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Integration of HVDC Transmission in Wind Energy

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Abstract— *HVDC transmission lines have become important to integrate renewable energy sources, such as wind and solar photovoltaics. They offer benefits such as lower cost and better control compared to AC lines for long-distance transmission. The objective of this document is to present a review of HVDC transmission and its integration with wind power generation, as well as describe the main characteristics and aspects of HVDC lines and how they have been integrated into related projects in Latin America. The main result of this research is the analysis of how HVDC transmission can facilitate the integration of variable renewable energy, such as wind power, over long distances through its unique characteristics and controllability.*

Keywords— *Alternating current, direct current, wind energy, IGBT, thyristor.*

I. INTRODUCTION

Since its discovery, electricity has been a fundamental part of the technological advancement of the human being to this day. Numerous scientific discoveries marked a milestone in the implementation of electricity for residential and industrial use, although this implied a series of limitations in the transport of the electricity supply. Arising from this predicament, the renowned 'War of the Currents' emerged approximately 130 years ago, led by two prominent scientists of the time. Tomas Alba Edison advocated the implementation of direct current, while Nikola Tesla opted for the insertion of alternating current for the transmission of electrical energy. [1][2][3].

Based on this situation, it was initially concluded that it was more feasible to transmit energy over long distances using alternating current, which dominated for several decades until problems began to appear and prevented the feasibility of these projects. The most important phenomenon that generates detriments is that of reactive power, which is the energy flow that constantly produces fluctuations in the charges of the electric and magnetic fields of the transmission lines to couple to the oscillations of current and voltage producing an increase in capacitance and inductance that proportional to the length of the line. It is concluded that due to this phenomenon, a point is reached where the transport of energy is not viable due to its high economic costs over long distances. [4][5][6].

On account of the above, the concern arose as to whether or not it was possible to implement the transmission of electrical energy in longer lengths using High Voltage Direct Current (HVDC). For this reason, in the last century, technological changes have been increasing that allow the feasibility of transporting energy in direct current. On the other hand, due to environmental problems that have been generated in the world by issues related to global warming and other difficulties that affect the population, the need has been generated to implement electricity generation systems that start from the use of renewable energies, such as wind energy and photovoltaic solar energy. [7][8].

Some of the main characteristics of renewable energies include the fact that they generate electrical energy in direct current, which is then converted to alternating current to be consumed. The drawback arises when this resource is generated over long distances away from cities or centers of consumption, a high cost is generated by losses, harmonics and another series of conditions that do not allow alternating current transport to be viable. From this point, the initiative to transport energy over long distances emerges either in direct current to mitigate the economic, technical and social impact derived from the high energy cost per kW/h generated. [9].

Building upon the earlier stated, this article aims to present a review of the issue of HVDC transmission and its integration into wind power generation. To achieve this objective, the characteristics and most relevant aspects of HVDC and how it has been integrated into related projects at the Latin American level are presented.

This article is organized in eight sections: Section 2 describes the HDVC transmission based on its definition, main features, configurations, types of connections, technologies, and components. Section 3 presents a comparison of the HVDC and HVAC transmission systems, analyzing the environmental, economic, and technical implications of HVDC lines. Section 4 states the advantages and challenges of wind energy, the main parts of a wind generator, and the differences between wind parks on land and at sea. Section 5 presents a Simulink model of a wind turbine system to analyze the benefits of using HDVC to integrate remote wind parks.

Projects in Latin America are discussed in Section 6 which describes some of the research in the area. Section 7 details recent innovations such as MT-HDVC control for wind integration, loss minimization in maritime HDVC networks, and the location of faults in HVDC lines. Lastly, Section 8 concludes regarding the use of HDVC transmission for wind energy integration.

II. HVDC TRANSMISSION

A. Definition

The transmission of energy in HVDC is a type of technology that commercially has generated great relevance in recent decades. Its main function is the energy transmission in direct current in short and long distances, allowing it to be a complement to the current transmission lines in alternating current since at great distances there are multiple problems related to harmonic distortions, and reactive power, among others. Its evolution starts from the first transmission line that was built in 1882 in the United States thanks to the American scientist Tomas Alba Edison, this could transmit a voltage level of 110 V at a distance of 1.6 km. In that same year in Germany, it was also installed the first transmission line transporting 2 kV over a distance of 50 km from the city of Munich to Miesbach. [5].

