DC Vs AC - War Of Currents For Future Power Systems: A HVDC Technology Overview

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Abstract: DC vs AC discussion began in 1880s with development of first commercial power transmission in Wall Street, New York. Later, when AC technology came into notice by efforts of inventor and researcher Sir Nicola Tesla, soon the advantages of AC transmission and AC devices overtook the DC technology. It was hoped that DC technology had lost battle of currents. Today, with researches going on FACTS devices and bulk power transmission, HVDC has again gained a reputation in power sector. Solution of this centuries old debate is to develop HVDC systems that assists HVAC systems for better performance, stability and control

Index Terms: DC, AC, HVAC, HVDC, VSC-HVDC, CSC-HVDC, LCC-HVDC, war of currents, bulk power

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1 Introduction

Historical background of DC vs AC power transmission goes way back to 1880s, at that time power transmission was only possible using Direct Current (DC) technology. First commercial power transmission was in Wall Street, New York. It was Sir Thomas Alva Edison, who pioneered DC technology, and up until then availability of DC generators and incandescent bulbs working on DC, made DC technology the only available power transmission option. The added advantage was DC could eventually even be stored using battery/batteries. Later around in that era, Sir Nicola Tesla and the American entrepreneur, Sir George Westinghouse, became the opponents of DC technology.

2 HISTORICAL OVERVIEW

History of AC vs DC is centuries old. This is one of the most discussed topic amongst power system professionals. The invention of the very first poly-phase AC induction machine by Nikola Tesla made his argument to support AC power transmission. The arguments and discussions, were named as war of currents [1]. DC technology enthusiast were inclined to support their views on DC power transmission only, the most famous negative demonstration of AC technology was, use of AC to electrocute people in an electric chair, as a capital punishment. Which was later briefly known as “westinghousing” [2]. Although, poly-phase AC induction machines were the supporting asset of AC power transmission technology, but the invention of the Power transformer by the French inventor Lucien Gaulard and John Dixon Gibbs, made a significant contribution in development of AC technology further. Now AC technology had the significant advantage over counterpart technology, as AC voltages were proved easier to be transformed, allowing a number of different voltage levels for generation, transmission and distribution. In addition to this, as need for long-distance power transmission came into the picture, need of high efficiency became prominent. Power transmission at high voltage with lower power losses became feasible with HVAC. Soon, as the technology got matured, the invention of poly-phase circuits and affordable induction motor, and other machinery, gave rise to AC Power Systems overhauling the DC Power Systems, which in fact had an early invention advantage. Most of the remaining DC systems and Networks were of low power ratings. They were also localized to large cities and had limited use in electric traction (trolley buses, elevators, railways and trains). Around 1970s, Stockholm deprecated its existing DC distribution system. In 1981, The Central Electricity Generating Board (CEGB) in the London, United Kingdom, had an exclusive 200 V DC generating station located at Bankside Power Station on the River Thames to power DC printing machinery in Fleet Street, back then it was known as heart of the UK's newspaper industry. This building was later on converted to an art gallery when it was decommissioned later in 1981. All DC systems were eventually replaced by AC systems, around November 2007, the last DC distribution owned by the known company Consolidated Edison was shut down in New York permanently [3]. AC was eventually replacing DC technology, and it did too. But engineers always had advantages of DC over AC power transmission in their mind. They chose not to support one system over the other. The workaround proposed by the engineers was to operate DC with AC systems, in order to have added advantages in mixed system. Current day technology which is named as FACTS, is used to overcome the disadvantages of AC systems by use of DC systems [4]. HVDC and HVAC can be compared briefly on various aspects [5] [6] [7].

- Economy of Transmission: After break even distance HVDC is more economical than HVAC.
- HVDC has always been preferred over HVAC for bulk power transmission.
- Connection to asynchronous grids [8].
- HVDC has better controllability because of advancements in controlling algorithms.

3 EARLY HVDC SYSTEMS

Although the war of the currents was won by AC, mainly because different voltage levels now can be obtained in power transmission by using transformers. It was Sir Marcel Deprez who analysed early power transmission system using DC, instead of using transformers for different voltage levels; generators and loads were connected in series [9] as it was done in the famous arc light systems of Charles F. Brush. In configuration of Brush's dynamos [10], current is kept constant, and when the increasing load demands more

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pressure, voltage is increased accordingly. French engineer René Thury developed this idea into the world's first commercial system for HVDC transmission (Fig. 1), system consisted of a number of prime mover driving coupled DC generators which were connected in series to attain high voltage for transmission [9] [11]. At the receiving end of transmission line, a similar number of DC motors which were connected in series also, used to drive low voltage AC generators.

