Technical and Economic Aspects of Tripole HVDC

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***Abstract*—This paper shows how, with simple modifications using either conventional or bidirectional valves, bipole and monopole systems can be connected in parallel and operated as a three pole configuration in which no earth return current flows in either normal or pole-out conditions. While slightly less efficient in terms of equipment utilization, the system reduces line losses for a given MW transfer and has better overload and internal redundancy; both of which enhance (n-1)-constrained loading of the parallel ac system. Because it makes full thermal use of three conductors, the tripole system improves both the technical and economic cases for converting existing three-phase ac lines to dc. Doing so increases power transfer much more than is possible with compensation or phase shifting transformers. The paper reviews the basic principles inherent in the tripole HVDC system and compares characteristics of both bipole and tripole alternatives in the context of an ac network.**

***Index Terms*-—DC-AC Power Conversion, DC Power Transmission, DC Power Systems, HVDC Converters, HVDC Substations, HVDC Transmission, Power Transmission, Transmission Lines, Transmission Line Theory, Valves.**

I. Introduction

HVDC links play an important role in powers systems throughout the world but their potential as an integral element within ac networks has yet to be fully exploited; In part because dc depends on communication and programmed logic to achieve the emergency response benefit that ac achieves through Kirchoff's laws. Furthermore reliability standards, derived largely from ac system operation, have been slow to adapt to HVDC's capabilities and characteristics. As to the first barrier, one need only look to the history of ac transmission systems to see its demise. AC systems, dependent to some degree on communication and control at the outset, have grown steadily more so; witness introduction of SCADA systems, remedial action schemes (RAS), Special Protection Schemes (SPS), and the growing acceptance of FACTS and real time phase angle-based operation logic. In addition, extensive research is underway on wide area managements systems (WAMS) to facilitate a "smart grid" to accommodate ac system weaknesses. As to the second barrier, it was only recently that NERC and most other planning groups accepted the fact that ac system N-1 criteria, which presumed total loss of an ac circuit, should apply not to an entire dc line but to one of its poles; the surviving pole presumably remaining in operation. [1] Those criteria would benefit further by explicit recognition of dc's overload and internal redundancy characteristics, both of which depend on dc configuration and station design. The analysis presented in this paper presumes that both system design and reliability criteria allow full exploitation of HVDC's characteristics.

II. Fundamentals of The Tripole HVDC System.

Figure 1 shows a bipole and monopole systems fed from the same bus and supplying a common receiving-end bus. Monopole earth return current is eliminated by two modifications - both using standard dc system components: (a) The monopole is equipped with an additional bridge connected in anti-parallel to the first [1] and (b) All thyristors and their heat sinks are rated higher than normal. Transformers and other station equipment are standard, both in design and rating. [2], [3]

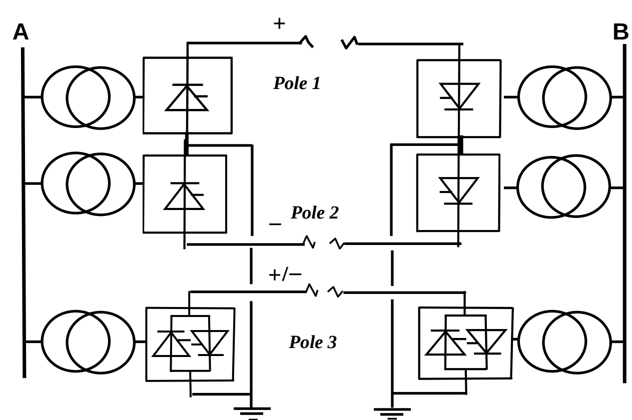

Figure 1 Parallel bipole and monopole HVDC systems.

Poles 1 and 2 of the "tripole" configuration of fig. 1 are unidirectional but of opposite polarity. Pole 3 is capable of reversing both voltage and current. At intermediate levels of power the three poles would operate as a bipole in which pole 1 carries positive current and poles 2 and 3 share the negative return current, thus minimizing losses. As power is increased

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[1] A function that could also make use of bidirectional valves, once commercially available.

pole 1 will reach its thermal rating first - the rating which poles 1 and 2 could sustain alone. That will be considered 1 pu current and power in subsequent analyses.

Power can be increased above 1 pu power, sustaining the split return operation described above, by periodically interchanging high and low current duty as shown in fig. 2.