This transmission system can be modeled using a basic scheme such as the one shown in Fig. 1, highlighting there the alternating current network that enters through the transformer and the filter, and then passes through the rectifier thus becoming pure direct current. After the realization of the energy transmission, this energy is then reversed to convert it back into direct current, in its output it is filtered and synchronized to be injected into the power line or in a specific use away from the network. [10][11] [12]

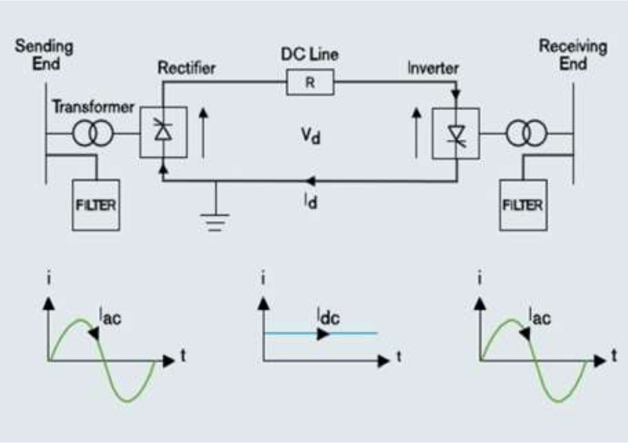

Fig. 1. Standard HVDC transmission circuit [4]

B. *Main Features*

The current High-Voltage Direct Current (HVDC) transmission lines exhibit the subsequent distinct attributes. [11][13][14].

1) *Losses:* The resistive transmission losses are lower compared to alternating current lines, thus being more efficient over long distances.
2) *Capacity:* They have greater energy transfer capacity compared to alternating current transmission lines with the same length.
3) *Control:* HVDC systems allow independent control of active power and reactive power, which provides better voltage management and stability in interconnected alternating current networks.
4) *Interconnection:* HVDC systems facilitate the interconnection of alternating current networks that operate at disparate frequencies or phases, thereby enabling the exchange of energy between regions characterized by grids that are inherently incompatible.
5) *Interference:* Because it is transmitted in direct current, there is less electromagnetic interference, and also there is a lower susceptibility to disturbance.
6) *Transmission*: These types of lines are commonly used to transmit energy from remote hydroelectric power plants, offshore wind farms, and photovoltaic solar parks, among others, to regional power grids. Its fundamental role is the integration of renewable energy sources, the improvement of energy efficiency, and the reliability of long-distance power transmission.

C. *Configurations in HVDC Systems*

The configurations that an HVDC system can take depend on the type of application that is required to perform at these systems [1][5][9]. The most relevant and currently used are:

1) *"Back to back":* It is used at low voltage levels, where its main use is the connection of asynchronous networks or synchronous networks that have different frequency regulations.
2) *Point to point:* In this configuration, energy is transmitted between two specific points. It is a single transmission line disconnected at the sending and receiving ends, these are used in long-distance transmission, as well as in the connection of remote sources of energy generation.
3) *Multiterminal:* For this case, there is the particularity of the implementation of several conversion stations to the grid, in this way several cases can be presented as if the stations were connected to the same voltage level or if failing that each of these worked at a different voltage level.
4) *Unitary:* It affects the connection between the rectifier and the generator, consequently recognizing a DC-type connection that can vary in frequency without the need to synchronize with the grid.

D. *Connection Types*

In HVDC transmission, several types of connections are used to link transport lines to alternating current systems at the sending and receiving ends. [4][2][15].

1) *Monopolar:* For this type of connection, a single conductor is used in the power transmission, while the return path is provided through land or sea. This system requires grounding electrodes or electrodes installed in the water at both ends of the HVDC lines. It is commonly used for long-distance submarine power transmission.

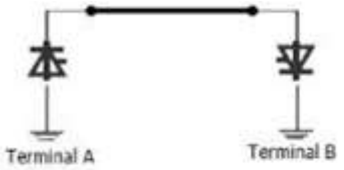

Fig. 2. Monopolar connection with return to earth. [2].

2) *Bipolar:* The connection for this case is twofold, its polarity is negative and positive. For each station, two converters are grounded. Its connection can be similar to a monopolar with a return by land or metal. If there is a fault in a conductor, it can become a monopolar connection, thus providing reliability to the system to continue working, even if its efficiency is half of its nominal capacity. [3][16].

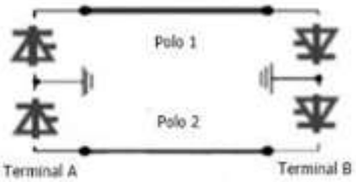

Fig. 3. Bipolar connection with metallic return by land. [2]

Homopolar: In this type of connections, one or more conductors that have the same polarity are implemented,

3) allowing the minimization of losses due to the corona effect. The return line can be by ground using electrodes or implementing conductors according to the requirement of the site. In the event of breakdowns in any conductor, it can continue its operation with the remaining conductors, therefore, guaranteeing the reliability of the system. [1].

E. *HVDC Technologies*

The technologies that are implemented in HVDC systems are two: Line-Commutated Converter (LCC) and Voltage-Sourced Converter (VSC).

