Comparative Evaluation of HVDC and HVAC Transmission Systems

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Abstract-- **Alternating current (AC) is the main driving force in the industries and residential areas, but for the long transmission line (more than 400 miles) AC transmission is more expensive than that of direct current (DC). Technically, AC transmission line control is more complicated because of the frequency. DC transmission does not have these limitations, which has led to build long HVDC transmission lines over the last 40 years. HVDC technology made possible to transfer bulk power over long distances. This paper presents a comparative evaluation of HVDC and HVAC transmission systems.**

Index Terms-- **HVDC and HVAC transmission, Transmission cost, Environmental impact.**

I. INTRODUCTION

THE first electric generator was the direct current (DC) generator and hence, the first electric power transmission line was constructed with DC. The basic discoveries of Galvani, Volta, Oersted, Ohm, and Ampere were in the DC field. Thomas A. Edison built the first electric central station in the world in 1882, on the Pearl Street, in the New York, which was the DC current. Despite the initial supremacy of the DC, the alternating current (AC) supplanted the DC for greater uses. This is because of the availability of the transformer, the induction motor, and polyphase circuits in the 1880s and 1890s [1]. The transformer is very simple and easy to change the voltage level for the transmission, distribution and use. The induction motors are the workhorse in the industries and work only with AC. That is why AC has become very useful for the commercial and domestic uses. But for the long transmission, DC is still more favorable than AC because of its economical, technical, and environmental advantages.

High voltage DC (HVDC) Transmission system consists of three basic parts: 1) converter station to convert AC to DC 2) transmission line 3) second converter station to convert back to AC. HVDC transmission systems can be configured in many ways on the basis of cost, flexibility, and operational requirements. The simplest one is the back-to-back interconnection, and it has two converters on the same site and there is no transmission line. This type of connection is used as an inter tie between two different AC transmission systems. The mono-polar link connects two converter stations by a single conductor line and earth or sea is used as a returned path. The most common HVDC link is bipolar, where two converter stations are connected by bipolar (±) conductors and each conductor has its own ground return. The multi-terminal HVDC transmission systems have more than two converter stations, which could be connected is series or parallel.

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II. HVDC VERSUS HVAC TRANSMISSION

Alternating current (AC) became very familiar for the industrial and domestic uses, but still for the long transmission lines, AC has some limitations which has led to the use of DC transmission in some projects. The technical detail of HVDC transmission compare to high voltage AC (HVAC) transmission is discussed to verify HVDC transmission for long distances.

Current and voltage limits are the two important factors of the high voltage transmission line. The AC resistance of a conductor is higher than its DC resistance because of skin effect, and eventually loss is higher for AC transmission. The switching surges are the serious transient over voltages for the high voltage transmission line, in the case of AC transmission the peak values are two or three times normal crest voltage but for DC transmission it is 1.7 times normal voltage. HVDC transmission has less corona and radio interference than that of HVAC transmission line [2]. The total power loss due to corona is less than 5 MW for a $\pm$450 kV and 895 kilometers HVDC transmission line [3-4].

The long HVAC overhead lines produce and consume the reactive power, which is a serious problem. If the transmission line has a series inductance L and shunt capacitance C per unit of length and operating voltage V and current I, the reactive power produced by the line is

$$Q_c = \omega C V^2$$

and consumers reactive power

$$Q_L = \omega L I^2$$

per unit length. If $Q_C = Q_L$

$$\frac{V}{I} = \left(\frac{L}{C}\right)^{1/2} = Z_s$$

where Z_s is surge impedance of the line. The power in the line is

$$P_n = VI = \frac{V^2}{Z_s}$$

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and is called natural load. So the power carried by the line depends on the operating voltage and the surge impedance of the line. Table I shows the typical values of a three phase overhead lines [1], [5].

TABLE I
VOLTAGE RATING AND POWER CAPACITY

Voltage (kV)	132	230	345	500	700
Natural load (MW)	43	130	300	830	1600

The power flow in an AC system and the power transfer in a transmission line can be expressed

$$P = \frac{E_1 E_2}{X} \sin \delta$$

E_1 and E_2 are the two terminal voltages, δ is the phase difference of these voltages, and X is the series reactance. Maximum power transfer occurs at δ= 90º and is

$$P_{\max} = \frac{E_1 E_2}{X}$$

P_{max} is the steady-state stability limit. For a long distance transmission system the line has the most of the reactance and very small part is in the two terminal systems, consisting of machines, transformers, and local lines. The inductive reactance of a single-circuit 60 Hz overhead line with single conductor is about 0.8 Ω/mi (0.5Ω/km); with double conductor is about 3/4 as greater. The reactance of the line is proportional to the length of the line, and thus power per circuit of an operating voltage is limited by steady-state stability, which is inversely proportional to length of line [1]. For the reason of stability the load angle is kept at relatively low value under normal operating condition (about 30°) because power flow disturbances affect the load-angle very quickly. In an uncompensated line the phase angle varies with the distance when the line operating at natural load and puts a limit on the distance. For 30° phase angle the distance is 258 mi at 60 Hz. The line distance can be increased using series capacitor, whose reactance compensates a part of series inductive reactance of the line, but the maximum part that can be compensated has not been determined yet [2].

