21, rue d'Artois, F-75008 PARIS
http : //www.cigre.org

2016 CIGRE-IEC Colloquium
May 9-11, 2016
Montréal, QC, Canada

Prospects for Compaction of HVDC Transmission Lines

M. SALIMI[1], I. BARTHOLD[2]* D. WOODFORD[3], A. GOLE[1]
[1]Univ. of Manitoba, Canada [2]Imod, USA, [3]Electranix, Canada,

SUMMARY

Many of the technical issues associated HVDC compaction differ from those involved for HVAC lines. Furthermore the very high MW ratings achievable with HVDC lines and the prospect of their forming "supergrids" overlying existing HVAC systems, make it even more important that new rights-of-way be found for their construction. For either HVAC or HVDC, compaction facilitates construction of new transmission lines both by gaining public acceptance through use of aesthetic pylons and by allowing their construction on narrower rights-of-way.

"Compaction" as considered in this paper, refers to reductions in tower height and required right-of-way width. Conductor sag is the principle factor effecting tower height for a given voltage and minimum ground clearance and therefore also the major factor in conductor blow-out at high winds and the corresponding right-of-way width requirement. Principle recourses for reducing sag are (1) shortening spans and/or (2) high-temperature, low sag (HTLS) conductors. Blow-out's influence on right-of-way width can also be minimized by using conductors with compact stranding and/or conductor bundling that minimizes wind force.

Unique to ground clearance limits for HVDC is the prospect of annoyance from ground-level field effects; specifically ground-level electric field and the density of ions flowing to ground near conductors. Criteria suggested for both appear to be conservative based on annoyance histories which also appear limited to in areas under the negative pole. Mitigation of ground-level fields can be achieved by increasing conductor suspension height, reduction of sag, or in special cases, by installation of under-built ground wires in low clearance areas.

Modern pre-manufactured towers have a number of advantages in compaction including slimmer appearance, lower installation cost, and somewhat lower profile for a given conductor suspension point while maintaining the required ground clearance at mid-span.

KEY WORDS
HVDC Transmission, Transmission Line Design, Compact Transmission, Right of Way (ROW)

