Overview of the Configuration and Power Converters in High Voltage Direct Current Transmission Systems

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***Abstract*—In this work are described in detail High Voltage Direct Current systems motifs for their application, the basic structure and types of HVDC systems, as well as the advantages and disadvantages of the High Voltage Direct Current systems in comparison with the traditional High Voltage Alternating Current systems. In the context of operation are detailed described components of the HVDC system, with a particular focus on the thyristor valves, electrically-triggered thyristors, light-triggered thyristors, thyristor inverters, the principle of operation of the 6-pulse and 12-pulse thyristor converter, comparison of their characteristics, and the effects of their use.**

***Index Terms*—High Voltage Direct Current, High Voltage Alternating Current, thyristor, 6-pulse, 12 pulse, converter.**

I. INTRODUCTION

In recent decades and years, the dynamic development of power electronics, as well as the fact that the possibilities of High Voltage Alternating system (HVAC system) has almost reached its peak, has led to increased investment in research, development and promotion of the usagage of High Voltage Direct Current system (HVDC system).

HVDC systems are systems for the transmission of electrical energy, which are based on the useage of the various components of power supply systems with significantly improved characteristics (e.g., maximum allowable withstand voltage stress, the maximum allowable time withstand current stress, etc.), i.e. the systems that provide greater efficiency of high power delivery over long distances and better power control. In particular, the working principle of HVDC transmission system is based on the conversion of alternating current (produced by generators of electricity) to DC power using the AC/DC converter (inverter), the transmission of direct current over long distances, and finally conversion (converting) DC in AC power using the DC/AC converter (inverter) to voltage levels that require electricity consumers. Example basics and general principle of work and construction of the HVDC transmission system is shown in Fig. 1.

The main reasons for the introduction of HVDC systems, ie. the main results arising from the usage of HVDC systems are the increased capacity as the transmission power, reduced transmission losses (due to inevitable transmission of reactive power) reduces heat losses due to the skin-effect, the possibility of connecting three-phase systems of different nominal frequencies or systems with the same nominal frequencies, the ability to control the direction of power transmission, the ability to connect to an extremely large distances by means of the submarine cable for electric power transmission, the limitation (limiting) the short circuit current in the event of a malfunction, reduced negative impact on the environment, as well as lower capital costs [1] .

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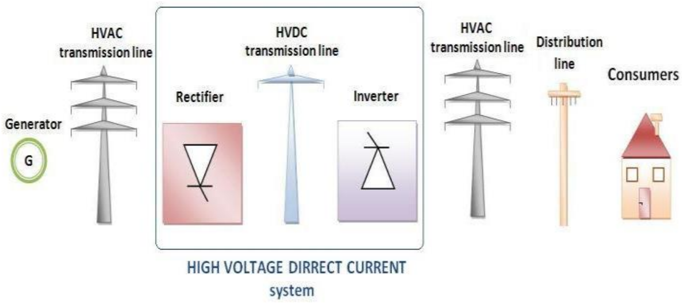

Fig. 1. General principle of work and construction of the High Voltage Dirrect Current.

In terms of construction, the main parts of HVDC system for the transmission of electricity are the two converter stations (one at the beginning and the other at the end of the transmission line) transmission line (overhead line or underground/underwater cable) and grounding system.

The Key element for efficient operation of the HVDC transmission system are the converter stations. Within the transducer cells different types of transducers are used, all of which are. A significant contribution to the dynamic development, usage and efficient operation HVDC electricity transmission system was the appearance and introduction of thyristor valves. The most commonly used transmitters in the converter stations are 6-pulse and 12-pulse thyristor converter, which will below be described in more detail.

Given the large investments in the field of HVDC systems for electricity transmission, in recent years there has been a dynamic development and widespread usage of new HVDC technology HVDC Light and HVDC Plus. HVDC Light HVDC represents a new solution, which increases the

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reliability and economy of the HVDC transmission system and which are used for connection of renewable energy sources to the AC system (especially wind farms), ground connection, connection of the asynchronous network, as well as in public applications [2]. HVDC Plus technology transfer is one of the newest techno-economic solutions based on the use of the latest technologies MMC (Modular Multilevel Converter) converters. This HVDC transmission technology used for connecting renewable energy sources to the system (especially wind power plants at sea – offshore wind plants), the power of large consumer areas (megacities), and is suitable in cases where the required control voltage AC system, black start, as well as places where the space for the converter station is very small [3].

