

# **Transmission Systems: HVAC vs HVDC**

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## **Abstract**

With the increasing use of renewable energy (RE) sources located in remote or distant areas, long distance transmission systems are required to incorporate these alternative sources of energy into the existing power grid. This research paper presents a comparison between two transmission systems: high voltage alternating current (HVAC) and high voltage direct current (HVDC) transmission systems technology. Comparative analysis of the following transmission systems is conducted: the HVAC transmission system, the conventional HVDC with line-commutated converters (LCC), and the HVDC with pulse-width modulation (PWM) - voltage source converters (VSC). The best suited system to use in conjunction with a 1000 km transmission distance will be based on the analysis of economic, technical and environmental considerations for the HVAC and HVDC systems.

## **Keywords**

HVAC transmission system, HVDC Transmission system, Line Commutated Convertors, Voltage Source Convertors

## **1. Introduction**

Due to the decreasing supply of fossil fuels and the increased demand in electrical energy, new sustainable methods for electricity generation are being explored (Publishing et al.). Renewable energy (RE) sources (e.g. wind, PV) are being developed in distant areas and even offshore to harvest maximum energy generation. This renewable energy needs to be incorporated into the existing grid with the use of long distance transmission systems.

Direct current (DC) was originally used for the transmission and distribution of electrical energy and was later replaced with alternating current (AC) due to power losses in the DC conductors. AC was deemed more efficient as the voltage could be stepped up for long distance transmission and was soon accepted as the only practical method for generating, transmitting and distributing electrical energy (Meah and Ula, 2007). However, with the recent advances in electronic devices, High Voltage Direct Current (HVDC) transmission is becoming more efficient over long distances. It is used worldwide for long distance power delivery and the interconnection of asynchronous power systems, control of active and reactive power, long distance sub-marine transmission and the integration of renewable energy systems (Oni et al., 2016). It is also used to counter environmental impacts such as reduction in the right of way (ROW) compared to HVAC systems. HVDC transmission systems use converters to change AC to DC (rectifier) and converting DC back to AC (inverter) (DTU and Cutululis). For this type of conversions, there are two main technologies. These technologies are the line commutated converter (LCC) and the voltage source converter (VSC). With developments in power electronic technology, these devices have become highly successful in these operations. (Bahrman, 2008, Müller et al., 2013).

## **2. Types of Transmission**

### **2.1 HVAC Transmission system**

In HVAC transmission system, electrical energy is generated and transmitted using the AC voltage and current signals. From the generation station, the voltage is stepped up by a three-phase transformer, which allows the transmission of energy with lower power losses, and then stepped down again at the distribution side using three-phase transformer for medium or low voltage consumer-loads.

#### **2.1.1 Flexible AC Transmission system (FACTS)**

Although HVAC is the preferred electricity source, transmission system is a challenge due to its production of reactive power. It is, however feasible to use in shorter distance applications. Flexible Alternating Current Transmission Systems (FACTS) systems were developed to increase the efficiency of long distance transmission using AC technology by enhancing the power flow via the regulation of voltage and current signals (Hingorani, 1993). The operation of FACTS is described using Figure 1. Power transmission between two nodes of a transmission line, depends on the voltages,

impedance and the angle difference at each end of the interconnection. FACTS devices, such as the static compensator (STATCOM) and static-var compensator (SVC), can actively control and enhance the power flow in the system. (Povh and Retzmann, 2003).

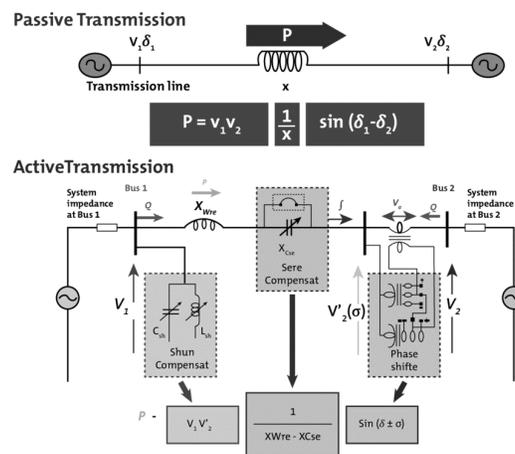


Figure 1. Schematic diagram of FACTS system

### 2.1.2 SVC AND STATCOM

SVC's have been in use since the 1970's and possess the largest share amidst all FACTS devices. SVC's include thyristors, which have more efficient control of the system voltage and require more complicated controllers compared to conventional mechanical switched devices (Singh, 2012). SVC's are essentially a parallel connected static var generator or load capable of generating or consuming the systems reactive power. The SVC's output can be adjusted to produce or consume capacitive and inductive currents. This helps to control variables in the power system such as the SVC bus voltage (Darabian et al., 2013). Usually SVC's are connected to the transmission lines, thus having high voltage ratings. One of the major reasons for installing a SVC is to increase the systems loadability by improving the dynamic voltage control (Mithulananthan et al., 2003).

A further improvement in FACT's systems is STATCOM. These use voltage source converters. STATCOM is a new variety of compensators for reactive power using VSC technology. Although synchronous condensers have similar characteristics, STATCOM is superior as it is not a mechanical device and does not have inertia (Singh, 2012). The advantage of this technology is its lower investment, operating and maintenance costs as well as better dynamics as it is an electrical device.

SVC and STATCOM devices both provide control for the systems voltage and power, as well as damping of power oscillation. The main difference between SVC and STATCOM is their operations. While STATCOM works as a controllable voltage source, SVC works as a dynamically controllable reactance connected in parallel. STATCOM can deliver the maximum available reactive current even at low voltage levels while SVC cannot. This is made possible as the injected reactive power varies linearly with the voltage at the point of common coupling. Comparatively, for SVC there is a quadratic relation between the reactive power and the voltage at the PCC. This means that and SVC system will have to be higher capacity to a STATCOM system for the same transmission capacity.