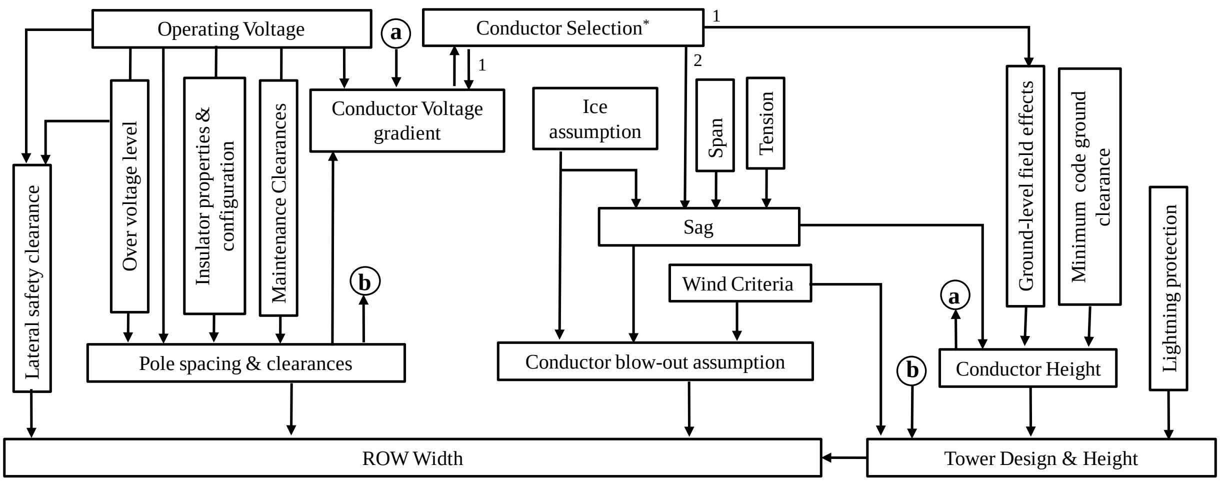
*imod@roadrunner.com

INTRODUCTION

In the late 1970's the industry turned some of its attention, previously focused on ever higher AC voltages, to the compaction of intermediate voltage AC lines. The resulting reviews of design criteria and structural innovations led to major increases both in aesthetic acceptance and MW utilization of transmission rights-of-way (ROW). Today, as the industry's use of HVDC increases to the point where major DC overlays are now foreseen both in Europe and North America, compaction has again moved onto the industries agenda – not only to lessen the visible impact of new lines but to adapt them to ROW too narrow for conventional construction, e.g. road- or rail-side routes.

Compaction simply amounts to maximizing the power transmitted on a given ROW cross-section or, inversely, minimizing that cross section for a given power transfer requirement. Closely linked to the electrical issues associated with compaction is the issue of public acceptance which, in turn, depends on visual appearance of towers as well as their height…both related to span length and other factors. While compaction is normally an issue with new transmission lines, many of the same issues arise in prospective conversion of AC lines to DC. In that latter case the challenge being to maximize MW capacity with fixed conductor and tower dimensional constraints [1].

The variables effecting HVDC tower height and ROW width are very complex and interdependent as shown in Fig. 1. The figure does not relate to design procedures but illustrates that virtually every design variable effects either tower height, ROW width, or both and is therefore germane to the compaction issue. Considering that complexity, this paper will limit discussion to those variables having the greatest impact on the vertical and/or horizontal ROW requirement.



*1 *Conductor diameter and bundle configuration*
2 *Conductor type, weight, thermal and current loading characteristics.*

Figure 1 Functional relationships effecting tower height and ROW width

OVERVIEW OF COMPACT DESIGN CRITERIA

Compaction amounts to minimizing both tower height and right-of-way (ROW) width requirements for a given voltage and MW rating. ROW width, comprised mainly of the pole-to-pole spacing, conductor outswing and lateral safety clearances can be formulated as follows [2]

$$ROW = [(R + L + S) \sin\theta + d_{min}] \times 2 + PS \quad (1)$$

Where:

d_{min} = lateral clearance for operating voltage and safety
R = bundle radius (m)
L = insulator string length if I- string (L is zero in this formula for V-string insulators)
S = conductor sag
θ = maximum swing angle due to max. wind (e.g. 50 year return)
PS = pole to pole spacing

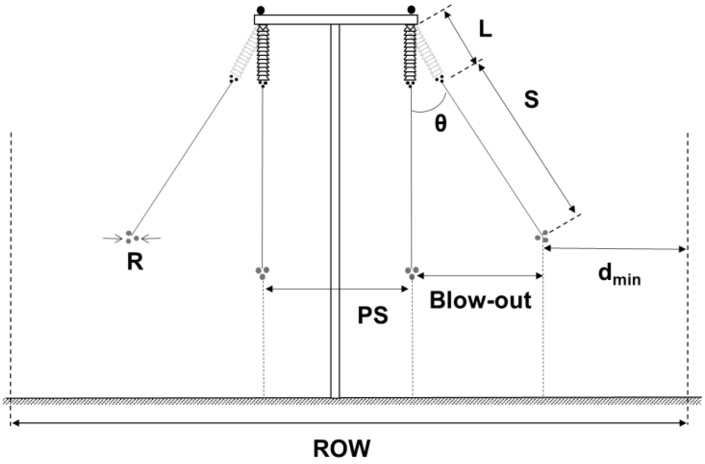


Figure 2 ROW width determinants

- Pole to pole spacing, controlled by tower top geometry, must ensure adequate electric clearances both between the high voltage conductors and tower structures and between conductors along the span. Minimum pole spacing must also limit the maximum surface gradient of pole conductors to a reasonable level [3].

- Conductor mid-span outswing depends on insulator configuration, conductor sag and the assumed wind-dependent swing angle, θ [4].

- Lateral clearances, d_{min}, are based on safety standards between the conductor and the ROW edge under maximum assumed swing. They are a function of operating voltage, overvoltage levels and the proximity of any neighboring structures [5].

