Study on AC loss measurements of HTS power cable for standardizing

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\textbf{Abstract.} High-temperature superconducting power cables (HTS cables) have been developed for more than 20 years. In addition of the cable developments, the test methods of the HTS cables have been discussed and proposed in many laboratories and companies. Recently the test methods of the HTS cables is required to standardize and to common in the world. CIGRE made the working group (B1-31) for the discussion of the test methods of the HTS cables as a power cable, and published the recommendation of the test method. Additionally, IEC TC20 submitted the New Work Item Proposal (NP) based on the recommendation of CIGRE this year, IEC TC20 and IEC TC90 started the standardization work on Testing of HTS AC cables. However, the individual test method that used to measure a performance of HTS cables hasn’t been established as world’s common methods. The AC loss is one of the most important properties to disseminate low loss and economical efficient HTS cables in the world. We regard to establish the method of the AC loss measurements in rational and in high accuracy. Japan is at a leading position in the AC loss study, because Japanese researchers have studied on the AC loss technicadly and scientifically, and also developed the effective technologies for the AC loss reduction. The JP domestic commission of TC90 made a working team to discussion the methods of the AC loss measurements for aiming an international standard finally. This paper reports about the AC loss measurement of two type of the HTS conductors, such as a HTS conductor without a HTS shield and a HTS conductor with a HTS shield. The AC loss measurement method is suggested by the electrical method.
1. Introduction
High temperature superconducting cables (HTS cables) use HTS wires, which perform zero resistivity and high current density, in a cable conductor. The HTS cable has a low transmission loss and a compact size compared to the copper or aluminium conventional power cables. DC current can flow in a superconductor with zero resistance. However, concerning with AC power cables, the superconductor generates AC loss due to a magnetic-flux flow by an electrical magnetic force generated by an AC current flowing. Moreover, a coupling loss and an eddy current loss induced in metal matrix of HTS wire add the AC loss of the cable. It is important to reduce the AC loss for realizing economical advantage and energy-saving of the HTS cable. AC loss reduction is most important and recently the low AC loss of 1 W/m is achieved in the 3 kA HTS cable.
Since methods of the AC loss measurement have been proposed by many laboratories, there is not the standard method that all researchers recognized. A lot of AC loss measurement methods have been conducted and proposed in the all over the world. Recently AC loss in the operated condition is important, because the value of the AC loss decide a capacity of the cooling system, and estimate the performance of the HTS cable to customers. Therefore, to commercialize the HTS cable, the AC loss measurement is required not only in objectivity and accuracy but also in easily for the manufacturers.
Researchers and engineers in Japanese domestic committee of IEC 90 have discussed about the method of the AC loss measurement to standardize it under supporting by Ministry of Economy, Trade and Industry.

2. Survey of AC loss measurement
The AC loss measurements have been conducted by a lot of laboratories around the world. There are two methods to measure the AC loss. One is the electrical method, which is called an AC four terminal method[1]-[5], and the other is the calorimetric method[6]-[9], in which we measure the heat generated from the AC loss.

2.1. Electrical method
A typical electrical method of the AC loss measurement is the procedure of putting voltage taps on the both ends of the cable conductor and of measuring the cable voltage during loading current. Since the cable voltage consists of the voltage from inductance (L component) and from resistance (R component), it is necessary to omit the large amount of voltage from L component. The two methods of omitting the L component are proposed. One is to use a lock in amplifier, which measures the same phase voltage as the phase of the current. The other is to use a data recorder, which measures the voltage and the current at short time interval, and to summarize multiplications of the voltage and the current for one period with a computer. In some cases, to raise accuracy of the measurement the L component is cancelled by using the pick-up current. Many studies about how to arrange the return current pass and how to conform the voltage tap and the voltage lead were conducted for accuracy improvement of the measurement. A suggestion of AC loss of a conductor with a shield was also studied. The electrical methods provide AC loss measurement with measurement range from 10^-14 W/m to 10 W.

2.2. Calorimetric method
The calorimetric method measures a minute calorie generated by AC loss in the cable conductor. Procedures of the measurement of the heat flux were explained three methods that, such as measuring of temperature rising of the conductor, measuring of boil off of the evaporated nitrogen gas, and measuring of temperature difference between inlet nitrogen and outlet nitrogen. In all methods, it is important to remove inversion heat from the cryostat pipe, joule loss in electrode, and conducting heat from cable ends.
3. Recommendation of AC loss measurement
An industrial standard needs not only reliability and accuracy but also simple for the measurement, because cost of the measurement adds price of a HTS cable. The high cost prevents to spread the HTS cables to the market, and doesn’t provide benefit to the manufacturers and the users. We propose the electrical method as the simple and easy method. We describe the procedure of the measurement in following.

3.1. AC loss measurement of the conductor without HTS shield
An open type bath that has enough volume for entering a test sample is filled with liquid nitrogen, and a HTS cable sample is immersed in it. Electrodes that use for applying current are formed on the both end of the HTS cable sample. The voltage taps are put on the surface of the conductor at inside of the electrodes. The electrodes are connected to an AC current source with insulated Cu cables. AC current applied to the sample is measured using a current detector such as shunt-resistor, a current-transformer, a Rogowski-coil, etc. The voltage lead wires connected on the voltage taps generally are disposed on the surface of the conductor, and two lead wires are twisted at the center of the conductor and twisted wire is connected to a voltage measurement device.