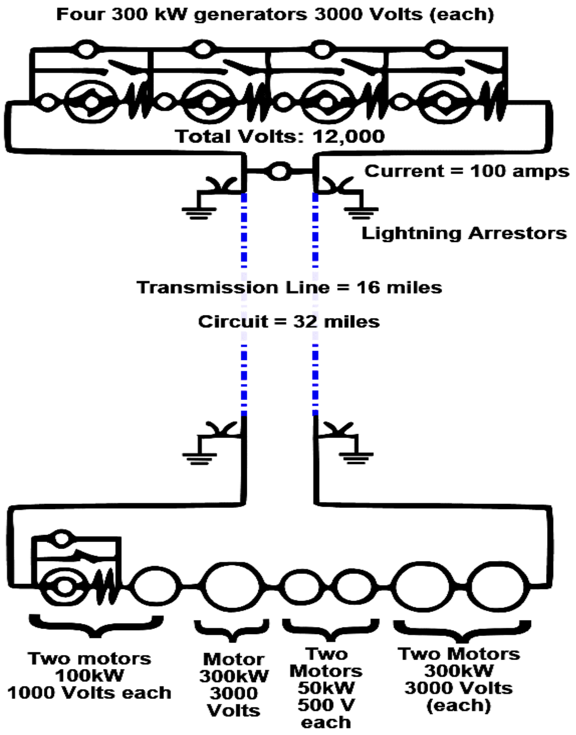


Fig. 1 *Representation of Thury System balancing voltage of supply with voltage of load*

In 1889, the first system was brought into operation in Italy by the Acquedotto de Ferrari-Galliera Company. During the early days company was focused on whether turbines can reduce excess pressure. At Galvani station, first turbine of 140 hp (100kW) was installed which operated the two Thury 6-pole dynamos that each have 1000-1100 V, 45A rating. In order to keep the current constant, turbine speed was varied from 20 to 475 rpm by changing the water flow rate through turbine. There were several limitations to Thury system, but the main limitation was the series distribution. Whenever number of devices are connected in series, current must flow through all the devices. That means the current rating of all devices has to be high. Also, if one of the devices gets damaged/open, current will stop flowing in circuit. This means all devices are subjected to opportunity for power failures. DC machines also had several limitations that made the Thury system unfavourable for higher order power ratings and need for further developments in DC technology would rather require static converters than operating motor-generator sets. In 1930s, new developments came in the field of mercury arc valves, it was then only when DC technology was taken back into consideration as a viable alternative for the transmission of energy.

4 DC Vs AC Transmission

The comparison between DC and AC transmission can be done on various aspects of power transmission.

4.1 Economy of Transmission

The cost of power transmission is dependent on two factors which are namely, investment cost and operational cost. Investment cost includes cost of conductors, insulators, towers, RoW, and terminal equipment. While on the other hand operating cost is mainly due to losses and maintenance cost. Considering the insulator cost, if it is assumed that insulator characteristics are same for AC and DC, then it could be said that insulation level depends upon the peak level of voltage applied with respect to the ground. If the power transmission grid is designed considering the above said assumption, then for the same power level DC transmission is capable of transmitting as much power with 2 conductors (2 in Bipolar configuration, 1 in monopolar with ground return) as compared to AC transmission with 3 conductors (in 3 wire single circuit line). This states that in DC transmission, cost of insulators is reduced, cost of conductors is reduced, so as the cost of towers and RoW. As far as losses are concerned, corona losses are less in DC as compared to AC. There is no presence of skin effect and proximity effect. Dielectric losses in case of DC cables is less. DC line don't require line compensation.

