ENVIRONMENTAL CHARACTERISTICS OF HVDC OVERHEAD TRANSMISSION LINES

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1. INTRODUCTION

The range of applications of HVDC (High-Voltage Direct Current) technologies for electric power transmission is defined by the well-known technical and economical advantages of HVDC technologies. The most important of these advantages are:

- Simpler requirements for line tower construction in comparison with HVAC (High Voltage Alternating Current) transmission lines, and also lower per-unit costs, including costs per km of line and per MW of transmitted power;
- Significantly lower costs for cables of the same transfer capacity (relative to HVAC lines);
- The possibility of interconnection of power systems with different nominal frequencies (50 and 60 Hz) and systems using various frequency regulating standards;
- There are no limits imposed by stability considerations on the transfer capacity of HVDC lines;
- Additional reactive power compensators are not necessary when using long HVDC transmission lines;
- There is the possibility for independent power flows and frequency regulation in power systems that are connected via HVDC lines;
- Using HVDC power transfer significantly decreases the mutual influence of emergency processes in interconnected power systems;
- There is the possibility that power transfer can continue via one pole of a bipolar line even in when the second pole trips during an emergency.

In any specific transmission line application, one or several of the advantages listed above may take precedence in selecting HVDC transmission. At the same time, accounting for the environmental characteristics of power transmission is also of considerable importance.

The possible influences on the environment caused by *High Power Electricity Transmission Systems* can include:

- The effects of electric fields;
- The effects of magnetic fields;
- Radio interference;
- Audible noise;
- Ground currents and corrosion effects;
- The use of land for transmission line and substation facilities that was previously used for other purposes; and

- Visual impacts.

HVDC power transmission systems have particular characteristics related to all of these environmental influences. These HVDC-specific characteristics have to be taken into account in the process of choosing transmission line routings and in planning of a transmission line project. In comparison with HVAC transmission lines, several of these characteristics can be considered as "positive", that is, they are offer some environmental advantages to HVDC transmissions. Other HVDC characteristics are "negatives" from an environmental point of view, relative to corresponding characteristics of HVAC lines.

In the sections of this paper that follow, each of the ecological characteristics of transmission lines noted above are discussed with specific reference to the technical features of HVDC transmission systems.

2. EFFECTS OF ELECTRIC FIELDS

It is well known that the electric fields produced by a HVDC transmission line are the combination of the electrostatic field created due to the line voltage and the space charge field that is due to the charge produced by the line's corona. This means that presence of a charge between the conductors and the ground has an impact on the total electric field produced by the DC line.

Investigations of the environmental influence of HVDC transmission lines' electric fields were performed in several scientific centers, with the first studies done in IREQ (Institut de Recherche d'Hydro-Québec, Quebec, Canada). A Sizeable amount of work on this topic was also performed using the experimental transmission line section at NIIPT (the High Voltage Direct Current Power Transmission Research Institute, St. Petersburg, Russia). These investigations have shown that under a HVDC transmission line the typical discomfort to humans that is typically felt under HVAC transmission lines is not observed. This discomfort includes spark discharges from humans to bushes, grass and other vegetation. Discharges also occur under the influence of the HVDC transmission line electric fields. These discharges, however, are quite infrequent in contrast to the discharges caused by HVAC transmission line fields (which can be 100 discharges per second at 50 Hz).

Results of investigations performed by IREQ and by EPRI (the Electric Power Research Institute, California, USA), have shown that with a single discharge the level of streaming discharge perceptible to humans is 3 μK and with a repeated discharge the perceptible level is about 0.3 μK.

Using the experimental line section at NIIPT, measurements of the ionic current streaming through a human standing under a HVDC line at voltage level of ±1000 kV (kilo-Volts), and of the capacitive current under a HVAC line at a voltage 1150 kV were performed. These experiments indicated that the difference in current between the two technologies was approximately 100-fold (2-3 μA for the HVDC line, versus 0.2 mA for the HVAC line).

Subjectively, the sensation perceived by a human standing under a HVDC overhead line will usually not go beyond the electrostatic stimulation of hair movement on the head.

An interesting study was done in Canada, in which volunteers were exposed to DC fields of up to 50 kV/m and ion current densities of up to 120 nA/m^2. The objective of the study was to assess the ability of humans to detect the presence of these field conditions. The average threshold of detection was 45 kV/m. High ion current densities were associated with a substantial lowering of sensory thresholds in the majority of observers.

