DC Cable Thermoelectric Rating Design

Ziyi (Uta) **HUANG**, Marco A **SALVATORE;** Mott MacDonald, (UK), uta.huang@mottmac.com, marco.salvatore@mottmac.com

ABSTRACT

With the growing number of high voltage dc (HVDC) cable interconnectors operating at or being designed above 320kV, the rating calculation no longer only depends on the conventional IEC 60287 thermal network analyse, but also gets constrained by the insulation thermoelectric limit. Several publications in the past have unanimously attributed this limit to the electrical conductivity of cable insulation under dc, and several failure mechanisms have been proposed. Thus, qualitative understanding of these failure mechanisms and associated mathematical models is of great value. Moreover, this paper quantitatively compares two of mechanisms, with aims to distinguish the respective application regime.

KEYWORDS

HVDC power cable, Interactive thermal runaway, Intrinsic thermoelectric failure, Apparent thermoelectric failure, Thermoelectric rating

INTRODUCTION

At present, the rating calculation for dc electric cables largely follows the IEC60287-1-1 [1], which simply removes the dielectric loss, sheath loss, and armour loss from the basic ac cable thermal rating formula. This approach works purely in the thermal domain, i.e. 2D thermal network analogy, when the dc cable insulation leakage current losses can be safely disregarded.

However, for HVDC cables, the so-called 'dielectric field inversion' phenomenon becomes prominent [2] [3] where the max. dielectric stress is explicitly insulation temperature drop dependent, or implicitly cable loading dependent [4]. In certain extreme theoretical situations, the dc dielectric leakage current loss could also contribute to the insulation failure and can no longer be ignored [5] [6]. Fundamentally, it is due to the insulation electrical conductivity under dc being dependent on both temperature, *T*, and electrical stress, *E*. Several forms of the semi-empirical electrical conductivity/ resistivity formula were available in literature and the following is the most widely recognized [2] [3],

$$\sigma(T,E) = \sigma_0 e^{\alpha T} e^{\gamma E} \tag{1}$$

$$\rho(T,E) = \rho_0 e^{-\alpha T} e^{-\gamma E} \tag{2}$$

Where; σ_0 and ρ_0 are the reference electrical conductivity (S.m^{-1}) and resistivity (Ω.m) at 0°C and 0 kV.mm^{-1}, α the temperature dependency coefficient (°C^{-1}), and γ is the electrical field dependency coefficient (mm.kV^{-1}). As both the thermal field and electrical field are interlinked through the conductivity and resistivity equations, the subsequent analyses fall in the thermoelectric domain.

Based on both the temperature continuity and the leakage current continuity equations, either Eq. 1 or Eq. 2 can be implemented to calculate the temperature and electrical field distribution across the dc cable insulation thickness [5] [6]. In doing so, several insulation thermoelectric failure mechanisms were proposed in literature which all link the failure to the dc cable conductor current loading. Therefore, the associated conductor current limits under these failure mechanisms are defined as cable thermoelectric rating, different from the conventional thermal rating defined in IEC 60287-1-1.

In this paper, three distinct thermoelectric failure mechanisms, namely interactive thermal runaway, intrinsic thermoelectric failure, and apparent thermoelectric failure, are firstly reviewed and explained with physical interpretation. Subsequently, closed-form mathematical formulae for the last two failure mechanisms are introduced with references. Finally, numerical calculations were performed with aims to distinguish the respective application regime.

INTERACTIVE THERMAL RUNAWAY

The classical dc cable insulation thermal runaway theory was developed in 1950s and 1960s and documented in [7] [8] [9]. It models the ambient medium external to the cable insulation layer as a constant thermal resistance which is also adopted in IEC 60287-2-1 [10] under steady state. As results, plot of the heat intake by ambient against insulation-ambient boundary temperature, θ, is a straight line according to thermal network analogy. Conversely, the total heat output (i.e. joule losses from cable conductor and insulation leakage current under dc) plot against the same boundary temperature is an upward concave alike curve. Fig.1 below illustrates the thermal runaway where any intersection indicates a potential steady state thermal balance attainment between heat generated rate from the cable conductor and insulation (curve B) and the heat dissipation rate into the ambient (line A).

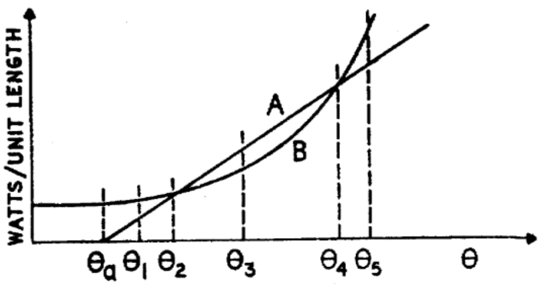

Fig. 1: Interactive thermal runaway illustration [5]

Assuming a constant insulation terminal dc voltage and conductor loading, the conductor loss and insulation loss can be approximated by I^2R_c and U^2/R_{ins}. Initially, the total cable loss stays almost invariant against the boundary temperature under a negligible insulation leakage current loss. This is because R_{ins} shall remain very high under low temperatures and the ambient (e.g. bulk soil) shall have sufficient thermal capacity to intake certain heat output without changing its terminal temperature (till θ_a in Fig.1). Between θ_a and θ_2, the total cable heat loss increases very slowly along with a slowly increased boundary temperature as the ambient gradually charged up. At θ_2, the first thermal