On the other hand D.C transmission has no reactance problem, no stability problem, and hence no distance limitation.

III. ADVANTAGES AND DISADVANTAGES OF HVDC

A. *ADVANTAGES*

- Greater power per conductor.
- Simpler line construction.
- Ground return can be used.
- Hence each conductor can be operated as an independent circuit.
- No charging current.
- No Skin effect.
- Cables can be worked at a higher voltage gradient.
- Line power factor is always unity: line does not require reactive compensation.
- Less corona loss and radio interference, especially in foul weather, for a certain conductor diameter and rms voltage.
- Synchronous operation is not required.
- Hence distance is not limited by stability.
- May interconnect A.C systems of different frequencies.
- Low short-circuit current on D.C line.
- Does not contribute to short-circuit current of a A.C system.
- Tie-line power is easily controlled.

B. *DISADVANTAGES*

- Converters are expensive.
- Converters require much reactive power.
- Converters generate harmonic, require filters.
- Multiterminal or network operation is not easy.

IV. ECONOMICAL ASPECT

Bulk power could be transferred using HVDC or HVAC transmission system from a remote generating station to the load center. Direct cost comparisons between AC and DC alternatives should be conducted before make a decision. In order to compare the cost, all main system elements must be taken into consideration. For the DC alternative, capital cost for the converter terminals, AC input/output equipment, filters, the interconnecting transmission line must be accounted. For the AC alternative, capital cost for the step-up/step-down transformer, the overhead line, light load compensation if required, reactive power compensation, circuit breaker, building should be evaluated. Control system cost need to be considered for the both case. Table II shows generic cost comparison elements [6-7]. For the preliminary planning stage, the capital cost for the terminals and transmission line are the main concern. For example, Nelson River HVDC Transmission line Bipole 1 is considered here for economic analysis.

A. *AC STATION COSTS*

Alternating current switching and substation plant may include the cost of following major items:

- power circuit breakers,
- power transformer,
- disconnect switches,
- reactors,
- shunt capacitors,
- static capacitors,
- synchronous compensators,
- series capacitors,
- buswork,
- protection and control systems
- structures and
- control houses.

TABLE II

GENERIC COST COMPARISON ELEMENT

System cost elements for given power (MW) transmitted and line length	
A.C	DC
Right-of-way	Right-of-way
Load density per acre of right-of-way	Load density per acre of right-of-way
Transmission voltage	Transmission voltage
Line-Conductors Towers	Line-Conductors Towers
Substations or switching stations Breakers and disconnects transformer Reactive power (Capacitive and Inductive) Shunt capacitors and reactors Series capacitor Static var systems Protection control Station civil work	HVDC converter stations Breakers and disconnects transformer Filters and var supply Valve assembly and smoothing reactor Ground electrode and metallic return transfer Breaker. Protection control Station civil work
Losses-Line & Station	Losses- Line & Station
Communications	Communications
Operating characteristics	Operating characteristics
System reinforcement	System reinforcement
Environmental impact	Environmental impact
Consequences and recovery from Short-duration line faults Long-duration line faults	Consequences and recovery from Short-duration line faults -ong-duration line faults
Stability enhancement- Dynamic and Transient	Stability enhancement- Dynamic and Transient
Recovery from system breakup	Recovery from system breakup
Fault magnitude and breaker interrupting duty	Fault magnitude and breaker interrupting duty
Base of tapping for intermediate loads	Ease of tapping for intermediate oads
Energy availability	Energy availability
	Conversion of A.C lines to DC

Estimate the costs is not a straight forward calculation, because the equipments' costs are always varying and also it varies from place to place and company to company. For this calculation, the installed cost of each of these items includes cost of materials or equipment, construction, land, material handling, surveys and usually overhead charges. At the beginning of the survey several transmission arrangements were investigated for the Bipole 1, but preliminary examination narrowed down to 500 AC or ± 450 DC. The cost comparison between them is discussed here. Installed costs for 500 kV AC substation for the Nelson River Bipole 1 is shown in Table III [6-7]

The estimate cost for the circuit breaker and transformer include the approximate cost of related control and protection, buswork, disconnect switches, related structures, and control houses. Total cost for the sending and receiving end AC stations is $37.69 million. All costs are calculated on the basis of year 1985. The cost of electrical and electronic equipments varies time to time; naturally the cost goes down with newer technology. The HVDC and HVAC system consist of not only the equipment cost but also the labor cost, which goes up with the time. If both costs compensate each other, the present cost would be the same as 1985's cost. By taking inflation into account, the costs in 1985 can be converted to the present equivalent cost, and the multiplying factor is 1.73 [8].