II. TYPES OF HVDS SYSTEM

In terms of connectivity HVDC transmission system, depending on the location, type and purpose of use, as well as the choice of cable, there are several configurations and types of HVDC transmission system. The main types of connections HVDC electricity transmission system are:

- Monopolar,
- Bipolar,
- Back-to-Back,
- Multiterminal, and
- Tripolar HVDC configuration.

Monopolar configuration HVDC transmission system consists of two converter stations and the DC transmission line that connects them. In this HVDC configuration the return line must be earthed, and can be connected to the return line of another converter station. Lately, monopolar HVDC transmission system configuration is rarely used in practice. Configuration monopolar HVDC transmission system is shown in Fig. 2.

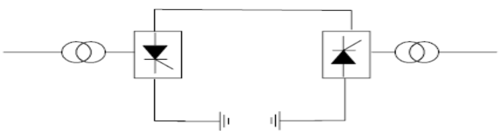

Fig. 2. Monopolar HVDC configuration [1].

Bipolar HVDC transmission system configuration represents a parallel connection of two monopolar HVDC system for the transmission of electricity. The main advantages of bipolar HVDC transmission system configurations are continued operation in the event of failure, and the ability to change the flow of energy. In case of failure (failure - outage) one of the two power transmission lines, the second transmission line continues to work in monopolar principle of operation (configuration), using the country as a return line. Changing the current power realized (realized) in the case when one passes from the converter rectifier in inverter mode, a second converter station yarn from inverter to rectifier mode (regime of work). Due to the possibility of changing the direction of power, bipolar HVDC transmission system presents a configuration that is commonly used in practical applications in the high-voltage DC transmission. Configuration bipolar HVDC system for the transmission of electricity is shown in Fig. 3.

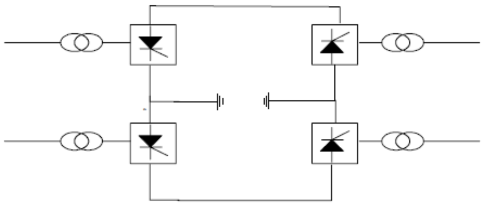

Fig. 3. Bipolar HVDC configuration [1].

Back-to-Back HVDC transmission system configuration consists of two converter stations located in the same location. The main characteristics (specificity) of this configuration is the fact that it does not use the DC transmission line of electricity. More specifically, within a configuration Back-to-Back HVDC transmission system, the rectifier and the inverter are in the same transferring cell [1]. Back-to-back configuration of the HVDC transmission system is used and ensures the connection of two systems with different AC frequencies (asynchronous interconnections) and/or a second AC system and the same frequency [1]. Configuration of Back-to-Back HVDC transmission system is shown in Fig. 4.

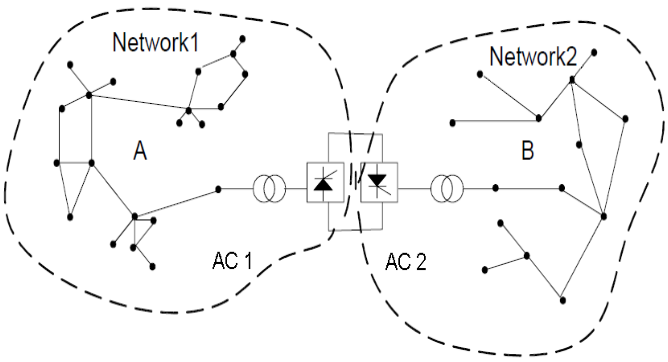

Fig. 4. Back-to-Back HVDC configuration [1].

Multiterminal formula HVDC transmission system consists of a transmission line/cable, and more than two of the converter which can be connected sequentially or in parallel. In addition, the converter in most cases covers large geographical distances. The main advantage of the configuration multiterminalnog HVDC transmission system is to link different AC transmission systems. Configuration Multiterminal HVDC transmission system is shown in Fig. 5.

