HVDC Cable Rating Methodology: Thermal, Electrical, and Mechanical Constraints

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ABSTRACT

To construct a European super grid, High Voltage DC cable circuits will be crucial for long-distance bulk power transmission, both onshore and offshore. Therefore, an accurate cable rating becomes paramount for an efficient and safe operation of transmission network. This paper summarises new developments for HVDC cable rating calculations, subject to thermal, electrical, and mechanical constraints. Details are given on the understanding of each constraint type and how the corresponding rating changes with operational/ ambient conditions. Available analytical rating calculations are outlined with references, which help to form a comprehensive rating system for HVDC cables.

KEYWORDS

Cable rating, Multi physics analysis, Power transmission

INTRODUCTION

With the rapid growth in energy consumption worldwide, the move towards a European wide super grid will cause significant changes in how modern transmission and distribution (T&D) networks are operated. As long-distance bulk power transmission between maritime nations is normally carried out through high voltage dc (HVDC) cable circuits, fundamental to this is the need to accurately know or determine their available ampacity. Otherwise, insulation failure (e.g. electrical breakdown, premature ageing/ degradation) due to overrating may result in high costs for cable maintenance or replacement.

At present, the thermal limit is the most well studied and straightforward rating constraint. It simply specifies a maximum conductor temperature to prevent excessive thermal ageing to the insulation. Although the standardised thermal-limited rating [1] has been successfully implemented for traditional ac cable networks for over 50 years, HVDC applications impose extra physical constraints (i.e. electrical and mechanical) on the cable rating and are not thoroughly considered by any standard rating approach.

Electrically, the maximum dielectric stress increases with the increasing cable current due to the field inversion phenomena [2]. This means that a dielectric electrical breakdown may occur before the normal upper thermal constraint is breached. Therefore, a rating methodology taking the maximum dielectric electrical strength into consideration is very useful.

Mechanically, the presence of unacceptably high pressures or pressure drops are occasionally reported at the insulation-sheath interface of MI-type HVDC cables during loading cycles [3], due to a strong impregnant thermal expansion or contraction. Consequently, dielectric cavities might be introduced if a plastic deformation of the cable sheath occurs. As the initial thermal excitation is closely linked to cable loading, including the mechanical constraint for modern rating calculations is also of great value in preventing any internal mechanical damage.

This paper will explain the reasoning of each physical constraint, summarise the corresponding rating calculation in a concise format, and outline the application of these calculations to show how the practical rating changes with various operational/ ambient conditions. It is believed that this work may provide valuable information for future international HVDC cable rating standards.

THERMAL-LMITED RATING

For cable ratings, the well-recognised thermal constraint is the most direct affecting factor. Based on the nature of cable insulation material, the maximum permissible conductor temperature is specified to prevent the dielectric thermal ageing. According to [4], several common dielectric types and the corresponding temperature limits are listed in Table 1. Note that following values do not consider the implicit temperature reduction requirement from electrical stress concerns, as they will be dealt with separately.

Table 1: Dielectric based temperature limit

Dielectric type	Maximum permissible temperature (°C)
Cross-linked polyethylene (XLPE)	90
Polypropylene laminated paper (PPL)	80
Low-density polyethylene (LDPE)	70
Mass impregnated paper	50

Subject to the thermal constraint, the cable thermal-limited rating calculation is standardised by IEC60287-1-1 [1], which adopts a simple lumped 1D thermal network analogue for radial heat transfer within the cable cross section (i.e. IEC60287-1-1) and solve partial differential equations for longitudinal heat transfer (IEC602878-3-3 [5]). The general continuous thermal-limited rating, $I_{thermal}$, for a single ac cable is calculated by:

$$I_{thermal} = \left[\frac{\Delta\theta_{max} - W_d[0.5T_1 + n(T_2+T_3+T_4)]}{R_{ac}T_1 + nR_{ac}(1+\lambda_1)T_2 + nR_{ac}(1+\lambda_1+\lambda_2)(T_3+T_4)}\right]^{0.5} \quad (1)$$

Where; $\Delta\theta_{max}$ is the maximum permissible temperature rise of the conductor above ambient temperature (K), R_{ac} the ac resistance of conductor at maximum operating temperature ($\Omega.m^{-1}$), W_d the dielectric loss per unit cable length ($W.m^{-1}$), λ_1 the sheath loss factor, λ_2 the armour loss factor, n the number of conductors, and T_1, T_2, T_3, T_4 are the per core thermal resistances of insulation, armour bedding, serving, ambient medium respectively ($K.W^{-1}$).