The Future of Transmission Technology

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Historic Perspective

The AC transmission systems of the early 20th century were remarkable. Power could be injected where convenient and taken out where needed. For the most part it traveled on paths most able to accommodate it and when a line was lost, redistributed itself along alternative paths. All of this without controls. Utilities kept plenty of reserve generation and built enough transmission to allow dispatch and exchange flexibility. Higher voltages were adopted as needed. The rate base absorbed all of this. Systems were robust.

"Camelot" was first threatened in the 60's when environmental sensitivity began restricting new line construction. Deregulation finished the job by segmenting the industry, imposing a new market paradigm, and diffusing responsibility for reliability.

Pressure to increase the capability of a near-static matrix of transmission lines, the once-simple AC network began adding fixes. Phase-shifting transformers, series capacitors, reactive power sources, once rare, became commonplace. Power electronics is making them "smart" as well. New flow enhancement options are introduced every year…devices which, sensing an increase in line current, take in slack on limiting spans to prevent excess sag…Sausage-shaped devices which insert a small series quadrature voltage on a span-by–span basis. . This paper will make no attempt to summarize these adjuncts to AC systems, but will focus instead on more fundamental transmission options.

New AC Transmission Line Options

The pressures cited above prompted many engineers to seek ways to increase the *inherent* capacity of new AC lines by inventing better conductors and arraying them to achieve lower impedance. Conductors are now available with composite reinforcement (ACCR) that doesn't expand much with temperature…a boon in sag reduction both for new lines and where existing lines are up-rated for higher current.

In the mid 1960's it was observed that rather than going to higher voltage, the number of phases could be increased from three to six, twelve, or more, each step reducing impedance but requiring no more transmission cross section area. The limit: - an anisotropic tube that conducts longitudinally and insulates circumferentially. [1]

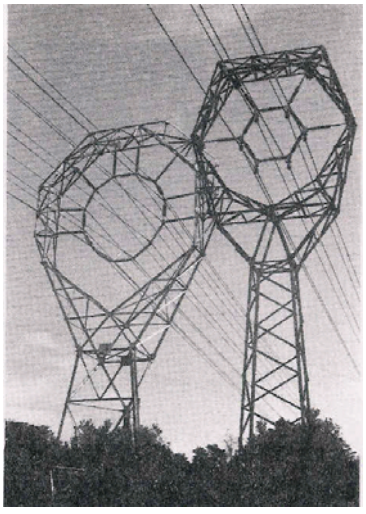


Fig. 1 12 and six-phase 138 kV towers

In the late 1970's both six and twelve phase lines were built, tested, and shown to work as predicted. [2] Other theoretical work was done on compact lines and the idea of suspending a circuit as though it were an insulated conductor bundle. It could, with the aid of ACCR conductors, allow some low voltage single circuit towers to carry three separate circuits. [3]

A less dramatic but quite practical idea, now in use both in Russia and Brazil, greatly expands mid-span intra-bundle spacing thereby achieving very low reactance and higher than normal reactive power generation. [4] Thus the last trick on AC line configuration has probably not yet been invented.

HVDC's Role

HVDC, first introduced in 1934, is still advancing technically. Voltage source converters now broaden the range of economic applications while cost efficiencies continue to be made in conventional terminals. With these advances, it's tempting to ask, "At what point in the growing power-electronic-dependence of AC systems, is it better to simply convert selected lines to HVDC, thus boosting capacity, limiting short circuit current, limiting system oscillations, and better adapting the system to the energy marketplace?"

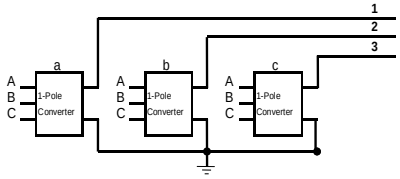
Fig. 2 Example Segmentation of the N. American system

A few more courageous engineers have already suggested that the US interconnection be segmented, each piece operating as a more natural AC system and the pieced linked asynchronously; a direction China has taken. Their major AC systems are coupled only by HVDC, thus allowing interchange without risk of propagating disturbances.

Unfortunately conversion of AC lines to DC is a costly proposition. Terminals are very expensive when compared to AC system adjuncts. The cost of DC terminals, installed for conversion, is based on the total DC rating, but must be written off over just the *incremental* capacity achieved. Furthermore, at least for single circuit lines, bi-pole HVDC uses only two thirds of a very expensive transmission line asset.

