The operating voltage of power transmission lines

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INTRODUCTION

We may see it said that a high voltage AC power transmission line operates at a voltage of “230 kV” or such. And we may see that a high voltage DC transmission line operates at a voltage of “800 kV”, or perhaps at “±500 kV”, or such. But what do those voltage numbers mean? Especially for the DC lines, the conventions are not always clear, nor consistent. This article reviews this matter.

1 HIGH VOLTAGE AC TRANSMISSION LINES

1.1 Three-phase basis

The preponderance of high power, high voltage transmission lines in the US operate on a three-phase AC basis (the meaning of which will be explained shortly), I will limit my discussion of AC transmission lines to that formulation.

I will work from Figure 1.

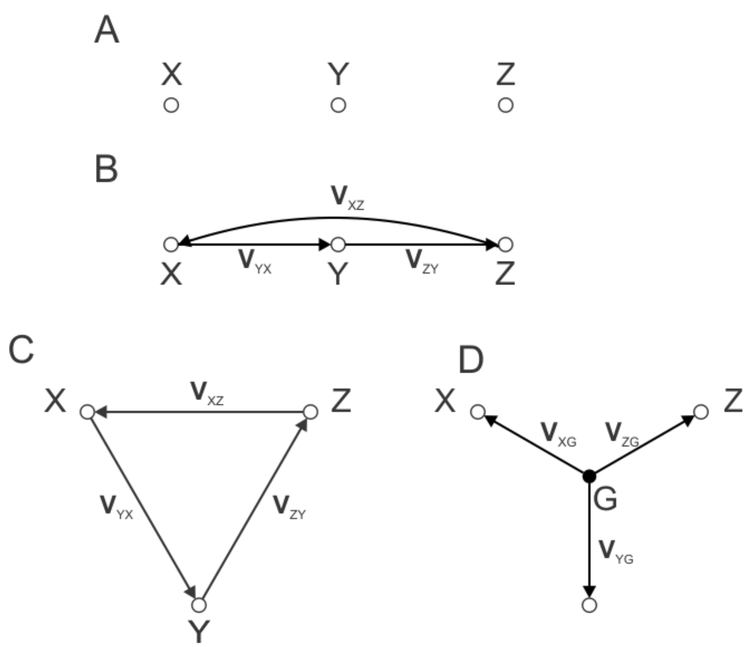

Figure 1. Voltages in a high voltage AC transmission line

1.2 Three conductors

These power lines almost universally use three essentially identical conductors, often arrayed in the same plane, as suggested by panel A of the figure, arbitrarily labeled there as conductors "X", "Y", and "Z".

In panel B, we see labeled three voltages with which we will be mostly concerned (the interconductor voltages), using "voltage arrow" notation. The subscripts indicate between which two conductors the voltage is defined; for sample, voltage V_{YX} is the voltage of conductor Y measured with respect to conductor X.

As is usual with AC circuits, it is ordinarily the RMS value of the voltage that is considered.

This view of the voltages in a three phase circuit—the interconductor voltages—goes with the "delta" outlook for a three phase circuit.

1.3 Phase angles

Ideally the magnitudes of these three interconductor voltages are the same, but the three voltages have different phase angles, equally spaced at an interval of 120°. It is from this that the moniker of this transmission configuration—"three phase"—comes.

Panel C shows these voltages in phasor notation. (A phasor is a geometric vector that portrays the magnitude and phase angle of an AC waveform. It is often called just a "vector".)

Rather than showing those three phasors on an absolute basis (each phasor radiating from the origin of our plot), I have drawn them on a "floating" basis, so as to graphically show their summation as we "go around" this three-phase circuit. And I have drawn at each of the nodes the small circles that represent the three conductors of this circuit so as to remind us of how the three voltages are defined.

1.4 The sum of the three phasors

We note that the three interconductor voltage phasors make a closed figure, meaning that the net voltage "around the circuit" must be zero, as required by Kirchhoff's voltage law for any closed path through a circuit.

1.5 The voltages to ground

There is no implication that the voltages to ground from the three conductors will be equal, but in practice steps are usually taken so this will be so. In panel D, we see the three phasors for the conductor-to-ground voltages in that situation. It can easily be demonstrated by trigonometry that the magnitudes of the conductor-to-ground voltages are $\sqrt{3}/2$ times the the magnitudes of the interconductor voltages (that is, times the "stated operating voltage" of the transmission line).