1) *HVDC LCC*: It is the traditional technology that has been implemented in the last century, its main particularity is that each of the power converters it uses are structured in semiconductors of the SCR type and thyristors. The problems arising from its use is that semiconductors only allow to control their ignition, in this way only the active power can be inspected, so an additional configuration would be necessary to intervene in its cut or in the treatment of the reactive power. To solve the last-mentioned problem, a series of capacitor banks or SVC are implemented that allows injecting the reactive power required by the supply station. Another characteristic of these technologies is that the current flow circulates in the same direction, letting energy transmission over large amounts of power and length. [15].

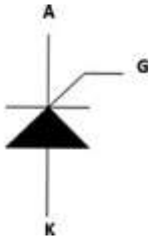

Fig. 4. SCR Thryristor. [2].

2) *HVDC VSC:* For these types of technologies, Insulated Gate Bipolar Transistor (IGBT) power semiconductors are implemented. The level of power that is handled with this technology is not very high, but it has some peculiarities that highlight them by being more efficient than its predecessor. It allows switching at high frequencies, thus increasing its response speed as well as the mitigation of harmonics in the lines, additionally allows the individual control of the active and reactive powers and does not require additional devices that allow the exchange of semiconductors, since independently the IGBT has the characteristics of ignition and cut. [2][15][17].

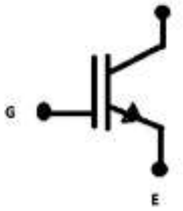

Fig. 5. IGBT Transistor. [2].

The choice of HVDC transmission technology depends on factors such as transmission distance, power capacity requirements, system configuration, grid integration needs, and cost considerations.

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F. *Components*

The elements that make up an HVDC system are mentioned below. [17][18][19].

1) *Investor:* It is an element that allows the transformation of alternating current to direct current and vice versa.
2) *Transformer:* Element that allows to increase or reduce the level of electrical voltage that a transmission line can carry.
3) *Filtros:* It is a device that allows the decrease of the ripple of the signal. Another type of filter implemented is the one that allows the mitigation of harmonics that occur in alternating current signals.
4) *Reactance* : It is generally inductive and has the function of mitigating leakage currents after the application of filtering, as well as the prevention of resonance in the circuit.
5) *Capacitors:* In the case of HVDC-LCC systems, the capacitor allows control the reactive energy necessary to stabilize the voltage level in the converter. In their topology, they are connected in parallel with some types of switches to alternate their functionality.
6) *Lines:* The transmission lines used in this system are air, underground, and maritime.
7) *Switches:* They allow to control the ignition and cut of the systems, as well as more specific functions related to faults.
8) *Grounding System:* It is implemented using connectors or ground conductors thus generating protection for the system in case of leakage currents or other damage due to a short circuit.

III. RISKS IN HVDC LINES

A. *Comparison between Electric Power Transmission Technologies.*

Electric power transmission lines are a vital part of the energization of any sector or area where there are power lines to the country's generation centers, which is why their great importance lies in the capacity and distance in which they can transmit. As has been discussed in advance, this type of technology is divided into two, the lines in HVDC and HVAC. [5][14][17].

Part of the physical limitations that accompany HVAC lines are their thermal imperative, which limits the transmission capacity as is the case of a 500 kV line where its losses are around 2300 MW. Other existing types of restrictions are those related to the stability of the system, which is why over long distances the transport capacity is not viable. [5].

As for HVDC lines, it is recognized that they are more efficient since in massive energy transfer, they can cover distances of up to 1000 km in overhead lines, thus recognizing that their transport capacity is greater than that of an alternating current line [5].

B. Environmental Implications

Some of the environmental implications that occur in transmission lines in HVAC and HVDC are the following. [19][20][21].

1) *Habitat destruction:* The construction of transmission lines may require the clearing of large areas of land, leading to the destruction and fragmentation of natural habitats. In the medium term, it puts wildlife species at risk, thus damaging biodiversity.
2) *Visual impact:* This type of transmission line visually impacts the landscape, since it changes the conditions of the natural environment leading to potential damage to areas where ecotourism is located and also affects the valuation of surrounding properties.
3) *Noise pollution:* Some transmission lines can produce low-frequency noise that can disturb both wildlife and nearby residents.
4) *Electromagnetic fields:* High-voltage transmission lines emit a certain amount of electromagnetic fields, raising concerns about potential health impacts on humans and animals living nearby.
5) *Management of the right of way:* Maintaining the transmission line right-of-way often requires the use of herbicides to control vegetation, which can have adverse effects on local ecosystems and water quality.
6) *Bird collisions:* Birds can collide in transmission lines, causing injury or death, especially in the case of large raptors and migratory birds. [5].
7) *Restrictions on land use and access:* Transmission lines can limit the use of and access to land for agricultural activities, recreation, and development.
8) *Climate change :*While the transmission line itself does not contribute directly to greenhouse gas emissions, it allows the transport of electricity, which could be generated from fossil fuels and thus contribute to current climate change.

