http : //www.cigre.org

Paper 404 Cigré SC B4 2009 Bergen Colloquium

Tripole Transmission with Voltage-Source Converters

L.O. Barthold
Imod, Inc.
USA

D.A. Woodford
Electranix, Inc.
Canada[1]

W.F. Litzenberger
Consultant
USA

SUMMARY

System planners have focused intensively on ways to make existing transmission systems work harder; ways to better *allocate* flow among circuits and ways to allow critical circuits to *accommodate* higher flows. Phase shifting transformers and FACTS devices are the principle solutions to the allocation issue; dynamic conductor ratings, selective reconductoring and "smart grids" the main approaches to improve flow accommodation. Conversion of selected ac lines to dc achieves both objectives simultaneously and will, in many cases, produce an increase in path flow equivalent to that achievable through construction of a new ac circuit comparable to the circuit being converted. Its viability has recently been enhanced by:

a. Introduction of a "Tripole" bridge configuration which makes full use of all three ac phase positions and demonstration that this configuration can realize the economic and operating advantages of VSC's [1,2],

b. Technical advances in VSC valves and bridge configurations, including their extension to overhead line applications,

c. Improved understanding of the degree to which dc characteristics, if taken full advantage of, influence allowable loading of parallel or contiguous ac systems [2].

The tripole consists of a conventional bipole paralleled by a monopole; both configured and operated to exploit the thermal rating of all three phase positions without causing earth return current. In so doing it achieves 37% more MW transfer using all three conductors of a single-circuit ac line than would a bipole which sets aside one phase position as a metallic return. Furthermore if a dc link with its inherent control capability is considered an integral element of an ac system, it may increase the (N-1)-allowable dispatch on parallel or contiguous ac circuits. The tripole shows particular advantage in this regard and, if equipped with VSC's for two of its three poles, also gains the reactive power generation advantage of conventional VSC schemes. Detailed computer simulation shows the VSC-based tripole configuration capable of restoring supply to a dead busbar even after loss of one of the VSC poles.

DC's economic case is maximized when the dc circuit, with its redundancy, overload, and independent control capabilities, is treated as an integral element of the ac system and used to increase reliability-constrained flows within that system.

---

[1] daw@electranix.com

A series of EPRI-sponsored studies have established approximate dc voltage limits for example ac circuits ranging from 138 kV to 765 kV and have estimated the boost in path transfer that might be achieved by conversion of each. [3] In addition, three specific circuits in the Western US have been subject to detailed load-flow studies and have shown in one case a MW path increase 1.7 times the rating of the terminal necessary for conversion. [2]

KEYWORDS

HVDC, AC-to-DC Conversion, VSC, Tripole

I. The Tripole DC Configuration

The "tripole" configuration, illustrated in fig. 1, is essentially a bipole and monopole system in parallel, operated in a manner which eliminates earth return current [1]. As such it requires no new equipment technology. Poles 1 and 2, make up a conventional bipole, using either line- or source-commutated valves. Pole 3 is a monopole thyristor-based converter capable of reversing both current and voltage by virtue of two anti-parallel bridges. Thus the monopole can be made to operate in parallel with either pole 1 or pole 2. Inasmuch as the tripole exploits the full thermal capability of three conductors, it is particularly well suited to conversion of single circuit ac lines to dc.

At low and intermediate load levels, the tripole configuration would likely operate as a traditional bipole with two conductors sharing return current; thus lowering losses 25% below the level resulting from simple two-conductor operation. For maximum loading the monopole (pole 3) alternately assumes a share of the positive current, then the negative current – thus allowing the higher of the two current levels in poles 1 and 2 to temporarily exceed the nominal conductor rating. If the period of reversal is in the order of five minutes, excursions in *average* conductor temperature are very small. At peak power operation the ratio of high to low current can be chosen to impose an equal (average) thermal load on all three poles and allow the tripole to carry, on three conductors, $(1+\sqrt{3})/2 = 1.37$ times the power a bipole does on two…1.37 rather than 1.50 because the form factor of the current wave shape on poles 1 and 2 is slightly less than 1.0. The tripole uses no special hardware [4]. Because of the long period of the tripole cycle, there is ample time for current ramping and, on pole 3, voltage and current reversal as shown in the expanded-time illustration on the right of fig. 1.

