Evaluation of ampacity using FEM electromagnetic-thermal analysis of AC/DC XLPE cable considering cable formation

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ABSTRACT

In recent years, the demand for the convert from AC to DC has been increasing. Accordingly, we evaluated the applicability for AC cables in DC operation by verifying the consistency of an FEM analysis model by calculating ampacity considering cable formation. The recently published Cigre 880 Technical Brochure to ensure consistent reasoning for ampacity by supplementing the existing IEC 60287 standard. Therefore, Electric field analysis and transmission power comparison was conducted based on the CIGRE880. The validated model shows that DC transmission power can increase 1.18 times in flat formation and 1.29 times in trefoil formation.

KEYWORDS

AC/DC Cable; FEM Design; XLPE Cable; Ampacity; Electric Field Analysis; Consistency Verification.

INTRODUCTION

DC system has advantages such as an increase in capacity due to lower transmission losses and fewer corona issues, allowing for securing higher operating voltage and better stability [1]. With the development of renewable energy technologies, there has been increasing interest in DC cable systems for distributed power utilization and integration. However, the cost of replacing existing AC cables with DC cables is significant. Therefore, studies such as [2-5] are being conducted to evaluate the applicability of existing AC cables in a DC operation.

One of the key factors for evaluating the applicability of cables in a DC operation is the accurate calculation of the ampacity and operating voltage. Generally, manufacturers provide their own ampacity standards based on the IEC 60287 standard [6, 7] in their product catalogs. However, they are often calculated under limited conditions as well as the values may differ depends on manufacturers. Furthermore, there are ambiguous sections in the standard that specify parameters and equations for calculations, resulting in different results even in the same cable and causing confusion. A study on the correction and verification of the current rating formula in the IEC standard has been reported in papers such as [8] to complement these shortcomings. As a result, a newly revised version of the CIGRE 880 technical brochure [9] was published in 2022 to supplement it. The revised CIGRE 880 ensures consistent inference on ampacity by providing interpretation on the ambiguous IEC standards.

Therefore, In this paper, we designed an electromagnetic-thermal analysis model using FEM that can simulate more complex environments, and verified the model by comparing it with the revised CIGRE ampacity. Additionally, based on the thermal analysis results of the validated model, we analyzed the DC electrical characteristics with temperature dependence. Finally, we evaluated the applicability of AC cables in DC operation by accurately calculating the ampacity and operating voltage.

METHODOLOGY

Simulation Basic Theory

Electromagnetic induction effects to be considered in cable analysis

Based on Maxwell's equation (1), in the case of AC cables, Since electromagnetic induction phenomenon caused by the applied sinusoidal current. Therefore additional losses occur due to the induced current in the sheath as well as in the main conductor. In contrast, in the case of DC cables, Since a steady current flows through the conductor the loss generated by the sheath can be neglected.

$$\begin{gathered} \nabla \times H = J,\ B = \nabla \times A \\ E = -j\omega A,\ J = \sigma E + j\omega D \end{gathered} \qquad [1]$$

Furthermore, unlike DC cables, current density imbalance occurs in AC cables due to proximity and skin effects [10]. These are expressed by the skin effect factor (y_s) and proximity effect factor (y_p), respectively. Therefore, according to the following equation (2), more heating (loss) occurs in AC than in DC even if the same current flows. The linear resistance of a conductor, which increases as temperature rises, is expressed by equation (5) [11].

$$R_{AC} = R_{DC}(1 + y_s + \mathrm{y}_p) \qquad [2]$$

$$R_{DC} = R_{20}[1 + \alpha_{20}(\theta_c - 20)] \qquad [3]$$

$$R_{20} = ((1.02 \times 10^{12}) \times \rho_{20}) / \mathrm{A}_c \qquad [4]$$

$$\sigma_{cond} = \frac{1}{\rho_0(1 + \alpha_{20}(T - 20))} \qquad [5]$$

where, α_{20} is temperature coefficient for copper at 20°C, θ_c is conductor temperature, ρ_{20} is resistivity for copper at 20°C, A_c is cross-sectional area of conductor, ρ_0 is thermal resistivity of insulation.

Electric Field Characteristics in cable Insulation

The temperature distribution inside a cable is determined by Joule heat of conductor, which is the product of current squared and resistance. In particular, the DC electric field characteristics have a property that depends on the electrical conductivity of insulation, unlike the AC electric field characteristics. Since the electrical conductivity of insulation depends on temperature and electric field strength, if a temperature gradient occurs inside the cable,