## 2.2 HVDC Transmission system

In an HVDC-substation or converter substation, rectifiers and inverters are placed at both ends of the transmission line as seen in Figure 2. The rectifier section converts the AC voltage to a DC voltage, while the inverter section converts the DC voltage back to an AC voltage. DC transmission is used over long distances as it decreases the losses and improves the overall system efficiency. A system consisting of two converter stations and a single transmission line is known as a 'two terminal DC system' or a 'point-to-point system'. Similarly, if a substation has more than two converter stations and interconnecting DC terminal lines, it is known as a multi-terminal DC substation (Long and Nilsson). There are two main types of switching devices used in converters required for HVDC systems, namely thyristors and insulated gate bipolar transistor.

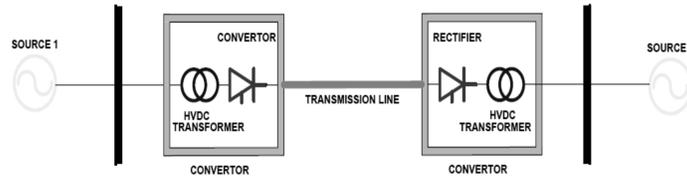


Figure 2. HVDC system layout

### 2.2.1 HVDC-VSC

HVDC-VSC are self-commutated converters that utilize Insulated Gate Bipolar Transistor (IGBT) valves as switching devices. VSC technology also uses the same transformer as a standard AC system. They require 40% to 50% less site area as opposed to HVDC-LCC systems. These systems also allow black start capability as it can self-commutate (Vormedal). One of the major advantages of VSC technology is that it uses Pulse Width Modulation (PWM) for switching control, which allows for high controllability with regards to amplitude, phase angle, active and reactive power of the system (Oni et al.).

#### 2.2.1.1 Analytical analysis of VSC-HVDC

The power converter of a DFIG can be considered as a point to point VSC system with a specific configuration shown in Figure 3.

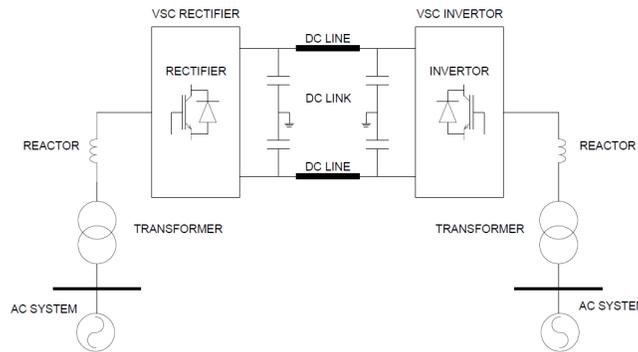


Figure 3. Simplified HVDC-VSC layout

For the rectifier side, the equations for the current and voltage is shown in Equation (1).

$$\begin{bmatrix} U_{sa} \\ U_{sb} \\ U_{sc} \end{bmatrix} = L \frac{d}{dt} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} + R \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} U_{ca} \\ U_{cb} \\ U_{cc} \end{bmatrix} \quad (1)$$

In Equation (1),  $U_{sa}$ ,  $U_{sb}$ ,  $U_{sc}$  are the supply voltages of the AC side respectively.  $U_{ca}$ ,  $U_{cb}$ ,  $U_{cc}$  are the three-phase voltages of the rectifier converter side (Li et al., 2014). The relation between the AC side supply voltage and the DC side voltage of the converter can be determined by Equation (2).

$$\begin{bmatrix} U_{ca} \\ U_{cb} \\ U_{cc} \end{bmatrix} = \frac{mU_{dc}}{2} \begin{bmatrix} \sin(\omega t + \delta) \\ \sin\left(\omega t + \delta + \frac{2\pi}{3}\right) \\ \sin\left(\omega t + \delta - \frac{2\pi}{3}\right) \end{bmatrix} \quad (2)$$

In Equation (2),  $m$  and  $\delta$  represent the modulation ratio and angle respectively. As the power losses are negligible, it can be ignored. As the active power is linear to the DC current, the active power, shown in Equation (3), and reactive power, in Equation (4), can be determined as follows,

$$P = \frac{3}{2} U_{sd} i_d \quad (3)$$

$$Q = \frac{3}{2} [i_d u_{sq} - i_q u_{sd}] = -\frac{3}{2} u_{sd} i_q \quad (4)$$

and the decoupling control strategy of the VSC can use the relationship between the power and current components in the system.

## 2.2.2 HVDC-LCC

HVDC-LCC is a mature technology, which has been in use for many years. They are line commutated converters that utilize thyristor valves as switching devices. For LCC to commutate a large voltage source is required, this hinders its ability to be used in black-start operations. One of the main advantages of LCC technology is its high power rating, higher than all other converter technologies. LCC systems have 10% to 15% lower costs than VSC systems and contain less components, making the system more reliable and easier to maintain (Van Hertem and Delimar).

### 2.2.2.1 Analytical analysis of HVDC-LCC

A simplified model of the LCC system can be seen in Figure 4. When working as a rectifier, the output voltage can be calculated by using Equation (5). When it operates as an inverter, the voltage can be calculated by using Equation (6).

$$U_{d01r} = 1.35U_{rlmean} \cos(\alpha) - \frac{3\omega L_r I_d}{\pi} \quad (5)$$

$$U_{d01i} = 1.35U_{rlmean} \cos(\gamma) + \frac{3\omega L_r I_d}{\pi} \quad (6)$$

In the above equations,  $U_{d01r}$  and  $U_{d01i}$  are the output DC voltages and  $U_{rlmean}$  is the effective values of the AC line voltage.  $\alpha$  and  $\gamma$  are the trigger angle and the extinction angle, respectively.  $L_r$  is the inductance of the loop, while  $I_d$  is the DC current of the converter.