This view of the voltages in a three phase circuit—the interconductor voltages—goes with the "wye connection" outlook of a three phase circuit (that word is a spelling of "Y").

1.6 The "stated" operating voltage

By convention the "stated" operating voltage of the transmission line is the interconductor voltage.[1]

2 HIGH VOLTAGE DC TRANSMISSION LINES

2.1 Introduction

The first high power, high voltage DC (HVDC) power transmission lines were built several decades ago, but it took modern technology to allow widespread attainment of the full potential of this approach. Today, many DC transmission lines using very high voltages are in operation or under construction, using a number of configurations. I will discuss several of those here.

2.2 Caveat

I show the AC-DC and DC-AC converters involved in this technology as simple "black boxes", but (especially due to the extremely high voltages involved) they are actually very complex, intricate, and clever. And there are ever so many variations in implementation. The details of this are not necessary to the points being made by this article, and are beyond its scope.

But one reality is that this diversity of implementation can blur somewhat the boundaries between what I simplistically speak of as "different" configurations.

That having been said, this simplified outlook should nonetheless adequately provide for explanation of the way in which the "operating voltage" of a high-voltage DC transmission line is stated.

Nonetheless, in a later section we will "peek a little" into the details of a typical AC-DC converter circuit.

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[1] This is sometimes spoken of as the "delta connection" voltage of a three-phase power circuit,

2.3 About “poles”

It is very common in the field of high voltage DC transmission lines to speak of the (usually) two conductors of the transmission line as its “poles”. This is consistent with the common description of the two terminals of a DC power supply as its “poles”. That notwithstanding, I will speak here of the transmission line conductors as “conductors”.

2.4 The unipolar ground-return configuration

2.4.1 *Description*

This configuration is illustrated in Figure 2.

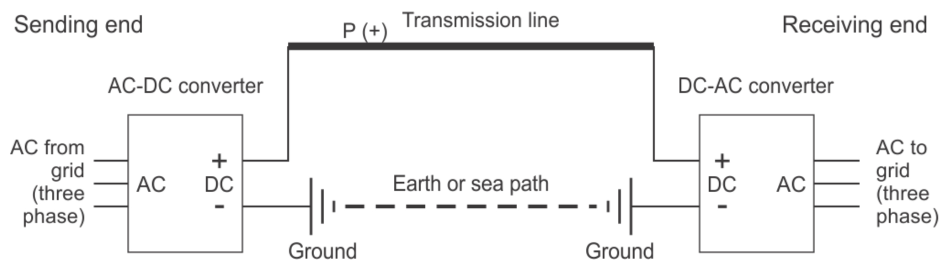

Figure 2. HVDC transmission line—unipolar ground return configuration

Here, at the sending end, one side of the output of the AC-DC converter is connected to the sole transmission line conductor. For various reasons, most commonly it is the positive side of the converter output that goes to the line conductor (and accordingly I have labeled it, for consistency with following illustrations, “P”).

The other side of the DC converter output (here, the negative side) goes to ground, an earth ground if the transmission line is “over ground”, but perhaps a sea ground if the transmission line is over a body of water (preferably sea water).

I note that this ground might be (for an earth ground) an elaborate “field” of interconnected ground rods driven into the earth. It might in fact not be immediately adjacent to the sending “station”, but might be at some distance (at a location where the earth conditions are “better” for this purpose), connected to by a conductor of some sort (often buried, even if the transmission line conductor is “aerial”).

Correspondingly, at the receiving end, there is a DC-AC converter. Its input is connected between the line conductor and ground, this again perhaps being an elaborate ground field, again perhaps not immediately adjacent to the station.

The overall circuit path is thus carried through the earth (or sea). This saves the cost of a second line conductor, but can bring its own problems. Most notably, the currents through the earth (or sea) can cause electrolytic corrosion of other structures, such as buried telephone cables, metallic pier structures, and the like.

And of course there is typically substantial energy loss in the effective resistance of the "ground" path, which might at best be substantial.

2.4.2 *The "stated" operating voltage*

Quite naturally, the "operating voltage" of such a system is stated as the voltage of the DC output of the sending AC-DC converter, which is also the voltage to ground of the (sole) transmission line conductor.

