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journal or publication title	Physics Procedia
volume	58
page range	326-329
year	2014-10-10
URL	http://hdl.handle.net/10228/5821

doi: info:doi/10.1016/j.phpro.2014.09.080

Available online at www.sciencedirect.com

ScienceDirect

Physics Procedia 58 (2014) 326 – 329

Physics Procedia

26th International Symposium on Superconductivity, ISS 2013

AC loss of ripple current in superconducting DC power transmission cable

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Abstract

As a method of largely reducing the transmission loss in the electric power grid, superconducting direct current (DC) power transmission cable has been investigated. Using superconducting DC power transmission cables, large amounts of current and energy can be transferred compared to conventional copper cables. In this case, an alternating current (AC) is converted to DC and superposed AC which is known as ripple current, and the energy loss by the ripple current is generated. Therefore it is desired to estimate the energy loss density for the case of DC current and superposed AC current for a design of DC transmission cable system. In this study, the hysteresis loss for DC current of 2 kA rectified from 60 Hz alternating current is calculated using the Bean model, and coupling loss was also estimated. The diameter of the cable was 40 mm. The ripple currents generated by multi-pulse rectifiers, 6-pulse, 12-pulse, and 24-pulse were considered. It is found that the total AC loss including the hysteresis loss and the coupling loss is considerably smaller than the supposed heat loss of 0.5 W/m which is obtained with a newly developed cable.

Peer-review under responsibility of the ISS 2013 Program Committee

Keywords: AC loss; ripple current; superconducting DC power transmission cable

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1875-3892
Peer-review under responsibility of the ISS 2013 Program Committee
doi:10.1016/j.phpro.2014.09.080

1. Introduction

As a method of largely reducing the transmission loss in the electric power grid, superconducting DC power transmission cable has been attracting a great deal of attention [1]. The transmission loss of superconducting DC power transmission cable is estimated to be ten times less than that of superconducting AC power transmission, and thirty times less than the transmission loss of ordinary AC power transmission by copper cable [2]. Using superconducting DC power transmission cables, large amounts of current and energy can be transferred efficiently compared to conventional copper cables. In this case, an AC current is rectified and converted to DC current and superposed AC ripple current which generates energy loss [3, 4].

In our previous work, it was found that the AC losses with and without DC were the same when the magnetic field dependence of critical current density was ignored [3]. This case corresponds to Bean-London model and the hysteresis loss can be calculated by Hancox formula [5].

In this study, the hysteresis loss of the ripple current on DC of 2 kA rectified from 60 Hz alternating current is calculated using Bean model, and coupling loss is also estimated. The ripple currents generated by multi-pulse rectifiers, 6-pulse, 12-pulse, and 24-pulse are considered.

2. Theory

We consider a p-pulse rectified current wave form as follows,

$$I_p(t) = \cos\left(\omega t - \frac{n\pi}{p}\right), \tag{1}$$

where ω is angular frequency of the alternating current, $|\omega t - n\pi/p| < \pi/p$, n is integer. Fig. 1 shows the rectified current waveforms of Eq. (1). This wave form can be expressed by Fourier series as

$$I_p(t) = \frac{p}{\pi}\sin\frac{\pi}{p}\left[1 - \sum_{n=1}^{\infty}\frac{2}{(pn-1)(pn+1)}\cos(pn\omega t)\right]. \tag{2}$$

From Eq. (2), it is found that the rectified current consists of DC current of the magnitude of $(p/\pi)\sin(\pi/p)$ and the ripple current of the magnitude of $[1-\cos(\pi/p)]/2 = \sin^2(\pi/2p)$. The ratio k_p of the ripple current to the DC current is given by $k_p = (\pi/2p)\tan(\pi/2p)$.