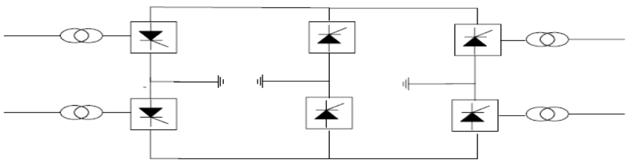

Fig. 5. Multiterminal HVDC configuration [1].

Tripolar configuration HVDC transmission system is the latest configuration of the HVDC system for the transmission of electricity, which is based on the use of the latest technologies MMC (Modular Multilevel Converter) converters. Specifically, within the structure of this configuration, the rectifier and inverter consist of a three-phase six-bridge arms modular multilevel converter (MMC), and two converter valves are arranged on the DC side of the rectifier and inverter respectively. The midpoint of upper and lower converter valves of the rectifier and inverter are connected with a pole 3 DC line by a smoothing reactor. Triggering of the upper and lower converter valves is controlled to change the DC voltage polarity of the pole 3 periodically, and tripolar DC transmission is realized by modulating the current orders of the three poles [4]. The main advantages of the configuration tripolarnog HVDC transmission system are the maximum usage of the three conductor cables for power transmission, high reliability, very suitable dimensions that take up little space in the converter stations, as well as low total cost of conversion. Also, the configuration of the HVDC transmission system is particularly effective for usage in crowded urban areas, where it is necessary to increase the capacity of transmission lines of electricity. Configuration of a three polar HVDC system for the transmission of electricity is shown in Fig. 6.

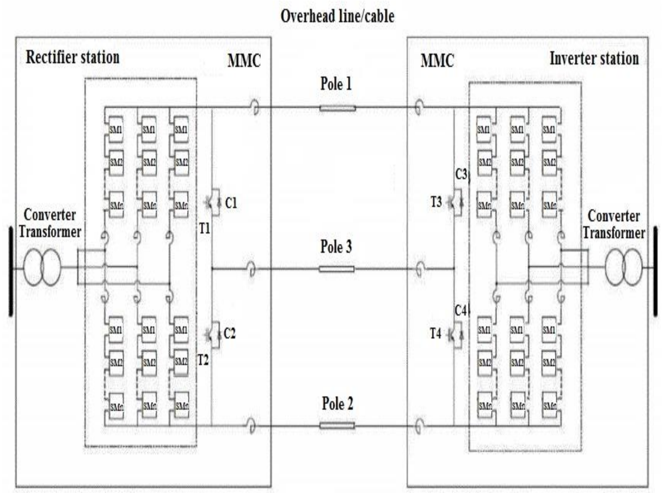

Fig. 6. Tripolar HVDC configuration [4].

III. THYRISTOR CONVERTERS

The main parts of HVDC system for the transmission of electricity are:

- converter station (rectifier),
- overhead line or underground/underwater cable for transmission of the electricity,
- converter station (inverter), and
- ground electrode (earth or metal return).

As for the technology of the HVDC transmission system, two main types of converters are:

1. line-commutated HVDC (LCC-HVDC), and
2. voltage-source HVDC (VSC-HVDC).

Line-commutated HVDC (LCC-HVDC), also known as Current Source Converter HVDC (CSC-HVDC), represents the type of the HVDC converter which is based on thyristor-based technology for its converters. Voltage-source HVDC (VSC-HVDC) is a type of HVDC inverter which is based on Insulated Gate Bipolar Transistor (IGBT) and/or Gate Turn-Off Thyristor (GTO) based technology. Schemes of the basic configuration and structure of converter CSC and VSC in the HVDC transmission systems are shown in Fig. 7.

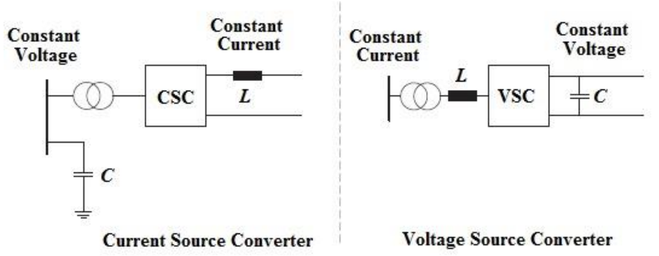

Fig. 7. Schematics of the configuration of the converter structure of the CSC-HVDC and VSC-HVDC types [5].

The basic scheme LCC-HVDC with VSC-HVDC transmission systems are illustrated in Fig. 8.

