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Research article

Adapting AC Lines to DC Grids for Large-Scale Renewable Power Transmission

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Abstract: All over the world, governments of different countries are nowadays promoting the use of clean energies in order to achieve sustainable energy systems. In this scenario, since the installed capacity is continuously increasing, renewable sources can play an important role. Notwithstanding that, some important problems may appear when connecting these sources to the grid, being the overload of distribution lines one of the most relevant. In fact, renewable generation is usually connected to the nearest AC grid, although this HV system may not have been designed considering distributed generation. In the particular case of large wind farms, the electrical grid has to transmit all the power generated by wind energy and, as a consequence, the AC system may get overloaded. It is therefore necessary to determine the impact of wind power transmission so that appropriate measures can be taken. Not only are these measures influenced by the amount of power transmitted, but also by the quality of the transmitted power, due to the output voltage fluctuation caused by the highly variable nature of wind. When designing a power grid, although AC systems are usually the most economical solution because of its highly proven technology, HVDC may arise in some cases (e.g. offshore wind farms) as an interesting alternative, offering some added values such as lower losses and better controllability. This way, HVDC technology can solve most of the aforementioned problems and has a good potential for future use. Additionally, the fast development of power electronics based on new and powerful semiconductor devices allow the spread of innovative technologies, such as VSC-HVDC, which can be applied to create DC grids. This paper focuses on the main aspects involved in adapting the existing overhead AC lines to DC grids, with the objective of improving the transmission of distributed renewable energy to the centers of consumption.

Keywords: renewable energy integration; distribution lines; power upgrade; VSC-HVDC; DC grid

1. Introduction

Nowadays, in a world with a constantly growing population, fossil fuels still represent the main primary energy source [1]. However, the drawbacks associated to this energy source (limited resources, climate change, etc.), along with a population that in 2030 is expected to reach 8.3 billion people (an additional 1.3 billion people will need energy [2]), result in an undeniable conclusion: there will be a time when fossil fuels will not be able to provide energy for the world's population.

This way, with the fossil fuel era showing slight signs of decay, renewable sources of electricity are seen as a realistic source of energy for modern societies in the 21st century. Within the many different renewable sources that are used all over the world, the ones with a higher potential seem to be the ceaseless wind power (with a great potential located on the sea along the coastline) and solar thermal energy (with the best solar radiation conditions located in deserts). Therefore, marine renewable energies, and particularly, offshore wind energy can be considered as a promising alternative in this slow but global shift to renewable sources of electricity. Additionally, Desertec organization wants to develop a promising project with the objective of supplying the energy demanded by Europe, Middle East and North Africa using renewable energy sources, taking advantage of the huge potential of solar power from deserts [3]. Other projects are also currently in progress, carried out by different organizations [4,5].

Although renewable energy sources appear to be the solution to a sustainable energy supply in the not-so-distant future, they have to be properly integrated into the power system. This large-scale integration arises as a great challenge, since the conventional power system is not adapted to transmit large amounts of clean energy over long distances. Consequently, the development of new infrastructures adapted to this situation becomes more crucial than ever and, in this new context, HVDC systems might appear as an interesting option for the required integration of renewable sources.

Traditionally, HVDC systems have been applied in high power transmissions over long distances, undersea cables and connection of asynchronous systems. Some of the most relevant characteristics associated to these systems include a flexible and quick control capacity, low losses and an increase in the stability of power systems. Currently, the number of HVDC systems that are being put into operation is increasing considerably. Since these HVDC lines must interact with the widespread AC grids, a mixture of the predominant AC lines and HVDC lines seems to be the best final solution.

In this paper, the possibility of integrating renewable generation by means of future DC grid topologies is analyzed. To be precise, different options are analyzed in order to use the existing overhead AC lines to transmit DC power, so that DC grids can be developed, focusing mainly on the power enhancement that can be reached with each option.

2. DC grid topologies

Although there are many renewable energy sources around the world, these energy sources tend to be rather dispersed and not always close to the centers of consumption. Therefore, it is necessary to deliver the power generated by renewable energies to final consumers, taking special care of their unpredictable character. If these sources are interconnected, their inherent variability will be considerably smoothed.

