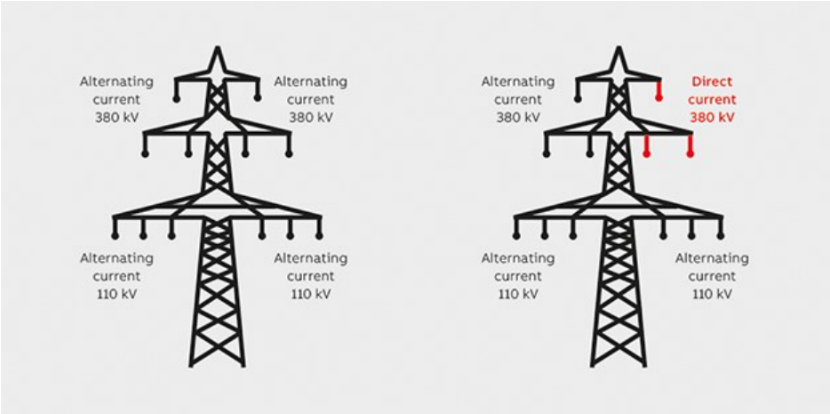


Figure 3.1: Suggested hybrid transmission tower configuration for UltraNet project[19]

In Table 3.2 the location of the different conductors which are going to be considered for the simulation are summarized. The base of the tower is considered as the origin of coordinates (0,0).

Table 3.2: Tower configuration: conductors coordinates in meters

HVAC	HVDC	Ground wire
x=5 ; y=30	x=4 ; y=40	x=0 ; y=50
x=9 ; y=30	x=9 ; y=40	
x=13 ; y=30		

Chapter 4

Analysis of individual AC and DC systems after a fault

Several assessments are conducted in order to evaluate different fault topologies at three different fault locations. An individual HVAC system, pure AC system, and a HVDC system, pure DC system, are simulated separately. These two models are analysed and are used as a reference for the future hybrid, in which both systems will share the same transmission line.

4.1 Pure AC system

4.1.1 Model

For the AC system, a source connected to an impedance is considered at each end of the line. A series resistance of 1Ω, a parallel resistance of 1Ω and an inductance of 1H constitute the RRL impedance, entailing a short-circuit power of 24067MW.

The following system is simulated, Figure 4.1, to assess the behavior of the HVAC system under different fault topologies: 3-phases to ground $(RST \rightarrow G)$, 2-phases to ground $(RS \rightarrow G)$, 1-phase to ground $(R \rightarrow G)$ and phase to phase $(R \rightarrow S)$. Moreover, faults at three points of the line are studied: 1/300 (1km), 1/4 (75km) and 1/2 (150km) from the sending end of the line.

The closer the fault occurs to the sending point of the line (Bus A), the higher the expected current value is at that point. Figure 4.1, represents the modeled system at rated conditions without considering any kind of fault. The fault resistance is considered 1 Ω in every scenario. Hence, the voltage at the fault point does not reach 0V.

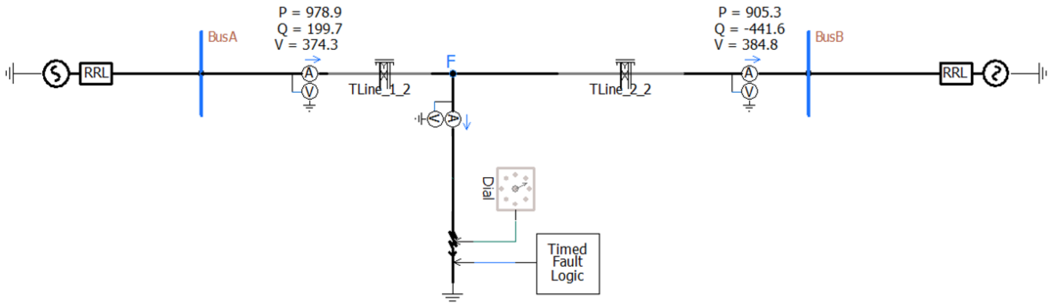
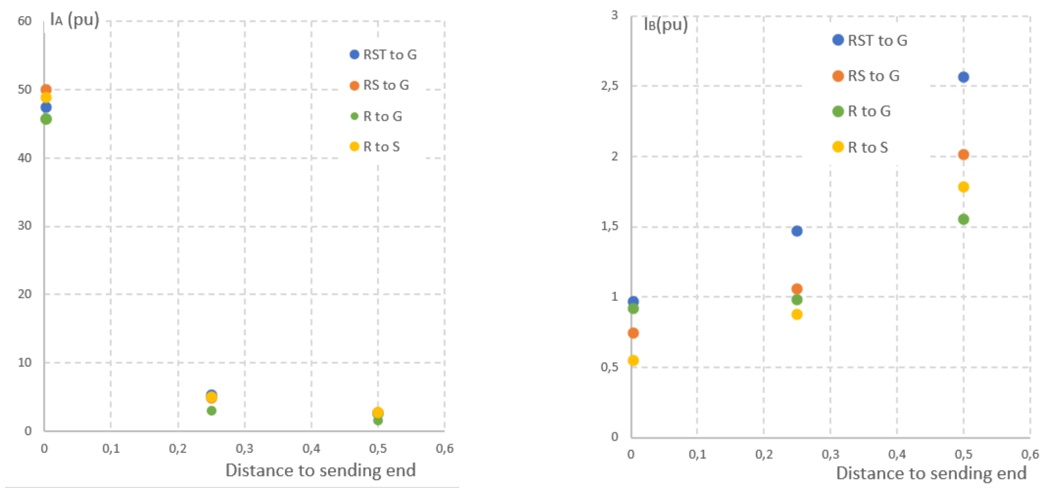


Figure 4.1: Pure AC system - simulation model

As explained in 2, the currents along the system will present a DC component which decreases exponentially with time after the fault occurs. The DC component is highly dependant on the time the fault happens, hence the maximum value the currents reach depend on when the fault occurs as well. However, since the aim of the AC system assessment is to do a future comparison with the AC-DC hybrid model, as long as the fault occurs at the same point of the voltage waveform a comparison can be made.

4.1.2 Analysis of the results

Twelve simulations, considering the different combinations between fault topology and distance from the sending end, are conducted. Figures 4.2a collect the steady state currents at the sending ('A') where the highest values are reached.



(a) Current sending end

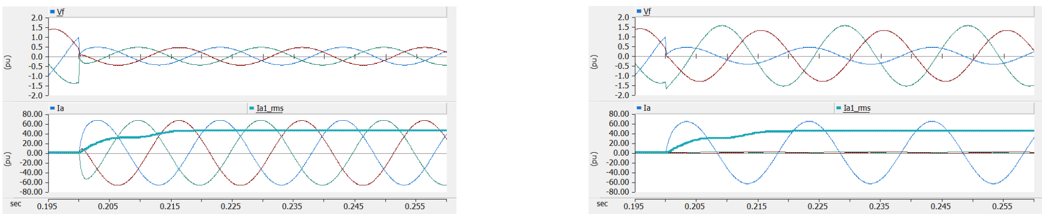
(b) Current receiving end

Figure 4.2: Pure AC system - Steady state current to distance for different faults

As expected, the current at the sending point, I_A, increases the closest the fault occurs to that sending point. Similar values are reached for the fault current, I_F, current which flows towards ground or between phases during the fault where it takes place. Kirchhoff's first law (nodal rule) can be applied. Furthermore, also the values reached at the end of the line, I_B, will increase as the fault gets closer to that point as plotted in Figure 4.2b. When the fault occurs in the middle of the line, the values at each end are equal, I_A and I_B. The graphs represent the steady state value (rms) of the faulted phase.