The AC loss of the superconductor with ripple current consists of the hysteresis loss and the coupling loss. The hysteresis loss due to the ripple current in the superconducting cylinder can be estimated using the Bean model with a constant critical density with respect to the magnetic field. The hysteresis loss Q_h per unit length per cycle is given by the following equation [6, 7]

$$Q_\mathrm{h} = Q_0\left[(1-i_\mathrm{m})\ln(1-i_\mathrm{m}) + \frac{(2-i_\mathrm{m})i_\mathrm{m}}{2}\right], \tag{3}$$

where $Q_0 = \mu_0 I_\mathrm{c}^2/\pi$, $i_\mathrm{m} = I_\mathrm{m}/I_\mathrm{c}$, I_m is the amplitude of AC in the cylindrical superconducting wire, and I_c is the critical current. Eq. (3) can be applied to superconducting wire with a circular or an elliptical cross section. This equation was derived by Hancox for cylindrical case and Norris for elliptical case, and is also known to agree well with experimental results of superconducting tape.

Fig. 2 shows a high temperature superconducting (HTS) DC cable consisting of N superconducting tapes. The hysteresis loss P_h of the DC cable per unit length can be obtained by

$$P_\mathrm{h} = Q_\mathrm{h} f p N, \tag{4}$$

where $f = \omega/(2\pi)$, and Q_h is calculated assuming $I_\mathrm{m} = k_p I_\mathrm{dc}$, $I_\mathrm{dc} = I_\mathrm{DC}/N$, I_DC is the total DC current.

The coupling loss Q_c of a superconducting tape per unit volume per cycle can be calculated based on the block model shown in Fig. 3 [8] and is given as follows:

$$Q_\mathrm{c} = \Gamma_\mathrm{c}\frac{B_\mathrm{m}^2}{2\mu_0}\frac{2\pi f\tau_\mathrm{s}}{(2\pi f\tau_\mathrm{s})^2 + 1}, \tag{5}$$

where Γ_c is a constant, $B_\mathrm{m} = \mu_0 I_\mathrm{m}/(2\pi R)$ is the external magnetic field, R is the radius of the cable, $\tau_\mathrm{s} = \mu_0(l/2)^2/(2\rho_n)$ is the coupling time constant, l is a twist pitch length, and ρ_n is resistivity of the block of the normal metal. The constant Γ_c is given by $\Gamma_c = 4\pi[2s/(s+2n)]/3$, where s and n are the thickness of superconductor and the normal metal, respectively. Assuming that $s \cong n$ and that the coupling frequency $f_c = 1/2\pi\tau_s$ is very smaller than 1 Hz ($f_c \ll 1$) for longer twist pitch or non-twisted DC superconductor tapes such as (Bi, Pb)-2223 tapes, the coupling loss per unit length per unit time can be obtained as follows [8],

$$P_c = Q_c f N w t \cong \frac{4\pi B_m^2 f_c N w t}{9\mu_0} \ll \frac{4\pi B_m^2 N w t}{9\mu_0}. \tag{6}$$

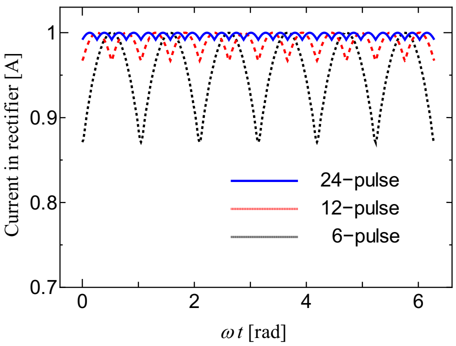

Fig. 1. Current in three-phase 6, 12, 24-pulse rectifiers.

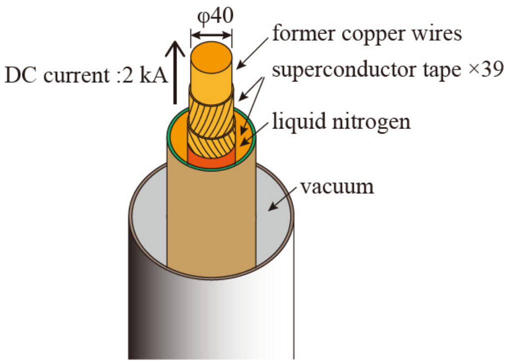

Fig. 2. HTS DC cable.