4.2 Bulk Power Transmission

For the objective of bulk power transfer, HVDC systems are preferred over the HVAC system. If the variations between costs and line length are drawn, then after a particular distance, cost of transmission reduces for DC as for AC increases. The distance after which DC transmission becomes more economical than AC is known as, break-even distance. Typical breakeven distance can vary from 500 to 800 km in overhead line. This variation can be seen in Fig. 2

4.3 Asynchronous Grids

AC systems that don't have same voltage and nominal frequency are referred to as asynchronous. When to connect two AC systems, these values are to be matched, which can be a tedious task in rather a big power system. So, HVDC system plays a significant role as they can be connected to any rated voltage and receiving frequency [8]. Hence back to back HVDC is mainly used to connect large AC systems in many parts of the world. For example, the NORDEL power system in Scandinavia and UCTE grid in western continental Europe; are not synchronous, although the nominal frequencies are the same [8]. Similarly, the power system of the eastern USA and western USA, Texas or Québec aren't synchronous. HVDC links between Japan and South America connects networks with different nominal frequencies (50 and 60 Hz).

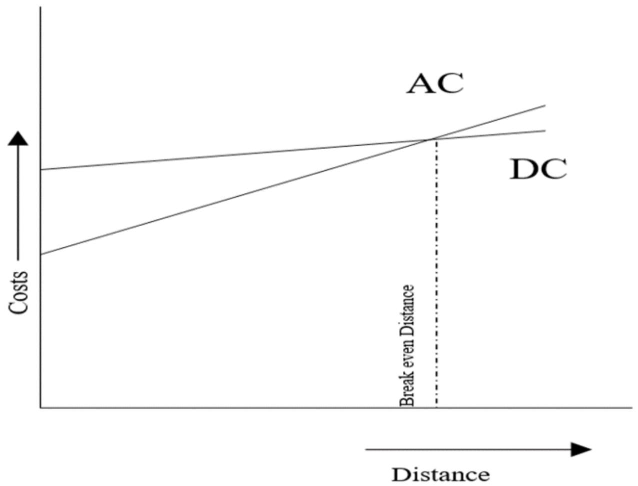


Fig. 2 *Variations of Costs with Distance*

4.4 Long Distance Transmission

In long distance AC transmission, the reactive power flow due to significantly large line capacitance limits the maximum possible power transmission distance. In HVDC there is no such limitation; this is why for a very large distance power transmission HVDC is chosen as viable option.

4.5 Controllability

Most important advantage of HVDC system technology is the ease of controlling active power in the DC link. The main control action is based upon constant power transfer. The control actions in HVDC technology are made to operate after fulfilment of certain criterions. HVDC links can also be used in improvement of AC power systems by additional control actions. These additional control functions can allow safe increase of power transmission capability in AC transmission lines where stability is a main concern. These control functions mainly include constant frequency control, redistribution of the power flow in the AC network, damping of power swings in the AC networks, etc.

4.6 Low Short Circuit Currents

For a high power HVAC transmission which connects a power plant to a large load center, the short circuit current level increases at the receiving end. If the short circuit current is extremely large, it could create a need to replace existing circuit breakers and other protective devices if their ratings is too low. But with the advantage of HVDC this problem can be resolved. HVDC links don't contribute in short circuit current of interconnected AC systems. So it is advised to connect the new power plants to load centers via DC links.

5 TYPES OF HVDC CONFIGURATIONS

DC links are broadly classified into following types, which are:

5.1 Monopolar Link

It has one conductor, which is usually of negative polarity and uses ground or sea return (Fig. 3(a)). Sometimes metallic return is also used because of its less insulation requirements at low voltages. Ground return when used has significant cost reduction in DC link, otherwise is not advised. Reason being its impact on other buried metallic structures near in the vicinity of electrodes causing the structures to corrode. [12]

5.2 Symmetric Monopole Link

As compared to monopolar link, symmetric monopole uses two conductors of different polarity and is only earthed using a high impedance, hence there is no earth current flow. (Fig. 3(b)) This scheme is used primarily in VSC-HVDC links [13] [14] [15]

5.3 Homopolar Link

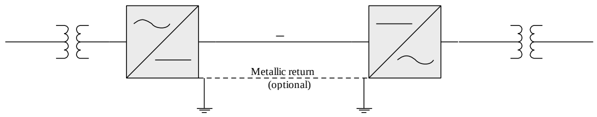
Has two or more number of conductors all having same polarity (most of the cases negative) and operated always with ground or metallic return. (Fig. 3(c))

5.4 Bipolar Link

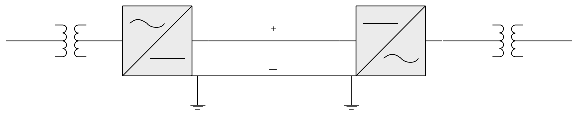
It has two conductors of different polarity i.e. one positive and other negative. (Fig. 3(d)) Each conductor could be a bundled conductor in EHV line. Rectifier and Inverter ends, both have two sets of converters which are connected in series on DC link side. Under normal conditions both conductors operate at same voltage magnitude, so technically there is no ground current. [12] [15]