A DC grid can be a good way of integrating massive renewable energy sources into the power system. This DC grid could be defined as an electricity transmission system, mainly based on direct current, which would be designed to facilitate large-scale sustainable power generation in remote areas and its transmission to the centers of consumption. One of its fundamental characteristics would be the enhancement of the electricity market [7].

In this respect, it should be noted that HVDC is a mature technology that has been used since 1954. Nowadays, there are HVDC installations spread over the five continents using two different technologies: classic thrysistor-based Line-Commutated Converters (LCC-HVDC) and self-commutated Voltage-Source Converters (VSC-HVDC) [8]. Classic LCC-HVDC systems are suitable for long distance high power transmissions. One traditional application of HVDC systems is the transmission of hydropower (e.g. Itaipu and Three Gorges). Flexible VSC-HVDC systems present several properties that make them the most suitable option for DC grids. For instance, due to their ease of controllability, active and reactive power can be independently controlled. Moreover, the power flow can be changed without reversing the voltage polarity, unlike LCC-HVDC systems. Such characteristics are the key factors for using VSC-HVDC technology in DC grids.

Many DC grid topologies have been proposed or studied by different institutions [3,5], some of which are briefly described below [9,10]:

- *Multi-terminal system.* The simplest topology is composed of several multiterminal converters, connecting each DC line to the adjacent one, forming a DC bus. It is adequate to strengthen the AC power system, although this topology presents no DC meshes and no redundancy, since it just constitutes an alternative path for the AC grid. For this reason, it is questionably designed as a grid, but it may be the preliminary step of future DC grids.
- *Several independent DC lines composing a DC grid.* There are two converters for each DC line and both converters are connected to the AC grid. Hence, there are several converters in each node. This is precisely its major downside for a large-scale deployment, which makes this topology the most uneconomical option considering the high price of converters. Furthermore, this topology is not advisable for grids with a high number of branches and recurrent changes in load flows. On the contrary, DC lines are fully controllable and the characteristics (technology, voltage level, etc.) of each HVDC system can be different, which is suitable for integrating the existing HVDC lines into a new grid.
- *Meshed DC system with several connections between AC and DC systems.* Some DC nodes are connected to each other without any converter in between. The DC system is generally meshed, so multiple paths between nodes are possible and the reliability is improved. This option requires just one converter per node; hence, it is more economical and presents fewer losses than the previous topology. These characteristics make this topology a good option for DC grids, although the protection system should be adapted to fit in with a meshed system.
- *Meshed DC system with additional converters.* This topology is similar to the previous one, but there are additional converters connected in series with the DC grid that are also connected to the AC grid. These additional converters aim to improve control possibilities and may be VSC, LCC or even DC/DC converters. The most feasible ones seem to be small Modular Multilevel Converters (MMC) [11] and dual thyristor converters [12].

3. Adapting overhead AC lines to DC grids

The development of a large-scale DC grid is a complex process that, similarly to AC grids, involves several stages that may take a very long time. Despite the fact that there are currently several technical limitations to build DC grids, they are expected to be solved in the foreseeable future [9].

The first step in this process would be the deployment of conventional point-to-point HVDC distribution systems that, in the long term, would be integrated into a DC grid. Unfortunately, aside from the time needed to accomplish this task, it may be very difficult, if not impossible, to build a new overhead line due to social, economic or even environmental aspects. Consequently, it is necessary to consider other alternatives and, amongst them, the use of existing overhead AC lines to transmit DC power emerges as one of the best options.

This way, it is possible to make use of the existing AC infrastructures in order to upgrade their transmission capacity and, at the same time, solve the problems in nearly overloaded lines. Moreover, apart from solving the current problems of some AC lines, this conversion from AC to DC lines would add the inherent benefits of HVDC transmission, such as controllability, stability, etc. In this respect, VSC technology is an exceptional option to be used considering a future integration of a specific line into a DC grid. The adaptation of the line is essentially simple: the existing AC lines are able to transmit DC power, either modifying the towers in order to adapt them to the HVDC configuration or just making the necessary changes in the line.

On the one hand, adapting the existing AC lines to DC lines by implementing tower modifications has already been discussed to some extent [15–20], proving that substantial power upgrades are attainable. However, the high cost of these modifications should not be neglected, since some of the possible changes may be important: new head geometry, new crossarms, changes in conductor configurations, change of insulators, reinforcement of the towers, etc.