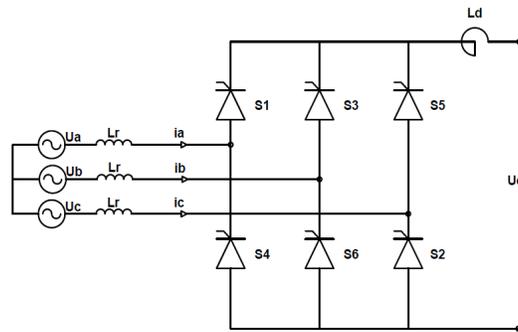


Figure 4. Schematic diagram of rectifier

## 2.3 Types of HVDC links

HVDC converter can be arranged in a various number of configurations for effective operation. Converter bridges can be arranged in either monopolar or bipolar configurations, as shown in Figure 5 and are described as follow:

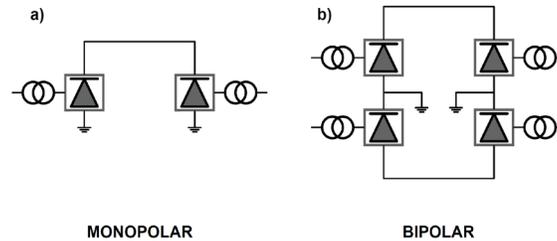


Figure 5. Monopolar and bipolar arrangements

### 2.3.1 Monopolar HVDC system

In a monopole configuration link, one of the terminals of the rectifier is grounded, while the other is connected to a transmission line (Eremia et al., 2016). Earth returns instead of a dedicated neutral conductor can be considerably cheaper for long-distance transmission, but it can lead to problems, to avoid these issues, a metallic return conductor may be installed between the two ends of the transmission line. In Figure 5 (a), there is only one insulated transmission conductor installed and the ground is used for the return current.

### 2.3.2 Bipolar HVDC system

In bipolar transmission, two conductors are used. Since these conductors must be rated for the full voltage, transmission line costs are higher than a monopole with a return conductor. However, advantages such as, negligible earth-current, operation during fault and lower conductor costs due to lower current, can make it an attractive option. Bipolar configuration is the most commonly used configuration of HVDC power transmission systems (Oni et al.). The bipolar circuit link, is shown in Figure 5 (b).

## 2.4 HVDC Configurations

HVDC systems have various configurations that can be used. The selection of these configurations depend on the function and location of the converter stations.

### 2.4.1 Back-to-back HVDC system.

In back to back configuration the two converter stations are located at the same area and usually the same building. This requires no transmission line or cable between the converter stations. They may be connected either monopole or bipolar.

### 2.4.2 Point to Point HVDC

Point-to-point configuration is used when it is feasible to transfer electrical energy through DC transmission from one geographical location to another. The AC power is converted to DC by the rectifier station and is transported to the other inverter station in a different location. Point to point is one of the commonly used systems with HVDC. The link may connect two non-synchronous systems or connect two substations within one interconnected.

### 2.4.3 Multi-terminal HVDC transmission system

The interconnection of two convertor stations is one of the most common arrangements of HVDC links. The use of multi-terminal HVDC links, for the connection of more than two points, are rare but are becoming more needed and useful. Multiple terminals can be configured in either series, parallel, or a hybrid configuration (a combination of series and parallel connections). Parallel multi-terminal DC, shown in Figure 6 (b), can be used if all the substations in the system are connected to the same voltage. If the converter bridges are added in series, then the system is series multi-terminal DC as shown in Figure 6 (a). These systems are more difficult to justify economically as the cost of the additional substations of the multi-terminal DC systems are extremely high.

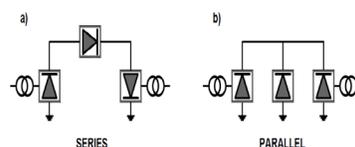


Figure 6. MTDC Connections

## 2.5 System Components

### 2.5.1 HVAC transmission system

Transformers: AC systems require transformer to step up the voltages generated to allow transmission with lower losses.

Series Compensation: This is used in longer distance AC systems to compensate for power quality.

Harmonic filters: Filters are also used in HVAC systems to provide the AC line with the reactive power compensation.

### 2.5.2 HVDC system

Converter transformer: HVDC LCC systems use a different type of transformer from the conventional AC transformer. It follows a different configuration and has special features such as on load tap changes. HVDC VSC systems use the same transformer as the conventional AC transformer.

Smoothing Reactors: These reactors are used for the removal of DC current ripples as well as to limit the rise of the fault current on the DC line.

Harmonic filters: These are connected to the converter terminals to provide a low impedance path to ground for removal of harmonics current. Filter used also provide the AC line with the reactive power compensation (Oni et al., 2016).

## 3. Comparison of HVAC and HVDC

The merit of each mode of transmission should be compared based on the following factors:

- Transmission system Costs
- System Reliability
- Technical Performance

### 3.1 System Costs

HVAC has a higher line cost than DC, for the same transmission capacity, as it requires at least three conductors while DC systems only requires two. Although the line costs are lower, the converter stations are more expensive in HVDC schemes. The costs of transmission cables, right-of-way costs as well as operating and maintenance costs are lower in the HVDC case (Kim et al.). The break-even distance is the distance at which the cost of the AC and DC systems are the same. It is understood from Figure 7 that a DC line is economical for longer distances which are greater than the break-even distance (Sharifabadi et al., 2016). Above the break-even distance, the HVDC alternative will always give the lowest cost. The break-even distance depends on several different factors, such as the transmission medium, permits, cost of local labour and right of way. A project specific analysis must be made for each individual case.