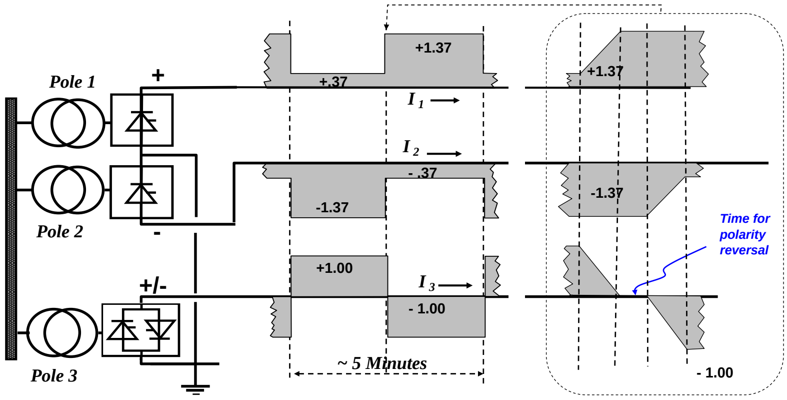

Fig. 1. Simplified schematic of tripole operation at maximum loading

II. A DC link as an AC System Element

AC system transfer capability is limited by contingency states in which one or more elements are out of service…the (N-1) rule. Reliability calculations supporting that rule assume (a) a transmission line has no internal redundancy and (b) that the pre- and post- contingency flows are determined by Kirchoff's laws. Neither is the case for a dc transmission element. Under many operating standards, including those of the National Electric Reliability Council (NERC) in the US, a first contingency outage of a dc line is a *pole* rather than a *circuit* outage. Furthermore both pre- and post-contingency dc flows can be controlled to respond to system needs. Both dc attributes are critical to dc's economic case. Both depend strongly on dc configuration. For example

1. Redundancy

If a bipole circuit looses one pole at full load, it retains 50% of its transfer capacity; a redundancy of 57% given credit for a 15% (example) overload capability. That redundancy depends on earth return current unless a full-capacity metallic return is in place. On the same basis the tripole, after loss of any pole, drops from 1.37 times maximum bipole rating to 1.15 times that rating, a redundancy of 84%. It does so without the need for metallic or earth return current. Redundancy has particularly high economic value where (a) a new circuit, or a converted circuit would, without redundancy, be the limiting outage case for (N-1)-allowable path flow or (b) where the prospect of full circuit loss imposes operating limitations or cost penalties on either receiving or sending systems.

2. DC Overload Ratio

Where an ac circuit, part of a multi-circuit parallel path, is converted to dc, it can be shown that [1]:

$$\Delta P_{path} = P'_{dc} - P'_{ac} \tag{1}$$

Where ΔP_{path} is the gain in total path, i.e the sum of increase in flow on the converted circuit plus the increase in [N-1]-constrained flow on the parallel ac system, P'_{ac} is the emergency power level assumed by the circuit prior to conversion (usually less than its full thermal capability) and P'_{dc} is the emergency loading of the line once converted to dc (made to exploit the conductors' full thermal capability by virtue of dc controls). Any dc configuration can be designed with a high P'_{dc}/P_{dc} ratio to maximize conversion cost-effectiveness, the economic limit of that ratio probably being the order of 1.7; the maximum reasonable ratio of continuous to short term forced cooled rating of transformers. High ratio's favor the tripole inasmuch as, where emergency earth return is allowed, the tripole can revert to operation as a parallel bipole and earth-return monopole configuration making full use of its existing valve rating. That rating must be 1.37 times its rms current to accommodate several minutes of dc current during tripole maximum current operation of the tripole cycle.