On the other hand, when adapting AC lines to DC requirements with no tower head modifications, the general structure of the tower is maintained and, consequently, the changes involved in the process are not excessive. Only the necessary modifications to adapt the existing line to the new requirements are made, which may include insulator replacement (depending on the new DC voltage), revision/change of conductor fittings or, in some specific cases, change of conductors. Therefore, the economic implications of this adaptation are strongly reduced with respect to the previous case and, at the same time, the required time for the whole process is shortened. In fact, it could be considered as a mere maintenance work. Notwithstanding that, the fact that regulatory clearances must be maintained with the new DC voltage should always be taken into consideration.

When it comes to adapting single- and double-circuit overhead AC lines to DC lines, with no tower head modifications, there are different possibilities depending on the AC line configuration. Whereas single-circuit AC lines can be adapted to bipolar, tripolar and modulated bipolar DC lines, double-circuit AC lines can be adapted to one bipole, three bipoles and two modulated bipoles. Adaptation to monopolar DC lines has not been considered in this paper. Some of these monopolar DC lines may cause or suffer from several technical problems (corrosion, interferences, etc.), especially when crossing gas pipes and telecommunication cables. Nevertheless, these concerns can be eliminated when using a metallic return instead of earth return.

This variety of configurations is explained more widely in the following subsections. In fact, the adaptation of single-circuit AC lines is analyzed more in depth because of the complexity associated with its odd number of conductors. Furthermore, VSC-HVDC systems are considered in this analysis, because of their previously mentioned suitability for DC grids. Finally, other important aspects related to the adaptation are introduced, such as insulation requirements, clearances and protection.

3.1. Single-circuit AC lines

Considering that single-circuit AC lines only have three conductors, the existing towers (which have been designed for three-phase AC lines) must be adapted to two-pole DC lines. As previously mentioned, there are three different options to perform this adaptation, which are analyzed below.

3.1.1. Bipolar DC line

Since VSC-HVDC systems have two poles with opposite polarities, a conductor per pole is used for the DC line (Figure 1), whereas the third conductor (free) can work as a return conductor in an emergency situation. The HVDC line will have three circuits with one conductor per pole.

The power transmitted by the DC bipolar line is shown in (1).

$$P_b = I \cdot U_{PG} + I \cdot U_{PG} = 2 \cdot I \cdot U_{PG} \tag{1}$$

where P_b is the power transmitted by the DC bipolar line, U_{PG} is the pole-to-ground voltage and I is the rated current of both poles.

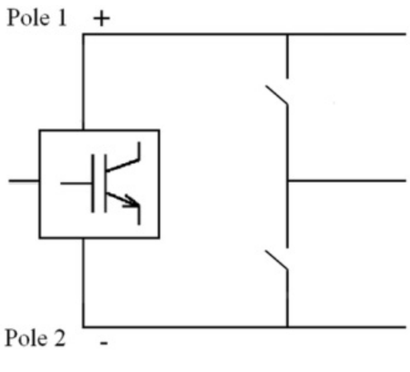

Figure 1. VSC-HVDC bipolar configuration.

This is the simplest procedure to adapt single-circuit AC lines to DC lines. Although it is a simple and economical configuration, its main drawback lies on the limited transmitted power, because of the lower number of operating conductors. Other configurations provide better upgrades.

3.1.2. Tripolar DC line

Tripolar systems were originally implemented with LCC converters and later with VSC-HVDC systems. In the scheme considered in this paper, the last option is taken into account. This way, a tripolar DC line comprises the two poles of a conventional VSC-HVDC system (with opposite polarities) and a third pole that changes its polarity (Figure 2). This third pole is composed of a thyristor-based monopolar system with an extra valve, which provides capacity to reverse current and voltage [21,22,23].

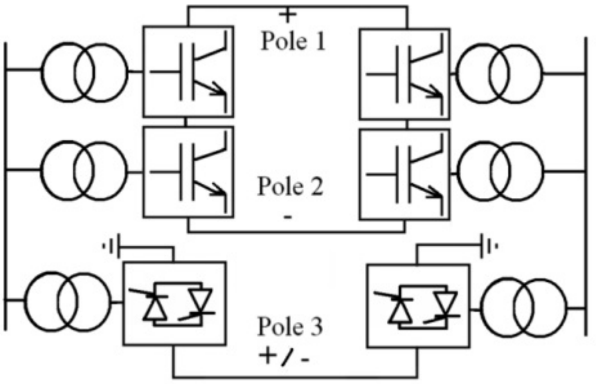

Figure 2. VSC-HVDC tripolar configuration.

