Investigations into the Upgrading of Existing Transmission Lines from HVAC to HVDC

P. Naidoo, *Senior Member, IEEE*

Abstract– **In general, HVAC transmission lines have an inherent design inefficiency whereby the conductor current carrying capability remains largely unused. With increasing system voltages and the consequential increase in conductor bundles; this design inefficiency worsens. When the same transmission line is converted to carry direct current, the full conductor current carrying capability can be fully employed. The net result is much higher power transfers, more economic utilization of existing assets and the removal of the need for new power line routes, rights of way and servitudes. HVDC also introduces many key technical and economic benefits such as lower power losses for bulk power transfers, creation of asynchronous power systems, advanced controllability of large power systems having both speed of response and intelligence of control. The paper presents the results of investigations into the power transfer constraints of and the benefits of converting HVAC transmission lines for higher power transfers under HVDC application.**

Index Terms—**Power Transmission, Power Transfer, HVAC and HVDC Technology, Surge Impedance Loading, FACTS**

I. Introduction

Cost effective higher current rated power electronic technology makes possible the conversion of high voltage alternating current circuits for high voltage direct current employment. This strategy is promoted so as to yield greater power transfers by using the same physical power line and installed conductor cross sectional area [1]. The strategy of recycling is being developed and promoted for the case of limited availability of new power line servitudes, to overcome transmission congestion and bottlenecks in interconnected power networks; to recycle existing assets for greater power transfer efficiency, to promote bi-directional power transfer under different system operating conditions, to promote electrically separate power islands within a greater and growing interconnected power system thereby enhancing power system stability and controllability and to introduce the new technology HVDC control computers for rapid real time ancillary services energy management [1].

II. Review of Surge Impedance Loading

In general, for an increasing distance in power transmission coupled with higher power transfers, the use of higher system voltages is promoted. With continued increase in customer loading and increasing transmission distances, the AC system natural or surge impedance load became the next constraint in power transmission [2]. The surge impedance or natural load (SIL) of an AC system transmission line is given by:

$$SIL = U^2 \div Zc \ldots\ldots\ldots\ldots\ldots (1)$$

U = Nominal System Voltage
Zc = Characteristic or surge impedance of the transmission line [3].

These technical factors impose limits on the operation of a transmission line and this limits the power transfer capability. Maruvada [3] notes that for the case of thermal conductor rating, the power transfer limit can be up to 3 times SIL for distances up to 80km, for the case of voltage regulation limits, the power transfer limit is 1,3 to 3 times SIL with a distance range of 80 to 320 km and for the case of system stability and for distances greater than 320 km, the power transfer limit is less than 1,3 times SIL. Hence to transfer large blocks of power over long distances, lines with increasing higher levels of surge impedance loading are required. As power system planners, we have a choice on how we maximize equation (1). To achieve a higher SIL, we can either increase the nominal system voltage U or we decrease the characteristic impedance Zc.

III. Decreasing Characteristic Impedance Zc

The classic work of Hingorani [4] on FACTS covers extensively on how the characteristic impedance can be lowered and controlled in real time. We shall leave Zc as a subject that is understood in both theory and application.

Dr P Naidoo is past Senior General Manager of Transmission of Eskom South Africa; currently as Resident Engineer at Pat Naidoo Consulting Engineers Inc RSA 2009/211947/23 (e-mail:pat@patnaidoo.co.za).

Paper Submitted and Accepted for Presentation 2011 GM Detroit, USA 24 to 28 July 2011

IV. INCREASING NOMINAL SYSTEM AC VOLTAGES

Increasing the nominal system voltage appears to be an innocent action and higher AC voltages of 400 kV, 765 kV, 1000 kV and 1200 kV is commonly discussed. This innocent action introduces a highly expensive result in that much of the expensive phase conductor that is installed is never used.

The phase conductors generally form half the cost of new transmission lines. It is known that higher bundle order is a practical way of managing AC generated conductor corona. However, the larger the bundle, the larger is the unused gap between the conductor current carrying capability and the surge impedance load (SIL).

From a survey of operational transmission lines [1], we record in table 1 the following characteristics of commonly used quad zebra 400 kV line and six bundle zebra 765 kV line.