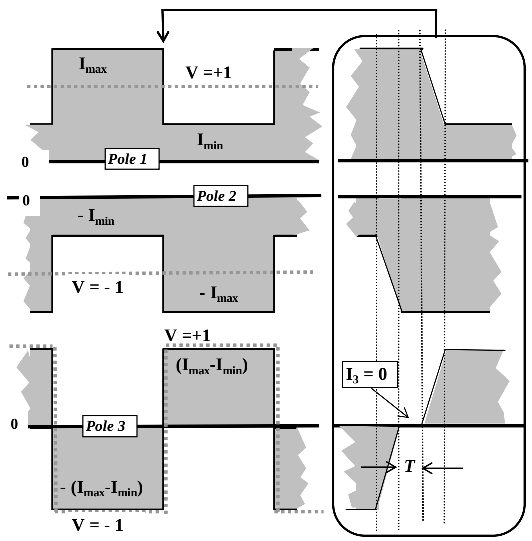

Figure 2 Current-time diagram of current in Poles 1, 2 and 3.

Pole 3 periodically relieves a portion of the current carried by pole 1 - then a portion of the current carried by pole 3. The ratio I_{max}/I_{min} can be sustained at 2 while power is increased up to 1.265 times the bipole level. If that ratio is then increased to 3.73, power is equally divided among all three poles and the total power is 1.37 times the level achievable with just two conductors and a bipole converter. The tripole/bipole ratio would be 1.5 but for the form factor of the tripole current.

The period of the high/low current cycle will depend on the thermal characteristics of line conductors. If made the order of four or five minutes, conductor temperature excursions will be a few degrees C above and below what it would be with constant current of the same root means square value. That variation is roughly the same as would be seen by normal changes in wind or cloud cover.

The inset in fig. 2 shows that current ramps can be modest in slope, e.g. one or two seconds and that ample time can be allowed to reverse voltage on pole 3. – all with continuous total power. Comprehensive simulation of the tripole system on actual configurations, using PSCAD shows no unusual problems in reactive power requirement, flicker control, or harmonic generation.

III. Overload and Redundancy Characteristics

A. Overload Characteristic

It is reasonable to assume an inherent 15% thirty minute overload capability for both bipole and tripole schemes. The tripole gains an additional 9% if short term earth return current is allowed or if corresponding provisions are made using insulated shield wires. This results from reversion to classical bipole/monopole operation, thereby increasing form factor to 1.0 and output from 1.37 to 1.5 prior, prior to overload. That 9% advantage will increase (n-1)-constrained loading on parallel ac lines since it allows dc to assume greater emergency back-up role.

In dynamically constrained ties where high transfers in the 0 to 1 second time frame are important, dc transmission has important advantages. AC systems develop synchronizing power only *after* an angle excursion has developed while dc can provide synchronizing power virtually the instant it is prompted by its controls. Furthermore thyristors are generally capable of 1.5 times overload for the order of one second, giving dc an advantage in the *magnitude* of short term synchronizing power transmittable. Both attributes may leverage the dc rating by allowing higher flow on parallel ac lines.[4] Because of its valve rating characteristics, the tripole can transmit three times more short term (~ 1 second) power than a bipole sized for the same three-conductor system, assuming adequate reactive power support in both cases.

B. Internal Redundancy

The continuous rating of a conventional bipole system drops by 50% after loss of a pole – by 43% if a 15% overload capability is assumed. This presumes a two conductor system with either earth or a metallic ground return. If three fully insulated conductors are available, as with conversion of an ac line, mechanical switching can restore full bipole capability assuming the outage is due to the line, not the converter. To achieve that redundancy the bipole system must go through a zero power interval in the order of one second; a dynamic difficulty for some systems.

If a tripole looses either a bridge or line conductor, power will, in the worst case, drop momentarily from 1.37 to half value or .685, then ramp to 1.15 assuming overload capability. That excursion will be somewhat less than 1 second. Earth return current will flow for a fraction of a second.

The high redundancy of a tripole design means the (1) higher allowable loading on parallel ac where loss of a dc pole is limiting or (2) a higher allowable HVDC rating for the same ac system impact on loss of a pole.

IV. COST PREMIUM

The tripole system will cost more per kW than a bipole of equal rating since (1) the monopole requires one extra, reverse polarity bridge, though no other additional station equipment, (2) At full power $I_{max} = 1.37$ will be sustained for some minutes ("continuous" as far as thyristor ratings are concerned) requiring that heat sinks be proportionately oversized. (For some ratings that factor may also force a move from 100 mm to 125 mm thyristor elements) and (3) its form factor of less than unity results in a 9% reduction in useful MW rating per aggregate rating of equipment.