IMPORTANCE OF TOWER TOP GEOMETRY

The tower top geometry is governed, large measure, by clearance requirements and the number, type and configuration of insulators used. Horizontal clearances between pole conductors and tower members or, absent an intervening structure, between pole conductors themselves, depend on the maximum expected overvoltage. Overvoltages result from lightning strikes, switching overvoltages or pole-to-ground faults. They may also result from the control process inherent in HVDC terminal operation or from DC-side resonant impedances. In line commutated converter (LCC) systems, lightning and switching overvoltages are generally in the range from 1.8 to 2.3 pu [2].

Most HVDC projects use either symmetrical monopoles or grounded bipole configurations – now combined with voltage source conversion (VSC) terminal architecture. The modern Modular Multilevel Converters (MMC) with full-bridge and half-bridge modules offer significant benefits over older VSC technologies. Design of controllers for MMCs, especially with full-bridge converters, can reduce the overvoltage levels formerly associated with LCC cases, thus reducing clearance requirements and facilitating compaction.

INSULATOR CONFIGURATION

The number of DC disc insulators or the length of long-rod insulators is based principally on DC voltage withstand under pollution conditions prevailing on the ROW. The resulting withstand is then adjusted, if necessary to accommodate anticipated switching overvoltages. Performance of DC insulation for a given contamination exposure is governed largely by surface creepage distance, the latter somewhat more effective as insulation angle departs from the vertical somewhat less as multiple insulators are put in parallel. Insulator types and materials differ over a range of roughly 1.3 to 1 in their ability, for a given length, to sustain dc voltage under pollution conditions. Test show a clear advantage for polymer long-rod units [6],[7].

Adequacy of clearances to tower and guy wires must be verified considering insulator swing due to wind. Fig. 2 shows that V strings or other constrained insulator configurations have an advantage over I strings in minimizing ROW width requirement [2]. As an example, it can be shown that a 500 kV HVDC tranmsission line with a tower width of 1.7 meters at the conductor suspension level, using 4 subconductors with 45 cm subconductor spacing would result in pole-pole spacing of about 9.3m – a distance that would have to be between 12.5 m to 14 m for an I-string depending on conductors assumed [2].

Insulator configuration also effects tower height. For example a 30% gain in pollution withstand per meter of string length, combined with a shift from tangent strings to 90^o V strings could, for typical 500 kV line dimensions, shorten the suspension distance (and the tower) by the order of 1.3 meter [7].

INFLUENCE OF SPAN AND SAG ON ROW WIDTH REDUCTION

For a given conductor choice, stringing tension, electrical loading and weather context, sag is approximately proportional to the square of the span length in a flat terrain [8]. Therefore reducing the spacing between towers has a dramatic effect in reducing sag, and consequently tower height and conspicuousness. In the general range of spans used for HVDC lines, cutting span length in half will reduce the sag by 75%, that reduction translating directly to reduction in tower height. That gain is obviously requires more towers per km, though each with proportionately less wind and weight loading. More towers per km increase aesthetic impact, but lower towers reduce that impact and are more likely to blend into the background.

Fig. 3 shows an example 500 kV DC tower with a typical span of l_1 = 488 meters, conductor height at the tower of 33 meters, and a mid-span clearance of 13.2 meters [9]. It also shows a hypothetical low-profile tower of equal voltage and MW capability with identical conductors and tension, but with span length of l_2=264 m and, as a result, sag reduced from S_1 = 19.8 meters to S_2 = 5.8 meters. As shown in Fig.3 the minimum clearance established either by safety codes or ground level field effects, discussed later, must be maintained for both structures.