Equation (1) assumes that 1 MW of post-conversion increase in a circuit's power pick-up capability will translate into 1 MW increase of (N-1)-allowable loading of the parallel ac system. That's been shown to be a conservative assumption where the prospect of overloading the converted line, in its ac incarnation, limited the loading of a higher voltage ac line. The relationship shown by (1) obviously does not apply in system configurations where continuous dc rating and redundancy govern path flow, e.g. in an essentially radial tie.

3. DC Effectiveness

"DC Effectiveness" (DCE), a measure of economic feasibility, is the ratio of increase in MW path flow achieved by conversion, to the MW rating of the terminal necessary to achieve that increase without paying (and waiting for) new line construction. DCE for the tripole can approach or exceed 1.0 and in one actual system reached 1.7. Bipole DCE is generally substantially lower as shown in fig. 2 which shows results of example conversion cases studied and representing various ac line configurations ranging from 138 kV to 765 kV [3]

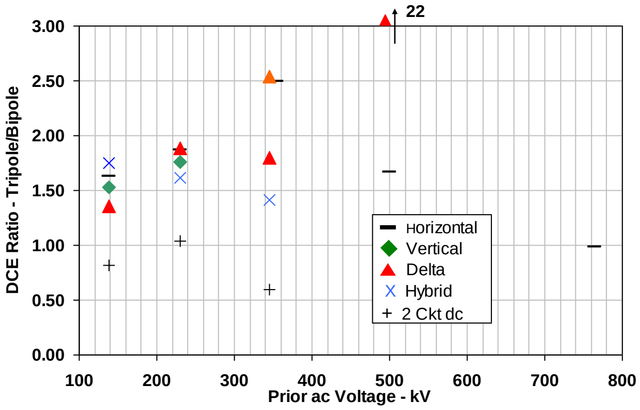

Fig. 2 Ratio of Tripole to Bipole DCE for a variety of conversion cases

The tripole configuration has no advantage where both circuits of a double circuit tower can be converted to dc, thus allowing full utilization of all conductors and a "super bundle" configuration in which all conductors in one circuit are made positive and those in the other made negative. If situations can be found where both circuits have common terminals and neither has taps, the latter will allow a relatively high dc voltage and a very large increase in transfer capability.

III. VSC Technology

The past decade has seen rapid advances in voltage-source converter technology; not only in valve elements themselves, but also in converter configurations capable of application to overhead transmission lines. VSCs have very important advantages in cost, the ability to supply rather than consume reactive power, thus giving voltage support during emergency conditions, and to serve tapped loads.

VSCs' initial embodiment as a center-taped monopole configuration offered no redundancy in the event of a pole outage. In some recent applications, however, it achieves normal bipole redundancy. Furthermore if VSCs are used for both constant polarity terminals of a tripole, the third pole consisting of line commutated converters with bidirectional valves as shown in fig. 3, all the advantages of VSC operation are combined with high redundancy, reactive power support and full utilization of three ac phase positions.

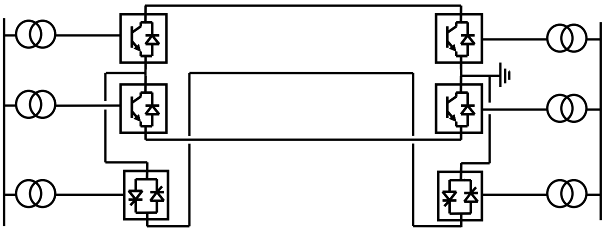

Fig. 3. A Tripole configured with both voltage source and line-commutated converters.

Reactive power support from the VSC poles is a decided advantage when a rapid increase in power through the tripole is requested from a special protection system responding to loss of an ac line or generation. If the same rapid increase in power is required from an LLC-based tripole, the ac voltage of the terminating busbars may require significant supplementary support by ac voltage controllers such as SVCs, STATCOMs or synchronous condensers.

The fast ac voltage control capability of VSC converters on poles 1 and 2 also suppresses ac voltage flicker created by pole 3 when it reverses polarity. With conventional line commutated converters (LCC) in poles 1 and 2, the suppression of flicker to within limits required by standards [5] places a limit on the minimum ac system short circuit ratio (SCR) to no less than 3.0. This SCR restraint is eliminated with VSC converters and judicious design practice.