To mitigate these impacts, several measures can be employed, such as careful route planning to avoid ecologically sensitive areas, the use of bird flight diverters to reduce bird collisions, and the exploration of alternative energy sources to reduce the need for extensive transmission line networks. In addition, technological advances could reduce some of the concerns, such as the use of underground cables to minimize visual impacts and habitat.[2][3][5][7][8].

C. Economic Implications

1) HVA

Some of the key impacts of alternating current transmission lines are as follows:

Infrastructure investment: The construction and maintenance of high-voltage transmission lines requires a significant initial investment, this includes the cost of towers, conductors, substations, and related equipment. Based on this premise, the initial capital expenditure can be substantial, but it is necessary to ensure a reliable supply of electricity to maintain stability in the power lines. [22].

Distance: For this type of lines when they must be implemented over long distances, the losses generated by energy waste are enormous, thus preventing an alternating current project from being economically viable.

2) HVDC:

While this type of transmission line proves to be more efficient over extended distances, it also entails economic repercussions. Several of these impacts are as follows:

Construction costs: Building HVDC transmission lines can be expensive due to the need for specialized equipment, materials, and construction techniques. Costs may vary depending on the length of the ground transmission line and the complexity of the project. [23].

System integration costs: Integrating these types of lines into the existing power grid may require investments in network infrastructure and upgrades to accommodate new technology. These costs can be huge, but they are usually necessary to get the full benefits of the direct current transmission line in the medium and long term. [24].

Transmission efficiency: For these lines, there are generally lower transmission losses over long distances compared to alternating current lines. By reducing energy losses during transmission, these lines generate cost savings for utilities and consumers in the long run. [24].

Electricity prices and market dynamics: these lines can allow the transport of electricity from remote areas to populated regions with a high energy demand, this influences electricity prices and the stock market of the national energy market thus providing stability in energy prices to promote greater competition in the market. [23].

Grid reliability and stability: This type of transmission can improve grid reliability and stability by facilitating better control over power flow and reducing the risk of blackouts and voltage fluctuations. Better stability can provide cost savings for energy service companies and users. [22].

Investment in power generation: The implementation of these lines can exert an influence on decisions regarding infrastructure investments in power generation. In this way, these transmission lines can be integrated with renewable energy generation sources such as photovoltaic solar energy and wind energy. [23].

International electricity trade: This type of lines also enables cross-border trade in electricity, because of this, countries can import or export energy depending on demand and availability, thus producing economic cooperation and energy security between neighboring nations.

Generation of employment: For the construction of this type of lines it is necessary to have qualified labor for construction and continuous maintenance. As a result, these projects generate job opportunities and stimulate the local economy. [24].

Incentives in costs and financing: for this type of transmission lines, it is expected that its point of return of recovery is around 20 years, in this way a high economic flow is guaranteed in the nation where this type of transmission system is installed and that is why local regulations or energy regulations provide support and incentives to companies to implement This new technological system. [22].

In general terms, these types of economic impacts can vary significantly depending on the project specified, the regulatory environment, energy policies and the needs of the nations involved.

The following fig shows the cost-benefit ratio of direct current and alternating current transmission lines. [7][16].

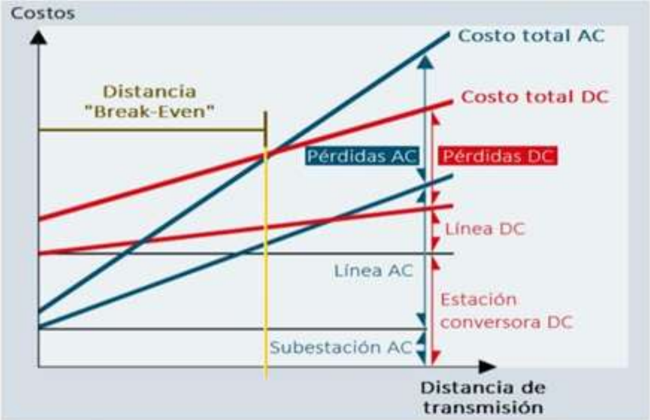


Fig. 6. Distance-cost ratio between HVDC and HVAC lines. [16].

D. *Technical implications*

Related to transmission capacity, alternating current lines have limitations in distance as a result of their inductive effects. This type of problem results in a difference of phase at the beginning and end of the line, which is why for the transmission of active power an excessive consumption of reactive power is needed, thus leading to unstable transmission systems. Among some options to stabilize the system the implementation of FACTS can be found. They allow the injection of reactive energy in order to compensate for the transmission of power in the line. [16].

On the other hand, related to direct current transmission lines, this type of inductive effect is null therefore, the active power transmission is complete providing stability over long distances.

It can be indicated that they are not 100% reliable in energy transmission, due to the losses that occur in line converters and transformers. Although it is estimated that this type of loss does not exceed 3%. Despite the multiple advantages of this type of transmission lines, some disadvantages of the technical type can be identified, such as the following:

- Generation of harmonic distortions in converters: to mitigate this type of distortions, filters are implemented in order to guarantee stability in the current and voltage of the system. [26].
- Step-up and step-down transformers: for this type of lines there are drawbacks when implementing transformers that change voltage levels. [8].