Two of the fault topologies are more relevant for further study than the others. First, 3-phase to ground is considered, being the worst case scenario as all phases reach higher current values simultaneously. However, 3-phase to ground is an unlikely scenario and 1-phase to ground is the most common type of fault. Hence, 1-phase to ground is also suitable for more detailed analysis. Moreover, the 1-phase to ground scenario generally reaches the lowest current values which are also relevant for the future design of the protection system. Since an overload in the system might increase the current momentarily, that overload case must be distinguishable from an actual fault scenario.

Therefore, the voltage and current waveforms for the two mentioned kind of faults are plotted. In the first place, a fault occurring at 1km from the sending point (1/300 of the line) is considered in Figures 4.3a and 4.3b for each fault respectively. The steady state at the sending point, 'A', is reached almost immediately in both cases. The reached values are extremely high, with a value of 47.481pu equivalent to over 70kA-rms in the worst case scenario, 3-phase to ground.



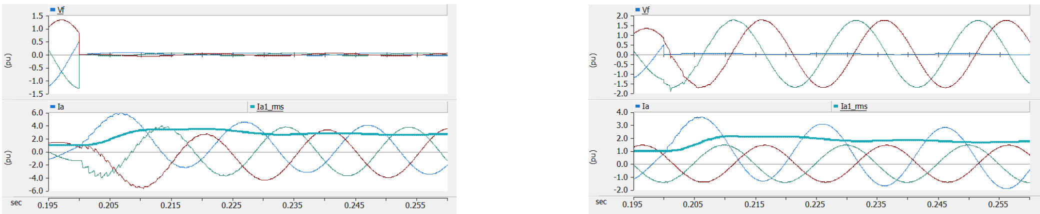
(a) 3-phase to ground

(b) 1-phase to ground

Figure 4.3: Fault at 1km from sending point

Next, a fault in the middle of the line is assessed, collecting the voltage at the fault location and current at the sending end in Figure 4.4.

Since the fault occurs farther from the sending point, the current values at 'A' will not reach as high values as in the previous case of a fault at 1/300 of the line. In addition, the steady state is not reached immediately and the current experience its peak value right after the fault occurs due to the DC component that appears after the fault. If the fault had happened while the voltage of the faulted phase was crossing zero, the peak value would have been higher.



(a) 3-phase to ground **(b)** 1-phase to ground

Figure 4.4: Fault in the middle of the line

A summary of the peak values for each point of interest as well as when they are reached at 'A' is collected in Tables 4.1, 4.2 and 4.3 for all kind of faults at each studied point of the line.

Table 4.1: Pure AC system fault at 1/300 of the line (pu)

Fault 1/300	$I_{A,rms}$	$I_{F,rms}$	$I_{B,rms}$	$I_{A,pk}$	$t_{A,pk}(ms)$	$I_{B,pk}$	$I_{F,pk}$
$RST \to G$	47.481	46.745	0.967	-	-	2.100	-
$RS \to G$	50,041	49,140	0,746	-	-	1.690	-
$R \to G$	45.713	44.946	0.917	-	-	1.773	-
$R \to S$	48.904	48.326	0.546	-	-	2.339	-

Table 4.2: Pure AC system fault at 1/4 of the line (pu)

Fault 1/4	$I_{A,rms}$	$I_{F,rms}$	$I_{B,rms}$	$I_{A,pk}$	$t_{A,pk}(ms)$	$I_{B,pk}$	$I_{F,pk}$
$RST \to G$	5,243	6.529	1.673	10.960	9.75	3.662	14.072
$RS \to G$	4.913	5.631	1.057	8.941	5.57	2.844	7.611
$R \to G$	2.961	3.359	0.982	6.270	6.44	2.272	7.611
$R \to S$	4.972	5.539	0.874	8.293	5.52	3.388	9.852

Table 4.3: Pure AC system fault at 1/2 of the line (pu)

Fault 1/2	$I_{A,rms}$	$I_{F,rms}$	$I_{B,rms}$	$I_{A,pk}$	$t_{A,pk}(ms)$	$I_{B,pk}$	$I_{F,pk}$
$RST \to G$	2.638	4.857	2.567	5.900	6.81	5.509	10.929
$RS \to G$	2.663	4.327	2.012	5.405	5.69	4.382	9.186
$R \to G$	1.633	2.557	1.551	3.587	6.19	3.317	6.047
$R \to S$	2.758	4.234	1.780	5.195	6.28	5.042	8.495

The peak values of I_F and I_B will be reached with a delay, less than 5ms, comparing to when I_A reaches its peak value. The fact that the fault generally occurs closer to bus A, the phase difference between the sending and receiving end and I_F being composed of I_A and I_B explain this delay.

The tables also include their steady state values (rms). The rms value of the faulted phase is considered, evaluating phase R for all cases. Even though, the cases 2-phase to ground and phase to phase have different waveforms since what characterize the fault is different, they reach similar values.

In the case of a fault at 1/300 of the line, peak values at 'A' and 'B' are not included as they reach the steady state without presenting a higher peak value as showed in the previous graphs, Figure 4.3. As the fault is happening very close to the sending end, the inductance effect is reduced.

Later, these values will be compared with the results obtained in a hybrid system (HVAC-HVDC) to analyse how different both networks behave.

4.2 Pure DC system

4.2.1 Model

The DC system is composed of two AC sources at each end of the line along with LCC (line-commutated converters) to convert the energy from AC to DC. The model is based on a different one provided by PSCAD: "Bipolar HVDC Transmission System" [20]. The converters will provide a voltage of $\pm 500kV$ at the transmission line.

The PSCAD model has four converters: two rectifiers and two inverters, one of each for each pole of the HVDC. The converters consist of a 12-pulse LCC converter made of thyristors. Between the converters of the given model, a HVDC transmission line with the specified requirements for the assessment (Chapter 3) is set. Moreover, a LC filter is implemented into the given model at each end of the line to decrease the oscillation of the current and voltage waveforms since they are too high. An inductance of $L = 1.6mH$ and a parallel capacitance of $C = 26.0\mu F$ are considered. These values are inspired by the monopolar HVDC PSCAD model.

If a simpler design is modeled, where DC sources are considered at each end of the line eliminating the converters (Figure 4.5), the voltage at the beginning of the line would drop to a different value depending on the impedance associated to the sources. If there is no impedance the voltage would not change. On the other hand, the voltage can drop to zero if the impedance is large enough representing a weaker grid. However, the control system of the converter will have a large impact in the behavior of the system during a fault. Therefore, the control system is also relevant for the protection system and will highly influence the behavior of the system after a fault.

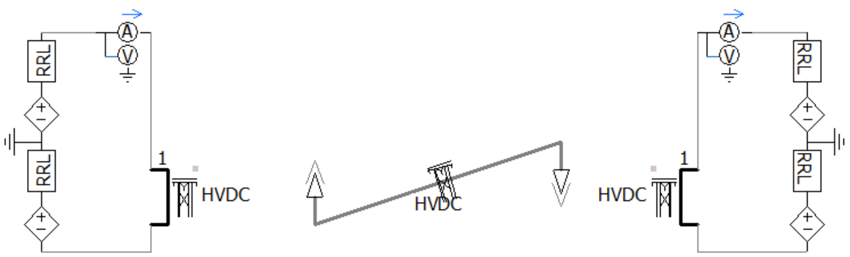


Figure 4.5: Pure DC system - Simple model without converters

The PSCAD provided model is configured in order to drop to nearly zero the DC voltage instantly when a fault happens. Then, the VDCOL (Voltage dependent current order limit) is activated and sets the current to a referenced value, 0.55pu in this case. Hence, the inverter operates in gamma control mode saturating at 90º.

Figure 4.6 represents a simplification of the model that is used for the assessment. The representation is simplified as the line is divided into two alike segments (similarly to the pure AC system case) with different lengths to place the fault at different locations.