5.5 Back to Back DC Link

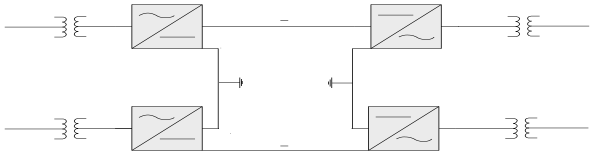
In back to back DC link, both the converters are kept in same area, usually under same building. The length of transmission line is kept as minimum as possible. (Fig. 3(e)) One of the examples is, coupling of electricity grids having different frequencies in Japan and South America; and the GCC interconnection between UAE and Saudi Arabia having grid frequency 50 Hz and 60 Hz respectively.



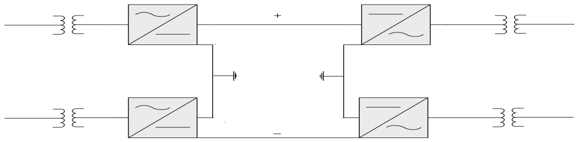
a) *Monopolar Link*



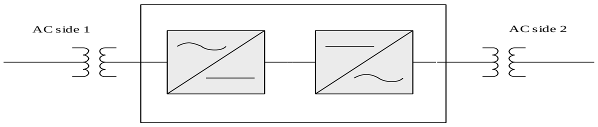
b) *Symmetrical monopolar Link*



c) *Homopolar Link*



d) *Bipolar Link*



e) *Back to Back HVDC*

Fig. 3 *HVDC link configurations*

6 LCC-HVDC

In current day power sector, most of the commercial HVDC systems are based on line commutated current source converters. In LCC technology thyristor valves are used. Thyristors have only one degree of freedom i.e. they can be brought to conduction region from forward blocking with the help of applied gate pulse. For turning off, the commutation is carried out by the ac system voltage only. When LCC is connected to a weak grid, there is no saying of reliable commutation to take place. A weak grid has a high line impedance. Also under fault conditions commutation is not reliable [16]. Even though these limitations exists, LCC HVDC is still a mature technology and will continue to be used in bulk power transfer up to several hundreds of MW. Because of the advancement in development of LCC HVDC, this technology is able to provide efficient, reliable and cost effective power transmission for many applications. In early phases, mercury arc valves were used. Major problem with mercury arc valve was arc-back faults, which is reverse conduction path in valve caused by high peak inverse voltage. Later solid state devices like thyristor replaced mercury arc valves, also there were no arc-back faults in thyristor valves. In 1972, first thyristor based back to back HVDC system was commissioned at the Eel River for 320 MW [17]. The basic module used for a CSC HVDC link is a three-phase full-wave 6-pulse converter, also known as the Graetz bridge (Fig. 4). The advantage of this scheme is that by changing firing angle range, it can be made to operate either as a rectifier or inverter, hence power flow in both direction is possible. Thyristor being a unidirectional device, the direction of current is not reversed in LCC-HVDC to achieve power reversal rather voltage polarity is changed of the link. To form a monopolar CSC HVDC transmission scheme (Fig. 3(a)), two Graetz bridges are interconnected at the DC side. Similarly, back-to-back HVDC link (Fig. 3(e)) can be formed using two interconnected Graetz bridges, only transmission line has to be kept minimum along with localized converter i.e. both converter at same area. In the same way bipolar link can be formed by connecting two Graetz bridges in series on DC side, on each station. Some of major LCC HVDC projects are shown in Table 1

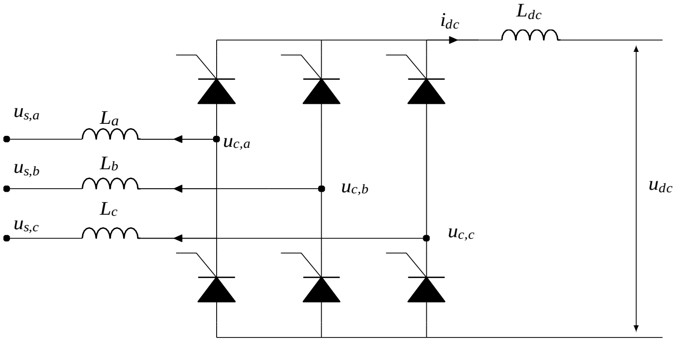


Fig. 4 *CSC HVDC 3-phase Graetz bridge*

Disadvantages of LCC-HVDC are as following:

6.1 High Reactive power requirement at converter station.

Least expansive way to obtain compensation is to provide switchable capacitor banks which are partly present in filter circuits.