In addition, the experimental fact that large machines with rubber tires (such as combine harvesters, automobiles, and some others) are not electrically charged to levels dangerous for a human when the machines are standing under HVDC overhead lines should be considered a significant result of the investigation. The electrical resistance in the tires of these machines (at about 10 MOhm) turns out to be enough to prevent the accumulation of a dangerous charge (via charge leakage) even when the machine is standing on dry asphalt. In the case of HVAC overhead lines, inducted capacitive currents on large machines may be lethal in some cases.

These results suggest that electrical fields below HVDC transmission lines are not sufficiently hazardous as to necessitate significant safety measures, as the environmental influence.of a HVDC transmission line's electrical field is very limited.

The results of measurements show that in good weather the ion current density under HVDC overhead lines can vary from 10^2 to $5 \cdot 10^2$ *n*A/m^2 (nano-Amperes/square meter), which lead to an increase in the concentration of positive ions in the air from normal levels of 10^2 - 10^3 to 10^5 - 10^6 cm^{-3}. During precipitation events, however, this value can rise several times higher. Positive ion concentrations higher than 10^4 cm^{-3} are considered detrimental to health under conditions in which there is prolonged exposure of humans' respiratory tracts.

The level of space charge from HVDC lines is changeable and difficult to predict, as it is a result of corona activity and depends, among other factors, on weather conditions. The space charge present in the DC electric field produces an ion current flux. The total electric field and ion current flux measured near a transmission line are not steady and can be described by statistical parameters. Due to the statistical character of the impact of electric fields, there are different approaches used to limit the fields' effects.

The following types of guidelines are usually used to limit the environmental impact of electrical fields from transmisison lines.

- limits imposed on the total electric field of a DC line by a certain level of space charge; and
- limits imposed separately on the electrostatic field and on ion current density.

Russian regulations are designed to ensure the safety of people working in DC electric fields, and prescribe the limits to time of exposure shown in the Table below:

Field conditions	Time of exposure
E=15kV/m, J=20nA/m^2	t=8h
E=l5-20kV/m, J = 25 nA/m^2	t=5h
E = 20 - 60 kV/m	$t = \frac{(E_m)^2}{(E+\beta J)^2} t_1 \; ; \; \beta = 0{,}25 \frac{kVm}{nA}$
Em = 60 kV/m	t$_1$=lh
E>Em	-

In the Table above, E = electric field strength, and J = ion current density.

Based on the standards shown in this table, exposure and field strength limits for public areas can be derived. Providing that people do not stay in exposure areas for more than 8 hours, the limits are E = 15 kV/m and J = 20 nA/m^2.

Those regulations on transmission line field strength used in other countries that are known to the author are not easily comparable with Russian regulations, as regulations in other countries are presented in a very different form.

Codes and regulations limiting the electrical field environment impact exert the largest influence on the choice of the techniques used for overhead line construction, and on the resulting technical and economic parameters of transmission lines. At the same time, the regulations that would be applied to transmission lines used for grid interconnections in Northeast Asia are still uncertain. The regulations applicable to electric fields from transmission lines in different countries have differ in a number of essential ways. The Russian regulations described above are quite stringent, relative to regulations in some other nearby countries.

3. EFFECTS OF MAGNETIC FIELDS

The environmental impacts of transmission line magnetic fields on humans have been much less studied than the impacts of electrical fields. According to various estimates, the limit on the magnetic field strength of an AC power transmission system varies from 10 to 50 μT (micro Tesla).

The magnetic fields associated with DC lines produce no perceivable effects. The DC lines' magnetic field is in the same range of strength as that of the Earth's natural magnetic field. Due to the fact, that existing limits to magnetic field exposure in Russia are much higher than the exposure that would be encountered under an HVDC transmission line, there are practically no guidelines relating to the design of DC lines relating to magnetic fields.

4. RADIO INTERFERENCE

The radio interference caused by electric power transmission lines is the result of the corona discharge around conductors, which is generated only at positive voltages. As a result, on a HVDC line radio interference is generated only by positive pole conductors, whereas with a HVAC transmission line radio interference is generated by all of the three AC phases.

There is a also difference between HVAC and HVDC lines with regard to the impact that different weather conditions have on line-induced radio interference. The electric field intensities recommended for AC lines take into account a 10 dB (decibel) increase in radio interference under rainy conditions. With DC lines, the radio interference decreases during rains. In order to assure acceptable radio interference levels, a surface voltage gradient of about 25 kV/cm should not be exceeded for DC lines.