The operation procedure of the three poles is quite similar to a bipolar operation (Figure 3). Two of the poles have a fixed polarity (Pole 1 and Pole 2 have positive and negative polarity, respectively) and they alternate between a high current state (I_{max}, exceeding the conductors' thermal limit) and a low current state (I_{min}, below the conductors' thermal limit). Therefore, conductors are periodically overheated during high current state and cooled down during low current state, so the heat generated in this process is approximately the same that would be generated by the rated current [21].

At the same time, Pole 3 periodically reverses its polarity, alternatively sharing positive and negative current with Poles 1 and 2, when these poles are in the low current state. However, in contrast to them, Pole 3 operates permanently at its rated capacity and, accordingly, a characteristic of this configuration is that all conductors use their full thermal capacity.

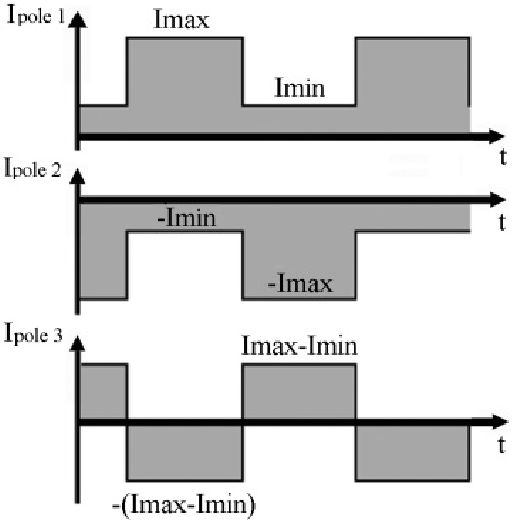

Figure 3. Current diagram for a tripolar configuration.

Consequently, the power upgrade that can be achieved is about 1.37 times higher than with the bipolar one (2).

$$P_{DC} = 1.37 \cdot I \cdot U_{PG} + 0.37 \cdot I \cdot U_{PG} + I \cdot U_{PG} = 2.74 \cdot I \cdot U_{PG} = 1.37 P_b \tag{2}$$

where P_{DC} is the power transmitted by the tripolar DC line, $1.37 \cdot I$ is the current of Pole 1 at a particular instant (high current state), $0.37 \cdot I$ is the current of Pole 2 at a particular instant (low current state) and I is the rated current of Pole 3 [21].

3.1.3. Modulated bipolar DC line

The modulated bipolar DC line has one positive pole, one negative pole and the third pole changes, alternatively, between positive and negative polarity. This configuration operates similarly to the tripolar one, but instead of building a third pole based on thyristors, the two poles of the VSC-HVDC system are commutated [24].

Since this configuration uses one conductor per pole, positive and negative poles are placed in the outermost conductors and the polarity of the central conductor is commutated with IGBTs, as shown in Figure 4. At the end of the line, a thyristor can be used to switch the central conductor.

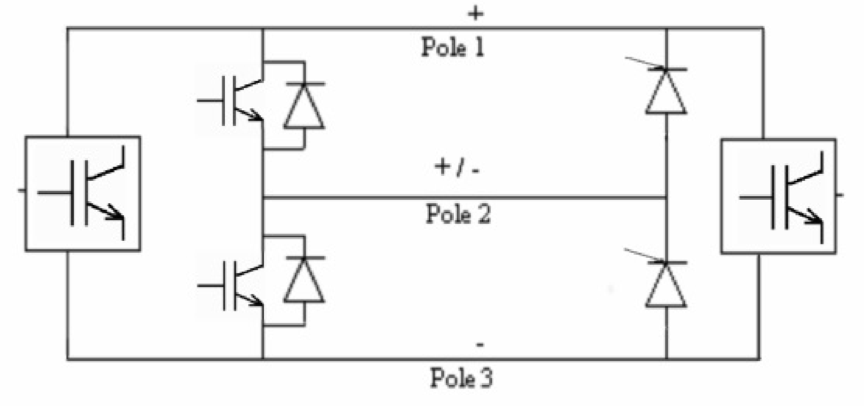

Figure 4. VSC-HVDC modulated bipolar configuration.