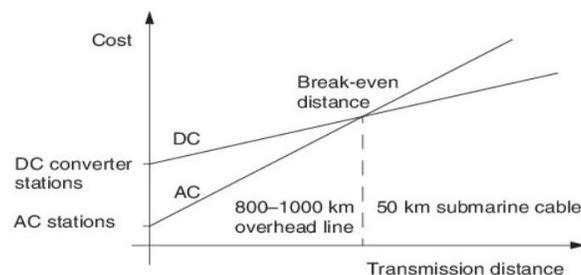


Figure 7. Break even graph

### 3.2 Ohmic losses

Although initial loss levels are higher in the HVDC systems, they do not vary with distance. Whereas losses are greater as the distance increases with in HVAC systems. An optimized HVDC transmission line has lower losses than AC lines for the same power capacity. HVDC transmission losses are lower than AC losses in all cases and HVDC cables also have lower losses than HVAC cables of the same size (Meah and Ula).

### **3.3 Long Distance Transmission line**

In long distance AC transmission, the flow of reactive power will limit the maximum transmission distance due to the cable's large capacitance. In HVDC systems, however, there is no such limitation therefore making HVDC the only viable option for long cable links.

### **3.4 Asynchronous Connection**

One of the fundamental advantages with HVDC is that it can very easily control the active and reactive power in the link and a HVDC transmission system does not contribute to the short circuit current of the interconnected AC system (Reidy and Watson, 2005). Due to stability reasons, it is sometimes difficult or even impossible to interconnect two AC networks. In such cases, HVDC is the only way to allow the interconnection between the two networks. There are also HVDC links used to connect systems with different frequencies (50 and 60 Hz) in Japan and South America (Larruskain et al.).

### **3.5 Fault Current**

When there is a fault on a transmission system, a fault current, also known as a short circuit current, arises. This is the flow of a large current through the system. This high current can largely affect the insulation of the equipment in the system, lead to power surges that damage equipment, or possibly charge the devices so that when they are touched, an electric shock is administered, sometimes resulting in death.

In the case of asymmetric faults, the high level fault current can affect the sending end bus, transmission line, and also the generator unit. Faults in particular subject the generator to stress beyond its design limits. When faults occur on HVDC power systems on the other hand, the fault current is localised and does not travel to the generator system or load, based on where the fault occurs. This allows for safer, more effective systems.

### **3.6 Charging Current**

A cable can be modelled as a long cylindrical capacitor. Per unit length, the capacity,  $C'$ , is about 160–600 nF/km (Shea, 2001). This value depends on the dielectric, the conductor cross-section, and the thickness of insulation. The charging current of a cable can be expressed as seen in Equation (7) and (8):

$$I_c = U_0 \times \omega \times C' \times l \quad (7)$$

$$I_c \approx U_0 \times \omega \times \epsilon r \times l \quad (8)$$

In Equation (8),  $U_0$  is the phase voltage,  $\omega$  the angular frequency,  $\epsilon r$  the relative dielectric constant, and  $l$  the cable length. This relation increases linear with the frequency. For DC, with a frequency of 0 Hz, the charging current is zero. For AC systems on the other hand, the charging current cannot be neglected.

### **3.7 Power Flow Control**

DC transmission is inherently suited to control the power flow through a line. At any time, the active power flowing through the connection can be set to a desired value within the DC system limits, as long as the AC grid allows this. When using VSC HVDC, the reactive power at both terminals can also be controlled dynamically. In the case of AC transmission, power flow control is only possible with usage of FACTS devices and phase-shifting transformers. As phase-shifting transformers are mechanical devices, the change of tap settings can take up to several minutes, which constraints the speed in power flow control. Another issue is that the maintenance interval of such transformers decreases with increasing number of switching actions. FACTS devices are mainly used for voltage control and stability. They can also can be used for power flow control in a limited range (Van Hertem et al., 2016).

### **3.8 Stability Limits**

The power transferred by a purely inductive AC line depends on the phase angle between the voltages at both line ends. The transferred power can be expressed as seen in Equation (9).

$$P_{12} = \frac{|U_1| \times |U_2|}{X_{line}} \cdot \sin(\delta_{12}) \quad (9)$$

For a given power level, this angle increases with rising distance as the line impedance becomes higher. The maximum power transfer is therefore limited because of steady state and transient stability. The power carrying capability of an AC line is inversely proportional to the transmission distance. DC lines, however, are not affected by this. Furthermore, by the decoupling through a DC link, oscillations are not (or to a lower degree) transmitted through the link. When properly controlled, the DC link can even contribute to damping of oscillations.

## 4. Performance of HVAC and HVDC

To analyse the performance of each system, a simulation is carried out to determine the system efficiency. Each system will be simulated and the overall system efficiency will be determined by looking at the sending and receiving end voltages for each system.

### 4.1 Simulation

Although LCC technology is growing, as it has a high reliability with its thyristor based technology, VSC is superior in efficiency and power control and allows for black start capability. In this simulation, only HVDC-VSC will be simulated and compared to HVAC. A later study can be done to compare HVDC-VSC and HVDC-LCC to determine the best performing system. To evaluate both systems, all parameters were kept constant. Power ratings for each generation station as well as transmission line lengths are equal. A single line to ground fault was also simulated on each system, to determine fault current levels and behaviour of each system.