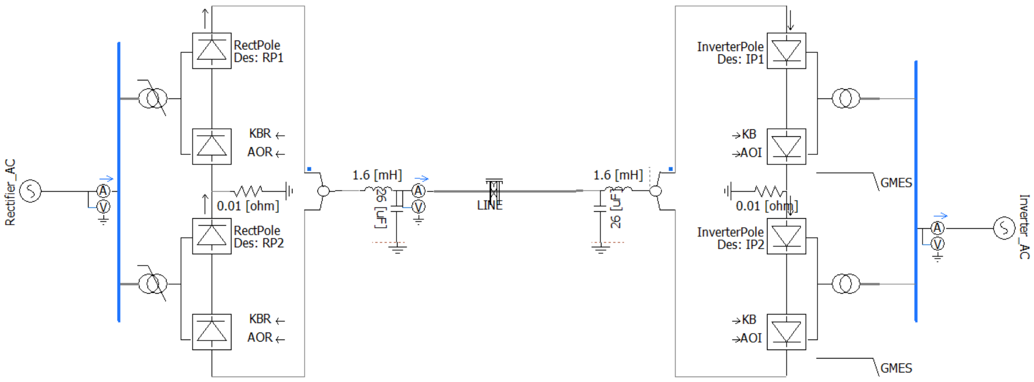


Figure 4.6: Pure DC system - simplified simulation model

Faults at different points of the line will be considered as in the pure AC system: 1/300 (1km), 1/4 (75km) and 1/2 (150km) from the sending end of the line. The fault topologies which will be considered are pole-to-ground (positive pole) and pole-to-pole faults. As in the previous case, 1Ω is considered as the fault resistance.

The fault current, I_F, is defined as the current flowing from pole to ground or from the positive pole to the negative one, depending on the fault topology, at the fault location.

4.2.2 Analysis of the results

Combining the different fault position and the two kind of faults to be assessed, six simulations are conducted. Since the system is current controlled, the steady state value of the current at the sending end, (I_A), and the fault current, (I_F), are approximately 0.55pu and 0.1pu respectively for all cases. Their steady state value is independent of the fault location and the topology of the fault. The voltage will drop to 0.01pu at the sending and receiving end in every case too.

However, there will be a difference between each fault topology in the case of the steady state current (AC) before the rectifier. It will reach a value of 0.585pu (rms) for pole-to-ground fault and 0.662pu (rms) for pole-to-pole fault. The voltage at the AC side also varies as well as the active and reactive power. However, the total apparent power is still equal for both kind of faults.

In Figure 4.7 the peak current reached at the sending end and the fault current are plotted. The peak values for pole-to-pole fault are higher than from pole-to-ground since the voltage difference is higher in the first case mentioned. As it happened in the AC case, the values are higher the closer the fault occurs to the sending end. Hence, a pole-to-pole fault close to the sending end entails the worst case scenario.

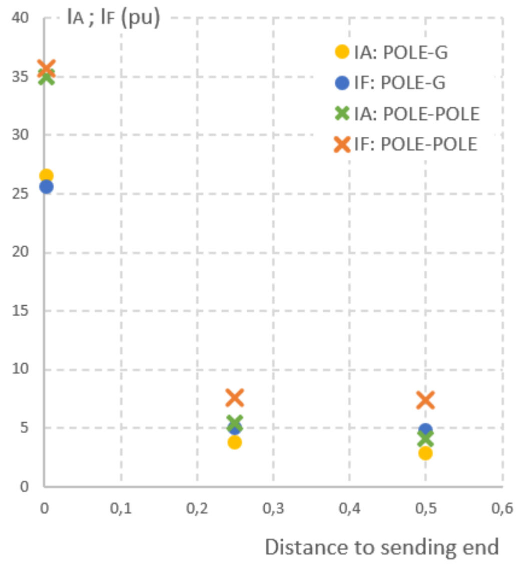
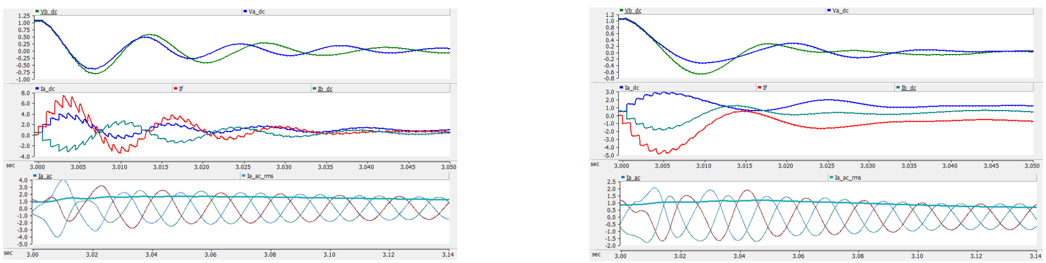


Figure 4.7: Pure DC system - Peak current to distance for different faults

Next, voltages at the sending and receiving end as well as currents at the sending and fault location are plotted. The AC current before the rectifier at the sending end is also plotted. Figure 4.8 collects the waveforms for a fault in the middle of the line while Figure 4.9 collects them for a fault close to the sending end, at 1km from it.

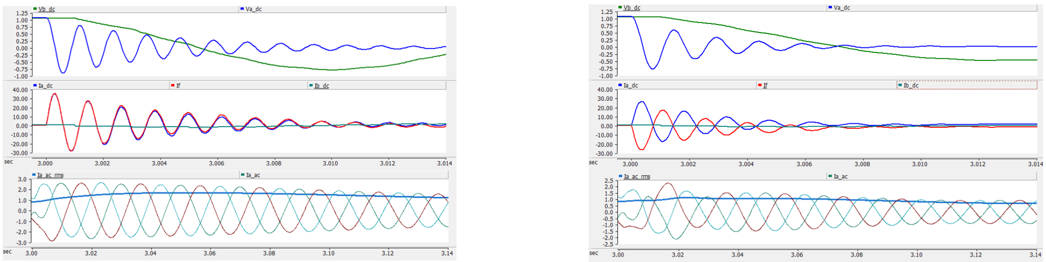


(a) Pole to pole fault

(b) Pole to ground

Figure 4.8: Fault in the middle of the line

It can be seen in Figure 4.8 that if a fault occurs at 1/2 of the line, the voltage and the current at 'A' is much less oscillatory than for 1/300 case, Figure 4.9. The



(a) Pole to pole fault

(b) Pole to ground

Figure 4.9: Fault at 1km from the sending end

frequency for the first few cycles of V_A will be close to 800Hz when the fault is close to ’A’, at 1km. Meanwhile, when the fault occurs farther to ’A’, in the middle of the line, the frequency is close to 70Hz. The oscillations derive from a resonance effect since the frequency is too low for reflections in the transmission line (around 150kHz for a fault at 1km from the sending end) to be the reason behind this phenomena.

Furthermore, it can be observed that the frequency of the voltage at the receiving end, V_B, will be lower (50Hz) when the fault occurs at 1/300 of the line. These differences in frequency may be useful for fault location. The voltage at the fault location, which is not plotted, will drop to its steady state value, 0.01pu, instantly.

In all cases, the steady state is reached in around 30-50ms, being too long to avoid any damage in the converter if no measures are taken. Therefore, the system protection should react before the steady state is reached. Blocking the converters or a DC chopper could be some possible solutions. [8, 18]

It is noticeable that if the current before the filter is considered, the current waveforms would not be as oscillatory. In Figure 4.10 the worst case scenario is plotted. It represents the current at the sending end, before (red) and after the filter (blue).