2.5 The unipolar two conductor configuration

2.5.1 *Description*

The problems mentioned above can be averted by having a second conductor in the transmission line, as seen In Figure 3.

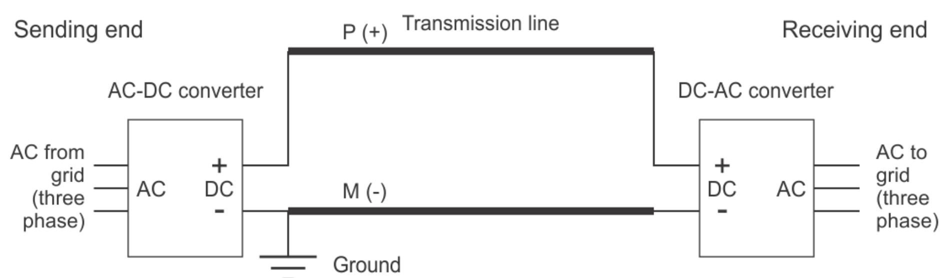

Figure 3. HVDC transmission line—unipolar two-conductor configuration

Here, the transmission circuit is through a two-conductor line, but one conductor is at ground potential (I have labeled it here "M", for "minus". The advantage of this is that this conductor does not have to be insulated from ground as it goes. This eliminates the substantial cost of the high-voltage insulators that would otherwise be needed for that conductor in an aerial line (or the cost of a second seriously-insulated conductor in an underground cable).

2.5.2 *The "stated" operating voltage*

Again quite naturally, the "operating voltage" of such a system is usually stated as the voltage of the DC output of the sending AC-DC converter, which is also the voltage to ground of the (sole) transmission line conductor.

2.6 The balanced unipolar configuration

2.6.1 *Description*

In this configuration, at the sending end there is (at least conceptually) a single AC-DC converter. Its DC output goes between the two conductors of the transmission line. We see this in Figure 4.

In order that the magnitudes of the voltage on the two conductors be nominally the same (we will learn shortly of one reason that is desirable), there is what we can think of as a “centertap” on the DC output of the converter at the sending end that is connected to local ground there, thus resulting in the magnitudes of the two conductor voltages to ground being essentially the same.

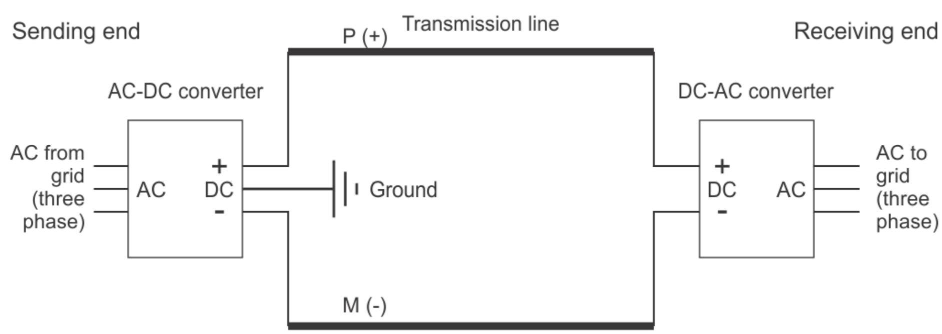

Figure 4. HVDC transmission line—balanced unipolar configuration

At the receiving end, there is (conceptually) a single DC-AC converter, the AC output of which feeds the recipient grid.

A major advantage of this configuration over the unbalanced unipolar configuration is that for the same voltage between the two conductors, the voltage to ground of both is only half the voltage to ground of the “hot” conductor in the unbalanced unipolar system.

There are a number of advantages of this. One is that, while we now need, simplistically, twice the number of insulators, since their cost typically varies faster than linearly with the voltage at which they must operate, the overall cost of the insulators may be less than for the unbalanced configuration.

2.6.2 *The “stated” operating voltage*

Probably because of the vision of the designers of systems of this type as being energized by a single AC-DC converter, it seems to be the most common to state the output voltage of that converter as the “operating voltage” of the system. (This is also consistent with the convention for AC transmission lines.) This is also the interconductor voltage of the transmission line.

2.7 The bipolar configuration

2.7.1 *Description*

Perhaps the most important configuration today is what is often called the "bipolar" configuration. In this, the transmission line principally (perhaps wholly) comprises two conductors (either aerial or in a cable). We see this in Figure 5.