Another advantage in use of VSC converters as part of a tripole configuration is when the receiving end is a "dead" system with load but no local synchronous ac generation capacity. In such a case two VSC poles can formulate the three phase fundamental frequency voltage with enough rigidity in magnitude and phase to allow the LCC-based tripole bridge to operate satisfactorily. The limit for the latter condition would be the case where one VSC pole is out of service and the tripole must operate as a bipole, one pole of which is the remaining VSC and the other the LCC pole. To test this case on PSCAD, a 200 km 115 kV ac feeder to an isolated and dead load was converted to operate as a tripole with VSC converters on poles 1 and 2. The rated dc pole current was 1.0 kA and rated dc pole voltage was 100 kV. With one VSC pole out of service, the load was supplied with a bipolar configuration with one pole a VSC and the other pole a LCC. Other details of the test system are provided in table 1. For purpose of simulation, simple 2 level VSC converters were applied with pulse width modulation (PWM). It is appreciated that less lossy VSC configurations are available [6].

The VSC pole controls at the sending end regulate ac bus voltage and dc pole voltage. At the receiving end with its isolated dead load, the VSC pole converters fix frequency and retain control of ac voltage. In this way receiving end load variation is automatically compensated by the VSC pole and its controls. The LCC pole follows the load in the VSC pole so that neutral return current is maintained at minimum or near zero. The LCC control is the conventional constant current at the sending end and extinction angle control at the receiving end.

Table 1. Tripole feeder parameters for testing operation into a dead load

Parameter	**Value**	**Parameter**	**Value**
Line length (km)	200	Ac system frequency (Hz)	60
Conductor (kcmil)	795	AC receiving end load (MW+jMVAR)	165+j28
Line dc resistance (Ω/phase)	16	Receiving end ac volts (kV)	115
LCC commutating reactance (%)	18	Rated dc line volts (kV)	100
LCC converter transformer (MVA)	116	Rated dc line current (kA)	1.0
VSC transformer impedance (%)	10	LCC ac filters (MVAR)	50
VSC transformer (MVA)	100	VSC converter with 1,980 Hz PWM	2 level

The receiving end ac system for the test was subject to a three phase fault for 12 cycles (200 msec). That system was represented as a series resistor and inductor in each phase. Fig. 4 shows the ac voltage of the receiving end and sending end busbars and the dc power in each pole. Fault recovery and operation is very stable.