6.2 Injection of harmonics in both AC and DC side.

These harmonics can cause distortion in voltage waveform, hence filtered out using tuned filters. The characteristic harmonics are dependent on pulse number, whereas non-characteristic harmonics are caused by AC unbalance. At DC side Ldc smoothing reactor is used to reduce harmonics. In 12 pulse converter, due to phase shift of 30◦ degree at secondary side of converter transformer (Y- Δ) the 5th and 7th harmonics are cancelled out. Although they don’t enter to grid, but the harmonic current still flows in transformer winding and hence transformer must be designed in such a way that it withstands to voltage stress and losses.

6.3 Problem of commutation failures.

Commutation failure refers to a condition in which extinction angle is not sufficient enough to allow thyristor to commutate when the reverse voltage appears across its terminals and as a result, thyristor starts to conduct again when forward voltage appears against its terminals, this happens even though gate pulse is not applied. As a result, a short circuit condition might appear at the DC link side.

6.4 Need of stiff AC system.

The SCR at PCC should be high. For low SCR systems, problems like dynamic voltage instability, harmonics resonance, voltage flicker, voltage spikes, and commutation failure might occur. To overcome this, CCC called as capacitor commutated converter, was developed. The scheme is to connect series capacitor between valve and the converter transformer [18]. Insulation cost is increased because of series capacitors. This scheme is however limited to back-to back HVDC configuration only where voltage ratings are low [19].

7 VSC-HVDC

Among other semiconductor devices, Insulated Gate Bipolar Transistor (IGBT) development opened up new possibilities for applications in HVDC. The Insulated Gate Bipolar Transistor characteristics are somewhat between a conventional Bipolar Junction Transistor, (BJT) and a Field Effect Transistor, (MOSFET) which makes it ideal as a semiconductor switching device. The IGBT takes the best parts of these two types of transistors, the high input impedance and high switching speeds of a MOSFET with having the low saturation voltage of a bipolar transistor, and combines them together to produce another type of transistor switching device that is capable of handling large collector-emitter currents with virtually zero gate current drive. The result of this hybrid combination is that the IGBT has the output switching and conduction characteristics of a bipolar transistor but is voltage-controlled like a MOSFET. The switching frequency of IGBT is up to 10 kHz. There are other switching devices with similar properties, but there has been little development by manufactures, reason being significant advantages of the IGBT. IGBTs with voltage rating up to 6.5 kV and current rating up to 3.6 kA are available. VSC HVDC links of rating 1200 MW and ±500 kV are in operation [20]. The ratings of VSC HVDC are still lower than that of CSC HVDC, mainly because LCC technology has been out there for a longer time and has been matured. However, it can be expected that ratings might increase as the VSC HVDC technology develops further. IGBTs in Voltage Source Convertor technology offers two degree of freedom i.e. turn on and turn off, both can be done. In 1990s VSCs were introduced to HVDC technology. A 3 MW, ±10 kV overhead line having two level VSC, was set up as an experimental line in Hellsjön – Grängesberg [21]. The first commercial project came into picture when it was commissioned in 1997. It was a connection on the island of Gotland in Sweden, with ratings of ±80 kV and 50 MW [22] [23]. Selected VSC-HVDC projects are shown in Table 2, and In Fig. 5, a typical 3 level VSC model has been shown.