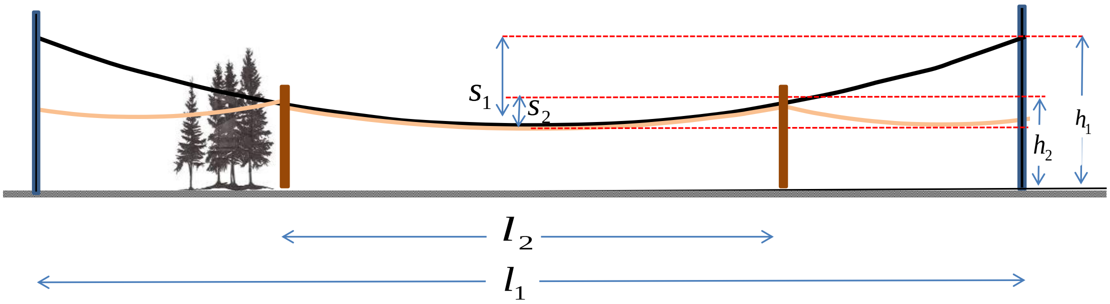


Figure 3 Comparison of longitudinal profiles

Figure 4 shows further the influence of sag on both tower height and ROW requirements. While Fig. 4 is based on a wind blow-out angle, θ, of 30^o, the actual angle will be governed by conductor configuration, wind assumptions and the risk of ice-loading…the latter also influencing sag itself. For example, assuming an insulator length of 6m for 500kV transmission line the blow-out distance for the conventional structures, referring to Fig. 3, is almost $2 \times (L+S)\sin(\theta) = 25.8$ m, and will be reduced to 11.8m for the low profile compact design illustrated in Fig. 3. Note that using a V-string insulator can reduce the blow-out distance further to 5.8m for the low profile structure with the same swing angle.

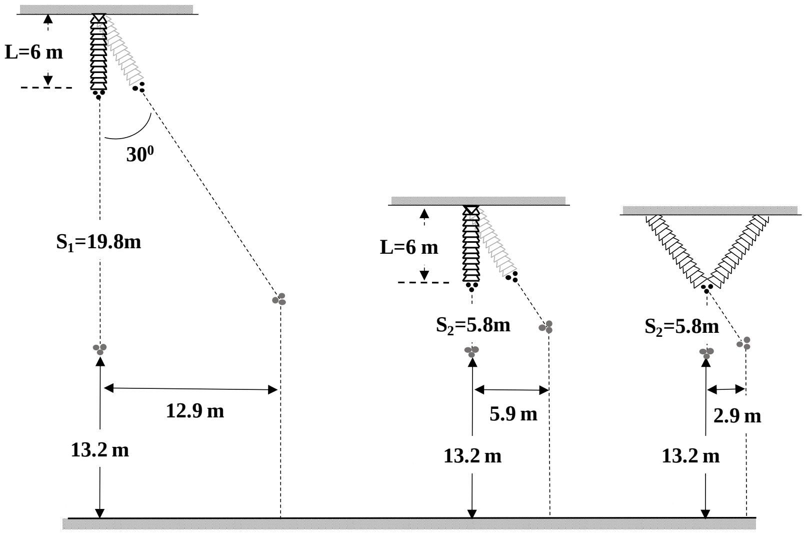


Figure 4 Sag's effect on tower height and ROW width

In most cases design optimization, absent concerns for compaction, will reduce the use of both structures and foundations per kilometer, ignoring ROW width [10], [11]. Moreover, on a forested ROW compaction means fewer trees are cut and correspondingly more carbon dioxide sequestered from the atmosphere. Furthermore wind force increases with height, so the wind force on conductors will be less in forested areas - particularly if the average conductor height is at tree level or lower.

CONDUCTOR SELECTION

For a given span length, conductor selection can have an important bearing on both sag and conductor blow out. For example flat stranded conductor can, for equal aluminum cross section area, reduce both diameter and wind loading by from 8% to 11% with corresponding reductions in conductor blow out and ROW requirement [12]. That reduction in wind loading would be roughly equivalent to a span reduction of from 16% to 21% with the approximation that sag ≈ $span^2$ [8]. Flat stranding also reduces ice loading and ice-burdened sag, where applicable.