In conclusion, only HVDC transmission systems are technically viable only when HVAC transmission lines have technical limitations due to distance or system stability. [1][4][10].

IV. WIND ENERGY

A. *Definition*

Wind energy is a type of renewable energy that harnesses the force of the wind to generate electricity. The term "aeolian" comes from Aeolus, the Greek god of winds. [18][19].

The basic principle behind wind turbines is simple: the force of the wind causes the turbine blades to rotate, with this rotation in turn driving a generator that produces electricity. The amount of electricity generated depends on the size of the wind turbine, wind speed and system efficiency. [22][24].

Some of the advantages of this type of energy are the following:

- Renewable: wind is an inexhaustible resource as long as the sun continues to shine depending on the earth's surface warming unevenly.
- Environmentally friendly: Wind energy does not produce greenhouse gasses and other harmful pollutants during that operation, making it a clean energy source that helps combat climate change and air pollution.
- Cost-effective: Once wind turbines are installed, operating costs are relatively low compared to fossil fuel power plants. Technology has improved over the years, making wind energy more economically viable.
- Local benefits: Wind farms can provide economic benefits to surrounding communities, including job opportunities and additional income such as those presented in land lease agreements.

However, wind energy also faces some challenges, such as intermittent power generation (wind does not always blow constantly), the need for suitable locations for wind farms, potential visual and noise impacts and the requirement for backup power source with wind is not present. Despite these limitations, wind energy continues to be an important and growing resource in renewable energy, contributing to a more sustainable energy future.

B. *Wind Turbines*

It is a device that converts the kinetic energy of the wind into electrical energy [22][24]. The main parts of a wind turbine are:

- Blades: they are connected to the central cube and rotate when the wind blows over them. The rotational motion revolves around a shaft connected to a generator to produce electricity. The number and length of blades vary depending on the turbine design.
- Nacelle: this sits on the tower and contains the main mechanical components, such as the gearbox, generator, brakes and control systems.
- Tower: holds the nacelle and rotor blades high up, where the wind speed is higher. Towers are usually made of tubular steel, concrete or steel latticework. The height ranges from about 30 to 100 meters.
- Yaw system: This mechanism rotates the nacelle and blades to rotate in the direction of the wind for optimal orientation. It allows the turbine to rotate (move left or right) to follow the wind.
- Generator: this element has the ability to use electromagnetic induction in order to convert the mechanical energy of rotation into electrical energy. Currently, the most common types of generators are

asynchronous and synchronous generators.

- Gearbox: in some wind turbines the gears connect the low-speed rotor to the high-speed generator allowing greater efficiency in the system.
- Vane: This element allows wind measurement and it communicates with the yaw system to correctly orient the turbine.
- Anemometer: allows the measurement of wind speed in order to exercise optimal control in the execution of the wind turbine.
- Controller: It is the electronic control system that monitors operation, optimizes performance and shuts down when necessary.
- Brakes: Wind turbines have a braking system that can slow down or stop rotor blades in high winds or during maintenance.
- Tilt: Many modern wind turbines have a tilt system that allows adjusting the angle of the rotor blades. This helps control the amount of energy captured from the wind and can be used to regulate the rotational speed of the turbine.

C. *Types of Wind Energy*

There are two main types of wind energy: onshore wind and offshore wind. Each type has its own characteristics, advantages and functionality. [18][19].

1) *Onshore Wind Energy*

Onshore wind refers to wind turbines that are installed on land, usually in areas such as fields, hills, or open landscapes. Its functionality will be detailed below. [18][22].

- Installation: onshore wind turbines are located in towers on solid ground. They are more accessible for maintenance and installation compared to offshore turbines.
- Advantages: Onshore wind power installations are generally less expensive to install than offshore ones. They can be installed closer to populated areas, reducing losses and transmission costs.
- Challenges: Local communities may raise concerns about the visual and acoustic impacts of onshore wind farms. Land availability can also be a constraint in densely populated or developed areas.

Fig. 7. Onshore wind farm in Denmark. [17].

2) *Offshore Wind Energy*

Offshore wind energy involves wind turbines located in bodies of water, usually in oceans or large lakes. Some of its specifics will be described as follows.

- Installation: Offshore wind turbines are placed on specialized structures fixed to the seabed or floating platforms. This sort of installation can take advantage of the strongest and most constant winds found offshore.
- Advantages: Offshore wind farms can make good use of stronger, more constant winds, resulting in higher energy production. They also have the potential to reduce visual and noise impacts on local communities.
- Challenges: The installation and maintenance of offshore wind turbines are more complex and expensive due to the challenging marine environment. There may be concerns about impacts on marine ecosystems and navigation.