Figure 5 shows the operation of the modulated bipole, by means of the three poles current. It can be seen that Poles 1 and 3 alternate sequentially between the high (I_{max}) and low (I_{min}) current states, whilst pole 2 changes its polarity.

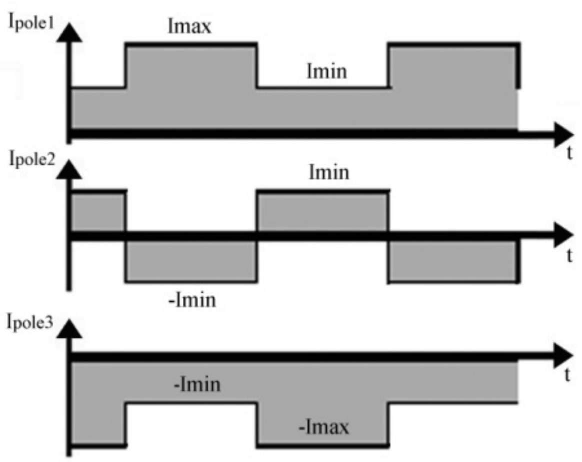

Figure 5. Current diagram for a modulated bipolar configuration.

The bipole can be configured with one sending conductor (two return conductors) or with two sending conductors (one return conductor). When the bipole has just one sending conductor, it withstands a higher current than its rated current and, therefore, it is overheated. The other two conductors share the return current and, consequently, the current in these two conductors is lower than their rated value (so they are cooled). This situation is maintained for a certain time, until IGBTs change their state.

Compared to the bipolar configuration, the power that can be transmitted is 1.26 times higher, as shown in (3).

$$P_{DC} = 1.26 \cdot I \cdot U_{PG} + 0.63 \cdot I \cdot U_{PG} + 0.63 \cdot I \cdot U_{PG} = 2.53 \cdot I \cdot U_{PG} = 1.26 P_b \tag{3}$$

where $1.26 \cdot I$ is the current of Pole 1 at a particular instant (high current state), and $0.63 \cdot I$ is the current of Pole 2 and Pole 3 at a particular instant (low current state) [24].

3.2. Double-circuit AC lines

Double circuit lines have an even number of conductors; accordingly, it is easier to adapt these AC lines to DC bipoles.

In this regard, one option is to adapt the double circuit AC line to three DC bipoles. This way, three converters would be necessary, so there would be three positive poles and three negative poles. Each pole corresponds to one conductor of the original AC line. The transmitted power is shown in (4).

$$P_{DC} = 6 \cdot I \cdot U_{PG} = 3 P_b \tag{4}$$

Another possibility is to create only one DC bipole, that is, only one converter with two poles, where each DC pole is divided into three conductors. Consequently, each pole is connected to one circuit of the original AC line. The transmitted power is similar for both options but the one DC bipole has a lower cost because of the three bipoles used in the previous configuration [24].

3.3. Other aspects of the adaptation

3.3.1. Insulation

Insulation is one of the most important aspects to take into consideration when adapting overhead AC lines to DC lines. Insulators must permanently withstand the rated voltage and, occasionally, also the overvoltages caused by faults or switching operations.

Apart from that, there are several differences between AC and DC insulators. The unidirectional current flow with non-zero crossing, along with the non-uniform electric field, cause uneven voltage distribution and irregular accumulation of pollution on the surface of DC insulators. In order to reduce this effect, the use of a zinc sleeve at the pin and on the cap is necessary [25]. Additionally, creepage has a large influence on the insulation. Unlike AC lines, creepage depends on the pollution level. In fact, for medium-level polluted environments, DC and AC creepages can be considered equivalent. But in highly polluted areas, DC creepage should be approximately 20% higher than the AC one. Moreover, it is also very important to consider the specific characteristics of the HVDC materials that are used. HVDC insulators require dielectric materials with high resistivity to prevent ionic migration as well as thermal runaway.