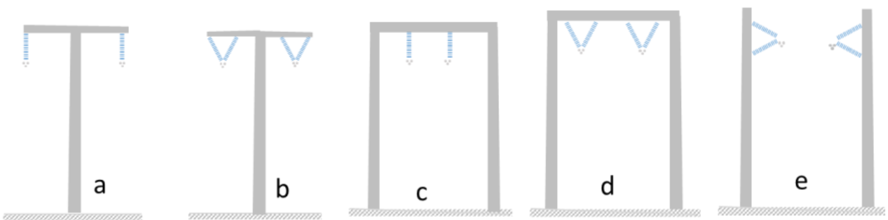
Conductors with solid aluminum alloy and aluminum strands or with aluminum strand and small carbon fiber center for strength are increasingly popular. Both are lighter than ACSR and can have less sag for equal tension.

Bundling of conductors, while having obvious advantages in gradient control, also increases lateral wind-loading and the consequent ROW width component associated with conductor blow-out. For a fixed total cross-section area per pole, the sum of conductor diameters against which wind force will be felt is, neglecting shielding effects, proportional to $\sqrt{n}$ where n is the number of conductors per bundle. Thus going from one to four conductors, for the same total area, will approximately double the wind surface exposure and blow-out force.

High temperature, low sag (HTLS) conductors can, in the limit, reduce sag by the difference between low and high temperature operation of a normal conductor. As an example 795 kcmil 54/7 ACSR conductor, the difference in sag over a temperature range from 120^o F (49^o C) and -20^o F (-29^o C) is approximately 3 meters over a wide range of span lengths [12]. Completely eliminating that sag difference for such cases would lower tower height by 3 meters while keeping equal ground clearance. It would also reduce ROW width required by $2\times3\ \sin\theta$ meters where θ is the blow-out angle assumed in Figs. 2 and 4 (6 meters for the $\theta = 30^o$ angle assumed in the figures).

TOWER DESIGN

HVDC lines use a wide variety of both lattice and steel pole tower designs. Fig. 5 illustrates their suspension principles only. The simplest T tower configurations in Fig. 5a or 5b may use either I or V insulator systems. Inverted U tower configurations as in Fig. 5c and 5d, allow closer pole-to-pole spacing while a variety of free standing support systems as in Fig. 5e are used; either for bipole systems or (singly) for monopolar systems. As shown before, constrained suspension configurations such as V string can reduce both tower height and blow-out related ROW width. Configurations which interpose no metallic structure between poles eliminate structure width as a component of minimum ROW requirement. The table in Fig. 5 indicates the factors to be considered in assessing the contribution of the tower itself to ROW width requirements assuming (a) the insulator configuration itself is adequate for both steady-state operation under representative pollution conditions and overvoltages to ground and (b) pole spacing does not result in excessive conductor surface gradient. Tower material is minimized with options a and b in Fig. 5 and increased in c, d and e of that figure.



Max. Overvoltage & Gap withstand	Pole-to-Ground	✔		✔		
	Pole-to-Pole			✔	✔	✔
Tower Thickness		✔	✔			
Insulator contribution to Blow-out		✔		✔		

Figure 5 Basic tower configuration options and configuration-related factors effecting poles spacing

Fig. 6 compares a conventional lattice tower with a low profile pole tower, both configured as the type a illustrated in Fig. 5 [9], [13]. Public acceptance of new HVDC lines can be enhanced by both compaction and aesthetically pleasing design as shown in Fig. 7. For example, a documented study from the United Kingdom, focused on public acceptance of the T-pylon design, asked 2500 people what type of tower they preferred [14], 39% were in favor of the lattice tower, 56% in favor of the T-Pylon. As for tower land use, the T-pylon is approximately 1.8 meters in diameter at ground level, requires 2.6 m^2 of total footing area uses no guys whereas the self-supporting lattice tower (7.85 ×7.85 m) requires a footprint of 61 m^2.