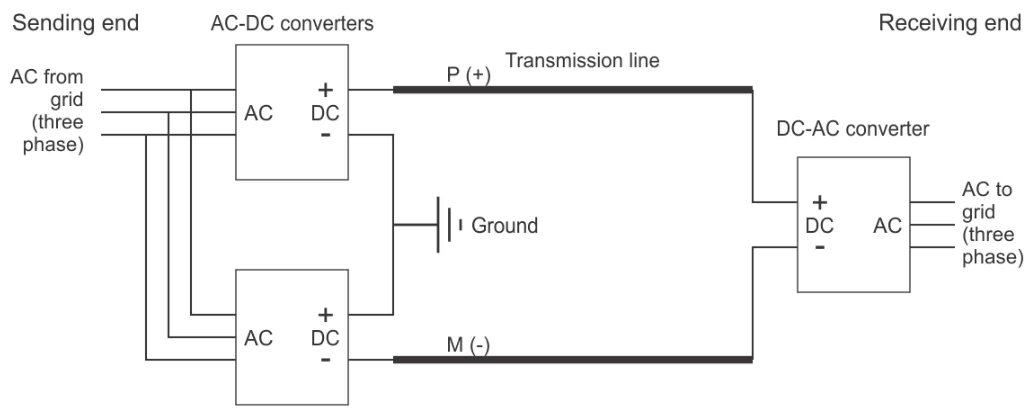

Figure 5. HVDC transmission line—bipolar configuration

At the sending end the two conductors of the transmission line are each fed (against ground) a high DC voltage developed by independent AC-DC converters. The magnitudes of the voltages on the two conductors are nominally equal, but the polarities are opposite. I have arbitrarily labeled these conductors for reference as "P" (the "plus" conductor) and "M" (the "minus" conductor).

At the receiving end, the voltage between the two conductors goes through a DC-AC converter, the output of which feeds the recipient AC power grid. It does this in such a way that it honors the frequency and phase of the grid voltage.

2.7.2 *Distinction rather arbitrary*

Note that the distinction between this configuration and the "balanced unipolar" configuration seen in Figure 4 is rather arbitrary, depending more on how we look at the sending end implementation than on any intrinsic difference in the actual transmission arrangement..

2.7.3 *The "stated" operating voltage*

Probably because of the vision of the designers of systems of this type as being energized by two separate AC-DC converters, it seems to be the most common to state the "operating voltage" of the system as the output voltage of that of either converter (that is, the magnitude of the voltage to ground of either line conductor). This is often stated in the form "±500 kV". The "±" is a hint of what this notation means.

But sometimes a "±500 kV" transmission line will be spoken of as a "500 kV" transmission line, or even as a "1000 kV"(or "1 MV") transmission line, the latter being based on the interconductor voltage (as is almost universally done for AC transmission lines).

2.8 The bipolar configuration with a neutral conductor

2.8.1 *Description*

In some cases, the two major conductors are accompanied by a "neutral" conductor, typically of smaller cross section than the major conductors (and thus having a lower current-carrying capacity and greater reactance per unit length).. We see this in Figure 6.

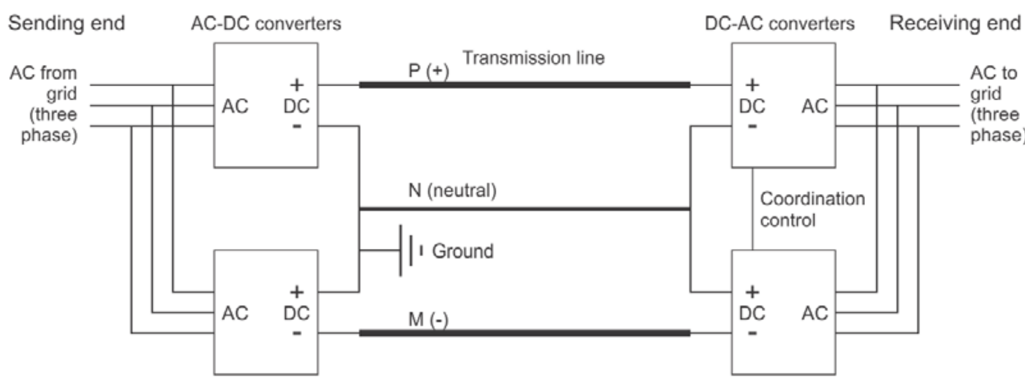

Figure 6. HVDC transmission line—bipolar configuration with neutral conductor

At the receiving end, there are two DC-AC converters, each operating from between one of the major conductors and the neutral conductor.