For a given insulation length, the ratio of continuous-working withstand voltage between AC and DC systems is as indicated in equation (5) [26].

$$k = \frac{\text{DC withstand voltage}}{\text{AC withstand voltage (rms)}} \tag{5}$$

Various experiments on outdoor DC overhead-line insulators proved that, due to the undesirable effects of pollution on insulators, a ratio of $k = 1$ should be at least considered. For example, if an overhead line is located in a reasonably non-contaminated area, k may well be $\sqrt{2}$, corresponding to the peak value of rms alternating voltage. However, for underground or submarine cables k should be at least 2.

Furthermore, power lines also have to be insulated for the overvoltages expected during faults, switching operations, etc. On the one hand, AC transmission lines are normally insulated against overvoltages of approximately 4 times the normal rms voltage. This requirement can be met with an insulation corresponding to an AC voltage of 2.5 to 3 times the rated voltage (6).

$$k_1 = \frac{\text{AC insulation level}}{\text{rated AC voltage } (U_{PhG})} = 2.5 \tag{6}$$

where U_{PhG} is the phase-to-ground voltage.

On the other hand, with suitable converter control, the corresponding DC insulation ratio is shown in equation (7).

$$k_2 = \frac{\text{DC insulation level}}{\text{rated DC voltage } (U_{PG})} = 1.7 \tag{7}$$

Therefore, it can be said that there is a relationship between the DC pole-to-ground voltage (U_{PG}) and the AC phase-to-ground voltage (U_{PhG}), as shown in (8).

$$\text{Insulation ratio} = \frac{\text{insulation length required for each AC phase}}{\text{insulation length required for each DC pole}} = \frac{\dfrac{\text{AC insulation level}}{\text{AC withstand level}}}{\dfrac{\text{DC insulation level}}{\text{DC withstand level}}} \tag{8}$$

Substituting equations (5)–(7) into (8), a general equation for insulation ratio is obtained (9).

$$\text{Insulation ratio} = \left(k \cdot \frac{k_1}{k_2}\right) \cdot \frac{U_{PhG}}{U_{PG}} \tag{9}$$

The abovementioned equations can be applied to different cases, with different configurations.

3.3.2. Other aspects

Additionally, in order to transmit DC power through a distribution line that has been designed as a conventional three-phase AC line, other important aspects must be analyzed. Particularly, the most critical ones are the clearances and the protection of the DC system, which are briefly commented below:

- *Clearances.* The head of the adapted tower must keep the clearances for the new DC voltage. Considering that towers in overhead AC systems are generally overdimensioned, regulatory requirements are usually complied in the adaptation and clearances are commonly within required limits. However, if the tower dimensions do not allow the required clearances, it is compulsory to make some reconstructions in the tower heads. In that case, a good solution may be a change of the crossarms.
- *Protection.* When a DC short-circuit appears, the current must be reduced to zero to deionize the arc, but the problem is that DC currents do not have zero crossing. The large DC fault currents, along with the specific characteristics of a VSC-HVDC system, could result in serious damage in the electronic components of the converters. Thus, the DC system must be properly protected. Different methods to extinguish these fault currents have been proposed throughout the years: DC Circuit Breakers, AC Circuit Breakers, extinction of the fault current components, using IGBTs as circuit breakers, etc. As the availability of DC circuit breakers is still limited in high power applications [27], the DC side of VSC-HVDC systems is usually protected with AC circuit breakers. Besides, some components of the VSC based system have an extremely limited overcurrent capability. In case of fault, those components must withstand the large fault current rise until the AC circuit breakers clear the fault, which can be too long. This way, AC circuit

breakers have the important disadvantage that they trigger all the lines connected to the converter station. This is unacceptable for a meshed system, where only the faulted line should be disconnected.

4. Study case. Results

The main ideas and most important concepts presented in the previous sections have been applied to a specific case, which is described in this section. Since the considered distribution overhead line has already been built and designed as a normal AC line, it is necessary to study all the elements that comprise the power line. This way, it can be determined if they would work properly when transmitting power in DC.

The voltage level in the study case is lower than in the case of EHV, so the cost of the electronic equipment is significantly lower than the cost of long transmission lines. Consequently, this adaptation represents a solution to the existing bottlenecks in power distribution, as nowadays many distribution lines (up to 110 kV) are on the verge of overload, and this voltage level can be considered as a good option for the integration of distributed renewable energy sources.