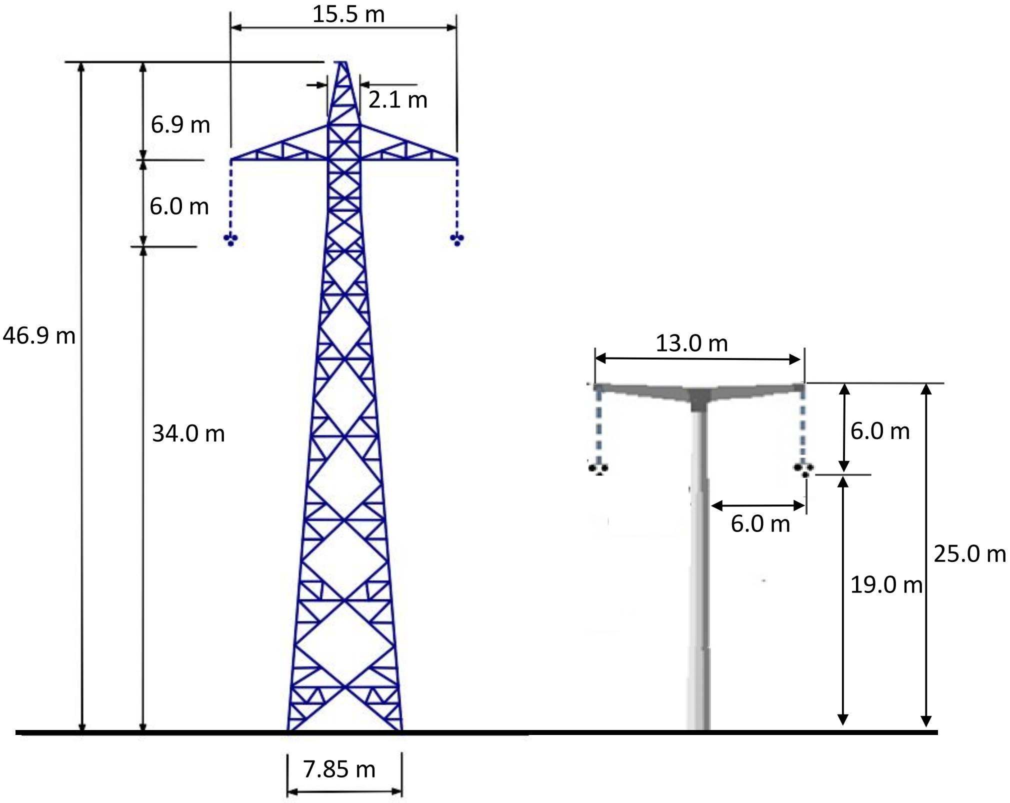


Figure 6 Comparison of HVDC Tower Options with equal mid-span ground clearance and thermal loading of 3800 MW at 500 kV [9],[13]

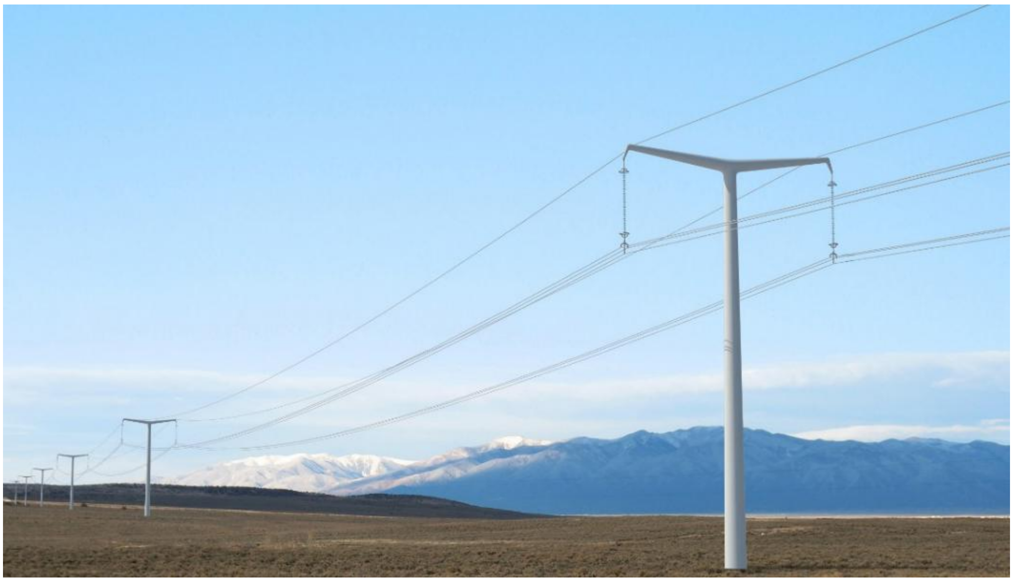


Figure 7 modern pole tower structure for HVDC Transmission (courtesy of Bystrup of Copenhagen)