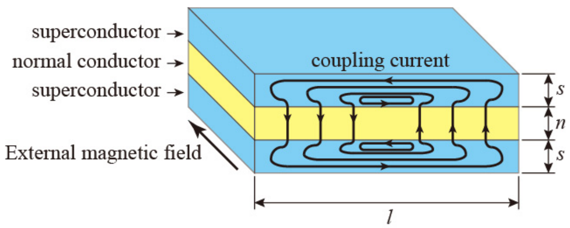

Fig. 3. Coupling current in superconducting flat tape.

3. Results and discussion

AC losses for various pulse rectified currents of the cable per unit length of (Bi, Pb)-2223 superconducting DC cable are calculated from Eq. (4) and shown in Table 1. The cable has a cylindrical superconductor which consists of 39 tape-wires, the diameter of the cable is 40 mm, and the critical current is $I_c = 100$ A. The width and thickness of the tape are $w = 4$ mm and $t = 0.2$ mm, respectively. When the cable carries the DC current of 2 kA rectified from 60 Hz 3-phase current, the amount of the DC current of each tape is given as $I_{dc} = 2000/39 = 51.3$ A. The obtained AC losses are found to be much smaller than the heat loss of 0.5 W/m which is obtained with a newly developed cable [1].

Fig. 4 shows the hysteresis losses of the DC cable as a function of rectified DC current I_{dc} for different critical currents of $I_c = 100$ A and $I_c = 200$ A. Since the AC component of the ripple current is very small ($i_m \ll 1$), Eq. (3) can be approximated as

$$Q_h = Q_0 \frac{i_m^3}{6}. \tag{7}$$

Making an approximation of $k_p \cong (\pi/2p)^2$, we have a simple equation of the hysteresis loss as follows,

$$P_h = \frac{Q_0}{6}\left(\frac{\pi}{2p}\right)^6 \left(\frac{I_{dc}}{I_c}\right)^3 f p N = \frac{\mu_0 \pi^5}{384} \frac{I_{dc}^3}{I_c} \frac{f N}{p^5}. \tag{8}$$

This equation shows that the hysteresis loss of the ripple current is inversely proportional to I_c and the fifth power of p. Therefore, the hysteresis loss can be decreased effectively by increasing the number of pulse p.

The coupling losses for $p = 6, 12, 24$ given by Eq. (6) are also shown in Table 1. Since the coupling frequency f_c

becomes very low for DC cables, the coupling losses are calculated assuming $f_c = 1$ Hz, and actually could be ignored compared to the hysteresis losses for the cases of $f_c \ll 1$ [9].

Table 1. AC losses for various pulse rectified currents of 2 kA DC power transmission cable.

Pulses	Hysteresis loss P_h (μW/m)	Coupling loss P_c (μW/m)
6	443	$P_c \ll 68.2$
12	13.0	$P_c \ll 4.12$
24	0.399	$P_c \ll 0.255$

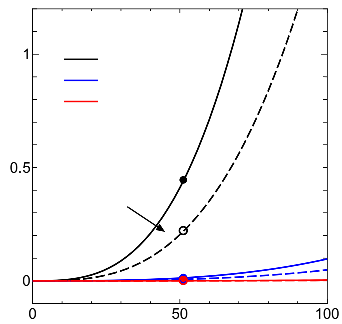

Fig. 4. Hysteresis losses for various pulse rectified current.

4. Conclusion

The AC loss due to the hysteresis loss and the coupling loss of the ripple current generated by multi-pulse rectifiers in the DC power transmission cable was calculated. The hysteresis loss is found to be inversely proportional to the fifth power of the number of the pulse, while the coupling losses are very small compared to the hysteresis loss and can be ignored. For 2 kA DC current transmission in (Bi, Pb)-2223 superconducting DC cable, AC losses of the DC cable with a critical current of 100 A are 443 μW/m, 13.0 μW/m, and 0.399 μW/m for 6-pulse, 12-pulse, and 24-pulse rectifiers, respectively. These AC losses are well below the heat loss of 0.5 W/m. These results would be useful to consider the multi-pulse rectifiers for superconducting DC power transmission cables.

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