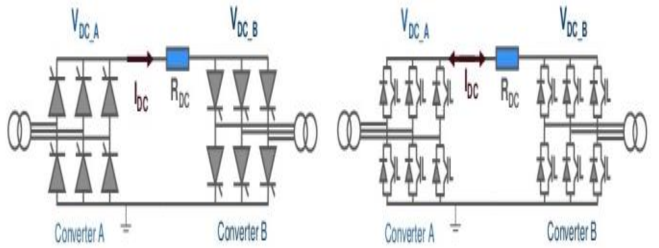

Fig. 8. Basic scheme of the LCC-HVDC and VSC-HVDC transmission system [6].

Comparison of the CSC-HVDC and VSC-HVDC is shown in Table I.

Comparison of traditional HVAC systems and the HVDC systems, or their combinations VSC solutions and/or LCC technology in terms of power range (power capacity) versus distance are shown in Fig. 9.

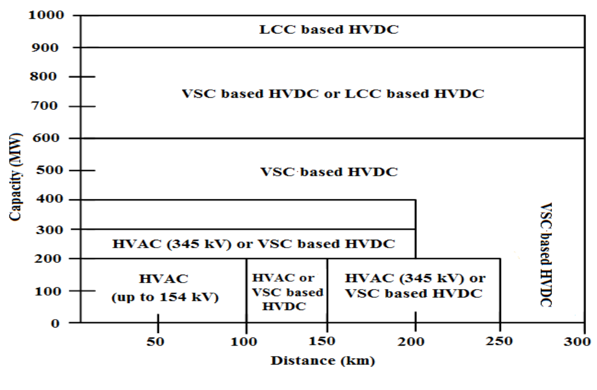

Fig. 9. Capacity/distance comparison between HVAC and HVDC transmission systems [8].

TABLE I
COMPARISON OF THE CSC-HVDC AND VSC [7]

Attributes	CSC-HVDC	VSC-HVDC
Converter technology	thyristor valve, grid commutation	transistor valve (IGBT), self commutation
Maximum converter rating at present	6400 MW, ± 800 kV (OH line)	1200 MW, ± 320 kV (cable) 2400 MW, ± 320 kV (overhead)
Relative size	4	1
Typical delivery time	36 months	24 months
Active power flow control	continuous ± 0.1 Pr to ± Pr (due to the change of polarity)	continuous 0 to ± Pr
Reactive power demand	reactive power demand = 50%	no reactive power demand
Reactive power compensation and control	discontinuous control (switched shunt banks)	continuous control (PWM built-in in converter control)
Independent control of active and reactive power	no	yes
Scheduled maintenance	typically < 1%	typically < 0.5%
Typical system losses	2.5 – 4.5 %	4 – 6 %
Multiterminal configuration	complex, limited to 3 terminals	simple, no limitation

One of the most important components of power electronics, which ensures safe and reliable operation of transducer cells HVDC transmission system are thyristor converters or thyristor valves. In order to obtain a high threshold voltage (for blocking), thyristors are connected in series. This way to connect a large number of thyristors is called a thyristor valve. Data related to the historical development of the thyristor in a high voltage system are shown in Fig. 10. At the present time, in the Ultra High Voltage Direct Current transmission systems are used thyristors (Controlled Thyristor Phase - PCT) with improved characteristics, diameter 150 mm, the value of the voltage to 8.5 kV and the current maximum value of 5 kA, respectively for blocking the voltage 6.7 kV and 7.2 kV and the current maximum value of 6 kA [9]. Predictions of the thyristors development predictions in high voltage systems are shown in Fig. 11.

The main two types of thyristors that are commonly used in HVDC transmission systems are:

- light–triggered thyristors (ETT), and
- electrically–triggered thyristors (LTT).

ETT represents a type thyristor which includes injection (excitation, bringing) electrons on the gate. The main role for the safe and reliable operation of the ETT thyristor has a thyristor control unit (Thyristor Control Unit - TCU) that is energized by the mains circuits (triggering is initiated by means of a direct optical pulse) and which serves to monitor labor protection thyristor ETT [11].