The converters are forced by coordination control circuitry to each draw from its supply conductor the same amount of current, so they equally contribute to the total AC power pushed into the recipient grid. Thus the net current in the neutral conductor is small (ideally zero), and thus there are no significant losses in it despite its relatively high resistance per unit length.

2.8.2 *The "stated" operating voltage*

The expression of the operating voltage of systems of this type is typically as described for the basic bipolar system in Section 2.7.3.

3 A CLOSER LOOK INTO THE AC-DC CONVERTER

3.1 Introduction

I said before that we need not be concerned with the internal configuration of the AC-DC and DC-AC converters for our purposes here. Yet by taking a peek inside, we can see why some of the distinctions made between types of DC transmission seem arbitrary. Keep in mind that these peeks inside are illustrative and simplified.

3.2 A "balanced unipolar" sending end comverter

In Figure 7, we see an illustration of the AC-DC converter at the sending end of what is considered a "balanced unipolar" system.

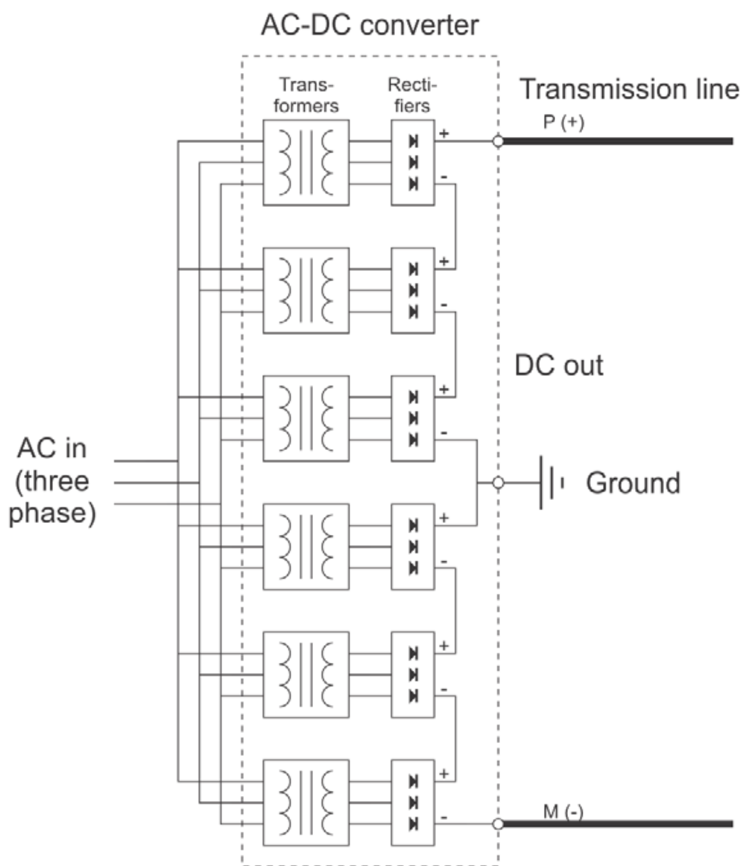

Figure 7. Unipolar AC-DC converter (balanced operation)

A challenge in the design of such a converter is that we do not directly have practical rectifier diodes that are suitable for operation at the immense voltages of these systems. One solution is as seen in the figure. The converter is actually made of a number of converter circuits, operating at more moderate voltages, with their outputs connected in series. Here we show such a configuration with six of these inverter circuits. There might in fact be more than that many.

The input is three phase AC (typically at a relatively high voltage). I show the "transformer" as a transformer symbol inside a box. This actually represents a three phase transformer, which might really comprise three transformers, interconnected, or might be special type of transformer with three "legs" to is magnetic circuit.

Similarly, I show the "rectifier" as three diode symbols in a box. This represents a special rectifier circuit that runs from three phase AC. Also, in reality, these rectifiers will usually use some sort of gated semiconductor device. This allows control of the DC output voltage of the rectifier in the face of variations of the input voltage and in face of various loads on the DC output.

We note that the "center tap" of such a converter, to be connected to ground, is easily arranged for.