Table 1: Survey Results of SIL Characteristics of Operational Transmission Lines

Conductors	Nominal Voltage kV	Line Length km	SIL MVA	Normal Conductor Capacity MVA
4 x Zebra	400	700	670	1796
6 x Zebra	765	450	2364	5152

The unused conductor capability is almost 1, 1 GW for the case of the 400kV line and 2, 5 GW for the case of the 765 kV line.

It is clear that the 1882 original challenge experienced by Thomas Edison at Pearl Street Substation sustains [2]. From DC to AC but AC is also constrained. It may be time to go back to DC.

AC has the strength of being a distributor within AC transmission grids. This is an advantage but distribution tasks should be adequately managed at lower transmission voltages of 132 kV and 275 kV as this mirrors a good match between loads to be delivered versus power transfer capability of the line. Higher loads to be delivered would naturally fall into the bulk category whereby other redistributors would take over “the last mile delivery” to customers. Bulk power transfers are suited for point to point power transmission [5].

In terms of cross over from AC to DC technology for power transmission application, table 2 provides the recommendation as based on investigations into the subject of SIL and higher operating voltages [6]. The cross over is not linear but dependent on distance of power transfer and SIL. From experience, the cross over to DC technology should start to occur at AC 400 kV.

Many of the national grids of the developed and developing countries would have installed many hundreds of kilometres of transmission lines. By definition, the bulk of these lines are under utilized. The application of FACTS is not widespread and the underutilization is much more than initially expected. In this era of smart grids and smart technologies, it will be smart if power system planners could go back and investigate how existing lines can be re-employed for higher power transfer application.

Table 2: Recommended Power Transmission Technology for Application based on Nominal System Voltage and Power Transfers

Nominal System Voltage kV	Recommended Conductor Bundle Order	Power Transfer Capability	AC Technology	DC Technology
132	1 x	80 MVA	100 km	
275	2 x	250 MVA	200 km	
400	2 x	350 MVA	300 km	
400	4 x	1500 MVA		400km
765/800	6 x	5000 MVA		500km
765/800	6 x	3500 MVA		3000km

V. SUMMARY OF RESULTS FOR AC TRANSMISSION LINES PROPOSED FOR UPGRADE TO DC

Research [6] has shown that higher order bundles of both 400kV and 765 kV AC transmission lines can be prepared for application with DC technology. The focus of the research study was to determine the technical feasibility of upgrading of existing HVAC circuits for HVDC application. It is assumed that the transmission line will remain as is in structure, layout and mechanical design. The changing of external line insulators to that of silicone rubber or strengthened glass using live line technology is an accepted modification to the original HVAC line, if required.

Table 3 presents the results when a 400 kV HVAC transmission line is converted to 500 kV DC with bipoles on the outer phases of a horizontal bridge of a lattice tower transmission line. Table 4 presents the case when a 765kV HVAC transmission line is converted to HVDC application with operating voltages of 500 kV DC, 600 kV DC and 800 kV DC. In both cases, the centre phase is bonded to earth to form a metallic earth return between converter stations. This affords the DC scheme both mono and bipolar operations.

Table 3: Case Study 4: 400 kV Triple and Quad Zebra HVAC Transmission Line

Phase Conductor Diameter = 28,62mm
Midspan height of phase conductors = 8,1m
Midspan height of earth wires = 13,8m
DC operating Voltage = 500 kV

Category	Triple Zebra	Quad Zebra	Quad Zebra
	HVAC	HVAC	HVDC
	400 kV	400 kV	500 kV
Maximum Surface Gradient kV/cm			
R Phase	15,29	12,54	23,99
W Phase	15,93	13,43	6,01
B Phase	15,29	12,54	-23.99
Earthwire 1	8,55	9,28	28,02
Earthwire 2	8,55	9,28	28,02
Audible Noise	3 zebra	4 zebra	4 zebra DC
L50 Wet dBA	45,2 < 53,1	34,6 < 53,1	32,1
L50 Fair dBA	20,2	9,6	38,1
Radio Noise @ 500 kHz			
L50 Wet dBA	59,5 < 72	48,2 < 72	28,5
L50 Fair dBA	42,5	31,2	41,5
Electric Field kV/m			
Within servitude	10,3	8,9	27,2
At Edge of servitude	1,5	1,1	3,5
Magnetic Field mG	411,7		669,3

The higher conductor bundle order further attenuates the conductor surface gradient profile and also that of the electric field. Under DC, we record that the environmental electrical and corona effects are reduced when compared to AC. For lower DC field levels, a DC operating voltage of 300 kV or 350 kV would be more than adequate for the given power transfers. There is no need to go to the high level of 500 kV.