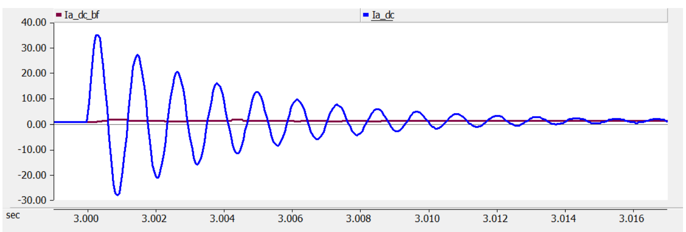


Figure 4.10: Pole-to-pole fault at 1km from sending end. Current before and after the filter

The filter reduce the harmonics and steady state oscillatory behaviour, but increases the oscillations and the peak value by a large margin during the transient. Figure 4.11 represents the current at the sending end when the filters are eliminated. The current is analogue to the one obtained in the previous Figure 4.10, before the current was filtered.

Thus, as stated, when a fault occurs, the filters worsen the behaviour of the system, highly increasing the peak value, since they entail the mentioned resonance effect. However, it is noteworthy the fact that without filters the settling time is longer. A better filter design could reduce the resonance effect between the filters and the line changing the resonance frequency. Moreover, a proper design could be used for fault location as stated before too.

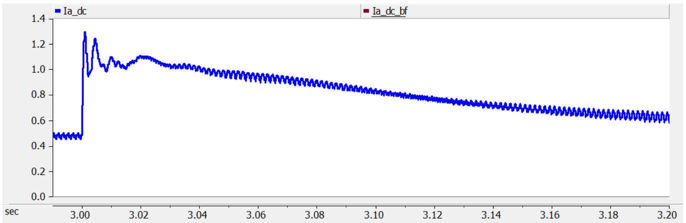


Figure 4.11: Pole-to-pole fault at 1km from sending end. Model without filters

Next, how the unfaulted pole behaves under a pole-to-ground fault is analysed. Figure 4.12 represents the current at 'A' for the pole which does not experience the fault, before and after the filter. The plotted case represents the current at 'A' for the worst case scenario. The fault effect in this pole is minor when compared with the faulted pole in the previous Figure 4.10. It reaches 1pu maximum while the faulted pole reached 35pu.

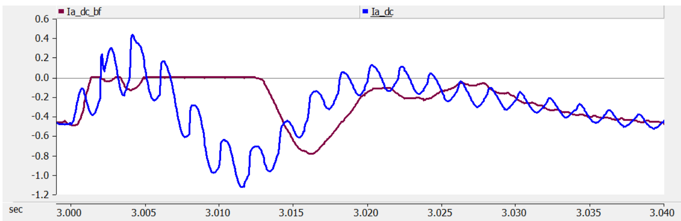


Figure 4.12: Pole-to-ground fault at 1km from sending end. Not faulted pole

To conclude, the peak current values at the sending point, at the AC side before the converter and the fault current are summarized along with the time when they are reached in Table 4.4.

Pole-to-pole fault not only reaches higher peak current values, as described before, but also faster. Therefore, in principle, it entails a larger risk for the system than pole-to-ground fault. The possibility to damage the system is higher due to the higher values and the fault must be cleared faster.

Comparing the values obtained in this assessment to the results of the pure AC

Table 4.4: Pure DC system fault (pu-ms)

Fault 1/300	$I_{A,pk}$	$t_{A,pk}$	$I_{F,pk}$	$t_{F,pk}$	$I_{B,pk}$	$I_{A,ac,pk}$	$t_{A,ac,pk}$
$Pole \rightarrow G$	26.569	0.36	26.591	0.36	1.487	2.272	16.56
$Pole \rightarrow Pole$	34.944	0.271	35.708	0.271	2.387	2.856	6.49
Fault 1/4	$I_{A,pk}$	$t_{A,pk}$	$I_{F,pk}$	$t_{F,pk}$	$I_{B,pk}$	$I_{A,ac,pk}$	$t_{A,ac,pk}$
$Pole \rightarrow G$	3.757	3.25	5.036	3.44	1.673	2.319	7.61
$Pole \rightarrow Pole$	5.427	2.35	7.596	3.09	2.631	4.202	6.95
Fault 1/2	$I_{A,pk}$	$t_{A,pk}$	$I_{F,pk}$	$t_{F,pk}$	$I_{B,pk}$	$I_{A,ac,pk}$	$t_{A,ac,pk}$
$Pole \rightarrow G$	2.913	4.89	4.864	4.41	1.882	2.045	11.14
$Pole \rightarrow Pole$	4.129	3.54	7.424	3.18	3.164	4.085	8.00

case, the steady state current values are lower in this case, due to the control system. Moreover, the peak values which are reached are generally lower than in the cases of the AC scenario. However, the pure DC system includes more fragile devices to the faults, the converters, which makes the time clearing fault crucial.

The peak at the AC side presents a significant delay compared to the DC side, which must be considered for the future protection system. The transformer before the converter and the converters themselves are the reason behind the delay. The detection of the fault should be done in the DC side as by the time it could be detected in the AC side it might have already harmed the converters.

Lastly, the case pole-to-pole-to-ground is simulated. The results obtained are almost identical to the pole-to-pole fault. The waveforms are analogue, being the peak current values slightly lower. Since a fault resistance is considered for each pole, the total resistance between each pole is double the value, 2Ω, being a reason behind the lower results. If 2Ω is considered as the fault resistance for a pole-to-pole fault, the results obtained would be even closer but still not the same.

Both cases do not reach the same values since some current will flow to ground initially as it can be seen in Figure 4.13. After the transient, a steady state is reached and no current flows to ground. This should be be considered when a comparison is made in the future with this scenario.

(a) Fault at 1km form sending end

(b) Fault in the middle of the line

Figure 4.13: pole-to-pole-to-ground, I_g:current flowing to ground

Chapter 5

Analysis of Hybrid AC-DC system after a fault

After an individual analysis of the AC and DC systems, the hybrid system, which combines both systems, is thoroughly evaluated. The previous studied models from Chapter 4 will be referred as "pure AC system" and "pure DC system". When referring to this scenario, "AC system" and "DC system" will be utilized to describe each part of the hybrid system. For the DC system, its "DC side" and "AC side" will be considered.

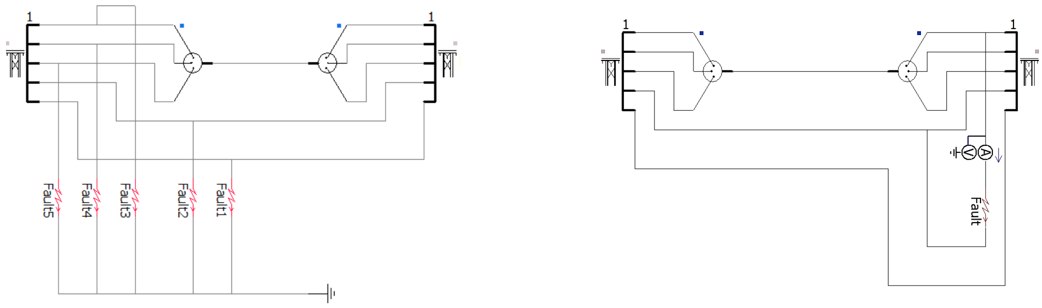
5.1 Model

The model for the hybrid system is composed of the pure DC and pure AC systems, previously described, in parallel, having Bus A and B in common. They do not share the same AC source, the DC system rectifies the voltage from a source different than the one utilized by the AC system. Due to limitations regarding the simulation program, ideal transposition only for the AC lines cannot be made. Therefore, the lines are not transposed entailing an unbalanced system, fact that has to be considered when doing comparisons with the pure models.

When the values are given in pu, the fact that the base values are not the same for each system has to be considered. For both systems a base power of 1000MW is considered. However, the AC system base voltage value is 380kV while it is 500kV for the DC system.