### 4.2 HVAC System

In this simulation, a HVAC system is modelled. The AC supply of 500 kV represents a generation station and a transformer steps up the voltage to 735kV for transmission. This power is stepped up to minimize the transmission losses. The generated power is then transmitted over a distance of 1000 km via an AC transmission line with series compensation, to increase the transmission capacity and power quality in the system. Circuit breakers are included to allow for protection in the event of a fault and a load is included to simulate the consumers. Figure 8 represents the three-phase, HVAC transmission system, simulated using MATLAB simulation software.

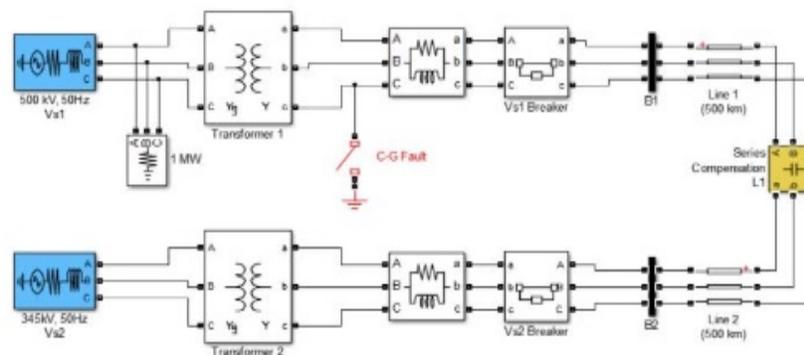


Figure 8. HVAC simulation model

### 4.3 HVDC System

Technical feasibility has been already proved for HVDC power transmission system with the development of power electronics devices. These devices make the efficient conversion from AC to DC and thus are the main component of any HVDC power transmission system. Figure 9 represents the simulation model of a HVDC transmission system using 12-pulse IGBT (Insulated Gate Bipolar Transistor) converters. The HVDC VSC system was simulated and parameters were kept identical to the HVAC system. A 500 kV supply and a 1000 km transmission line was simulated. The simulation also included a rectifier and inverter system as well as power filters and a load. The converters were modelled using the pre-set universal bridge block provided by Matlab.

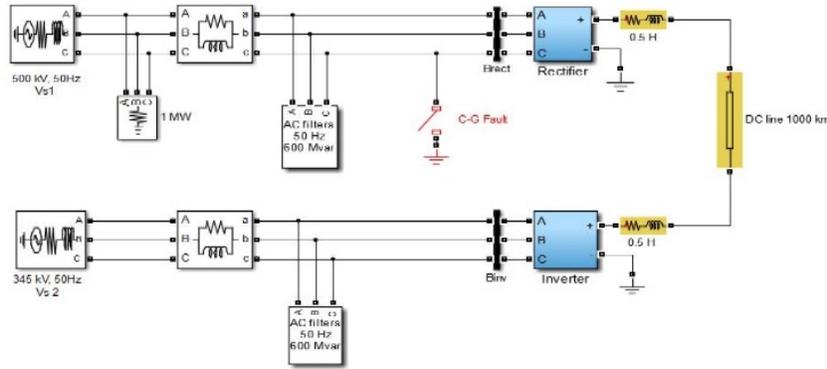


Figure 9. HVDC simulation model

Using the simulation software, normal operation will be simulated to determine the performance and efficiency of each system. To determine fault levels, fault conditions will be simulated to determine how these systems react during a single line to ground fault. This will help determine how each system reacts during a fault and will also help to determine systems costs, as higher fault levels will require more expensive protection systems.

## 5. Simulation Output

### 5.1 Normal Operation

Using statistical analysis each graph was analysed and the results were recorded. Table 1 shows the results of the data. Figure 10 and Figure 11 show the sending and receiving end voltages of the HVAC system respectively. From the graphs, it is clear that the HVAC transmission has a voltage drop of 60 kV over the 1000 km line. For the HVDC system the sending and receiving end voltages seen in Figure 12 and Figure 13 are only 30 kV difference. This shows that the HVDC system is 6% more efficient over the long transmission distance than the HVAC system.

Table 1: Voltage summary normal operation

	HVAC Voltage (kV)	HVDC Voltage (kV)
Sending End	500	500
Receiving End	440	470
Difference	60	30
Efficiency	88%	94%

From this information, the HVAC and HVDC system both have losses during transmission under normal operating conditions. HVAC has a higher loss as compared to HVDC. This is satisfied by literature as HVAC transmission lines have to overcome skin effect and corona losses, where HVDC does not (Behraves and Abbaspour, 2012). The result adds to prove the efficiency of HVDC over HVAC systems for long distance transmission.