The balance of this paper will address an idea which mitigates, in part, both of these cost barriers. It began with the question, "If you convert an AC circuit with three phase positions, why not use three poles?" Fig. 1 shows such a "tri-pole" terminal. It allows all conductors to actively conduct direct current. [5]

Fig. 4. Applying a DC converter pole to each phase of an AC transmission line



If pole 1 is positive, poles 2 and 3 could be negative, sharing the return current. If pole 1's current is above thermal rating and the two return currents below that rating, then the bridges can rotate the overload among poles. That way each conductor sees a high current a third of the time, relieved by a low current two thirds of the time. The levels of current can easily be adjusted to assure that the resulting current on each pole equals its rms current rating – a form of "thermal averaging." A regime of high and low currents of that sort with a period of four minutes would cause a typical overhead conductor swing +/- 2^{o} C in temperature…comparable to variations caused by puffs of wind or changes in cloud cover. With one exception, terminal equipment (transformers, filter reactors, etc.) is also capable of thermal averaging over a time period of that nature. The thyrite element of a valve, having a very short thermal time constant, must be rated for the highest current.

Modulation Options

Any means of rotating the over-current among poles requires that at least one pole be capable of reversing current. Voltage has to be reversed at the same time to keep power flowing in the same direction. Bi-directional valves of this kind are already in use with Static Var Systems. Alternatively, one could simply use standard valves connected in anti-parallel. If all three poles of

the tri-pole scheme are reversible in voltage and current, a variety of symmetrical modulation options are possible. Some are shown in fig. 5. The columns on the right show (1) the ratio of peak current to the current for a bi-pole option, (2) the ratio of tri-pole power to bi-pole power using two vs. three conductors, all at their full thermal rating and (3) tri-pole losses as a percent of bi-pole losses for the same power transmitted.

Because form factor (the ratio of rms to average current) differs for each modulation, full rms line current corresponds to different levels of transmitted power. Certainly the bi-pole (fig. 5a) with a form factor of 1 is most efficient but is limited to two conductors. Fig. 2c, showing the most efficient of the symmetrical modulation forms, transmits 41% more power than a bi-pole using only two of the three-conductor array. For the same transmitted power, its losses are 25% less than the bi-pole – not surprising since the current is deployed over three rather than two conductors.