As in the other two scenarios, faults at three different points of the line are considered: 1/300 (1km), 1/4 (75km) and 1/2 (150km) from the sending end. Two main fault topologies, represented in Figure 5.1, will be considered for the hybrid case:

5-phases to ground (the three AC phases and both poles) and a fault between an AC phase and a pole, phase-to-pole.



(a) 5 phase to ground fault

(b) 1-phase to pole fault

Figure 5.1: Hybrid AC-DC simulation model

Two other fault topologies will be also analysed: 1-phase to ground for the AC system and pole-to-ground for the DC system.

5.2 Analysis of the results

The 5-phase to ground fault will be compared to 3-phase to ground in the pure AC system and to pole-to-pole fault in the pure DC system. Since the AC system is not balanced due to lack of transposition, there is current flowing from where the phases meet to ground, which did not exist in the pure AC system. As explained in the pure DC system, pole-to-pole-to-ground behaves almost equally to pole-to-pole so the peak values can be compared considering the small difference.

On the other hand, phase-to-pole fault is study. Analysing how the system reacts when the AC and DC systems are directly connected is important since two different types of currents get involved. It is a new fault topology which can occur as both systems share the same transmission tower. It will be compared to 1-phase to ground and pole-to-ground for the respective pure models. They are compared since only one phase or pole of each system is affected directly by the fault. Instead of one phase being short circuit to ground, the systems experiences a short circuit with each other, being only one phase affected.

The current at the sending point, where the highest value in the transmission line is reached, is plotted in Figure 5.2 for each of the fault distances considered. For the AC system the steady state value is considered, while the peak value is considered for the DC system, as it was also done in the individual pure models. Hence a comparison can be made.

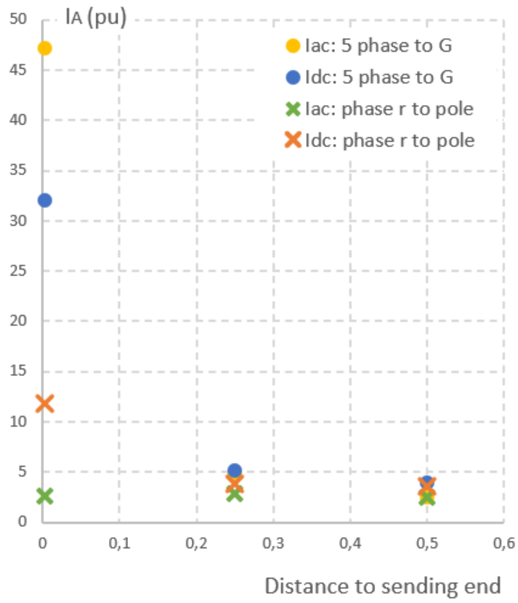


Figure 5.2: Current at sending point to distance for different faults

5.2.1 5-phase to ground

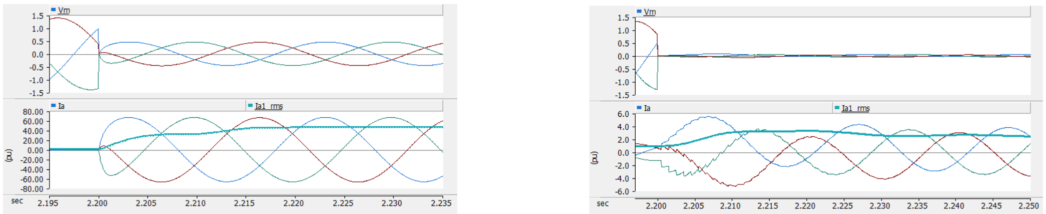
First, the case of 5-phases to ground fault is analysed. The current values obtained for this scenario are collected in Table 5.1 along with the time when some peak values are reached. I_F, fault current, is defined as the current which flows from
670 each phase to ground or from the positive pole to ground in the case of the DC system.

Table 5.1: Hybrid AC-DC: $RST, PP \to G$ (pu-ms)

AC SIDE	$I_{A,rms}$	$I_{F,rms}$	$I_{B,rms}$	$I_{A,pk}$	$t_{A,pk}$	$I_{M,pk}$	$I_{B,pk}$
1/2	2.548	4.413	2.492	5.658	6.65	10.289	5.376
1/4	5.019	6.271	1.625	10.8004	9.73	12.961	3.689
1/300	46.618	45.987	0.938	-	-	-	2.139
DC SIDE	$I_{A,pk}$	$t_{A,pk}$	$I_{M,pk}$	$t_{M,pk}$	$I_{B,pk}$	$I_{A,ac,pk}$	$t_{A,ac,pk}$
1/2	4.033	3.59	7.239	3.16	2.457	4.025	10.01
1/4	5.316	2.29	7.396	3.11	2.549	4.156	7.16
1/300	33.360	0.27	33.572	0.31	2.321	2.851	6.41

AC system

The AC system is analysed and compared to the 3-phase to ground. The steady state current values are lower than in the pure AC scenario. The difference resides in the unbalanced nature of the system when compared to the pure AC. To ensure this fact, the pure AC system is simulated again without considering transposition. The results obtained are exactly the same as the ones obtained for the 5-phases to ground scenario. The same happens with the peak values obtained in both cases. Also, the current waveforms, collected in Figure 5.3 for fault at 1/300 and 1/2, are analogue as the ones obtained in the pure AC system. Hence, the protection system used for a pure AC system is still appropriate.



(a) Fault at 1km form sending end **(b)** Fault in the middle of the line

Figure 5.3: 5-phase to ground fault, AC system

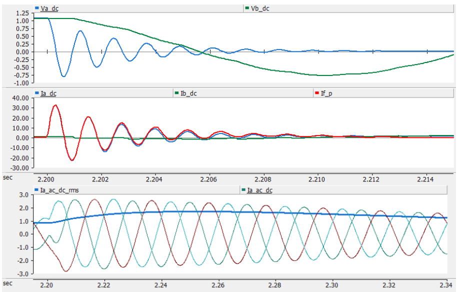
As stated before, since the system is not balance, some current flows from the AC phases to ground. Also, explained in the pure DC system, some current intitially flows to ground from the DC system when a pole-to-pole-to-ground fault occurs. The total current which flows to ground, I_g, is plotted in Figure 5.4. The current is represented in absolute values (kA) as both of the systems contribute to it. In the first few cycles, the contribution of the DC system can be observed through the oscillations which appear. Higher values are reached for a fault closer to the sending end.

(a) Fault at 1km form sending end **(b)** Fault in the middle of the line

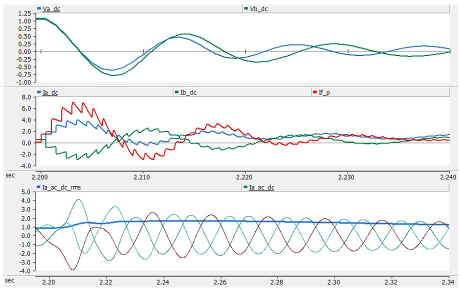
Figure 5.4: 5-phase to ground fault, current to ground

DC system

Next, the DC system is analysed in detail. Figure 5.5 shows the current waveforms of the DC side for the transient period right after the fault. The obtained values are sligthly lower than pole-to-pole fault in the pure DC model. While analysing the pure model, it was mentioned that also lower values were reached for a pole-to-pole-to-ground fault. Hence, the lower values are justified. Moreover, the lack of transposition in the AC system may have a mild effect during the transient, which will be further explained. However, the waveforms are analogue to that fault scenario.



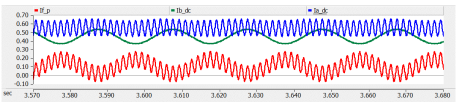
(a) Fault at 1km form sending end



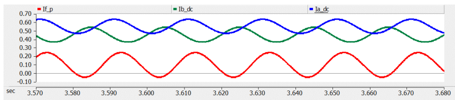
(b) Fault in the middle of the line

Figure 5.5: 5-phase to ground fault, DC system

The steady state DC currents are assessed and collected in Figure 5.6. Since the AC system is not balanced due to the lack of transposition, a coupling effect appears between the parallel AC and DC lines. Due to the asymmetrical configuration of the AC line and without considering ideal transposition, the electromagnetic fields are not canceled and they have an impact in the DC system.