The above notwithstanding, the per/kW premium will often be more than offset by (1) a reduction in the Net Present Value (NPV) of losses, (2) higher (n-1) constrained loading allowed on parallel ac circuits, (3) greater dynamic response capability and (4) in the case of ac to dc conversion, substantially greater utilization of existing transmission investment.

V. Conversion of AC circuits to DC

Reactive compensation and phase shifting devices are clearly the least expensive way to increase useful loading on ac transmission lines of low susceptance/ampacity ratio. DC achieves a far greater power boost and works for virtually any susceptance/ampacity ratio. Although expensive, dc conversion may be justified by eliminating the need for construction of additional ac circuits and by reduction of system losses. Its justification depends on several factors.

A. DC/AC Power ratio

The DC/AC power ratio is a product of several factors – one of them voltage. The dc voltage sustainable by an ac line depends on a number of design issues. In general the replacement of ac insulators with dc units, a concomitant of conversion, will result in creepage distance sufficient to at least sustain a dc voltage equal to line to ground crest ac voltage. The actual dc voltage limit will also be determined by clearances, either as found or altered by tower or suspension system modifications, sag amelioration, etc. Corona effects may actually be a more important limit to the applicable dc voltage. Matching both positive and negative poles to line-to-ground ac crest voltage results in a conductor-to-conductor voltage of 2.0 rather than 1.73 as in ac; a 15% increase. This would likely apply to both tripole and bipole conversions since operating with split return in the bipole case would have a strong loss incentive and would, in any case, have to be anticipated during pole-out conditions. A 15% voltage increase means an increase of about 6% in image-based electrical gradient for flat configurations.

DC operating current can usually be substantially higher than ac current. AC current is usually well below the conductor's maximum thermal rating because of (n-1) constraints and limitations in dispatch flexibility. It is reduced in usefulness to the extent the power factor is less than 1.0. A DC terminal can usually be rated to match *maximum* conductor thermal rating since in parallel ac and dc configurations total path flow will be determined by the dc's *emergency* rating, not its operating rating. DC operating current would probably be chosen to optimize losses. Fig. 3 shows a general range of DC to AC power ratios *before considering the effect of dc conversion on allowable flow on parallel ac circuits.*

The dashed curves in fig. 3 show a reasonable range of bipole conversion expectations and the solid curves the tripole range; both using the same existing conductor configuration. Reconductoring the circuit represented by fig. 3 to improve ampacity, logistically feasible as a part of non-disruptive conversion, would raise the multiples proportional to the increase in ampacity.

B. DC/AC Loss Ratio

Whether one diverts more load to an underutilized ac circuit by adding ac equipment or increases its capability by real time ratings or sag ameliorization measures, losses as a percent of load will increase proportional to load. This is shown for an example line by the ac curve in fig. 4; the solid line representing its normal loading limits and the dotted line the extension to those limits achieved by the above measures. The lower curves show losses for the same power level following dc conversion. DC losses, which include terminal losses equal to 0.85% of power per terminal, are roughly half the ac values for this case and extend the range of power transfer by a factor of 1.8 for the bipole case and 2.6 for the tripole case.

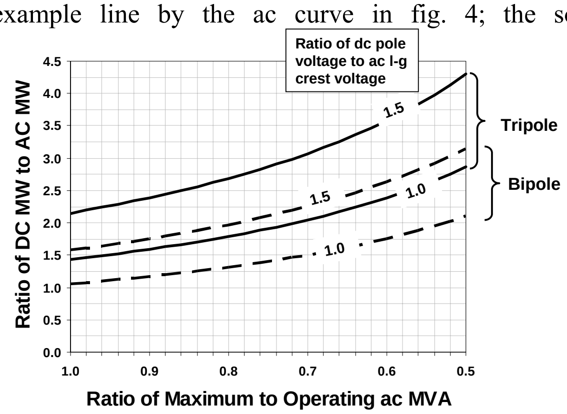

Figure 3 Example range of expectations in AC to DC transmission line conversion.