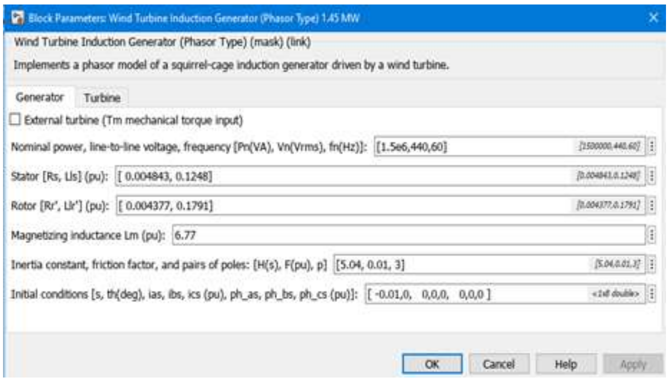
Fig. 8. Transport of electrical energy from offshore to land. [17]

Both onshore and offshore wind contribute to generating electricity from a renewable source, reducing greenhouse gas emissions, and addressing climate change. The choice between onshore and offshore installations depends on factors such as the availability of wind resources, environmental considerations, land availability, costs, and regulatory frameworks. As technology advances, both types of wind energy continue to play a crucial role in the transition to cleaner and more sustainable energy systems. [22][24].

V. HVDC AND WIND ENERGY

A. *Modeling of a Wind Generation System*

To understand the operation of small-scale wind energy, the model proposed in [13][14] is used to carry out the simulation of a 1.5 MW wind turbine at 60 Hz. Additionally, this model has a generator, a gearbox and a fuzzy logic controller to vary the speed of the generator.



Block Parameters: Wind Turbine Induction Generator (Phasor Type) 1.45 MW

Wind Turbine Induction Generator (Phasor Type) (mask) (link)

Implements a phasor model of a squirrel-cage induction generator driven by a wind turbine.

☐ External turbine (Tm mechanical torque input)

Nominal power, line-to-line voltage, frequency [Pn(VA), Vn(Vrms), fn(Hz)]: [1.5e6,440,60]

Stator [Rs, Lls] (pu): [0.004843, 0.1248]

Rotor [Rr', Llr'] (pu): [0.004377, 0.1791]

Magnetizing inductance Lm (pu): 6.77

Inertia constant, friction factor, and pairs of poles: [H(s), F(pu), p] [5.04, 0.01, 3]

Initial conditions [s, th(deg), ias, ibs, ics (pu), ph_as, ph_bs, ph_cs (pu)]: [-0.01,0, 0,0,0, 0,0,0]

Fig. 9. Parameters of the implemented wind turbine block.

Regarding the operation of the controller, it is recognized that it has two inputs that generate change in the output power (ΔP) and change in the speed of the generator (LΔω). On the other hand, input/output variables use fuzzy sets such as Negative Big, Zero, Positive Big defined by membership functions.[20][25].

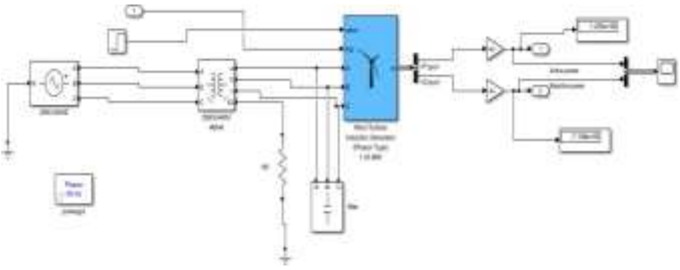


Fig. 10. MATLAB Simulink model of wind turbine induction generator. [20][25].

What's more, the transformer allows the reduction of the voltage from the generator in order to feed the rotor with reactive energy capable of generating flow at variable speeds. The wind speed is defined by the stepped signal that varies from 0 to 1. Finally, power measurements are made in P.U. in order to facilitate the model.

With what is proposed in fig 10, the initial behavior of the power generated by the mini wind farm can be emulated. In Fig. 11, an underdamped response where blue is the active power and yellow is the reactive power can be seen. [20][25].

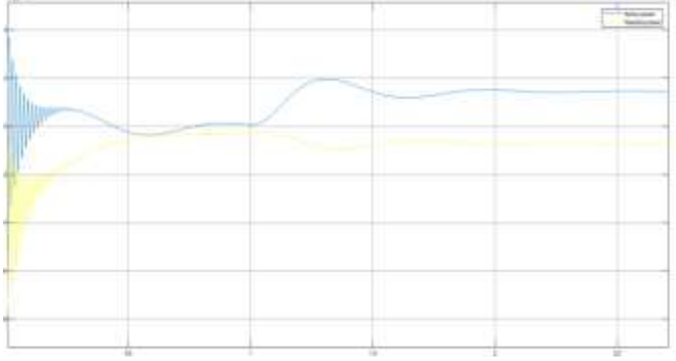


Fig. 11. Output signal of the active and reactive power of the model.