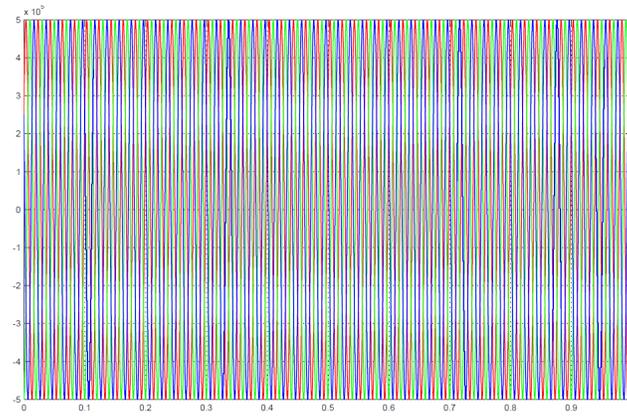


Figure 10. HVAC sending end voltage normal operation

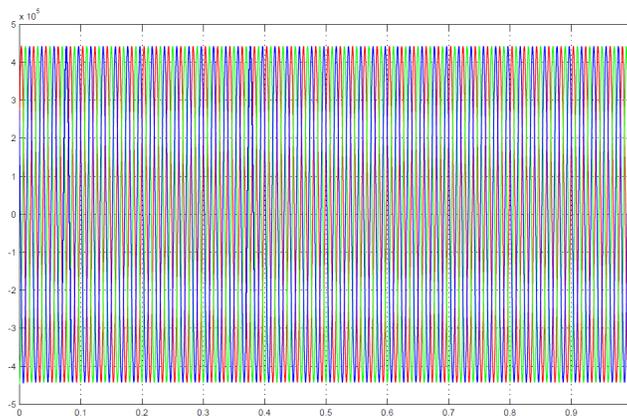


Figure 11. HVAC receiving end voltage normal operation

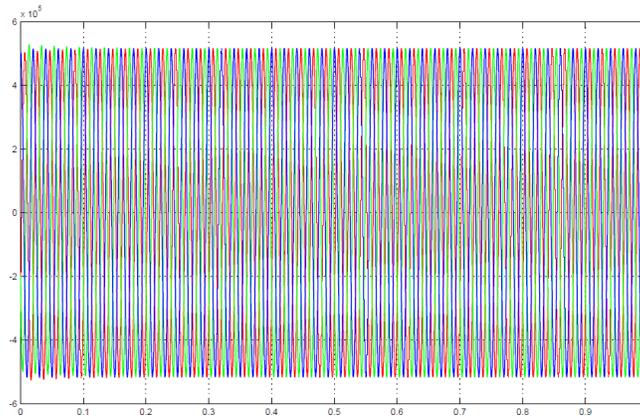


Figure 12. HVDC sending end voltage normal operation

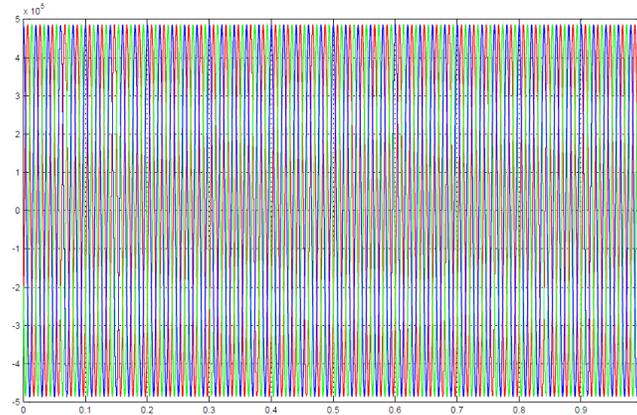


Figure 13. HVDC receiving end voltage normal operation

## 5.2 Single Line to Ground Fault

In the case of an asymmetric fault in HVAC transmission systems, the high level fault current can largely affect the transmission line, sending end bus section and also the power generation unit. Generators are regularly exposed to high-level fault currents (Ahmed and Manohar). In HVDC however, the fault current is said to only affect the faulted section and the fault current does not travel to the source based on the location of the fault (Yang et al.).

The figures below illustrate the fault current, sending end voltage and current and receiving end voltage and current respectively for the HVAC and HVDC systems.

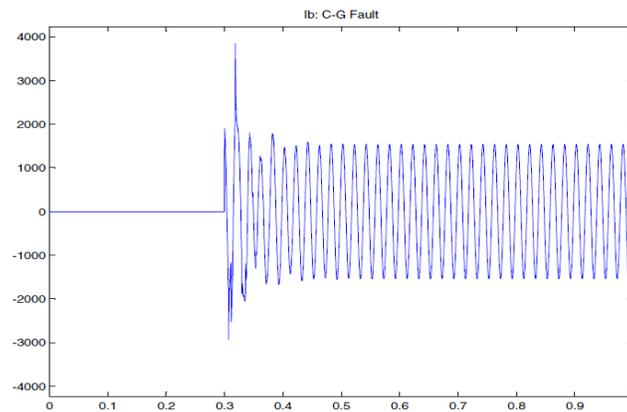


Figure 14. HVAC fault current

The fault current on a HVAC system during a single line to ground fault is shown in Figure 14. The fault current peaks at 4000A and drops to a constant of 2000A. In Figure 19, the fault current in the HVDC system peaks to 1500A but settles to a current of less than 800A on average. The effects of high fault currents in the HVAC systems, can include conductor motion and the breakage of conductors and insulators, all of which can be hazardous. To ensure these hazardous situations are avoided, costs will increase by adding in higher rated protection devices. From Figure 15, it is clearly seen that the fault occurs at 0.3s. The receiving end voltage on the unaffected phases are tripled and cause a major unbalance in the system. The voltage unbalance on the transmission system can affected all loads connected to it, causing heating of the electrical equipment and major damage to motors.