Assuming equal capacity conductors and maximum levels of electrical field intensity on the conductors' surfaces, the radio interference level of HVDC lines is typically lower by 6-8 dB than of HVAC lines.

5. AUDIBLE NOISE

Audible noise is one of the important design parameters for both overhead lines and substations. All known measures to decrease audible noise from these sources are quite costly.

In the substations used on HVDC systems, the main source of audible noise— the converter transformer—can be surrounded by screens when the noise level at the nearest premises is not acceptable.

Audible noise from DC transmission lines is a broadband noise with contributions extending to high frequencies. The noise is most prevalent in fair weather. Noise levels from a DC line will usually decrease during foul weather, unlike the noise levels on AC lines. As a rule, the audible noise from transmission lines should not exceed, in residential areas, 50 dB during the day, or 40 dB at night.

On the whole, the problem of limiting audible noise during HVDC and HVAC transmission line operation usually is addressed with the same types of measures on both types of lines.

6. GROUND CURRENTS AND CORROSION EFFECTS.

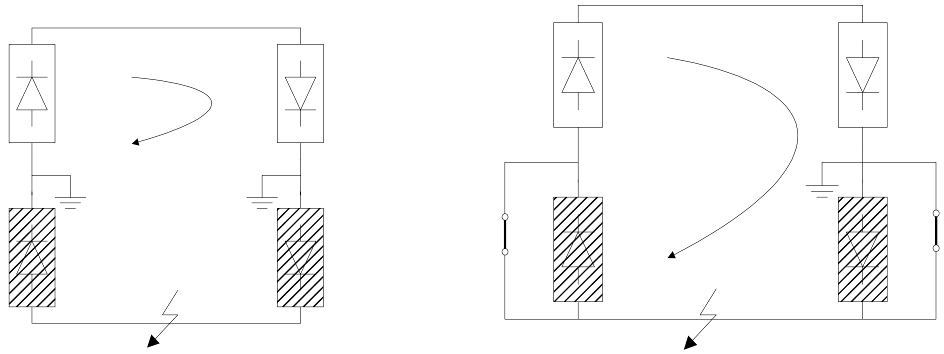
As was mentioned in the introduction to this paper, one of the advantages of HVDC transmission is the possibility of continuing power transfer even in the event of emergency outage of one pole of an HVDC bipolar system. Moreover, in some cases, monopole HVDC systems are used, mostly for submarine power transmission systems.

It is necessary to provide a return circuit for the current in order to utilize the capability of HVDC transmission to transfer power through one pole. Several possible circuit designs for use of the return current under conditions of nonsymmetrical operation are known. The choice of methods in each specific case is determined through a set of technical and economical computations.

For cable monopole HVDC transmission systems, current return is performed through the ground. In the case of an overhead line operating after an emergency outage on one pole, it is possible to use the wire of an emergency pole as the return circuit. Even in this case, however, it is necessary to provide the opportunity for the current to pass though the earth for some time. In several cases a special additional conductor, which normally serves as the lightning guard for the line, has been used to enable monopole operation of a HVDC overhead transmission line, . In case of quadrapolar line designs, that is, designs with two bipolar HVDC lines situated on one set of towers or routed through the same corridor, the overload capacity of the HVDC line's conductor can be used. Typically, a HVDC overhead transmission line conductor's effective cross section, which is determined by an economic computation process during the line design phase, can transfer redoubled current in comparison with its nominal capacity without any danger of overheating.

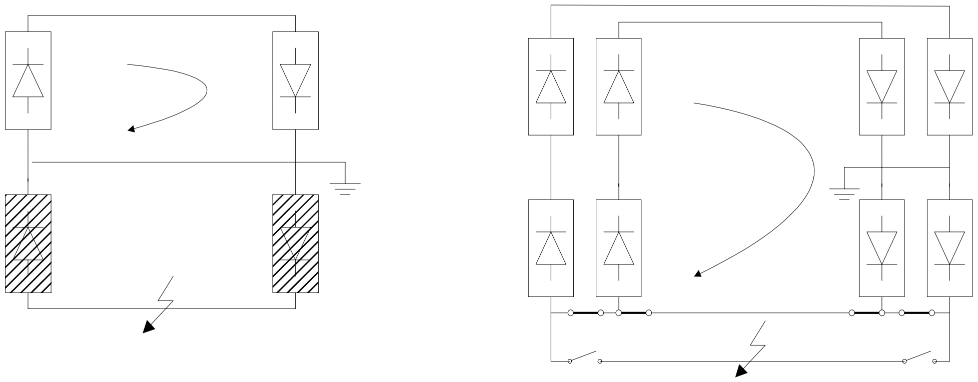
In Figure 1, all four of the aforementioned return current circuit variants are shown. Only in the first variant is the ground used as a conductor. In all other cases, the so-called "metallic return" is utilized. When the "metallic return" is utilized, HVDC power transmission does not introduce any additional environmental impact in comparison with HVAC transmission lines.