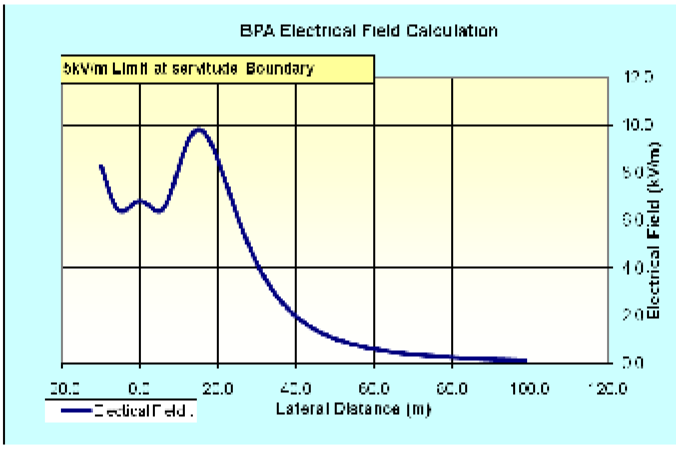
Table 4: Case Study 5: 765 kV six bundle zebra HVAC Transmission Line

Phase Conductor Diameter = 28,62 mm
Midspan height of phase conductors = 15m
Midspan height of earth wires = 27,6m
DC operating Voltage = 500, 600 and 800 kV

Category	765 kV HVAC	@ 500 kV DC	@ 600 kV DC	@ 800 kV DC
Max Surface Gradient kV/cm				
R Phase	16,33	15,73	18,88	25,17
W Phase	17,39	4,41	5,29	7,06
B Phase	16,33	-15,73	-18,88	-25,17
Earthwire 1	11,95	21,76	26,12	34,82
Earthwire 2	11,95	21,76	26,12	34,82
Audible Noise	dBA	dBA	dBA	dBA
L50 Wet	54,7	18,8	25,6	36,4
L50 Fair	29,7	24,8	31,6	42,4
Radio Noise @ 500 kHz	dBA	dBA	dBA	dBA
L50 Wet	61,8	11,5	18,4	29,1
L50 Fair	44,8	24,5	31,4	42,1
Electric Field kV/m	765 kV HVAC	@ 500 kV DC	@ 600 kV DC	@ 800 kV DC
Within Servitude	9,8	13,3	16,0	21,3
Edge of servitude	2.0	3.0	3,6	4,7
Magnetic Field mG	555.9	831.3	831.3	831.3

With a higher order conductor bundle arrangement and higher height above ground, we record very acceptable levels when the 765 kV line is upgraded to DC. Once again, for the case of conversion to DC, we need to find acceptable limits for the conductor maximum surface gradient (kV/cm) and for the electric fields (kV/m); both within and at the edge of the servitude. An interesting finding is that at the edge of the servitude, in all cases for upgrade to DC, the final attenuated electric field is less than the AC limit of 5kV/m. An example electric field profile for the case of 800 kV DC on a 765 kV AC line is presented in Figure 1.

Figure 1: BPA Calculated Electrical Field Plot for 800 kV DC



The study results concur in general with the literature review [7]. The static electric field of DC is less onerous than the time varying electric field of AC. With DC no induced effects are conveyed to humans and animals within the power line servitude.

VI. Summary of the Recommendations for the Upgrading of HVAC Transmission Lines for HVDC Applications

For HVAC transmission lines where the thermal capacity is close to the SIL, do nothing. In cases where the thermal capacities is higher than the SIL but of smaller phase conductor bundle order; add FACTS technologies for higher power transfers. In cases where the thermal capacities are much higher than the SIL and the phase conductor bundle order is large, then employ HVDC upgrade. Select the DC operating voltage such that all the electrical and corona electric fields are within generally accepted levels as experienced locally and internationally.