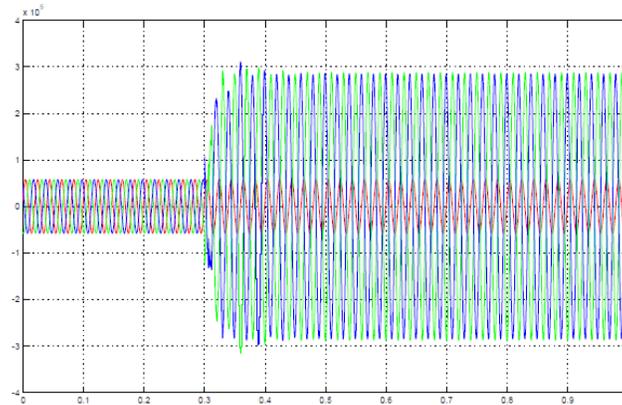


Figure 15. HVAC receiving end voltage fault operation

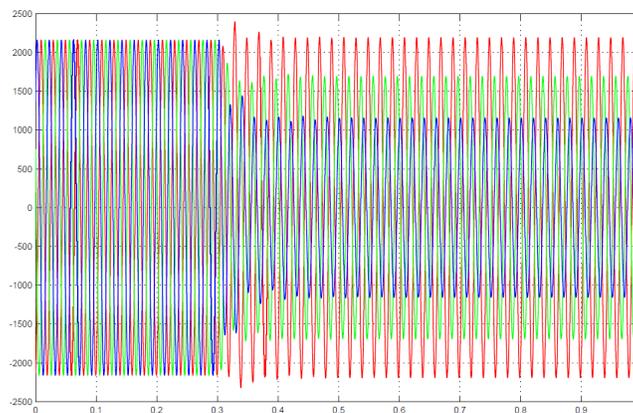


Figure 16. HVAC receiving end current fault operation

In the HVAC system, a single line to ground fault, not only affects the receiving end voltage and current but the fault travels upstream to the generator system. Figure 15, Figure 16, Figure 17 and Figure 18, show the sending end and receiving end voltages and currents respectively. From these graphs it is clear the amount of damage the fault can cause on a HVAC system. Although the fault occurs on the sending end of the system, the fault is carried to the receiving end and can cause damage to the entire system.

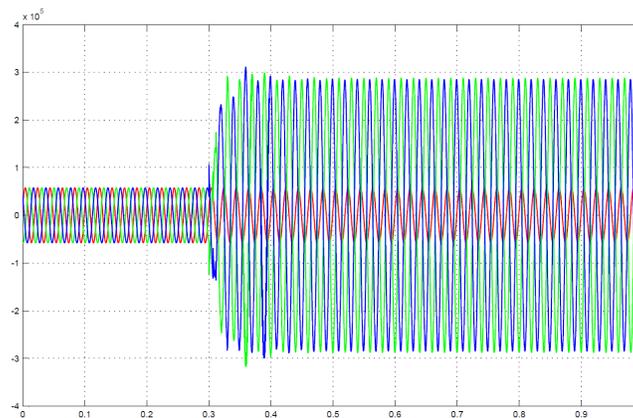


Figure 17. HVAC sending end voltage fault operation

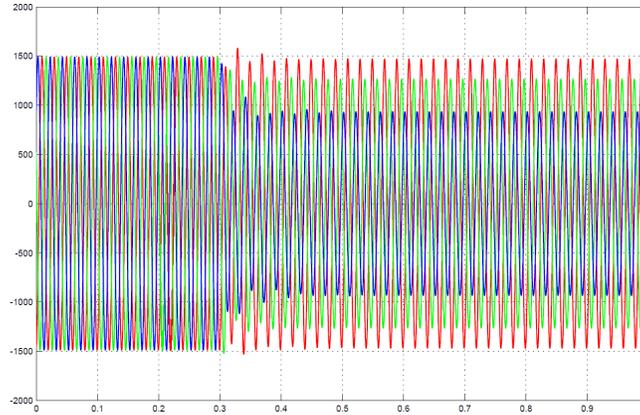


Figure 18. HVAC sending end current fault operation

The fault current effects for the HVDC system are represented by Figure 20 and Figure 21. Due to the single line to ground fault, receiving end voltage and current waveforms of the HVDC system are in approximate proper position, with the faulted line spiking. This fault is contained within the affected section and does not travel to the receiving end as seen in Figure 22 and Figure 23.

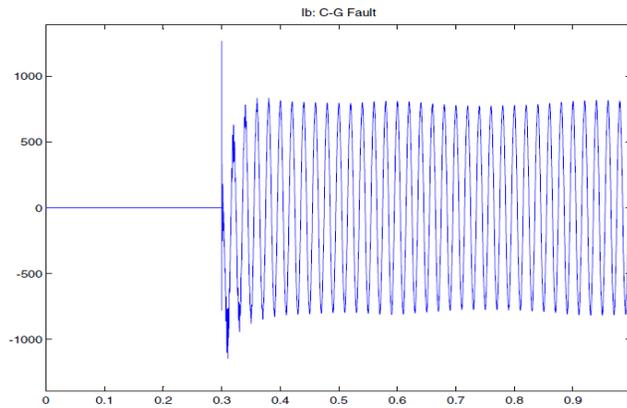


Figure 19. HVDC fault current

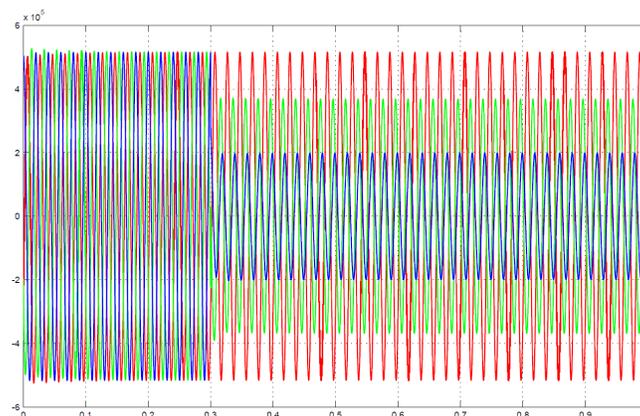


Figure 20. HVDC sending end voltage fault operation

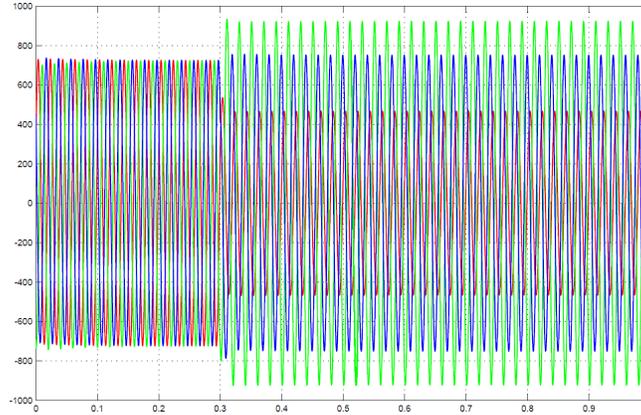


Figure 21. HVDC sending end current fault operation

The receiving end voltage and current shown in Figure 22 and Figure 23 show that the fault does not affect the receiving end of the system as it does in the HVAC system. This benefit will also allow for lower rated protection equipment and in turn reduce system costs.