TABLE III

A.C. SUBSTATION COSTS FOR BIPOLE 1

Type of equipment	Cost ($)
Circuit breaker	1500000.00
Transformer	1534500.00
Shunt Capacitor	1787500.00
Series Capacitor	2200000.00
Sialic var system	8250000.00
Shunt reactors	3575000.00
Subtotal	18847000.00

B. AC TRANSMISSION LINE COSTS

AC transmission line ROW needs bigger space and more construction cost than those of DC transmission for the same power capability and comparable reliability. AC transmission line has 3 power carrying conductors where as DC transmission has only two and theses reasons increase the AC transmission line costs significantly. A typical cost for 500 kV AC line is $955/kV-mile. Nelson River Bipole 1 is 895 km (556.2 miles); total transmission line cost is 265.6 million dollars. Total cost for the Nelson River Bipole 1 if AC transmission would be used is 303.29 million dollars.

C. DC STATION COST AND LINE COST

The main equipment of the D.C station is converters and more than 50% costs of HVDC transmission system are related to the converters. The converter stations are the key component to make an economical comparison between DC and AC transmission system. For an AC system the line costs predominate and station costs are small and for the DC system stations costs predominate and line costs are small. Table IV shows the percentage of each main component cost relative to the total station cost for DC system [6-7].

The Nelson River Bipole 1 is ± 450 kV DC, 1854 MW, and connected to 138 kV AC at Radisson and 230 kV AC at Dorsey. For the calculation 138 -230 kV was taken as a base. For 1854 MW, the $/kW cost range in per unit is 0.7 to 0.93;

for 450 kV, the multiplier is 1.15; and for 138 kV and 230 kV the multiplier is 1 [6-7]. The $/kW cost range in per unit for the system is 0.805 [0.7*1.15*1] to 1.0695 [0.93*1.1581]. Using 1 p.u. = $100/kW, the converter stations cost range is $\$149.24\text{x}10^6$ to $\$198.28\text{x}10^6$. The average is $\$173.5\text{x}10^6$.

The line cost for the DC transmission system is $320 -$370/kV-mile for ±400 to ± 700kV. If $345/kV-mile is taken for the ± 450 kV transmissions line the total line costs for 556.2 miles is $\$86.3\times10^6$. The total cost of DC transmission system for the Bipole 1 is $\$259.8\times10^6$, which is 43.49 million dollars lower than that of AC transmission system. Fig. 1 shows comparative costs of AC and DC Transmission system for the Nelson River Bipole 1.

TABLE IV
D.C. SYSTEM COSTS AS A PERCENTAGE OF TOTAL PROJECT COSTS

Equipment	Percentage of total cost
Converter transformers	20-25
Valves (including control and cooling)	20-30
Filters and var supply	5-20
Miscellaneous (communications, dc reactor, arresters, relaying etc.)	5-15
Engineering (system studies, project management)	2-5
Civil work and site installation	15-30

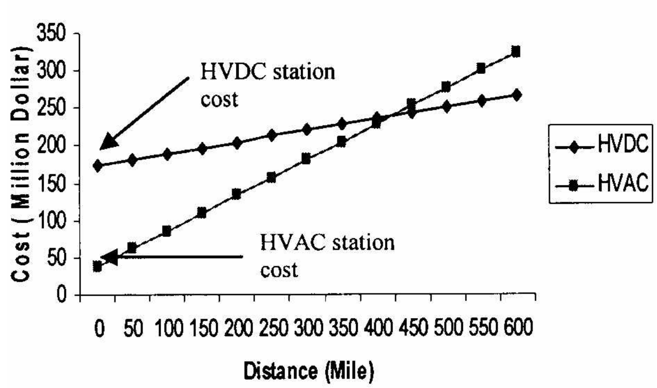

Fig. 1. HVDC and HVAC Transmission systems cost

V. ENVIRONMENTAL ASPECT

The purpose of the power transmission line is to carry energy from generation stations to urban or industrial places. To satisfy the growing need of the energy the transmission line capacity has been increased rapidly recent years, and this trend is continuing. The typical high voltage transmission line range is 400-1000 kV and this huge voltage has to cross all kinds of terrain - urban area, village, water, desert, and mountain. The effect of high voltage on the environment and human being is a topical and even controversial issue in recent year. This section discusses HVDC transmission effects on the environment in the context of Nelson River transmission system. The common effects of high voltage transmission systems are magnetic fields, electric fields, RF interference, corona effects, electromagnetic interference, electrodes, acoustic noise, and visual impact.