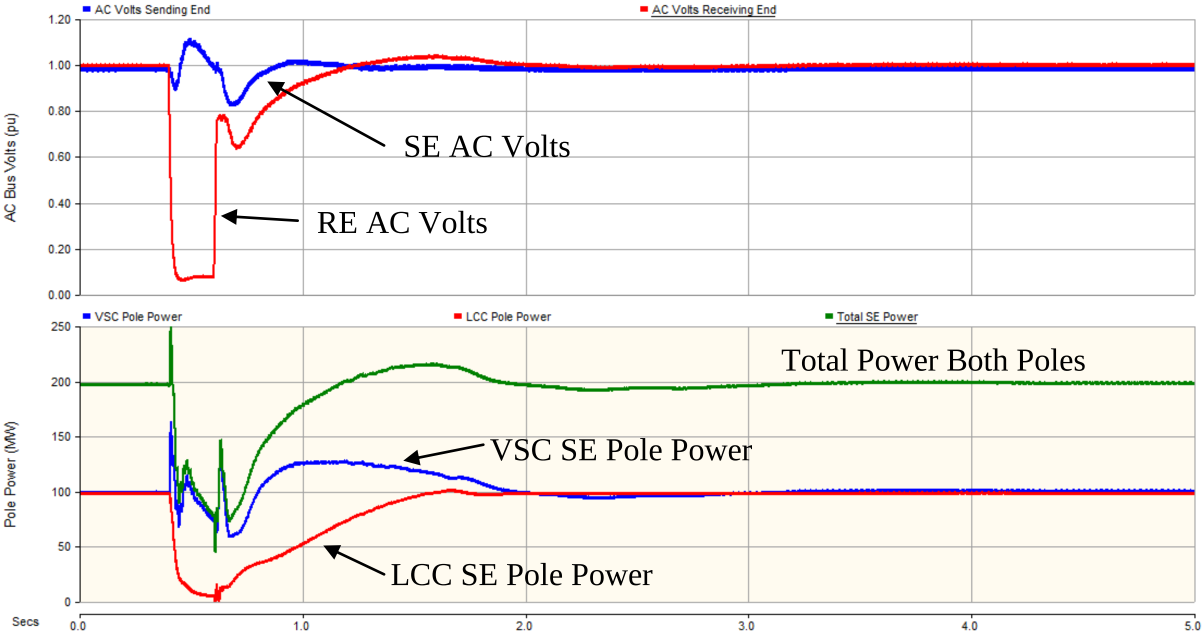

Fig. 4. Response to a three phase fault at receiving end fed by a tripole feeder with one VSC pole out of service showing sending end (SE) and receiving end (RE) simulated recordings.

The LCC pole is actually rated at 1.37 pu to accommodate tripole operation. Hence its ability to increase its power to that level immediately after the ac fault is cleared. The LCC pole is slower to recover due to its voltage dependent current limit settings.

If an ac transmission line parallels the VSC-based tripole circuit, then the controls of the tripole must accommodate synchronized operation at the receiving end system by synchronizing their phase locked oscillators to the ac voltage. If and when the parallel ac transmission is taken or tripped out of service, the tripole may immediately take over control of receiving end ac frequency, particularly if there is insufficient ac generation left in the load to regulate frequency. A special protection system must be in place to detect loss of the parallel ac transmission and immediately switch the phase locked oscillators to an independent clock to maintain receiving end ac frequency. It is this independent clock which enables the LCC pole to operate so stably as demonstrated in fig. 4.

IV. DC Voltage sustainable by an AC line

The MW rating of any circuit converted to dc, whether bipole or tripole, LCC- or VSC-based, will depend strongly on the dc voltage sustainable by the converted ac circuit. That voltage must be the most restrictive of (a) conductor gradient or audible noise criteria (b) Insulation criteria, (c) ground clearance criteria and (c) earth-level field criterion. Recent EPRI study, based on review of a number of actual lines ranging from 138 kV to 765 kV yielded the results shown in fig. 5.

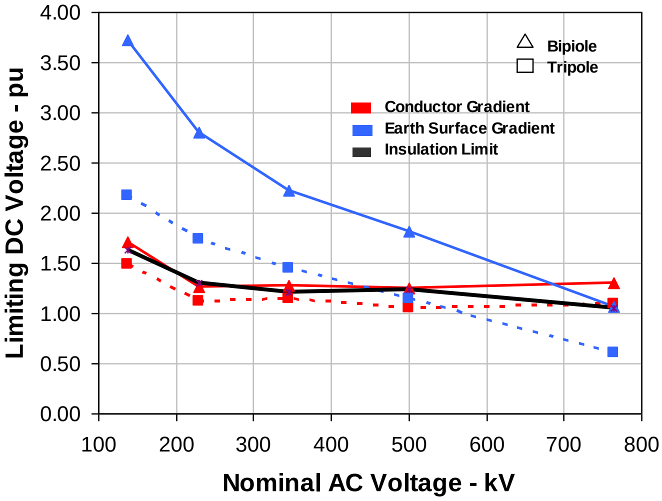

Fig. 5 DC voltage limitation imposed by various criteria in a number of example cases.

The envelope of lower bounds to curves in fig. 5 gives the general range of dc voltages, achievable through conversion of single circuit line to dc recognizing all the constraints cited above. Voltages are in pu of line-to-ground crest voltage. Assigning two adjacent ac phase positions with opposite voltage (the case for either tripole operation or bipole operation with the earth return pole temporarily substituted for a faulted pole) will have somewhat lower dc voltage than a bipole with opposing poles separated by an intermediate ground return.