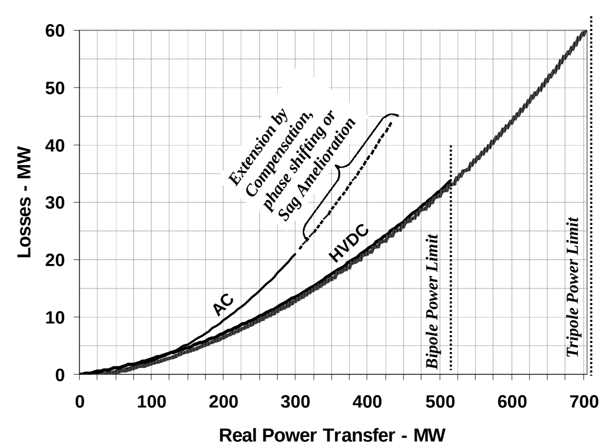

Figure 4 Comparison of ad and dc losses for equal power levels.

Table 1 shows an example 230 kV case in which it is assumed that ac measures are taken to extend the ac operating rating of 333 MVA by 15% to 383 MVA which, for a power factor of 0.9, corresponds to 345 MW. Conversion to HVDC assumes both ac and dc options satisfy the same annual load duration curve. In this example case the loss credit alone may justify the cost of converter stations irrespective of the major increase in capability achieved.

AC Voltage	230 kV	Years	30
DC Voltage	+/-200 kV	Energy Value	$60/MWhr
Distance	200 kM	Loss Factor	0.5
Conductor	1,272 kcmil	Ann'l AC Loss	121,431 MWh/yr
Resistance	.05 ohms/km	Ann'l DC Loss	74,440 MWh/yr
MVA max	514	Loss Savings	46,991 MWh/yr
MVA op	333	Savings	$2.9 Mil./yr
DC Rating	345 MW	NPV of Savings	$63 Mil.
Discount Rate	2%	Credit/term.	$94/kW

Table 1 Example NPV of losses for a 230 kV Line.

The discount rate cited in table 1 may actually be conservative in light of today's prospective escalation in energy values. Energy costs ignore the fact that much higher values may apply during periods when transmission losses are at their peak.

VI. ADVANTAGES IN APPLICATION

The advantages in service of the tripole system can best be illustrated by specific system circumstances. [5]

A. Increasing loading on one of several parallel ac circuits.

If one of several parallel circuits of equal pu susceptance, has higher ampacity than the rest, selectively reducing its susceptance by compensation will cause its flow to increase but force an equal reduction in the flow of parallel lines - at best simply redistributing loads without increasing (n-1)-constrained total path flow. Its ampacity advantage will be of no use. If that circuit is converted to HVDC, the circuit's ampacity multiple will increase a normal ac to dc conversion advantage of at least 2:1.

The same principle limits the advantage gained by adding an identical ac circuit in parallel to several others. Higher ampacity or lower reactance of a new circuit brings no advantage from an (n-1) perspective. If the new circuit is dc it can be made to assume a disproportionate share of load without violating (n-1) criteria.

Where several high voltage circuits overlay several intermediate voltage circuits, all comprising a common transmission path it may be practical to (a) withdraw one intermediate voltage circuit from ac operation, serving its intermediate loads from the others (b) convert the withdrawn section(s) to an "express" HVDC circuit, (c) reconductor those sections to make their HVDC capability comparable to overlying, higher voltage ac circuits.

In any dc application, whether new or the result of ac to dc conversion, the ratio of increase in total path flow to the terminal rating which achieves that increase may be defined as DC Effectiveness (DCE). DCE will be higher for new dc lines than for conversions since, in the latter case, one must subtract the pre-conversion ac power from whatever level is achieved by conversion. In the conversion case DCE values significantly less than 1.0 may be economically attractive since the construction cost of a new line is avoided.

B. Strengthening Transmission Supply to a highly developed Metropolitan area

Transmission in-feeds to high load density areas are often stretched to their system limits while the receiving system is already close to the short circuit current capability of station equipment. Adding a new dc circuit avoids worsening the short circuit problem. Converting an existing ac circuit to dc improves it.

The maximum allowable rating of a new in-feed, whether ac or dc, may be determined by the impact its (n-1) loss has on an already heavily loaded ac system. The tripole system's higher redundancy may allow the system to support a much higher dc power inflow for the same pole-out impact than would be the case for a bipole, at least to the point where second-level reliability criteria become limiting.

C. Making better use of inherent ampacity in long SIL-limited lines.

It has been shown that DC conversion may be particularly advantageous where the length of ac lines severely restricts use of the inherent current-carrying capacity of conductors whose size is determined by corona issues. [6] Very large gains in transfer can be achieved within (n-1) constraints by converting one of several parallel circuits to HVDC while leaving the others in ac operation.