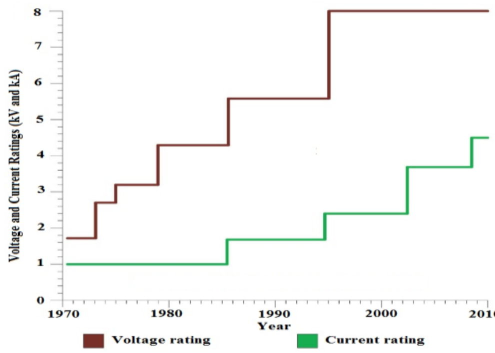

Fig. 10. Chronological development of the thyristors in the high voltage systems [10] .

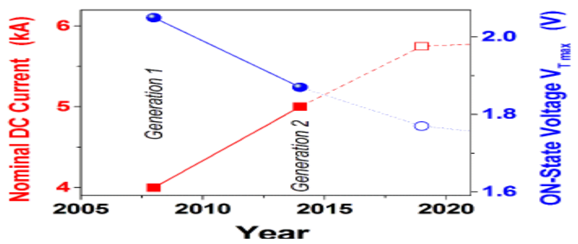

Fig. 11. Predictions of the thyristor development in high voltage systems [9].

LTT represents a new technology in which thyristors are engaging in the direct injection of photons at the gate via an optical fiber. The main role for the safe and reliable operation of the thyristor LTT has a thyristor monitor units (Thyristor Monitor Unit - TMU), which oversees the work of the thyristor LTT. Compared with a standard ETT thyristor technology, using thyristor LTT new technology significantly reduces the number of electronic components (up to 80%) are necessary in a thyristor valve triggering (trigger) and protection. In this way, significantly increases the reliability and availability of HVDC transmission system. Scheme of the basic circuits of the ETT and thyristor LTT are shown in Fig. 12. A comparison of their characteristics is given in Table II.

Detailed schemes of the Electrically-Triggered Thyristor and Light-Triggered Thyristor-are shown in Fig. 13.

Fig. 14. shows the main method (gating circuits) the trigger (firing) of the thyristor LTT [8]:

- electromagnetic coupling,
- indirect light triggering, and
- direct light triggering.

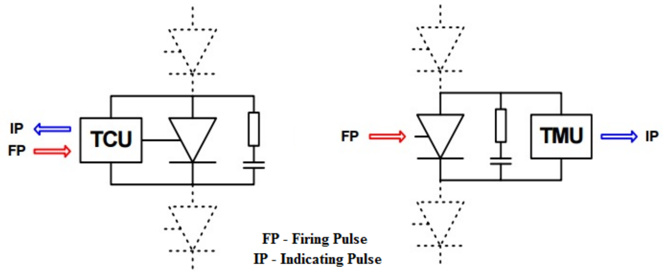

Fig. 12. Electrically-Triggered Thyristor and Light-Triggered Thyristor – basic circuit [11].

TABLE II [11,12]
COMPARISON BETWEEN ETT AND LTT

ETT	LTT
simple gate design because of powerful gate signal	complicated gate design due to low optical power
10 major wafer processing steps. Standard encapsulation and testing. High production yield	16 major wafer processing steps. More complex encapsulation. Reduced production yield
Precise external overvoltage protection in TCU	Temperature dependent internal overvoltage protection with large production spread
Highest voltage rating 8.8 kV	Highest voltage rating 8kV
electronics for firing pulse generation on High Voltage	no electronics on High Voltage → less components
energy for firing taken out of snubber circuit at High Voltage potential → after network blackout firing of thyristor is only possible for approx. 5 cycles	energy for light pulse supplied on Low Voltage level → firing of thyristor is possible in any case, even after a long network blackout

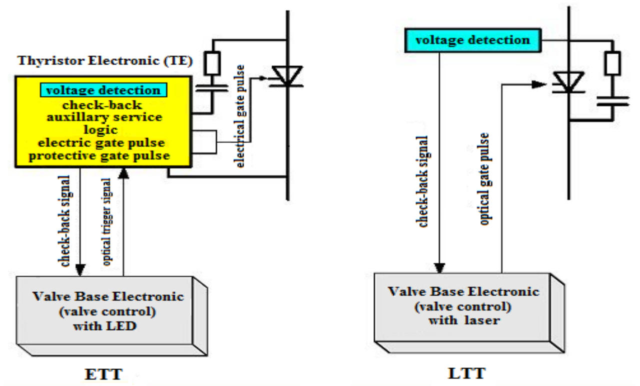

Fig. 13. Detailed schemes of the Electrically-Triggered Thyristor and Light-Triggered Thyristor [12].