3.3 A "balanced unipolar" sending end converter

In Figure 8, we see an illustration of the AC-DC converter system at the sending end of what is considered a "basic bipolar" system.

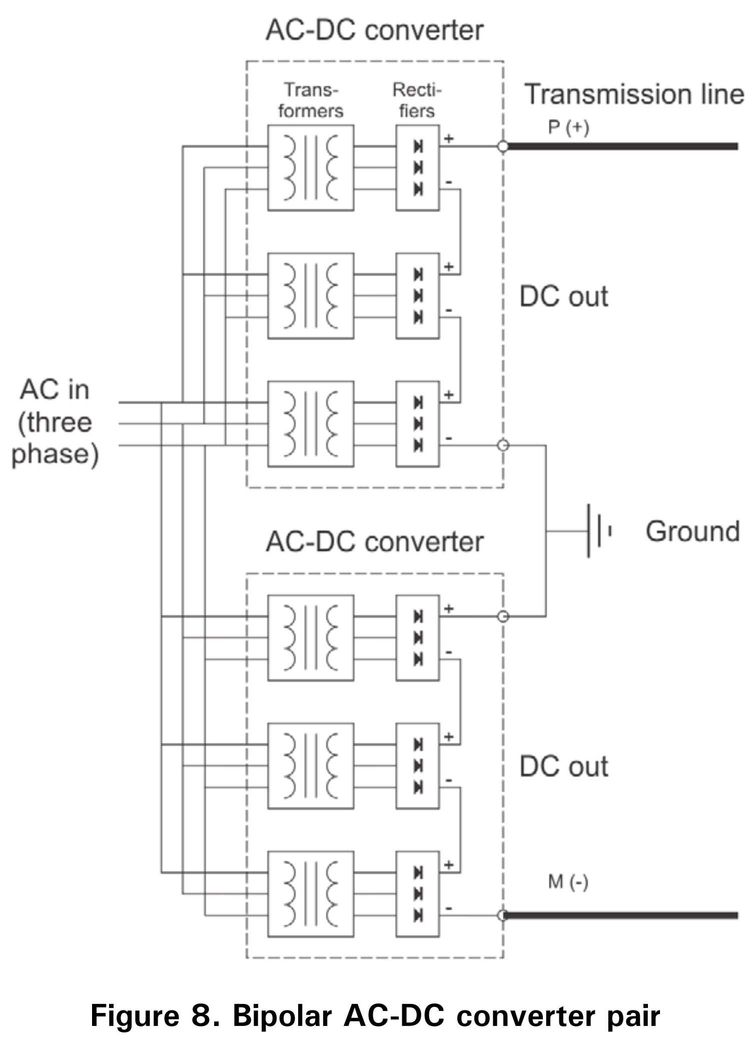

Figure 8. Bipolar AC-DC converter pair

I show each of the two converters involved with three inverter circuits, this being consistent with the previously illustrated system, if we assume that the conductor-to-conductor voltage is the same for each system, thus the output voltage of each inverter here is half that of the single inverter seen in Figure 7. So we might imagine that the needed number of inverter circuits, assuming essentially the same design, in each converter would be half the number seen in the earlier example.

3.4 A distinction without a difference?

I note that in this admittedly-simplistic view, the only real difference between the DC source in Figure 7 and that in Figure 8 is how much is included in the box(es) I label “AC-DC converter”.

Accordingly, we might well ask this question: “Is the center-tapped AC-DC converter seen in Figure 7 (and Figure 4) actually different conceptually from the pair of AC-DC converters seen in Figure 8 (and Figure 5)?” I think not really.

Thus my earlier observation that the *balanced unipolar* configuration and the *bipolar* configuration have different names only because of the history of their evolution.

4 IN PARTING

4.1 An inconsistency

Note that, perhaps because of the original implementation visions of the designers of two important kinds of systems (the distinction between which is today blurry at best), we have this inconsistency:

- For a system that is considered *balanced unipolar*, the operating voltage is most often expressed as the voltage between the conductors of the transmission line.

- For a system that is considered *bipolar*, the operating voltage is most often expressed as the voltage to ground of the conductors of the transmission line (sometimes, but not always, stated in the form “±500 kV”).

4.2 Beware

Accordingly, the reader is urged, when encountering mention of the operating voltage of an operating or proposed HVDC transmission line, to be cautious as to its meaning.

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