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AC Losses and Dielectric Losses in High Temperature Superconducting (HTS) Power Cables for Smart Grid Applications: A Comprehensive Review

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ABSTRACT

High Temperature Superconducting (HTS) cables are being used for effective power transmission and distribution as the losses in these HTS cables are less compared to those in conventional power cables. HTS cable constitutes of BSCCO-2233 or YBCO-123 with critical temperatures 110K at zero Tesla and 90K at zero Tesla respectively are highly opted due to larger handling current carrying capacity. During the operation of HTS cable, receives heat flux from the ambient, AC losses through the superconducting tape, dielectric losses from dielectric material, heat-in-leaks from the current leads.

Hence, it is essential to estimate the losses during the operation of HTS cable. Hence, in the present work, a method of estimating the AC losses during transmission and distribution is presented. Electric probe method and Calorimetric thermal methods are frequently used to measure AC losses. The dielectrical losses are increased due to raise in temperature from the heat fluxes. In this paper, different AC losses and dielectric losses are estimated and methods available in the literature to measure these losses are reviewed.

Keywords: HTS cables; AC losses; Dielectric losses; Calorimeter and Electrical methods ; Dielectric materials.

1. INTRODUCTION

High temperature superconducting (HTS) cables are emerging as substitute to next generation power transmission and distribution in power grid applications. These cables not only handle larger currents but also compact and have low losses as compared with conventional cables. Superconductors have zero electrical resistance and conducts electricity with no losses. However, when the alternating current is transmitted through the superconductors, different losses such as AC losses and dielectric losses are [1], [2] encountered. Hence, in designing the HTS cable the factors to be considered are presented in the following sections.

1.1. AC Losses

AC losses comprises of hysteresis losses [1]–[5] in superconducting tapes, eddy current losses [6] in sheath material and coupling losses[5], [6] between the mutlifilaments of HTS tapes. AC losses due to Self field are investigated in detail by Vyas et al [7] and found that the AC losses depend on the transport current. Further, the method of measuring these AC losses by calorimetric method [8], [9], electrical circuit method [9], [10] and contactless electrical measurement [11] are reported in the literature. Moreover, it was reported that the AC losses can be minimized by changing the gaps between the superconducting tapes [12] and reduction in AC losses up to 1.8/W/m/phase is achieved at 5kA [13].

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1.2. Dielelectric or tanδ losses

Based on the dielectrics, HTS cables are classified into warm dielectric and cold dielectric cables. Various dielectric materials used in the HTS cable are Cross Linked Polyethylene (XLPE) [14], and Poly-Propelene Laminated Paper (PPLP) [14]–[17], Kraft paper [17], polyethylene (PE) and PVC. However, PPLP is reported to be suitable material which can withstand electrical breakdown [18]. Moreover, liquid nitrogen (LN_2) is reported to have suitable dielectric properties which can be used as a coolant [19] in the HTS cable.

1.3. Other factors to be considered in design of HTS cables

Thermal losses such as conduction in the corrugated steel pipe, convection losses between the corrugated steel pipe and the cryogenic coolant and heat leaks from the surroundings through the thermal insulation are the other important losses to be considered in the design of HTS Cables. In addition, Mechanical issues such as torsion strain [20], strain tolerance, bending radius, fracture toughness and twist pitch of the HTS cable are mechanical issues to be considered while designing the HTS Cable.

As the losses increase, the critical values of current density, critical field and critical temperature are affected. Hence, it is necessary to investigate on the methods to reduce the losses. Accordingly, cooling strategies are to be implemented to enhance the performance of HTS cables. Few recent works on

Figure 1: Warm dielectric Coaxial cable

Table 1
Experimental, numerical and computational modeling of Superconductors

		AC Losses			Cooling		
		Experimental	*Numerical*	*Computational*	*Experimental*	*Numerical*	*Computational*
LTS	Superconducting Magnets	Park [22]	F.Grilli [23]	M.N. Wilson[24] Bottura [25]	Ohya [26]	Marinucci [27] Bottura [28]	R.S. Dondapati [29][30][31]
	Superconducting Cables	Daney [32] Zannella [33] Elschner [34]	Vyas.G [7] Wesche [1]	Grilli [35] Lehtonen [36] Campbell [37]	Mukoyama [38]	Fuchino [39]	R.S.Dondapati [21] Ashworth [40]
	Superconducting Motors	Pei [41] Muta [42]	Malé [43] Nasar [44]	Leveque[45] Fu [46]	Chen [47]	Hong [48]	Yang Kai [49]
	Superconducting Generators	Sakamoto [50]	Magnusson [51] Oberly [52]	Zermeno [53]	Intichar [54]	Jo [55] Abrahamsen [56]	Ries [57]
HTS	Superconducting Fault Current Limiters	Park [58] Agnoux [59]	Otabe [60] Sugita [61]	Song [62]	Yang [63] Kar [64]	Chang [65]	Sousa [66]
	Superconducting Transformers	Ishigohka [67]	Nitta [68] Nab [69]	Formisano [70]	Janu [71]	Chang [72]	Smolka [73]
	Superconducting Magnetic Energy Storage (SMES)	Ohsaki [74]	Xu [75]	Xu[75] Han [76]	Na [77] Ren [78]	R.S.Dondapati [79]	Choi [80]