(a) Fault at 1km form sending end



(b) Fault in the middle of the line

Figure 5.6: 5-phase to ground fault, Steady state DC currents

A fundamental frequency (50Hz) and a noise current of 600Hz, a 12^h harmonic, due to the coupling, can be observed in the DC current. The coupling effect is already existing before the fault. Hence, it is related to the system and it is not specifically related to the fault. Since the project is focused on how faults affect the system, the origin of this higher frequency harmonic is not further studied.

However, the effect of the 12^h harmonic is more prominent when the fault occurs close to the sending end and it is barely noticeable when it occurs in the middle of the line. Moreover, the receiving end is also not highly affected when the fault occurs farther from it, fault at 1km from the sending end. The noise current will take the path with the least impedance explaining the different impact.

Despite the sinusoidal waveforms, the values are close to the pure DC model for a pole-to-pole fault topology. In addition, the steady state current value before the converter is identical to the pole-to-pole fault, $I_{A,ac} = 0.663pu$.

An analysis to see the behaviour of the system under balanced conditions is conducted. When the AC system is ideally transpose, the coupling effect is eliminated. As explained in the limitations (Chapter 1), a number of conductors multiple of three are needed to group and transpose them. Therefore, another conductor which ideally does not transport any current in the DC side is added to the simulation. Figure 5.7 shows how the extra conductor is implemented in the model. The coupling effect does no longer exist but, the peak DC values are not accurate because of the extra conductor which is transposed with the other two poles.

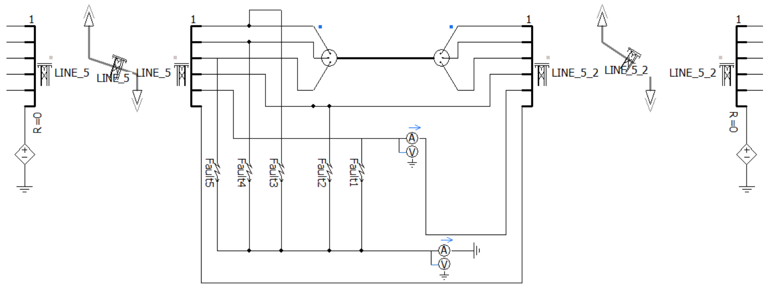


Figure 5.7: AC-DC hybrid model with an extra conductor without current

The system is simulated and as expected, no current flows from the AC system to ground. The transient results on the DC side are not fully accurate due to the existence of the new conductor, as mentioned. However, in this case, the steady state values and waveforms are equal to the pole-to-pole pure DC system, which where stablished by the control system: $I_A = 0.55pu$, $I_B = 0.45pu$, $I_F = 0.1pu$. Then, it can be concluded that, if the same conditions had being applied for the individual models, with a balanced system, same results would have been obtained.

If the system is balanced, the AC and DC systems sharing the same transmission tower leads to a similar behaviour as if both systems were not sharing it. Analogue protection can be used for the hybrid scenario when comparing to the pure individual cases.

However, if the system is not balanced, a coupling effect appears and harmonics are introduced in the DC system. The existence of this harmonics could affect the protection system entailing their malfunction. Nevertheless, as an specific frequency emerge, a suitable filter can solve this issue.

5.2.2 Phase to pole

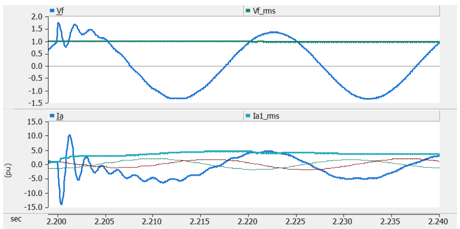
Next, a fault between an AC phase and DC pole is assessed. In Table 5.2 the relevant values are collected as in previous cases. I_F, fault current, is defined as the current flowing from the faulted AC phase ('R') to the positive pole of the DC system. The fact that the system is not balance will generally have an impact on the values obtained compared to the pure AC, which was balanced.

Table 5.2: Hybrid AC-DC: $R \rightarrow P$ (pu-ms)

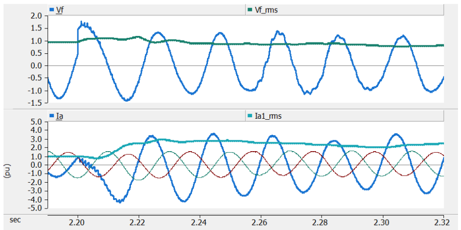
AC SIDE	$I_{A,rms}$	$I_{F,rms}$	$I_{B,rms}$	$I_{A,pk}$	$t_{A,pk}$	$I_{F,pk}$	$I_{B,pk}$
1/2	2.586	2.306	0.753	4.344	13.77	4.833	2.968
1/4	2.860	1.940	0.350	6.171	33.65	5.221	2.346
1/300	2.719	1.458	0.822	14.216	0.36	11.638	1.979
DC SIDE	$I_{A,pk}$	$t_{A,pk}$	$I_{B,pk}$	$t_{B,pk}$	$I_{A,ac,rms}$	$I_{A,ac,pk}$	$t_{A,ac,pk}$
1/2	3.513	35.11	2.674	23.46	-	2.648	18.81
1/4	3.890	33.08	2.892	23.27	-	3.057	47.56
1/300	11.832	0.36	2.771	22.91	-	3.027	45.77

AC system

In the first place, the AC system of the network is analysed. The waveforms of the voltage at the fault location and the current at the sending point ,'A', are plotted in Figure 5.8 for two fault locations.



(a) Fault at 1km form sending end



(b) Fault in the middle of the line

Figure 5.8: 1-phase to pole fault, AC system

The voltage at the fault location is evaluated. Initially the voltage experiments a very fast rise since it shorts circuits to a higher value (500kV). Then it reaches a steady state decreasing its amplitude slightly compared to the initial AC voltage. The offset associated to the exponential DC component which appears because of the transient, takes over 0.8s to disappear when the fault occurs at 1km from the sending end. For a fault at the middle of the line it takes several seconds, since the DC component decreases exponentially to the time constant, which depends on the inductance and resistance.

If the fault occurs farther from the sending end, the effect on the voltage is much more damped than when it happens close to the end, where it becomes oscillatory, Figure 5.8. Resonance effect between the filters associated to the DC line is the reason behind the oscillations. The resonance effect is also noticeable in the current waveform.

The system is simulated without the filter in the DC system. Figure 5.9 collects the voltage and current waveforms for a fault at 1km from the sending end. Resonance phenomena can no longer be seen.

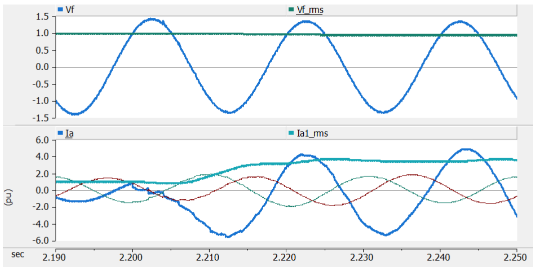


Figure 5.9: 1-phase to pole fault at 1km. AC system current without filter in the DC system

Next, the current behaviour is evaluated in detail. When 1-phase to ground fault happened in the pure AC system, the voltage at the fault location quickly decreased close to zero. Therefore, the voltage at the sending end was much higher that at the fault location and the current increased immediately. The steady state current value would depended on the fault location and how much impedance of the line was between 'A' and the fault point according to the Thevenin equivalent. Also, the peak value depended on the instant voltage value at the time of the fault.