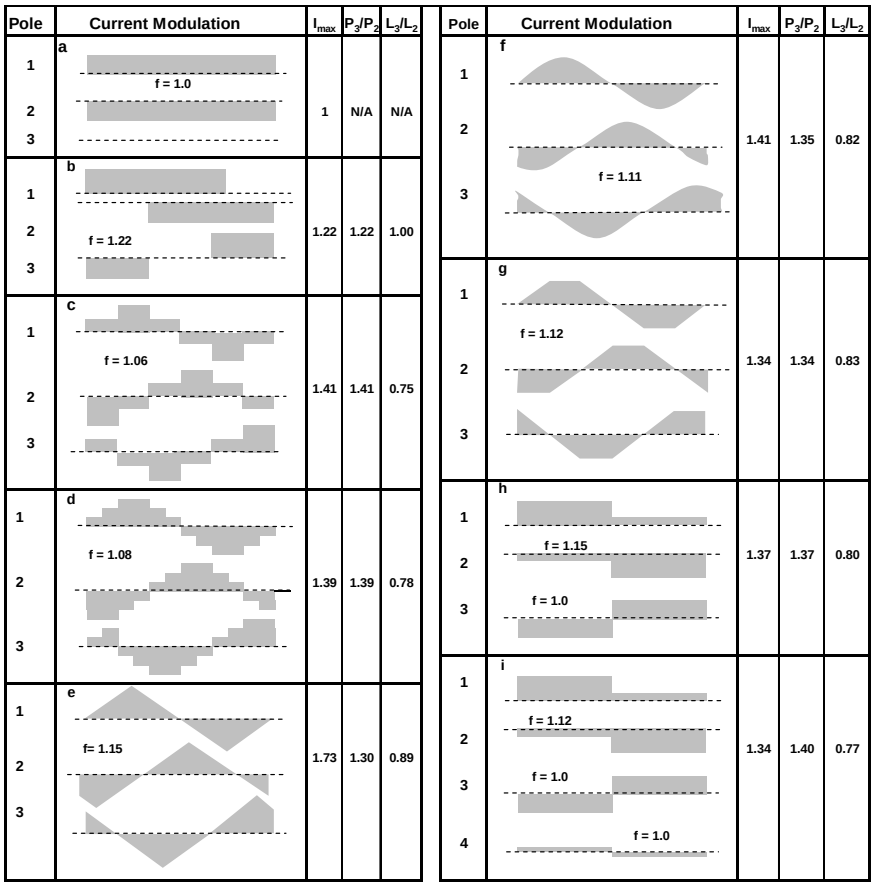


Fig. 5. Characteristics of various tri-pole

Fig. 2f shows a truly hybrid AC/DC system, but produces prominent 6th harmonic power pulses unless the current wave is caused to take a trapezoidal shape as in fig. 2g, in which case power is constant.

Fig. 2h shows a system of asymmetrical modulation in which case only pole 3, the modulating pole, must be reversible in polarity. That pole alternately relieves a portion of pole 1 current and then pole 2 current. The modulation ratio, r, is the ratio of maximum current to minimum current on poles 1 and 2. That ratio can be varied while still maintaining the condition that all poles are at full rms thermal rating. Table 1 illustrates the characteristics of three key values of r.

Even though each conductor sees equal rms current, the power transmitted on each pole differs except for the case where r = 3. At maximum rating, the asymmetrical system transmits 37% more power than a bi-pole. In actual operation the modulation ratio would probably be increased as line loading increased.

Detailed control simulation shows that the transition in state between high and low currents in poles 1 and 2 and the simultaneous reversal of current in pole 3 can be achieved without perturbation in power transfer.

Criterion	r	Power				Loss
		1	2	3	Tot.	
Minimum Losses	**2.00**	0.47	0.47	0.32	**1.27**	0.75
Equal Power/Pole	**3.00**	0.45	0.45	0.45	**1.34**	0.78
Maximum Power	**3.73**	0.43	0.43	0.50	**1.37**	0.80

Table 1. Effect of various modulation ratios

Table 1 assumes that each conductor may be considered independent of the others from a thermal standpoint. That's the case in overhead and submarine cables. Where cables share a common trench and the latter imposes an aggregate thermal absorption limit, the tri-pole's advantage drops to from 1.12 to 1.15.

Power Increase through HVDC Conversion

The rms current rating of a conductor for DC is marginally greater than for AC. As for voltage, if AC insulators are replaced with high-creep DC units of the same length, most lines will support a DC voltage at least equal to peak AC line-to-ground voltage. For many the upper limit will be determined by gradient. The ratio of DC-to-AC thermal capacity of each conductor, recognizing the voltage boost, is in the order of 1.5. However many AC lines are unable to operate at their thermal limit because of reactance, voltage control, or dynamic issues. If an AC line can operate at 75% of its AC thermal limit, then conversion to DC will allow an increase of 1.5/0.75 = 2. That is on a *per conductor* basis. Recognizing that a bi-pole will use only two of three conductors, the achievable increase for those assumptions is 2 x 2/3 = 1.33. The tri-pole will transmit 1.37 x 1.33 = 1.82 on the same conductor system. Lower ratios of allowed AC loading to AC thermal capacity will boost those multiples proportionately.

If a line is re-conductored at the time of conversion with ACCR, for example, both current and voltage limits can be increased significantly above those cited above; current by virtue of the low sag character of ACCR and voltage because (1) less sag allows more insulators and consequently higher voltage and (2) the conductor choice can keep gradient within allowable limits for the new voltage. With re-conductoring it is not unreasonable to consider 230 kV line capacities boosted to 1,500 MW or more with the tri-pole system.

Internal Redundancy

The internal redundancy of a transmission line is defined as the percentage of full power that can be transmitted continuously with one pole or phase position out of service. Table 2 summarizes that quality for several transmission options. If an AC circuit is converted for bi-pole HVDC operation, the unused conductor is be considered an emergency ground return path. It assumes that earth return current is permitted pending switch-over of the faulted pole.

Table 2 scores redundancy at full load only. If the tri-pole is loaded at or below the level achievable with a bi-pole, no power is lost with a single pole outage. The redundancy of a tri-pole line with no ground return is very nearly as high as single tower, double-circuit bi-pole line with ground return.