estimation of AC losses and implementation of cooling strategies with respect to Low Temperature Superconductors (LTS) and High Temperature Superconductor (HTS) devices are compiled in Table 1. Further, a typical view of the single phase warm dielectric HTS cable is shown in Fig. 1. To retain the superconductivity of the HTS tape, Liquid Nitrogen (LN2) is generally used to cool the HTS tape below to its critical temperature [21].

2. ESTIAMTION OF LOSSES IN HTS CABLES

2.1. AC losses

AC losses can be estimated using the calorimetric and electric circuit methods as follows.

1) Calorimetric method: In this method, a Micarta or G-10 [4] tube is used as thermal insulation for the HTS cable. When the current is passed through the current leads connected to HTS cable, generate AC losses and hence induce radial temperature gradient which can be measured using thermocouples.The range of accuracy of measurement depends on the sensitivity of the thermocouples.
2) Electrical method: This method is one of the advancements in estimating the AC losses in HTS cables. With the use of digital lock-in amplifier, the angle between the voltage and current signal and the voltage across the cable are measured. If the measured phase angle has a small error, a significant error will arise in AC loss measurement.

The AC losses in the HTS cables are given by [6] as

$$Q_{total} = Q_{self} + Q_{Ba} + Q_{Bc} \tag{1}$$

Where, Q_{self} = loss due to self field, Q_{Ba} = loss due to axial field, Q_{Bc} = loss due to circumferential field

According to the Sumitomo's cable

$$Q_{total} = Q_{self} + Q_B \text{ (W/m)} \tag{2}$$

Where, Q_B is equal to summation Q_{Ba} & Q_{Bc}.

According to Furukawa's cable

$$Q_{total} = Q_B + Q_{self} + Q_{eddy} \text{ W/m} \tag{3}$$

As the electrical shielding is not present in this cable, the magnetic fields, the axial field B_a and the circumferential field B_c causes eddy current losses. Further, self-field AC losses are calculated by using Norris equation [7] as given by

$$Qac = \frac{\mu_0 I_c^2 f}{\pi}[(1-\Gamma)\ln(1-\Gamma) + \Gamma - \frac{\Gamma^2}{2}] \text{ (W/m)} \tag{4}$$

$$\Gamma = \frac{I_{pk}}{I_c} \tag{5}$$

For $\Gamma \ll 1$

$$Qac \cong \frac{\mu_0 I_c^2 f}{6\pi}\Gamma^3 \tag{6}$$

$$I_{pk} = \sqrt{2}.I_{rms} \tag{7}$$

$$\Gamma = \frac{\sqrt{2}.I_{rms}}{I_{c,cable}} \tag{8}$$

$$P = V_{rms} \cdot I_{rms} \cdot \cos\phi \tag{9}$$

where, Γ is the normalized current, F_R is retention fraction, N is the number of tapes in the cable, V_{rms} = RMS voltage (V), I_{rms} = Transport current (A), cosΦ = power factor.

AC losses with the variable transport currents are calculated. As the critical current is increased, AC losses are found to be decreasing as shown in Fig. 2. Further, as the transport current increases, the AC loss is found to be increasing as shown in Fig 3.