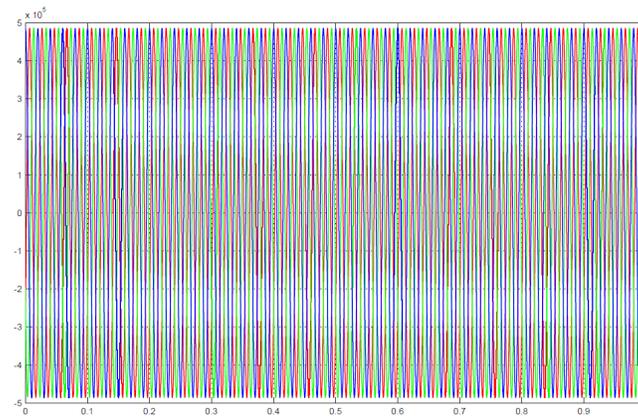


Figure 22. HVDC receiving end voltage fault operation

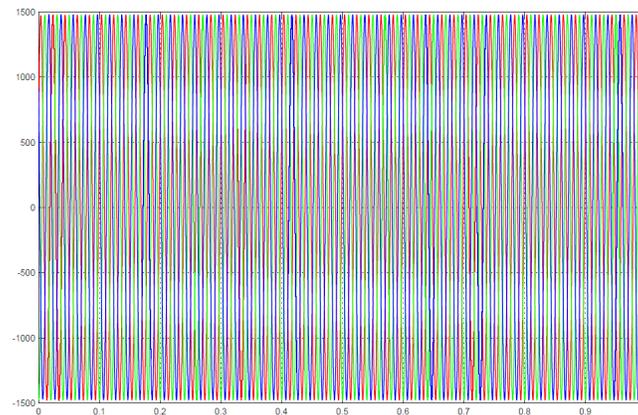


Figure 23. HVDC receiving end current fault operation

The results in Table 2 show that for the given single line to ground fault, the fault current in the HVAC transmission system is much higher than the HVDC transmission system. In addition, the effects of this fault current is highly damaging in HVAC while effects are less harmful to the system in HVDC transmission systems. The fault does not

affect the receiving end of the system as it occurs on the sending end whereas in the AC system the fault affects both the sending and receiving end of the system.

Table 2: Fault simulation summary

	HVAC	HVDC
Fault Current	4000 A	1500 A
Sending End	Voltage and Current Highly Affected	Voltage and Current Mildly Affected
Receiving End	Voltage and Current Highly Affected	Voltage and Current Unaffected

The data during the single line to ground fault, is seen in Figure 24. The data for both systems are shown and it is clear that the HVDC system is much better at handling a fault in the system.

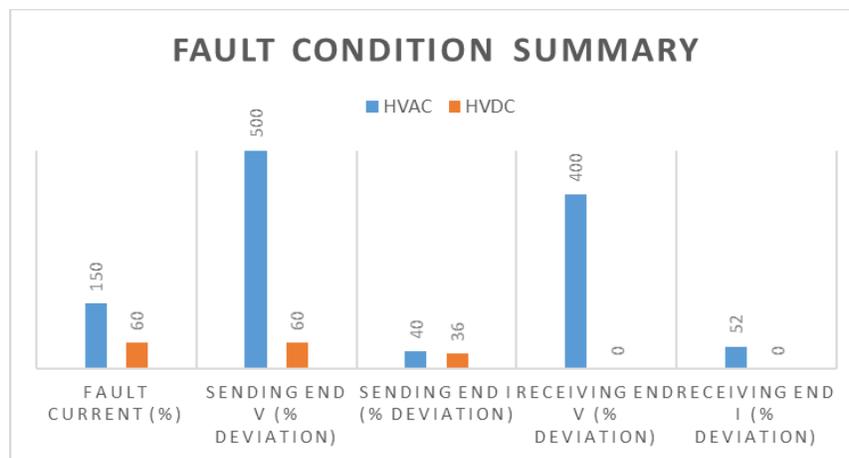


Figure 24. Fault condition summary graph

## 6. Conclusion

This paper has looked into the HVAC, HVDC-VSC and HVDC- LCC transmission systems to determine the cost and efficiency of these systems. It is clear that for long distances, over the break-even distance, HVDC is proven the cost effective solution. The system efficiency is also much higher in HVDC systems. Faults were simulated on each system and based on the fault levels as well as the effects on the transmission system, HVDC is seen to be better option as it has a much lower fault current and the fault only affects the faulted section and does not travel through the system. In today's society, with the high demand for renewable energy and the task of transmitting this energy to connection points on the existing grid, HVDC transmission systems are a step in the right direction.

Further research should be carried out on HVDC LCC and HVDC VSC as technology improves. These electronic devices are improving every day and in the near future, VSC and LCC technology may be improved even further and prove even more efficient than HVAC transmission.

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