The performance of insulators under DC conditions is known to be more onerous than under AC conditions due to the electrostatic precipitation of atmospheric dirt and pollutants. The absence of current and voltage zeros in a DC transmission system further complicates the flashover process as there is no opportunity for self recovery once leakage current growth is initiated. The use of silicone composite insulators promotes the surface beading of water [hydrophobicity] that arises from environmental wetting thereby continuously attenuating the growth and development of leakage currents. The use of silicone composite insulators is recommended as part of the proposal to upgrade the HVAC line for HVDC application. The change of insulators can be done with live working technology without disturbing power flows. The performances of silicone composites have delivered sterling results, zero fault, for many decades on the HV national grid of South Africa.

VII. Conclusion

The initial foundations for the super-grid and or smart grid has commenced with the addition of the power electronic converters at sending and receiving ends.

HVDC technology has the advantage and can be designed for a specific voltage drop between sending and receiving ends. Distance is not a limiting factor and for all practical purposes, the power transfer limit can be designed to be up to 3 times the SIL. HVDC further has the advantage of not introducing greater power transmission inefficiency such as that noted when operating voltage is increased.

The efficiency of HVAC 765 kV transmissions and higher voltage AC transmission schemes remains questionable as the unused conductor current rated capacity is the greatest.

VIII. Acknowledgment

The creative idea emanated from the student's participation at the B4 Study Committee proceedings of Cigre 2004, held in Paris, France. The initial idea was delivered by Mr. Lionel Barthold and involved the upgrade of a three phase alternating current transmission line to that of a tripole for direct current application. Mr. Barthold's advice and assistance in the research work is greatly appreciated and acknowledged.

The research work was submitted as a thesis in partial fulfillment of the requirements of the degree of Master of Science in Electrical Engineering at the University of Kwa Zulu Natal, RSA. The support of my direct supervisors Professor Nelson Ijumba, Associate Professor A C Britten and Dr Dzevad Muftic is much appreciated. The numerous discussions helped to guide the project development and to develop a solution for practical application. The comments and contributions from original equipment manufacturers, the laboratory and administrative staff of the HVDC Centre and fellow students and work colleagues provided continuous support and encouragement.

IX. References

[1] Naidoo,P., Muftic,D., Ijumba N. "Investigations into the Upgrading of Existing HVAC Power Transmission Circuits for Higher Power Transfers using HVDC Technology", Inaugural IEEE PES 2005 Conference and Exposition in Africa Durban, South Africa, 11-15 July 2005.

[2] Kundur, Prabha; Power System Stability and Control; 1994; Mc Graw – Hill, Inc. USA. ISBN 0-07-035958-X

[3] Maruvada P Sharma, Corona Performance of High Voltage Transmission Lines, Research Studies Press Ltd. 2000. Baldock, Hertford shire, England ISBN 0 863 80 254 0

[4] N.G Hingorani. FACTS – Flexible AC Transmission System. IEE Fifth International Conference on AC and DC Power Transmission Proceedings, p1-15, Sept 1991

[5] Arrillage, Jos. High Voltage Direct Current Transmission, 2nd Edition, 1998, The Institution of Electrical Engineers, London, UK. ISBN 0 852 96941 4
[6] Naidoo,P.,A.C.Britten,W.L.Vosloo,R.Stephen,G.Sibilant,D.Muftic, A.Burger,N.M.Ijumba. "Investigations into Electrical and Corona Effects for the Upgrade of HVAC Transmission Lines to HVDC." HVDC Conference, University of KwaZulu Natal, RSA, 2006.
[7] Naidoo P, R D Estment, D Muftic, N M Ijumba. "Progress Report on the Investigations into the recycling of existing HVAC power transmission circuits for higher power transfers using HVDC technology." 1EE 8th International Conference ACDC Power Transmission March 2006, London, UK.

Biography

Dr Naidoo is a registered professional engineer, a post graduate in Electrical Engineering from the University of Kwa Zulu Natal in South Africa, a postgraduate with an MBA from Samford University in the USA and a PhD from the DaVinci Institute for Technology Management. In 1994, Dr Naidoo received the South African Institute of Electrical Engineers young achievers award. In 2006, he was appointed Senior Member of IEEE and he jointly co-chairs IEEE Power & Energy Society activities in Africa. He is a Fellow of SAIEE, South Africa and a member of IET London, UK.