The line studied has been adapted to the different DC topologies presented in the previous section, analyzing the results in terms of transmitted power.

For this purpose, a study case of a 66 kV AC line is presented. The chosen DC voltage is ± 66 kV. The preferred technology is VSC-HVDC, which is considered as a good alternative for the integration of distributed renewable energy sources. Conductors, which are 147-AL1/34-ST1A type, are not expected to be changed in the adaptation. In case the conductors were changed, the upgrade would be remarkably higher. Results are calculated considering a lagging power factor of 0.9 and a maximum voltage drop of 5%. Two different line lengths are considered (10 and 20 km) and two different AC configurations are analyzed (single- and double-circuit AC lines). The results of this analysis are shown in Table 1 and Table 2.

Table 1 shows the results for the DC adaptation of a 10 km AC line, where the line operates within its thermal limits. Similarly, in Table 2, the line length that has been considered is 20 km, resulting in higher power enhancement ratios for all the configurations considered. Thus, it can be concluded that the power enhancement provided by the adaptation of AC lines to DC lines increases with the length of the line.

Table 1. DC adaptation of an original 10 km, 66 kV AC line.

Original AC line	Adapted DC line	66 kV P_{ac} (MW)	± 66 kV P_{dc} (MW)	ΔP (%)
Single-Circuit	Bipolar DC	43.53	55.85	28.30
	Tripolar DC	43.53	76.52	75.79
	Modulated Bip. DC	43.53	70.65	62.30
Double-Circuit	3 Bipolar DC	87.07	167.56	92.45

Table 2. DC adaptation of an original 20 km, 66 kV AC line.

Original AC line	Adapted DC line	66 kV P_{ac} (MW)	± 66 kV P_{dc} (MW)	ΔP (%)
Single-Circuit	Bipolar DC	28.89	55.85	93.32
	Tripolar DC	28.89	76.52	164.87
	Modulated Bip. DC	28.89	70.65	144.55
Double-Circuit	3 Bipolar DC	57.78	167.56	189.98

As can be seen from the previous tables, in single-circuit AC lines with no changes in the towers, the bipolar configuration gets the lowest upgrade. Therefore, this option is not very useful and it should only be considered when the voltage drop is a very limiting factor. On the contrary, the tripolar configuration gets the highest power increase among the single-circuit adaptations. In fact, it can nearly be compared to the figures of a double-circuit reconstruction. The modulated bipolar configuration gets slightly lower upgrades than the tripolar case, but the required converter configuration is simpler. Finally, the double circuit reconstruction gets the highest upgrade.

Additionally, Table 3 shows the increment in electrical clearances that the adapted DC line must maintain from the original AC line [28,29]. It is important to highlight that these increments are not very high.

Table 3. Increment of clearances, original 66 kV AC line adapted to ± 66 kV DC line.

Δ (Conductor-to-Earth) (m)	0.50
Δ (Conductor-to-Conductor) (m)	1.07
Δ (Conductor-to-Tower) (m)	0.66

5. Conclusion

Despite renewable energy resources offering a huge potential to supply energy all around the globe, the transmission of the renewable power on a large-scale is still a great challenge, not only technical, but also political and economical. In particular, the construction of new overhead power lines is more and more difficult nowadays, so it is necessary to consider alternatives that help to increase the power transfer capability of the existing right of ways, especially when large amounts of renewable power generation are currently on the increase.

In this context, the characteristics associated to VSC-HVDC systems make them an adequate technology to provide a solution. This solution lies in using existing AC lines to transmit DC power, taking advantage of the already built power lines, so that the economic cost is reduced. Additionally, when considering distribution networks, the adaptation is also more economical compared to transmission level, since the lower voltage level reduces the cost of power converters.

It is technically feasible to achieve a substantial power upgrade in existing AC lines through their adaptation to DC, by using the same conductors, tower bodies and foundations, but with possible changes in tower head and insulator fittings. This option will help in the development of multiterminal DC systems and can constitute the preliminary steps of a DC grid.

In this paper, a solution for that purpose is proposed. It has been shown that it is feasible to adapt distribution AC lines to DC grids, maintaining their general structure and obtaining a remarkable transmission capacity upgrade.

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Conflict of Interest

All authors declare no conflicts of interest in this paper.

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