D. Adding (or converting) a very long line interconnecting two regions

Several factors may suggest considering the tripole option for very long inter-regional HVDC links:

i. The NPV penalty of interrupted power is proportional to outage exposure which in turn is proportional to line length. The transmission investment interrupted by outages is also proportional to length. The product of these factors increases the importance of transmission redundancy for very long lines.

ii. Dynamic performance, important for long high capacity transmission lines connecting two already synchronous systems, is improved by the tripole's high one-second synchronizing power capability. Where a long tie connects asynchronous systems, transmission redundancy and overload capability can effect generation planning decisions in both sending and receiving systems.

iii. Since transmission line cost is less than proportionate to the number of conductors, the tripole circuit may carry no transmission line cost premium in $/MW-km yet offer a level of redundancy that would otherwise require two bipole circuits.

VII. ICE PREVENTION POTENTIAL

Commissioning procedures for conventional Bipole Systems include periods of "round power" operation during which both poles assume the same polarity so that full current flows in both but power is circulated rather than delivered to the load.

Fig. 1 shows that tripole power consists of three magnitude blocks; one associated with I_{max}, another with I_{min}, and a third with I_{max}-I_{min}. Each block is constantly active on one pole or another so that the power flow associated with any one block could be selectively reversed by appropriate timing of voltage polarity reversals. Other forms of modulation can create additional blocks. Thus it is possible, with the aid of tap adjustments and limited changes in firing angle, to sustain full current on all poles while reducing net delivered power from 1.0 to 0. It has recently been shown that doing so will inhibit ice formation only under mild icing conditions and that about *three* times rating is necessary under the worst. [7]

That multiplier is achievable with a recently introduced scheme based on use of insulated subconductor spacers and conductor-mounted low-voltage switches to reconnect subconductors, normally in parallel, into series connection over regions of ice exposure, thus at least tripling their current. [8]

VIII. BRUSH FIRE ACCOMMODATION

Brush fires reduce the break-down voltage of transmission lines both by reducing strength of air clearances and by local pollution of insulators. DC may have an inherent advantage is provisions are made for extended voltage reductions. The tripole system, in particular could (1) sustain an initial pole flashover with minimal power interruption, (2) reduce voltage on all poles, (3) restore voltage to the faulted pole (4) repeat the cycle following progressive flashovers until a voltage was found low enough to sustain a reduced level of power despite the fire condition.

IX. UNDERGROUND CABLE IMPLICATIONS

The above arguments differ in several respects for underground cable systems.

i. Where conductors are closely clustered or share a common heat sink, current is limited by *aggregate* rather than *individual* heat release. This limits the tripole benefit slightly unless all three poles are made reversible in voltage and current, in which case the tripole achieves $\sqrt{2}$ times the power that a bipole could achieve using just two conductors.

ii. DC energization of solid insulation tends to build up charge within the insulation which, upon voltage reversal, causes very high local electric stress. Sufficiently frequent voltage reversals, e.g. 50 Hz, finesse that problem due to the time constants of charge build-up and migration. It has yet to be determined whether reversals of several minutes will do the same. In any case this limitation appears to be diminishing with development of new insulating materials. [9]

iii. The redundancy advantage offered by the tripole scheme would in most cases be limited to converter terminal outages inasmuch as most cable outages are apt to involve all poles.

X. ACKNOWLEDGMENT

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XII. Biography

Lionel O. Barthold (M'1951, F'1965) graduated in Physics from Northwestern University in 1950.

After various assignments in apparatus and system transmission engineering, he was named manager of AC Transmission Engineering for General Electric's System Engineering Operation in Schenectady, NY in 1963. In that capacity he was also director of Project EHV, a major 500kV research station, and was instrumental in converting it to a UHV research facility in 1968.

Barthold founded Power Technologies, Inc. in 1969. Under his leadership PTI grew to become a leading supplier of high technology consulting services and software to electric utilities in all parts of the world. He retired from PTI in 1998 and is currently engaged in studies of HVDC conversion of AC transmission lines.

Active in IEEE's Power Engineering Society from the earliest days of his career, Barthold served as president of that society from 1981 to 1983 and is a recipient of its Power Life Award. He has authored or co-authored 70 technical papers, holds several transmission-related patents, and served on or chaired numerous technical committees of both IEEE and CIGRE. He was international chairman of CIGRE's Study Committee 41 "The Future of Electric Power and Systems" from 1976 to 1982. Barthold was elected to the U.S. National Academy of Engineers in 1981