A. MAGNETIC FIELD

The magnetic field around a conductor depends on the current flowing through the conductor and the distance from the conductor. The magnetic flux density is inversely proportional to the distance from the conductor. For ± 450 kV DC transmission line the flux density is about 25 µT, where the Earth's natural magnetic field is 40 µT [9].

B. ELECTRIC FIELD

Electric field is produced by the potential difference between the overhead conductor and the earth and the space-charge clouds produced by conductor corona. Directly under the conductor has the highest electric field and is approximately 20 kV/m for a ± 450 kV transmission line [10]. The electric field may change with the weather, seasonal variation and relative humidity. DC has less electric field problem than that of AC because of the lack of steady-state displacement current; thus HVDC require much less right-of-way (ROW) than horizontal AC configuration and less height than the AC delta configuration of HVAC transmission of comparable rating [2].

The potential difference between land electrode and line conductor is termed as step voltage, can cause shock current. The typical human body resistance of 1000 ohms, a limit value of 5 mA current can flow through the human body safely and DC has the less electric current density, which is 70 nA/m^2 for ± 450 kV transmission line [10].

C. CORONA

Corona effects on the surface of high voltage overhead power transmission lines are the principal source of radiated noise. The ion and corona effects on the DC transmission lines lead to a small contribution of ozone production. The natural concentration of ozone in the clean air is approximately 50 ppb (parts per billion) and in the city area this value may reach 150 ppb. The limiting values for persons risk is around 180-200 ppb. The HVDC overhead transmission line produces 10 ppb as compared with naturally occurring concentration [9].

D. RADIO, TV, AND TELEPHONE INTERFERENCE

The switching process of the thyristor valves of the electronic converters causes fast current commutations and voltage changes, which produces parasitic current. The parasitic current and operational harmonic cause disturbances in the kilohertz and megahertz region of the radio-frequency spectrum [9].

These high frequencies propagate to the overhead line through the converter transformers. Radio interference radiation can be reduced by electromagnetic shielding of the valve hall. The radio-interference level of an HVDC overhead transmission line is lower than that of HVAC overhead transmission line. For the HVDC it is 40 dB (µV/m) for 0.5 MHz, 300 meter from the conductor, for the 380 kV HVAC overhead transmission line the value is 50 dB (µV/m) [2].

The fair weather corona-generated line radio interference is about 35 dB at 30 m and 40 dB at 15 m from the outer conductor at ± 450 kV [10].

The power line carrier frequency interference can occur at the frequency band 30-400 kHz. The thyristor operation produces the harmonics, and this harmonic current induces potentials in the lines as results of their electromagnetic fields. These potentials can interfere with the telecommunication systems electrically and magnetically. This interference can be reduced using appropriate filter circuits.

E. ACOUSTIC NOISE

The main sources of acoustic noise are the road and rail traffic, and very small portion come from the industrial plant like power plant. The subjective perceptions of acoustic noise nuisance are dependent on the amplitude, frequency and duration of the noise [9]. The accepted limit of the acoustic noise for the industrial plant depends on the local conditions but is generally between 35 and 45 dB (A). The HVDC transmission system contains numbers of subassemblies and components which cause noise. The transformer is the principle source of noise, and its noise mainly depends on the core flux density. The no load operational noises are 10 to 20 dB (A) higher than that of the rated load operation. With converter transformers, on the other hand the sum of all load noises is approximately 10 dB (A) higher than the no load noises, and the frequency content of the emitted noise is evenly spread over 300 to 3000 Hz. The noise can be controlled or reduced using high quality low noise equipments, enclosure of equipment to attenuate noise emission, shielding room or separating the noisy equipment by distance. For a typical HVDC station has a noise intensity of less than 10 dB(A) at a distance of 350 m [9-10].

The HVDC transmission line has less width for the right-of-way compare to HVAC transmission line and hence, DC transmission has less visual impact.

In general, from all environmental aspect, the audible noise could only be the limiting factor for HVDC line in meeting existing or future regulations.

VI. CONCLUSION

Long distances are technically unreachable by HVAC line without intermediate reactive compensations. The frequency and the intermediate reactive components cause stability problems in AC line. On the other hand HVDC transmission does not have the stability problem because of absence of the frequency, and thus, no distance limitation. The cost per unit length of a HVDC line lower than that of HVAC line of the same power capability and comparable reliability, but the cost of the terminal equipment of a HVDC line is much higher than that of the HVAC line. The breakeven distance of overhead lines between AC and DC line is range from 500 km (310 miles) to 800 km (497 miles). The HVDC has less effect on the human and the natural environment in general, which makes the HVDC friendlier to environment.

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VIII. BIOGRAPHIES

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