Poles	No Ground Path		Full Ground Path	
	Pole Out	Line Out	Pole Out	Line Out
AC	0%	0%	0%	0%
2	0%	0%	50%	50%
3	73%	73%	73%	73%
4	75%	50%	75%	75%

Table 2. Redundancy of various options at full load

Economic Considerations

Conversion of AC lines to DC of any form is economic only when the cost of alternatives is extremely high and/or the functional advantages of DC are compelling. If Conversion is an interesting option at all, the tri-pole option may tip the scales in DC's favor. Even though tri-pole

converters will cost from ten to twenty percent more per kW than a bi-pole station, that premium is offset by three factors.

1. The real cost of conversion is not based on new capacity but rather on incremental capacity. The ability of the tri-pole to achieve a higher ratio of DC to AC capacity will more than offset the cost per kW premium of the terminals themselves.
2. The tri-pole option has an additional 37% advantage in utilization of the existing transmission asset.
3. The tri-pole's redundancy has economic value to the extent it permits greater loading on parallel circuits.

For moderately long lines in areas where new construction is expensive, DC conversion may be competitive with a new parallel AC circuits achieving comparable redundancy. The tri-pole alternative appears to be the less expensive DC alternative on an incremental kW basis and afford better redundancy as well.

The tri-pole system may be more economic for new circuits as well. The absolute cost of new transmission lines is driven largely by aggregate wind and weight loading. If a bi-pole line must support a full-conductivity ground return, the incremental cost of insulating that return at full voltage is very little. Where permitting and right-of-way acquisition is a high fraction of project cost, a tri-pole line, without ground return and a bi-pole line with ground return will differ very little though the former has a 37% higher capacity and higher redundancy as well. If the tri-pole option were 5% higher than the bi-pole for example, the difference in cost per kW-mile of the alternatives would be about 32%. There are many scenarios where that difference would offset any reasonable tri-pole cost premium.

Summary

New equipment options continue to allow existing AC circuits to achieve greater transfers, most based on power electronics, and to accommodate greater transfers as well. The industry needs to focus more on *allocating* that increase between normal operation and the transmission reserve needed for long term reliability.

Where new AC lines can be built, options exist to achieve higher power density on the same right-of-way. But it's time to seriously consider conversion of selected AC lines to HVDC. The power increase, reliability, and economics of that conversion is enhanced by a tri-pole system in which three, rather than two, conductors are in continual use. That system allows 37% more power than a bi-pole on the same conductor system. Though the cost per kW of a three-pole terminal is slightly higher, the difference is more than offset by a higher DC/AC power ratio and higher utilization of existing transmission investment. For new HVDC lines, where a full-capacity metallic ground return is needed, it appears more economic to insulate that conductor for full voltage, using it during normal rather than just emergency operation.

Its high internal redundancy puts tri-pole HVDC circuits in a reliability class with a double circuit, single tower, AC circuit. Tri-pole terminals use equipment already in common commercial operation and current/voltage transitions common in today's bi-pole lines. At least one control approach has been shown to support tri-pole operation in detailed simulation studies

Research Program Implications

Without attempting to address the growing field of "smart" equipment opportunities that aim to extend the usefulness of existing AC system, the following list cites a few research undertakings suggested by the thoughts developed in this paper:

1. The body of work on High Phase Order and Bundled Conductors undertaken in the 1970's and 1980's should be revisited to reassess applicability in today's world of increased pressure for right-of-way utilization recognizing the availability of ACCR.
2. System reliability and loading rules need revision to better recognize the AC system's growing dependence on power electronics and the redundancy advantage of new HVDC options. It's time research is undertaken to make those rules probabilistic. [6]
3. Because HVDC will be an important part of future systems, extension of bi-directional valve technology to higher voltages is important to (1) address the need for DC switching of tapped bi-pole lines and (2) reduce the cost of modulated HVDC terminals.
4. Tests are needed to determine whether oil-filled pipe-type cable circuits, converted to DC can continue to operate, if only temporarily, with a permanent fault on one pole. The reduction in I^2t for conductor-to-ground faults is the over of 10,000:1.
5. XLP cable is poorly suited to HVDC because charge and impurity migration leads to very high local gradients on polarity reversal. Considering the long time-constant associated with that migration, it is likely that periodic polarity reversals associated with symmetrical tri-pole modulation would render XLP cable suitable for DC conversion. Experiments are needed to confirm that.
6. All the equipment technology and operating actions inherent in the tri-pole terminals are regularly demonstrated in bi-pole terminals. But as with every new idea, someone needs to have the courage to be first. The fall-back result would be a high-redundancy, conventional bi-pole tie.

References

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