When current return is through the ground, however, several peculiarities appear. The current path between grounding installations of HVDC converter substations lies through the whole thickness of the globe (see Figure 2a) and its environmental impact on the surface is limited to the moderate area near grounding installations. If, on the other hand, there, is any accompanying conductor, for example a pipeline, current returns using this conductor (see Figure 2b).



1. Via permanent grounding installation.

2. With emergency pole's conductor usage



3. With lightning rope or special conductor usage

4. Quadrapolar transmission line overloading possibility

Figure 1. Basic variants of return current circuit organization for monopole operation

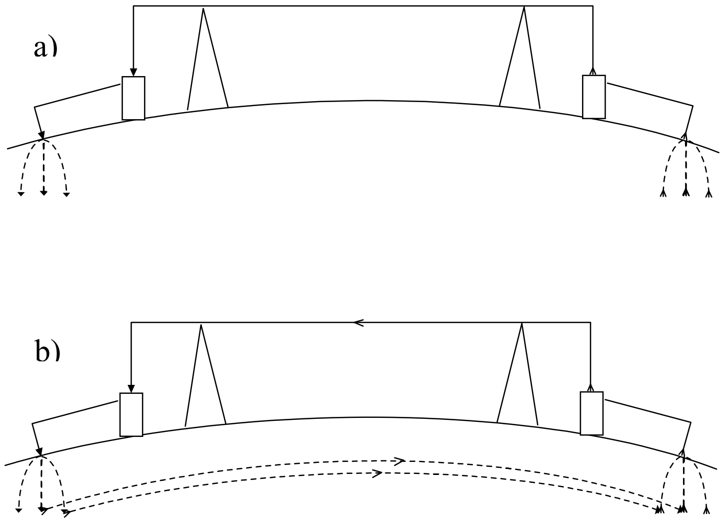


Figure 2. Current return via grounding installations

The latter path for current return presents a danger to buried metal infrastructure (for example, footings or pipelines) by way of electrocorrosion. The danger level depends on the one hand on the quality of electrical insulation and special defenses against corrosion used in the metal infrastructure present, and on the other hand, on the integral value of the current passing through the object (in A*h).

Overhead HVDC transmission lines are usually bipolar. That is why the operation of such lines as monopoles is typically transitory in nature. In all cases except operation with an additional conductor, however, some operation as a monopole cannot be avoided. Furthermore, because of the dissymmetry of the bipolar scheme, a prolonged current passing through the ground exists. Usually the dissymmetry current is estimated as 1-3% of the nominal current value.

The most complex grounding systems for the HVDC substation exists if there is no expected possibility of any variant of the "metallic return" being used. Usually, in these cases, grounding electrodes are situated in some distance from the substation (see Figure 3) to exclude the possibility of corrosion of the substation's underground components. The grounding installation must have a design that excludes the possibility of dangerous step voltages appearing in a grounding electrodes zone. Electrodes are made from the special materials. Special measures are applied to prevent the ground from drying or becoming fossilized (and thus, in both cases, losing its properties as a conductor).

If there are pipelines or other underground metal objects near the grounding installation, it is recommended that additional cathodic protection of such objects be provided to allow prevent rapid corrosion.

7. LAND USE CHANGE FOR TRANSMISSION LINE AND SUBSTATION.

The most important of environmental index related to transmission line construction is the conversion of land use for the transmission system. The land requirements per unit of transfer capacity for HVAC and HVDC substations are practically the same, because the converters themselves occupy comparatively small areas. In cases, however, where grounding installations for current return through the ground are necessary, additional land use for grounding installations and for the transmission line from the substation to the grounding installations add to the total land area needed (see Figure 3).

The largest amount of land used for HVDC or HVAC transmission systems is used for the overhead transmission line. Under the term "land use" the total area used for towers and also the for the transmission line right-of-way is included. In woodland areas the width of forest that must be cut to provide the transmission line right-of way has to be taken into consideration.