Now, 1-phase to pole, the voltage at the fault location increases as it short circuits to a 500kV line, Figure 5.8. In this case, the voltage at the sending end is lower than at the fault location. Hence, the current decreases its value to change the direction initially. After the transient, the steady state is reached. The peak value reached during the transient would depend on the instant voltage difference between the two points which short-circuit at the moment of the fault.

Furthermore, the most significant result is the low steady state values the current reaches not being higher than 3pu, Table 5.2. In the pure AC, 45pu were reached for the fault closest to the source. The voltage difference, as it shorts circuits to 500kV and not to ground, explains the lower values. Also, a sustained offset, a DC component in the steady state, is introduce to the AC current due to the intersystem fault topology.

In Table 5.2, it is noteworthy that, the rms current value at 'A' for a fault at 1km from the sending end is lower than when it occurs at 75km from it. Generally, if the fault occurs closer to the sending end, the current is higher at that point. The reason behind this contradiction is the existence of harmonics in the current which distortions it, showed in Figure 5.10. The introduction and origin of those harmonics will be further explained when analysing the DC system.

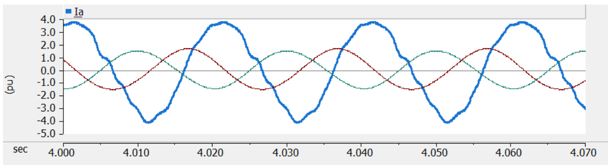
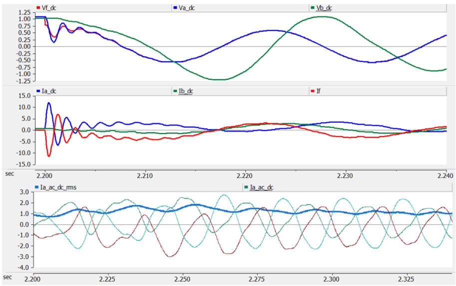


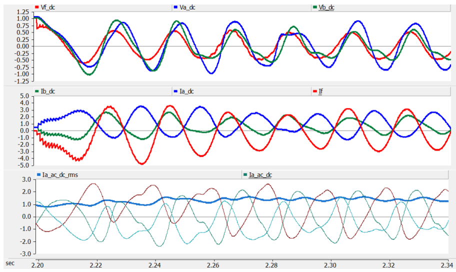
Figure 5.10: Steady state current at sending end, fault at 1km from it

DC system

Secondly, the DC system is analysed. In the pure DC scenario, after an oscillatory transient, DC current and voltages were established. In this case, the voltages and the currents present a 50Hz AC component in the steady state. It is introduced by the connection between both systems when they short circuit. It appears for all fault locations and at every point of the line as it can be seen in Figures 5.11. It is checked if the 50Hz AC component appears due to coupling effect. By adding an extra conductor to the DC system and transposing the phases, as in the 5-phases to ground fault, it is confirmed that the AC component is related to the fault topology.



(a) Fault at 1km form sending end



(b) Fault in the middle of the line

Figure 5.11: 1-phase to pole fault, DC side

As it happens in the AC system, the currents are initially more oscillatory the closer the fault occurs to the sending end due to resonant effect. The maximum value obtain in the system, $I_A, pk = 11.832pu$ for a fault at $1/300$ from 'A', is half the value reached at the pole-to-ground pure DC scenario. As with the AC system, since the voltage variation is lower than the case we are comparing it with (pole-to-ground), lower current values are reached. The instant when the fault occurs will have a large impact on this fact. For the other fault locations, the difference is not as significant since the oscillations due to resonance effect do not take place.

From Table 5.2, it is noticeable that sometimes the peak value is not reached immediately after the fault occurs and instead it might take one or more cycles (i.e. 35,13ms to reach peak value at 'A' for a fault in the middle of the line). This is due to the introduction of harmonics. The distortion caused by the harmonics also affects the AC side before the converters, Figure 5.11. Its rms value is not constant, which is why its value is not included in Table in 5.2, the oscillatory rms amplitude reaches 0.15pu.

The harmonics have several origins. As studied in the 5-phase-to-ground fault, harmonics are introduced due to coupling effect between the two systems. In this case, there are two other origins: the transformers associated to the converters and the converters themselves due to their control system. In Figure 5.12, the magnetization currents from the transformer associated to one of the 6-pulse LCC are plotted. After the fault, the transformer saturates entailing the introduction of harmonics in the system.

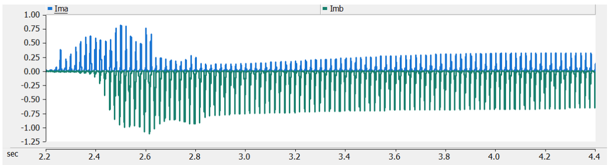
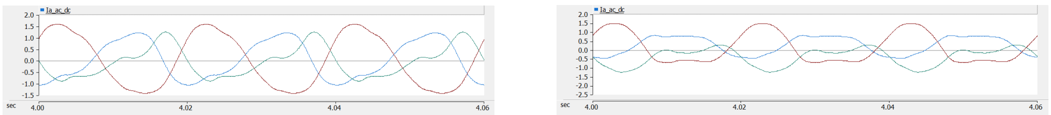


Figure 5.12: Magnetization currents in the transformers associated to the converters, fault at 1km from sending end

However, the harmonics distortion cannot only be explained by the saturation of the transformers. Figure 5.13 represents the AC side current of the DC system when the saturation in the transformers is enable and disable in the simulated model. There is still distortion in the current when the saturation of the transformer is not considered.



(a) Considering saturation

(b) Not considering saturation

Figure 5.13: 1-phase to pole fault, saturation of transformers effect on steady state AC side current of DC system

Further explanations are searched to clarify the existence of the remaining harmonics. The control system has a great significance while evaluating the behaviour of the system as it was explained in the pure DC system. The four converters are affected when a phase-to-pole fault occurs. When only one pole was affected in the pure DC, only the converters related to that pole saturated to gamma 90º. Meanwhile, the other pole's converter underwent a small disturbance to keep with the value it had before the perturbation happened. In this case, the rectifier's gamma oscillates between 110º and 80º while the inverter's gamma is set a bit over 90º. The converter behaves as a rectifier when gamma is lower than 90º and as an inverter while it is higher than 90º. This leads to an odd behaviour of the system.

In Figure 5.14 the gamma angles of the the rectifier and inverter are represented. The rectifier's angle should be lower than 90º in order to rectify the current. However, it oscillates between an angle suitable for a rectifier's and an inverter's behaviour of the LCC. When the fault occurs in the middle of the line, the rectifier's gamma oscillates between 89º and 140º having a behaviour more proper of a inverter. The inverter also has a transient but it settles a bit over 90º, angle suitable for the converter purpose.

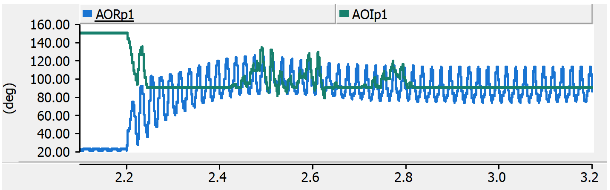


Figure 5.14: Gamma rectifier (blue) and invterter (green) associated to positive pole

Since the control system is based on the voltage and current of the DC link, the disturbances in them entail the malfunction of the control system. The control system is not suitable for this kind of fault topology and its odd behaviour can be reflected as well in the system by the appearance of harmonics. An appropriated protection system should be implemented along with a control system which considers this fault topology.