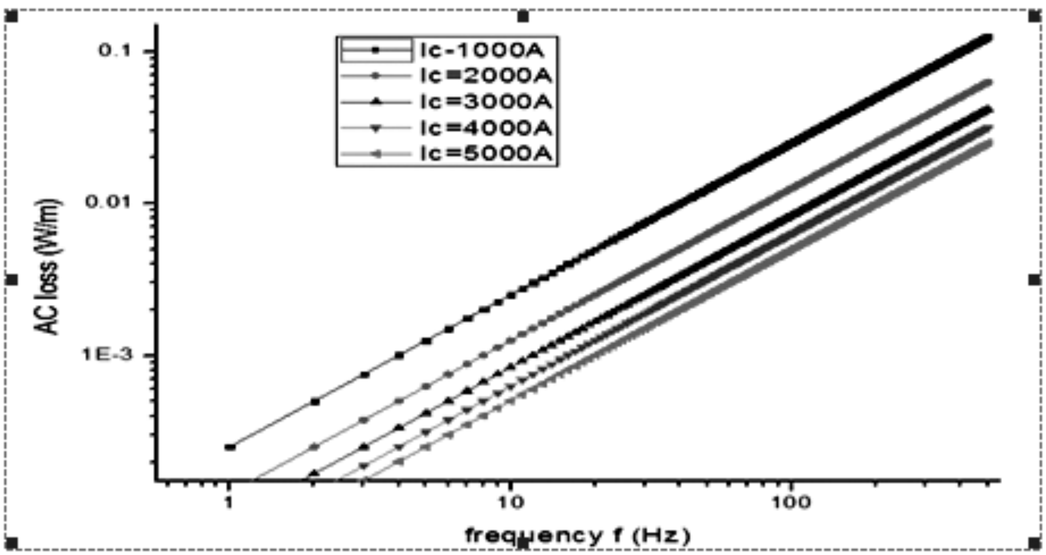

Figure 2: AC losses with frequency at various critical currents

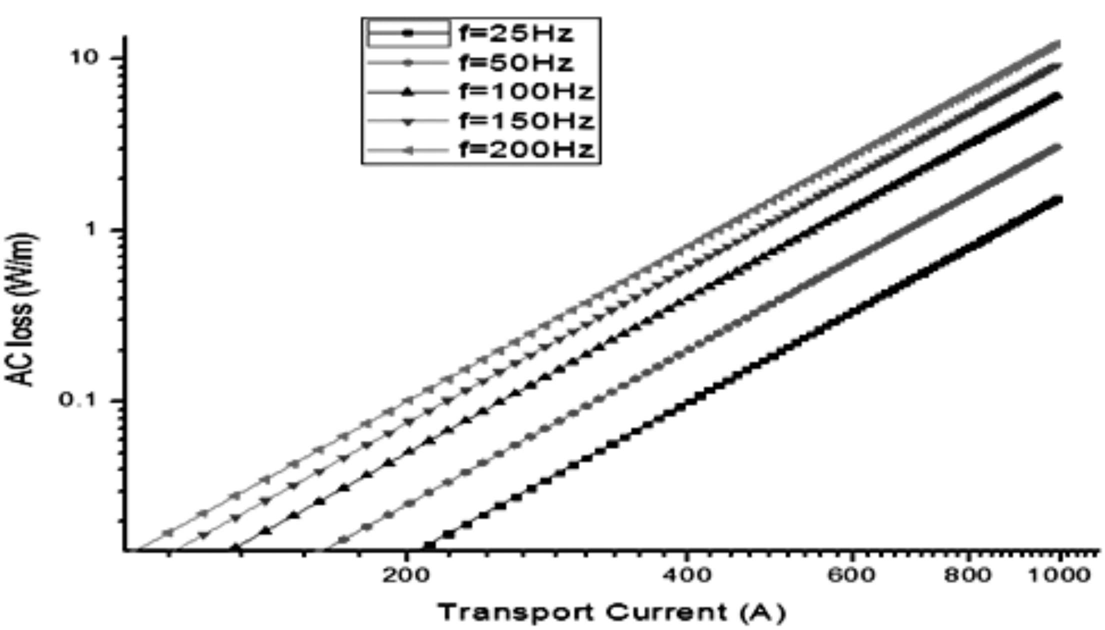

Figure 3: AC losses with transport current at various frequencies

2.2. Dielectric losses

The dielectric losses are also called as tand losses. These losses occur when the cryogenic fluid that is supplied could not cool the dielectric material due to the loads such as heat leak from the ambient through the insulation and protective shield.

The dielectric losses per unit length is calculated by [1]

$$P_d = 0.5\omega C U_P^{\ 2} \tan\delta = \omega U_P^{\ 2} \frac{\pi\varepsilon_0}{\ln(r_{od}/r_{id})} \varepsilon \tan\delta \tag{10}$$

where, C is the capacity of cylindrical capacitor and is given by $C = 2\pi\varepsilon\varepsilon_0 / \ln(r_{od}/r_{id})$ per unit length, ω is the angular power frequency given by $\omega = 2\pi f$, ε is the dielectric constant of the insulation, ε_0 is the permittivity of free space, U_p is phase to ground peak voltage, δ is the angle loss, r_{od} is outer diameter, r_{id} is inner diameter of the HTS Cable.

The dielectric losses are also calculated by [15] as given by

$$\frac{P_{ins}}{L} \approx S.\omega \int \partial f \, \varepsilon\varepsilon_0 \tan\delta E^2 \tag{11}$$

where, S is technical Carnot factor.

3. CONCLUSION

The following conclusions may be drawn from the present review.

1) Calorimetric method is slow process. However, it is a straight process. By using this method, AC losses in the range of 0.1W/m to 10W/m were measured.
2) Electrical circuit method is quicker and the range of measurment is high when compared with calorimetric method.
3) PPLP, XLPE, PE, PVC and krafted paper are used as dielectrics in the warm dielctric (WD) cables. LN2 and PPLP are used as dielectrics in the cold dielectric (CD) cables.
4) HTS cables with Direct current (DC) are free from losses as compared to those with Alternating Current (AC). However, DC transmission and storage requires a large equipment which adds to enormous cost. DC transmission is done with the CD cables only.
5) The AC losses are also reduced by the methods such as narrow filament diameter, twisting the filaments and introducing barrier between filaments for minimizing the coupling.

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