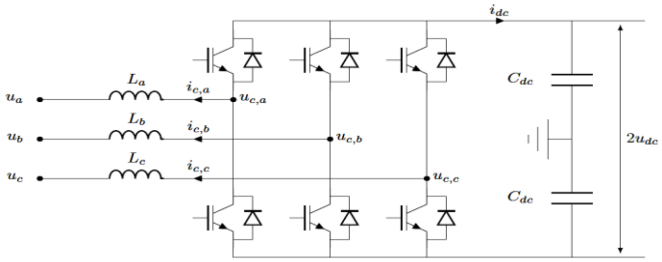


Fig. 5 *VSC HVDC 3-phase bridge*

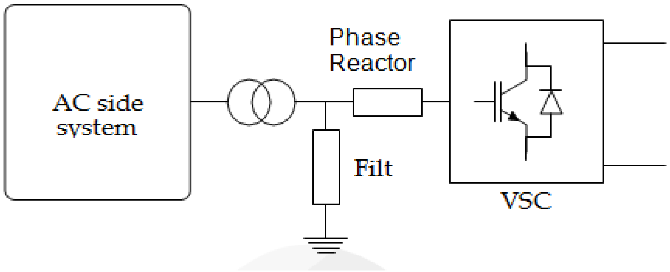


Fig. 6 *Typical VSC HVDC system*

Components of VSC HVDC systems as shown in Fig. 6, can be classified into following categories:

7.1 Converter

The basic configuration of VSC is 3 phase six pulse bridge. VSC is capable of operating as rectifier i.e. AC to DC conversion, or as an inverter working as DC to AC conversion.

7.2 DC capacitor

In VSC HVDC, the energy storing device is capacitor. The size of capacitor is dependent on the required DC link voltage.

7.3 Phase Reactor

It is one of the important part of VSC HVDC. It assists in control of both active and reactive power by simply controlling the amount of current flowing through it. Phase reactor also plays a significant role in suppressing higher order harmonics.

7.4 AC Filter

High frequency switching of the IGBTs in converter generates high-order harmonics in the AC voltage, to suppress these harmonics high pass filter can be used. One of the added advantage of filters is that they also act as a source of reactive power.

Table 1 *List of selected Major LCC HVDC Projects*

Project Name	**Converter station 1**	**Converter station 2**	**Total Length (km)**	**Volt (kV)**	**Power (MW)**	**Year**	**Remarks**
Xiangjiaba-Shanghai	China - Fulong	China - Fengxia	1980	±800	6400	2010	Supplier: ABB
Yunnan - Guangdong	China - Yunnan province	China - Zengcheng	1418	±800	5000	2010	Supplier: Siemens
Jinping - Sunan	China-Jinping	China-Suzhou	2090	±800	7200	2013	Supplier: ABB
Xiluodo - West Zhejiang	China-Xiluodu	China-Jinghua	1680	±800	8000	2014	
North-East Agra	India - Agra	India - Biswanath	1728	±800	6000	Planned 2016	UHV MTDC Supplier: ABB
Champa-Kurukshetra	India - Champa	India - Kurukshetra	1365	±800	2 x 3000	2016-2017	2 Bipoles. Supplier: Alstom
Nuozhadu - Guangdong	China	China	1413	±800	6400	2013	Supplier: Siemens

Table 2 *List of selected Major VSC HVDC Projects*

Project Name	**Year**	**Supplier**	**MW**	**Voltage**	**Converter**
Murray link- Australia	2002	ABB	220	±150 kV	3-level
Estlink- Estonia	2006	ABB	350	±150 kV	2-level
BorWin1- Germany	2009	ABB	400	±150 kV	2-level
Trans Bay Cable- USA	2010	Siemens	400	±200 kV	ML
Caprivi Overhead Link- Africa	2010	ABB	300	350 kV	2-level
East-West Interconnect - Leinster, Ireland	2013	ABB	500	±200 kV	2-level
BorWin2- Germany	2013	Siemens	800	±300 kV	ML

HelWin1- Germany	2014	Siemens	576	±250 kV	ML
DolWin1- Germany	2014	ABB	800	±320 kV	ML
INELFE (France to Spain)	2014	Siemens	2×1000	±320 kV	ML
SylWin1- Germany	2014	Siemens	864	±320 kV	ML
South-West Link -Sweden	2014	Alstom	1440		ML
HelWin2 - Germany	2015	Siemens	690	±320 kV	ML
Dolwin2- Germany	2015	ABB	900	±320 kV	ML

7.5 Converter Transformer

In VSC HVDC scheme, designing of converter transformer is different than in CSC HVDC scheme. Here, the VSC transformer is not subjected to any low order voltage harmonics as it was in CSC.

8 CONCLUSIONS

As explained in previous sections the benefits of HVDC and shortcomings of DC technology, it can be stated that the future of power transmission lies in HVDC grids. Although worldwide replacement of AC transmission is not possible and also not suggested, as it has been widely used in power industry. Most of current power sector industries are using AC systems. It is then suggested that a HVDC system operating with HVAC grid, has better feasibility of implementation.

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