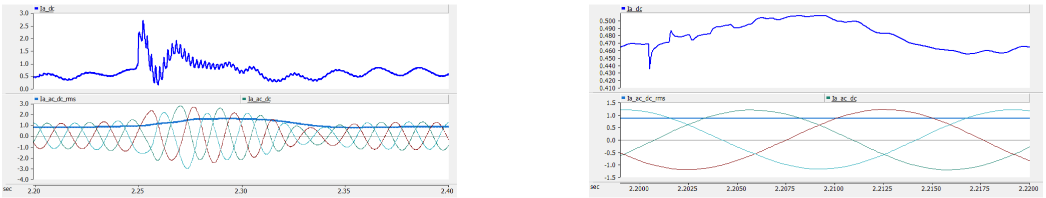
5.2.3 1-phase-to-ground & pole-to-ground

A cursory evaluation of these two fault topologies is conducted. The objective behind these analysis is to find if a fault in one of the systems would have a repercussion in the other system when they are located in the same transmission tower. If a fault in one of the systems affects significantly the other, an assessment in more depth should be conducted in a future work.

These two faults topologies, 1-phase to ground for the AC system and pole-to-ground for the DC system, are relevant since it is likely that only one phase of the five that define the whole hybrid system is affected. 85% of faults in an AC system affect only one phase and it is very likely that the percentage is equally high for a hybrid system.

Two groups of Figures are collected. Figure 5.15 collects the behaviour of the DC sytem when 1-phase to ground fault happens. On the other hand, Figure 5.16 collects the behaviour of the AC system when pole-to-ground fault occurs. In both cases a fault closer to the sending end and farther from it, in the middle of the line, are considered.

Where the fault occurs in both fault topologies is very important. When the fault



(a) Fault at 1km form sending end

(b) Fault in the middle of the line

Figure 5.15: 1-AC-phase to ground , DC system

(a) Fault at 1km form sending end

(b) Fault in the middle of the line

Figure 5.16: DC pole-to-ground fault, AC system

happens farther from the sending end, the opposite system, in which the fault does not take place, barely notice the fault. Figures 5.16b and 5.15b represent those cases. However, when the fault is at 1km from the sending end, the opposite system perceive a larger disturbance.

1-phase to ground and pole-to-ground can also be compare to each other with Figures 5.16a and 5.15a. A fault in the AC system has a larger impact in the DC system, compared to the effect a fault in the DC system has on the AC system. 1-phase to ground entails a peak value of almost 3pu in the DC system, being its steady state value around 0.5pu. On the other hand, when pole-to-ground occurs, the AC system reaches a peak current of 2pu, being the rated peak value 1.5pu.

The strength of the grid and the fragility of the converters which rely on the control system explains the difference on the faults repercussion to the other system.

In this quick assessment, only two cases are analysed. As it has been evaluated in the individual pure systems, the other fault topologies tend to entail higher current values and migh have a larger impact in the system despite being less frequent (ie. 3-phases to ground for the AC system and pole-to-pole for the DC system). A farther analysis for this kinds of faults should be conducted, being more relevant when they occur closer to the sending end.

Chapter 6

Conclusions and Future work

6.1 Conclusions

Three networks under different fault conditions have been studied: a pure HVAC system, a pure HVDC system and a hybrid HVAC-HVDC in which both systems shared the same transmission tower. Initially, a review on different protection systems which can be applied to an AC and DC system were presented. Then, the three sytems were modeled and simulated to study the effect a fault has in each of them. The main focus are the faults in the hybrid system, utilizing the individual systems as a comparison.

When analysing the **pure AC system**, the effect of different fault topologies are analysed. Not all fault topologies are equally damaging to the system, as higher values are reached for some kind of faults when compared to others. Also, the importance of the fault location is described. Higher values are reached when the fault occurs closer to the sending end. Moreover, the instant in which the fault occurs is key, entailing large differences in the reached peak values. These findings are also applicable for the AC system when it shares the transmission tower with a DC system constituting a hybrid system.

Afterwards, the **pure DC system** is analysed under different faults. Generally, pole-to-pole fault entails a larger risk for the system than pole-to-ground, since higher current values are reached. In this scenario, the importance of the fault location is also discussed. A fault closer to the sending end entails a larger peak current.

In this scenario there are several outcomes. Firstly, the importance of the control system is noticeable. As the system is current controlled, it will establish the steady state current values after the fault. It will also influence the transient behaviour.

The control system may be part of the protection system with the appropriate control. Secondly, a fault in the DC side also affects the AC side before the current is converted. Finally, it is noted that the implementation of filters have a large impact in the system due to resonance effects. They might improve the system during its normal operation. However, when a fault occurs and a disturbance is introduced in the system they worsen the behavior of the system right after the fault occurs, much higher values are reached. When installing filters, a comprehensive study must be conducted analysing how they would interact with the rest of the system under a fault.

When the protection system is implemented, the impact of these issues on the line must be considered. During the analysis, the fragility of the converters must be considered as a disturbance in the system might affect them. The issues this system brings will also be observed in a hybrid system.

Finally, faults in a **hybrid HVAC-HVDC system** are assessed. On the one hand, 5-phases to ground is analysed. No larger current values are reached when compared to the individual pure models. Moreover, it is concluded that if the system is balanced, the behavior of it after a fault would be equal to the behavior of two non-interrelated systems. Sharing the same transmission line does not entail a worse scenario if a fault happens.

Nonetheless, a non balanced situation is also studied. The lack of ideal transposition entails a coupling effect between the AC and DC lines and, AC components are introduced in the DC system which are noticeable in the steady state. Contrarily, the transient waveforms remain mostly analogue. However, coupling phenomena will directly affect the protection system, as it might happen with distance relays, as the impedance may vary. The different issues discussed in the individual pure models can also be noted, like the importance of the fault location or the resonance effect due the filters.

On the other hand, a fault between an AC phase and DC pole is evaluated. In this case, two systems with different nature of currents are directly connected. An AC component is introduced in the DC system as well as a DC component is introduced in the AC system. This must be considered for the protection system since they generally consider the nature of the current which they are associated with.

Usually, lower steady state current values are reached when compare to the other scenarios since the voltage difference is reduced. Nevertheless, other difficulties emerge. The harmonics content increases distorting the waveforms which may impact negatively in the protection system. Also, the control system malfunctions due to the disturbances in the current and voltage, which also affect the system during its steady state after the transient is extinct.

Finally, 1-phase to ground and pole-to-ground are briefly studied in the hybrid system. As it occurred along all the analysis, the location of the fault is a key factor. Only when the fault occurs close to the sending end, the system in which the fault does not take place, is more affected.

All the findings along the assessments must be considered for a future implementation of a suitable protection system.

6.2 Future work

The main focus for future work should be the implementation of protection systems and evaluating efficient relay solutions when an hybrid HVAC-HVDC system faces a fault. Based on the results obtained in this report, different protection systems should be evaluated in order to choose the most efficient one.

Furthermore, other fault topologies for the hybrid system can be studied. Appart from a more detailed assessment in the faults that only involve one of the systems, other combinations involving multiple AC phases may be relevant. This scenarios are unlikely but depending on the significance of their effect, the protection system should consider them.

Since the control system has a large impact in the DC system, different control systems should be evaluated. It was concluded that under some fault topologies, the control system does not work how it was intended to. The control system was design for an individual DC system and the fault topologies which can take place within it. Hence, new conditions and fault topologies must be considered when designing the control system. Moreover, different converters can be implemented in the system. VSC converters which are becoming more relevant nowadays, should be considered for a future work assessment.

Harmonic studies may be conducted. The coupling effect between AC and DC lines as they share the same transmission tower can be further assessed. The implementation of more suitable filters and how they interact with the systems is relevant for future studies.

Finally, changing parameters in the network can lead to different results. Different fault resistances or tower configurations could be considered. Depending on the configuration, the impedance of the system changes. Also, the probability of some fault topologies can increase. Moreover, considering a weaker grid might be relevant since the faults may have a larger impact.

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