In this way it can be concluded how through this type of approach to wind farms the behavior of the wind turbine can be manipulated through its active and reactive power control system.

B. HVDC Implementation

The use of HVDC lines provides multiple advantages when it comes to transmitting large amounts of energy over long distances with lower losses and better control of energy flow. When integrated into the grid, these lines make it possible to address situations associated with variable and distributed renewable energy sources. When applied in remote wind farms, this system allows to integrate this generated energy with the areas that require its supply. Another favorability of these systems is the voltage control, with which it is possible to guarantee stability in the network even if there is intermittency in the supply as it happens when transporting energy from the winds. Finally, this type of implementation also permits to meet the energy demand in near failure of an HVAC system in order to guarantee the reliability of the national interconnected system. The choice to implement this type of lines depends on the budget of each country and the amount of renewable energy supply it hosts at the moment.[1][5][17].

VI. PROJECTS IN LATIN AMERICA

Some of the projects in that part of the continent are described below.

A. Madeira Link

The HVDC link of Madeira is a VSC-HVDC system with a capacity of 2375 MW in charge of transmitting energy from new hydroelectric power plants located in northern Brazil to load stations in the southeast over an overhead power line distance of 1400 km [6][20]. There are some of the technical details:

- Terminals: Porto Velho and Araraquara
- Supplier: ABB
- Converter type: Voltage source converter (VSC)
- Voltage classification: ±600 kV CC

It uses overhead power lines as well as submarine and underground cables to pass through land [6][20].

B. Garabi Interconnection

The HVDC Garabi link is a VSC-HDVC consecutive interconnection of 2000 MW between Brazil and Uruguay, implemented since 2015. It connects the Garabi station in Brazil and the Melo station in Uruguay via submarine cables through the Uruguay River (140 km). It supports wind power transmission between the networks of the two countries with a back-to-back configuration and a voltage level of ±600 kV CC. [6][20].

C. Cobra Link

The HVDC Cobra link is a 2000 MW LCC-HVDC system in charge of transmitting hydroelectric energy since 1990. It travels from Comahue to Buenos Aires (Argentina) using overhead power lines over a distance of 1000 km. It connects the converter stations of Comahue and Ezeiza, using a CC nominal voltage of ±450 kV [26][27][28]. Some of its technical features are:

- Configuration: Point-to-point
- Year of initial operation: 1990
- Terminals: Comahue and Ezeiza
- Converter type: Line commuted converter (LCC)
- Voltage classification: ±450 kV CC
- Cables: Overhead line
- Supplier: ABB

D. SIEPAC Interconnection

The SIEPAC HVDC interconnection is a multiterminal VSC-HVDC link of 300 MW operating since 2014 that connects the networks of six countries in Central America throughout 1800 km. Some technical details include the following:

- Location: Connecting six countries of Central America

(Guatemala, El Salvador, Honduras, Nicaragua, Costa Rica, Panama)
- Capacity: 300 MW
- Technology: HVDC
- Configuration: multiterminal
- Converter stations: 5 stations in six countries.
- Converter type: Voltage source converter (VSC)
- Cables: 1590 km of high voltage cables (CC)
- Supplier: Siemens

It uses a CC nominal voltage of ±200 kV and high-voltage cables to improve the exchange of renewable energy in the region.

E. Guri Line

The Guri HVDC line is a 700 MW LCC-HVDC system built in the 1980s to transmit hydroelectric power through overhead lines from the Guri barrage in southern Venezuela to the San Cristobal converter station in the northern region. It covers a distance of 815 km, uses a CC voltage level of ±400 kV, and was supplied by ASEA (currently known as ABB) [6][20].

F. Charrúa-Ancoa Link in Chile

The Charrúa-Ancoa link is a 500 MW MMC-HVDC system set up in 2017 to transmit hydroelectricity over 753 km from the south to the north of Chile through overhead lines. It connects the converter stations of Charrúa and Ancoa and operates at a CC of ±400 kV. [27][28].

It is necessary that the implementation of transmission power lines spread throughout the continent in order to guarantee north-to-south connectivity without land-related limitations. Countries such as Colombia and Panama are currently working on a HVDC system between them to ensure complete interconnection for Latin America [6][20][28][29].

VII. CHALLENGES AND TECHNOLOGICAL INNOVATION

The implementation of HVDC lines with renewable energies has generated a series of challenges on which the scenarios in case the installation of these distribution networks would be massive worldwide. For this reason, the technological innovations that are currently being investigated are described.

A. Control of Multi-Terminal HVDC Networks Towards Wind Integration

Some projections of implementation of renewable energies that are estimated for the European continent towards the year 2050 generate the need to install MV-HVDC networks. These networks will allow the interconnection of wind farms, especially offshore ones, with continental electricity grids.