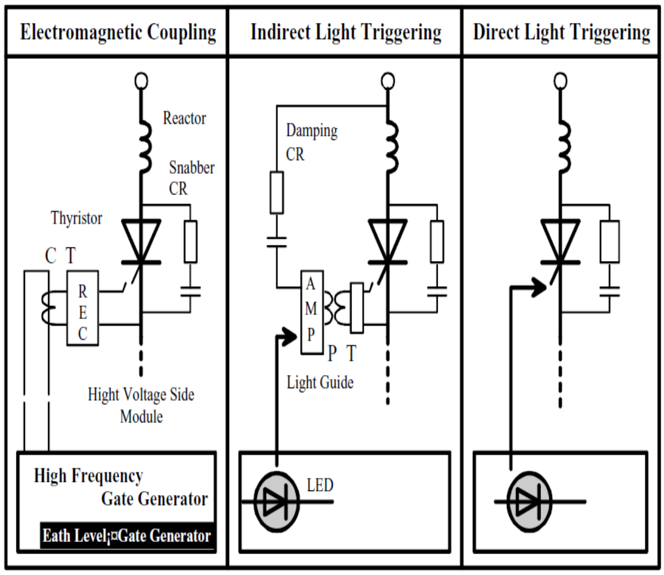

Fig. 14. Gating circuits light-triggering thyristors [8].

In HVDC transmission systems, two following types of converters are commonly used:

- 6–pulse thyristor converter, and
- 12–pulse thyristor converter.

6-pulse thyristor converter consists of six thyristor valves (three branches, in each of two thyristor) and the corresponding cooling systems. At the same time, for effective connection of the thyristor 6-pulse inverter to the AC system, the corresponding transformer. And topology diagram for a 6-pulse thyristor converters are illustrated in Fig. 15.

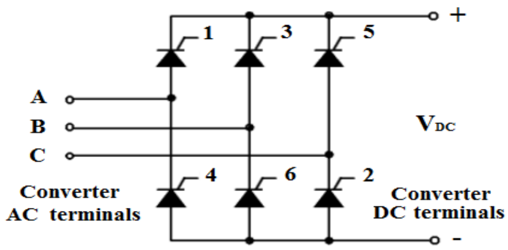

Fig. 15. Topology and schematic of the 6-pulse thyristor converter [13] .

Voltage waveforms of the 6-pulse thyristor converters are shown in Fig. 16.

When the thyristor is managed (operated) with the angle of delay (firing angle), average DC voltage is calculated according to the following mathematical formula (1):

$$V_{DC} = \frac{3\sqrt{3}\sqrt{2}V_{rms}}{\pi}\cos\alpha \qquad (1)$$

A 12-pulse thyristor converter is composed of the regular connection of two 6-pulse thyristor inverter. And topology diagram for a 6-pulse thyristor converters are shown in Fig. 17. In HVDC transmission systems, a 12-pulse converter requires the application of the two-phase system. In addition, these three-phase systems are mutually shifted by 30 or 150 electrical degrees, which is realized by means of the installation of the transformer on each side network, and the vector and Yd5 Yy0 groups [14]. Such a construction of the thyristor converter with a phase difference between the three-phase systems eliminate the 5^{th} and 7^{th} harmonic current at the AC side and 6th harmonic voltage on the DC side. More details in [14].

Wave forms of a 12-voltage pulse thyristor converter are shown in Fig. 18.