GROUND LEVEL FIELD EFFECTS

As more compact and lower profile means of HVDC transmission are sought, the prospect that ground field effects will impose a limit to DC voltage increases, as does the incentive for both a better understanding of those limits and of possible means for their amelioration. The prospect of human perception of DC fields is due both to human perception of the highly variable flow of positive or negative ions to the ground and the electrical gradient at ground level which is enhanced by the ion flow.

In an effort to establish guidelines for levels unlikely to produce human complaints, experts have recommended that, at ground level, electric fields as cited above, not exceed E=25 kV/m and that ion current density not exceed J=100 na/m^2 [15]. But levels of both E and J vary over an extremely wide range since ion generation varies with both dc operating voltage and weather while the flow of ions is affected by even slight wind currents. Thus software attempting to predict E and J values estimate levels that will not be exceeded a certain percentage of the time, either 5% or 10%, depending on the software used.

Before judging a proposed compact DC configuration too strictly by the above guidelines one should observe that calculated levels for a number of existing HVDC lines show E and J levels exceeding those guidelines yet have operated for many years without a history of complaints [16]. Furthermore field experience has shown that the negative pole results in substantially higher ground level electric fields and ion current density than the positive pole, opening the prospect of asymmetrical positive and negative voltages. When the Cahora-Bassa +/- 450 kV bipole line in South Africa, is operated at 533 kV, serious complaint problems occur under the negative pole but not the positive pole, the two poles, in this case, being separated by about 1 km [17]. A similar dominance of negative pole effects has been noted under 500 kV lines operated by the Bonneville Power Administration in the US and another by Furnas in Brazil [16].

Perception threshold is not an issue for most new HVDC lines since other design constraints normally result in reasonably low ground level field effects. That threshold has been shown much more important in studies of converting HVAC line to HVDC in which case, the line parameters being fixed, each incremental increase in allowable DC voltage translates into very large increments in the present worth of incremental transmission capacity. The economic incentive for establishing realistic ground level electric field and current density criteria is very high. It has been estimated that the value, per MW-km of representative transmission projects in the U.S. of approximately 200 km length was $1,000/MW-km. On that basis the value of an increase of 5% in voltage above 500 kV, otherwise limited by strict interpretation of the above criteria, assuming a current of 2,000 amperes would be approximately .05 x 2,000 MW x 200 km x $1000 = $20 Million [18]

GROUND FIELD EFFECT AMELIORATION

Given an HVDC line whose voltage is such that the resulting conductor surface gradients (as well as audible noise criteria) would allow still higher voltage but for limits imposed by a given criteria for ground field effects, that voltage can be increased further by amelioration measures, the most obvious of which is to raise conductor height by elevating certain towers or re-tensioning the conductors. Amelioration is also possible by placing ground wires below the conductor in low clearance areas, their height being equal to the *fixed* portion of conductor-to-ground clearance requirements. Calculations using ANYPOLE software show that, for representative 450 kV dimensions [16]

- At least four underbuilt ground wires would be required, two spaced roughly one meter to either side of the pole conductors.
- Those wires must be slightly larger than overhead ground wires to limit their gradient to acceptable levels.
- Their presence would allow an increase in line voltage of approximately 10%.
- That increase would be roughly equivalent to the pole voltage increase achievable with an increase in conductor height of 2 meters.

CONCLUSIONS

1. A number of design options may serve to reduce both the height profile and ROW width requirements of HVDC transmission lines. Their approximate effectiveness is suggested in table 1.