Based on this premise and according to studies [3], the hierarchical control structure that is usually used for MT-HVDC systems can be explained. It consists of current control levels, primary control, secondary control and tertiary control. Moreover, the authors review several primary control schemes for individual voltage source converter (VSC) terminals, including constant power, constant voltage, drop control, etc. These are crucial for sharing power properly between terminals. Following this approach, control strategies for sharing energy across the MT-HVDC network are analyzed, such as master-slave, margin voltage control, drop control, relationship control, priority control. Comparisons are provided based on reliability, power flow controllability, complexity, etc. Another analysis carried out is the use of MT- HVDC systems to provide frequency support, inertia emulation and oscillation damping toAC networks. This can improve the stability of the AC system. [10][30][31].

It is then concluded that it is necessary to adapt the control schemes for wind power terminals due to their energy-only capacity and their high variability. Moreover, in addition to steady-state power sharing, MT-HVDC systems can also provide dynamic grid services such as frequency regulation, synthetic inertia and damping. The aforementioned situation further increases the value of the implementation. [10].

B. Drop Control for Loss Minimization in HVDC Multiterminal Transmission Systems for Large Offshore Wind Farms.

A control scheme is proposed to minimize losses in multi-terminal HVDC transmission systems connecting large offshore wind farms to onshore AC grids. Based on the above, as indicated by the studies of [4], the proposed scheme consists of an optimal power flow (OPF) algorithm combined with a drop control of the grid-side converters. The OPF periodically calculates the optimal DC voltage benchmarks for grid-side converters to minimize total losses. Losses include both HVDC transmission losses and converter station losses. [7][32].

What’s more, the drop control scheme then regulates DC voltages based on these optimal references. This ensures stable operation even when OPF communications are lost. Steady state analysis in a 6-terminal test system is used to minimize different target functions: HVDC losses, converter losses, total losses. The compensations of the system are also analyzed. Dynamic simulations in a 4-terminal system demonstrate performance during wind variations and communication failures. It is shown that the control scheme works stably and optimally during transients. This scheme exploits the control capability of voltage source converters while retaining the robustness of drop control and does not need continuous communications. [7][33][34].

It can be claimed that minimizing losses is an important goal for the efficient operation of MT-HVDC systems connecting remote offshore wind farms. Another factor to consider is that an optimal power flow algorithm can be used to periodically calculate the optimal voltage references for grid-side converters that minimize HVDC transmission and converter losses. Finally, the OPF drop scheme is shown to be effective through steady-state analysis and dynamic simulations in the paper. Take advantage of optimal and robust decentralized control. [7][33][34].

C. DC Transmission Line Fault Location

This research focuses on demonstrating a new fault location method for HVDC transmission lines. The procedure combines the traveling wave method and the failure analysis method. The fault analysis method is used to obtain the current distributed along the line. The stationary wavelet transform (SWT) is applied to detect abrupt changes in the distributed current caused by the arrival of the fault wave. This process gives the propagation curve of the fault wave. Fault wave propagation curves from both ends of the line are combined to locate the position and timing of the fault. [35].

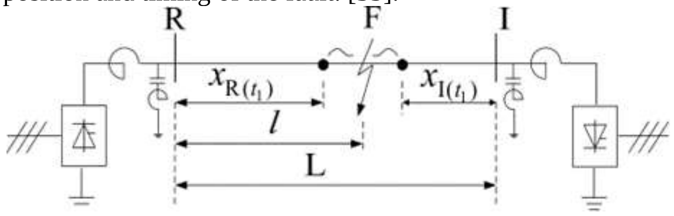


Fig. 12. Online fault traveling wave propagation. [35]

The method is fault-resistant of high transition resistance compared to simple traveling wave methods. The accuracy of the location is around 0.3% of the length of the line. The simulation results in PSCAD verify the effectiveness for different locations of faults and transition resistors. The advantages of the method include: high reliability, good accuracy and noise immunity. On the contrary, the drawback is increased computational complexity. [36].

It is deduced that the results of the simulation in PSCAD verify the effectiveness for different locations of faults and transition resistances. Supporting the above said, it could be argued that the advantages of the method are high reliability, good accuracy and noise immunity, the drawback is greater computational complexity. Finally, a new fault location strategy is proposed for HVDC transmission lines by synergistic combination of fault analysis and traveling wave approaches, the simulation results demonstrate its effectiveness. [37].

VIII. CONCLUSIONS

For wind energy integration, lines in HVDC help connect remote wind farms to load centers by enabling asynchronous connections. It provides better controllability for voltage and power flow.

The control of multi-terminal HVDC networks is crucial for the optimal operation and integration of wind farms. Hierarchical and decentralized primary control schemes have been proposed. Advanced control techniques can help optimize the operation of MV-HVDC, for example, to minimize losses or provide network support, such as frequency regulation. This improves the integration of wind energy.

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