The area of land use, as the major ecological index of a transmission system, depends mostly on the system reliability requirement for the line. Depending on the maximum allowed value, based on a probabilistic assessment, of the emergency power drop in the receiving part of a transmission system, the HVDC transmission system can be implemented as one bipolar line, as a quadrapolar line with circuits situated on one tower, as two bipolar lines in one corridor or, lastly, as two bipolar lines that are located in different corridors. In each of these cases, the land use per MW of transmitted power is quite different.

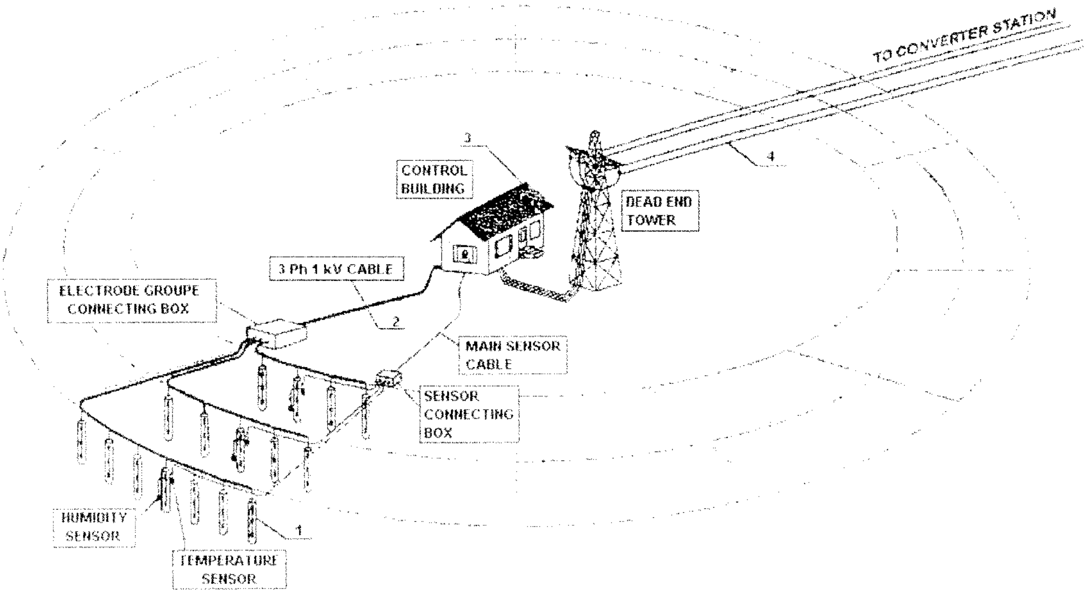


Figure 3. Connection of grounding electrodes

For estimating the absolute values of land use, the following data for a project using a ±500 kV, 2000MW bipolar HVDC transmission system with current "metallic return" can be presented as an example. In this case, the area for the converter substation of the transmission system is about 90000 m^2. The area required for the transmission line right-of-way is 100000 m^2 per km of line length.

A crude comparative estimate of overhead HVDC and HVAC transmission lines shows that in a case where equal transfer capacity is assumed for each technology, the reliability requirements and costs of environmental measures and the area of total land use and line right-of-way for an HVDC transmission line is 1.5 times less than (about two-thirds of) that for an equivalent HVAC line. Depending on the specific conditions, this ratio can be higher than or approximately equal to 1. The advantage of a HVDC systems over a HVAC system depends on the aforementioned ecological advantages and also on the HVDC systems' capability to provide continued power transfer via one pole of a bipolar line even in when the second pole trips during an emergency. Taking into account the large length of the line and the necessity in crossing densely populated areas, national parks, and woodlands with valuable trees species, the difference in land use between the two options seems to be quite important.

8. VISUAL IMPACT

When transmission lines cross populated areas and especially national parks, resorts and other territories where conservation of the natural landscape is important, special demands are placed on the transmission line's dimensions. For example, it is sometimes necessary to limit the height of the towers with the height of the trees in a woodland, so that the transmission line itself is largely obscured. Special demands are then placed on the aesthetics of the design of the line.

In cases where there are especially rigid aesthetic requirements, cable inserts have to be used, which leads to a rise in the cost of a transmission project. In cases where only overhead lines are utilized, the length of the route that a line must take increases if protected areas need to be avoided, or if different towers designs must be used. These changes also typically lead to increases in line expense as well.