Table 1 – General impact of measures to compact HVDC Lines

Recourse	Benefit			
	Tower Height	ROW Width	Aesthetic Acceptance	Field
Shorter Spans	High	High	Mixed	0
Tower Design	Medium	Medium	High	0
Conductor Selection	High	High	0	High
Insulator Configuration	Slight	Medium	0	0
DC Overvoltage Reduction	Slight	Slight	0	0
Underbuilt Gound Wires	0	0	Negative	Medium

2. The increase in significance of ground level field effects when going to compact construction of HVDC lines, taken together with the high economic impact of criteria adopted, suggest that attention be given to reassessment of criteria assigned to field effect limits.

3. Compact designs will improve the prospect of HVDC siting on existing road, and rail ROW.

4. Underbuilt ground wires may be an economic method for ground-level field effects remediation, particularly in mountainous terrain.

There is not yet reliable information on the total costs comparing an HVDC lattice tower with an equivalent aesthetic designed compact HVDC pylon. It is expected environmental, permitting and labor costs will be less for the compact pylon but material costs may be higher.

BIBLIOGRAPHY

[1] L. Barthold (iMod) & H. Huang (Siemens) “Conversion of AC Transmission Lines to HVDC using Current Modulation” IEEE Power Engineering Society Inaugural Conference and Exhibition in Africa. 2005

[2] CIGRE Technical Brochure 388 “Impacts of HVDC Lines on the Economics of HVDC Projects”, Joint Working Group B2/B4/C.17, August 2009

[3] CIGRE Technical Brochure 48 “Tower Top Geometry”, WG 22-06, June 1995

[4] IEC/TR 60 826 Design Criteria of Overhead Transmission Lines, 2003-10, 3rd edition.

[5] BULLETIN 1724E-200 “Design Manual for High Voltage Transmission Lines” U.S. Department of Agriculture

[6] Jiang X, Yuan J, Shu L, Zhang Z, Hu J, Mao F, “Comparison of dc Pollution Flashover Performances of Various Types of Porcelain, Glass and Composite Insulators,” IEEE Transactions on Power Delivery, Vol. 23, No. 2, April 2008

[7] S. Narain, V. Naidoo, R. Vajeth, “Upgrading the performance of the Apollo – Cahora Bassa 533kV links” Cigre 2012, Paris, France

[8] Thayer, E.S. Computing Tensions in Transmission Lines. Electrical World. July 12, 1924, Vol. 84.

[9] Bipole III project, Chapter three: Project description (http://www.hydro.mb.ca/projects/bipoleIII/eis/download/chapter3__project_description.pdf)

[10] Ghannoum, E.; Kieloch, Z., "Use of modern technologies and software to deliver efficient design and optimization of 1380 km long bipole III ±500 kV HVDC transmission line, Manitoba, Canada," in Transmission and Distribution Conference and Exposition (T&D), 2012 IEEE PES , vol., no., pp.1-6, 7-10 May 2012

[11] CIGRE Technical Brochure 638 “Guide to Overall Line Design” Working Group B2.51, December 2015

[12] “Aluminum Electric Conductor Handbook” The Aluminum Association 900 19th Street, Washington, DC, 2006

[13] Erik Bystrup, “Public Acceptance”, 3rd European Grid Conference, Royal Museum of Art and History, Brussels, 4 December 2013

[14] https://yougov.co.uk/news/2015/04/17/pylons/

[15] P. Sarma Maruvada, Corona Performance of High-Voltage Transmission Lines, Research Studies Press Ltd., Baldock, Hertfordshire, England, 2000.

[16] CIGRE Technical Brochure 473, “Electric Field and Ion Current Environment of HVDC overhead Transmission Lines” Joint Working Group B4/C3/B2.5

[17] https://www.bpa.gov/news/FOIA/Pages/RequestForm.aspx

[18] R. Adapa, L. Barthold, D. Woodford, “Technical and Economic Incentives for AC to DC line Conversion” CIGRE Paper B2-203, Paris 2010

[19] CIGRE Publication 417 “Technical Assessment of 800 kV HVDC Applications” Working Group B4.45

[20] EPRI ”HVDC Reference Book”, 1993, TR-102764