V. Circumstances Favoring Conversion

Longer line length obviously favors conversion, both because ac transfer tends to be reactance-limited and the alternative to dc conversion, i.e. construction of new circuits, more expensive. Given that observation, ac to dc conversion may be technically and economically feasible where:

1. Operating continuity is critical to the sending or receiving system, e.g. a single system interconnection, in-feed from a remote wind farm, etc.
2. The loss of the ac circuit to be converted, part of an important parallel path, is a limiting (N-1) event.
3. Post-contingency loading of the ac circuit to be converted limits transfer on a parallel higher voltage circuit
4. An ac circuit which, by virtue of length or system configuration, contributes emergency transfer support far less than its conductor thermal rating could otherwise sustain.
5. An ac circuit which, by virtue of dynamic limits, makes poor use of the inherent thermal capacity of its conductors during normal operation.
6. The dimensions, clearances, and conductor size of an ac circuit will support a substantial increase in voltage as a result of conversion.
7. An ac circuit feeds an area where equipment is already close to short circuit limits.

While the above opportunities will usually consist of a single line, it has been proposed that in areas consisting of relatively short double circuit lines, many of them tapped, line sections be abstracted from the network and connected in series to form a through path, up graded in capacity by dc conversion.

VI. Conclusions

1. The dc capability of an ac circuit will depend both on the dc configuration used and the dc voltage sustainable by the ac circuit. The latter is dependent on the more restrictive of:
    a. Conductor gradient or audible noise criteria
    b. Earth surface gradient criteria
    c. The ability of towers to sustain a sufficient length of dc insulation
    d. The ability to sustain adequate ground and tower clearances
2. A tripole dc configuration can make use of 91% of the inherent thermal capacity of the three ac phase positions compared to 66% for the bipole system.
3. Assuming an emergency overload rating of 15%, loss of one independent pole of a tripole, operating at full load, will reduce flow by 16% with no earth return current compared to a loss of 43% for a thyristor-based bipole system using full earth or metallic return current. On the other hand, a VSC transmission system with a center-tapped monopole converter has no redundancy as any loss of a component results in total interruption.
4. It is possible to combine VSCs and thyristor-based valves to achieve the advantages of dead load pick-up of VSC configurations with the high utilization efficiency and high redundancy of the tripole configuration.
5. Simulation has shown a VSC-based tripole configuration capable of restoring a “dead” system even if one of the VSC poles is out of service.
6. In some circumstances tripole conversion can more than double the rating of a single circuit ac circuit.
7. When an ac circuit is part of a parallel path, converting it to dc will affect the (N-1)-constrained dispatch of the parallel ac lines. That effect is generally positive for the tripole system, neutral or negative for the bipole system.
8. In some circumstances the conversion of one ac circuit to dc will increase path flow by more than the rating of the dc terminals used to achieve the conversion; essentially gaining the capability of a new dc circuit without the cost or delays inherent in new circuit construction.
9. The tripole system uses no equipment or ramp times not already used in existing bipole or monopole systems.

VII. References

[1] L.O. Barthold, D.E. Douglass and D.A. Woodford, “Maximizing the Capability of Existing AC Transmission Lines.” CIGRE 2008, Paris, France Paper B2-109

[2] Tools for Assessing Conversion of AC Power Transmission Lines to DC. EPRI, Palo Alto, CA: 2007. 007245

[3] DC capability of AC Transmission Lines, EPRI, Palo Alto, CA:2008. 1016072.

[4] L.O. Barthold, H. Huang, “Conversion of AC Transmission lines to HVDC using Current Modulation. Inaugural IEEE PES 2005 Conference and Exposition in Africa. Durban, South Africa. 11-15 July, 2005

[5] IEEE Standard 1453, 2004 “IEEE Recommended Practice for Measurement and Limits of Voltage Fluctuations and Associated Light Flicker on AC Power Systems.”

[6] J. Dorn, H. Huang, D. Retzman, “Novel Voltage-Sourced Converters for HVDC and FACTS Applications”, CIGRE 2007 Osaka Symposium, Paper 314.