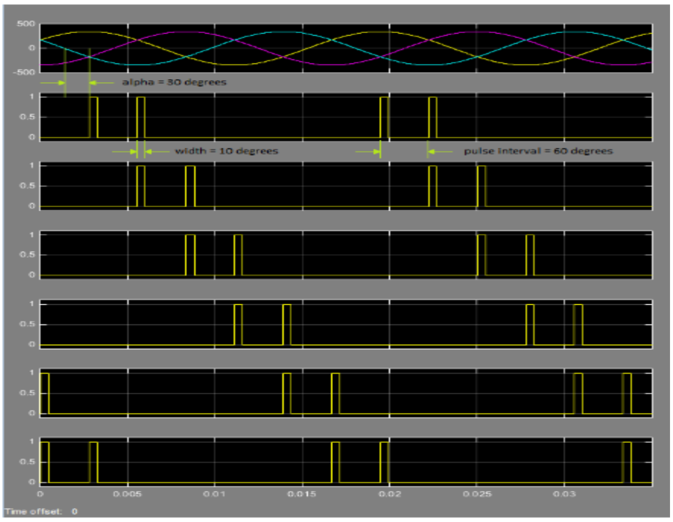

Fig. 16. Voltage waveforms of the 6-pulse thyristor converter [13] .

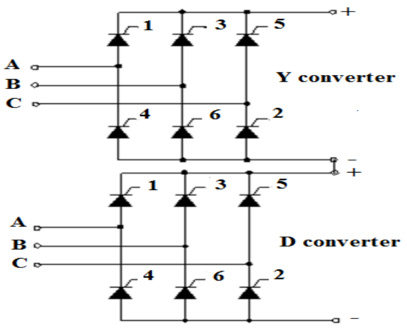

Fig. 17. Topology and schematic of the 12-pulse thyristor converter [15] .

IV. Conclusion

High Voltage Direct Current systems are a relatively new mode of electricity transmission, which, due to their structure and characteristics provide a number of advantages. In comparison with the HVAC transmission systems, HVDC transmission systems provide transmission of large power to the extremely large distances, greater control power, connection of the system with a different frequency (asynchronous connection) and/or a system with the same frequency, as well as the connection of submarine power cables.

High efficiency of electricity transmission, better control of voltage and power is provided by using different types of technology and thyristors and thyristor valves - ETT and LTT. The converter stations are the most commonly used power converters in HVDC transmission systems of the 6-pulse and 12-pulse thyristor converter. Finally, the construction of HVDC transmission system provides greater efficiency and lower environmental impact (lower construction costs - thin wires, the construction of low and/or avoiding the construction of new poles for the transmission of electricity). Economic price/distance comparison HVDC and HVAC transmission systems and their transmission lines are shown in Fig. 19.

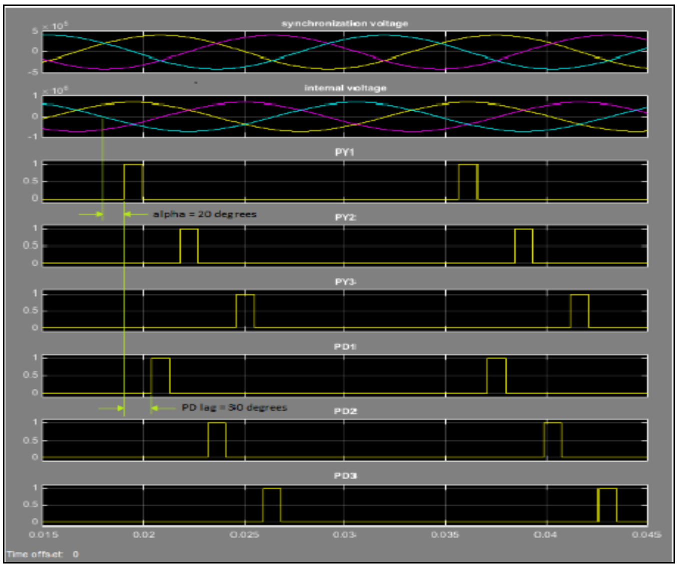

Fig. 18. Voltage waveforms of the 12-pulse thyristor [15] .

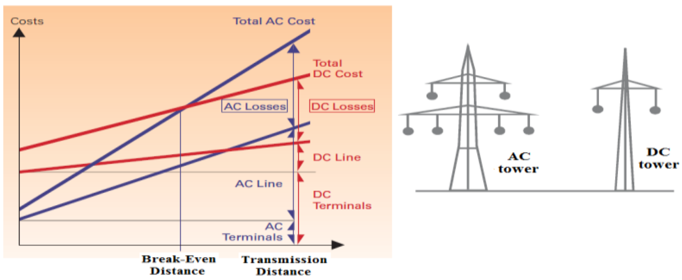

Fig. 19. Economic comparion of the HVDC and HVAC and their transmission lines [16] .

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