HVDC overhead transmission lines offer several advantages from the point of view of visual impact relative to HVAC lines of the same capacity. Bipolar HVDC transmission lines have two conductors and already because of that it are more simple in design in comparison with the three-phase structure of a HVAC line. HVDC lines require shorter tower heights in comparison with HVAC lines of equal capacity and comparable voltage levels.

If quadrapolar HVDC lines are used, then towers can be designed as flat towers or towers with 2 cross-arms, depending on the specific conditions in the transmission corridor. In Figure 4 a schematic view of these tower types for a ±500 kV HVDC line are shown, with approximate tower dimensions indicated. There is thus a choice of tower design options depending on the specific requirements for the line. In each case, however, the dimensions of the towers for the quadrapolar line are smaller than those for comparable double-circuit HVAC lines.

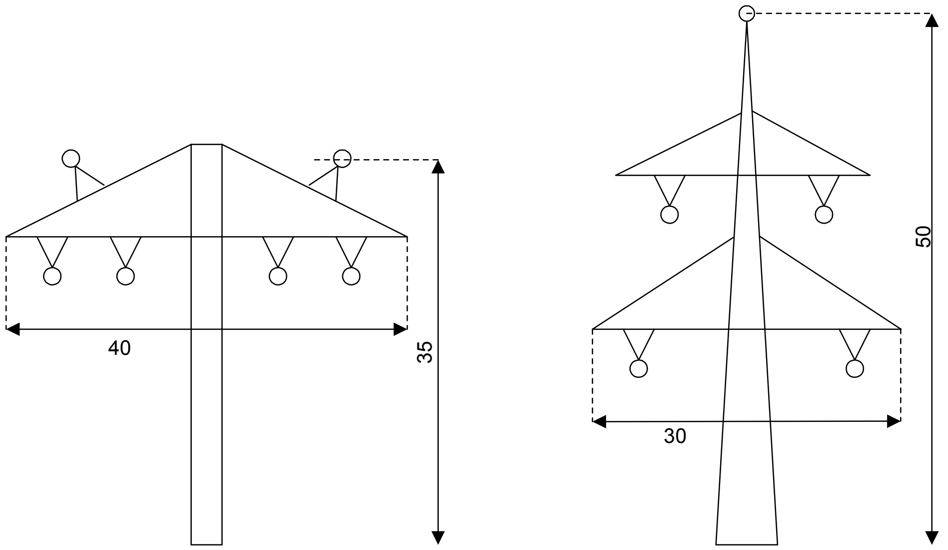


Figure 4. Schematic of two variants for construction of ±500 kV quadrapolar HVDC transmission line towers: with one (flat tower) or two crossarms

If there is a necessity for cable inserts to protect aesthetic values in certain areas, HVDC lines have economic advantages in comparison with HVAC lines, as HVDC cable is significantly cheaper than HVAC cable of the same capacity. If the length of a cable to be buried is significant, in the case of HVAC cables it is necessary to compensate for the surplus charge capacity of the buried cable.

In addition to aesthetic considerations, the necessity to include (buried) cable inserts in a line can also occur in cases where various obstacles are encountered in the routing of a transmission line. It is possible, for example, to lay cable in railroad tunnels crossing mountain massifs. In all of these cases, the more structurally simple HVDC cables offers advantages to HVDC transmission systems.

9. CONCLUSION

During HVDC transmission line project planning, nearly the same environmental impact characteristics that are considered in planning a HVAC transmission lines project should be taken into consideration. These characteristics include impacts from electrical and magnetic fields, radio interference, audio noise, the potential fast corrosion of metal installations due to electrical currents in the ground, the land alienation (use changes) involved in siting transmission line towers and substations and, also, the potential changes in and limits on land use under and near overhead transmission lines. In some cases, the visual impacts of lines also have to be considered

The combination of several specific physical characteristics and related technical aspects related to line construction and operation, HVDC transmission lines have advantages over HVAC transmission lines for a majority of environmental impact indices. These advantages allow environmental performance to be improved at lower costs when installing HVDC lines, relative to HVAC lines. The value of land use changes can be taken as an overall index for the comparative analysis of the environmental impacts of HVAC and HVDC transmission lines of the same relative capacity. Based on a rough estimate, this ratio is 1.5 in favor of the (lower cost) HVDC transmission lines. Thus, from the ecological point of view, a HVDC power transmission system as a whole is preferable to a system using exclusively HVAC transmission lines.