The AC loss is calculated by a time integration of current and voltage over one period. The current and the voltage are measured and are recorded with a data acquisition device at short time interval, the both recorded values of current and voltage are multiplied, and the multiplied values are numerical integrated for one period, for example using a computer. It is shown as the second term of equation 1. To improve sensitivity of resistive component of the voltage, some laboratories canceled the inductive component of the voltage by using current phase voltage from a coupling coil in the current loop.

When the current and the voltage are sine-wave with little deformation, the AC loss is induced with a lock-in-amplifier. The lock-in-amplifier can directly explain the phase difference ($\theta$) between the current and the voltage, and the AC loss is calculated by the third term of the equation 1.

\[ P = \frac{1}{T} \int_0^T I(t) \times V(t) dt = \sum I(t) \times V(t) = I_e \times V_e \cos \theta \] (1)

$P$ is AC loss, $I(t)$ is current in the conductor, $V(t)$ is voltage between voltage taps, $T$ is time of one period, $\theta$ is phase difference between $I(t)$ and $V(t)$, $I_e$ is effective value of the current, and $V_e$ is effective value of the voltage.

![Figure 1. Diagram of AC loss measurement. Measurement device of AC loss is used I-V a data recorder or a lock-in-amplifier](image-url)
3.2. AC loss measurement of the conductor with HTS shield

In the case of the HTS cable sample with a HTS shield layer, we propose the way of AC current flows in the conductor layer and the shield layer in a series by jointed the conductor and the shield at the one end with a Cu lead. In a long-distance HTS cable, actually AC current that flows in the shield layer is almost same volume with counter direction against the conductor current, because the shield current is induced from the magnetic field produced by the conductor layer and the shield layer of the long-distance cable has extremely small resistance in a cable operation current compared to the inductance of the shield layer. Therefore the current flowing in series between the conductor layer and the shield layer can be adopted to measure the AC loss for the standardization, when the commercial HTS cable will is estimated in the operation condition of the real grid.

We are studying three ways of the AC loss measurement in the cable with shield layer. The voltage taps that measure cable voltages are formed at each end of the conductor and the shield, the AC loss is derived from the current and the voltage measured with the voltage tapes. Methods of (2) and (3) are developed and examined its verification of by Sumitomo Electric.

1) Each Layer Individual Measurement Method

Figure 2 shows the measurement diagram for measuring of the AC loss in the conductor and the shield respectively. $V_{AB}$ of the end to end voltage on the conductor and $V_{CD}$ of the end to end voltage on the shield are measured with a data recorder or a lock-in-amplifier. The AC loss was derived from resistive component of the current and the voltage as equation 2.

$$Q = \int_0^T (V_{AB} \times I) \, dt + \int_0^T (V_{CD} \times I) \, dt = I \times V_{AB} \cos \theta_c + I \times V_{CD} \cos \theta_s$$  \hspace{1cm} (2)

![Diagram of AC loss measurement](image_url)
2) Connection Part Subtraction Method

Figure 3 shows the measurement diagram of AC loss measurement that derives from the total AC loss subtracted the AC loss of the joint part. The AC loss is derived from $V_{AD}$ of the end to end voltage between point A and point D and $V_{CD}$ of the end to end voltage between point B and point C measured with a data recorder or a lock-in amplifier. The AC loss was calculated by equation 3.

$$Q = \int_0^T (V_{AD} \times I) dt - \int_0^T (V_{BC} \times I) dt = I \times V_{AD} \cos \theta_{AD} - I \times V_{BC} \cos \theta_{BC}$$  \hspace{1cm} (3)

![Figure 3. Diagram of AC loss measurement (Joint Part Subtraction Method)](image)

3) Joint Part Differential Method

Figure 4 shows the measurement diagram of AC loss measurement by a lock-in-amplifier, which operate differential mode of input A and input B. $V_{AB}$ of the end to end voltage is inputted to terminal A of the lock-in-amplifier and $V_{CD}$ of the end to end voltage is inputted to terminal B. The AC loss of the cable is measured from the voltage of (A-B), the current, and the phase difference by equation 4.

$$Q = I \times (V_{AD} - V_{BC}) \cos \theta$$ \hspace{1cm} (4)

![Figure 4. Diagram of AC loss measurement (Joint Part Differential Method)](image)
4. Principal of electrical measurement.

4.1. Poynting vector

The electrical method (AC four-terminal method) is being proposed as AC loss measurement. We examine a validity of the AC four-terminal method for the AC loss measurement theoretically.

One of evaluation methods of AC loss generated in superconductor is a calculation method that integrate Poynting vector \((E \times H)\) on closed surface. The Poynting vector shows flow of electromagnetic energy. Divergence of vector product \((E \times H)\), where \(E\) is electrical field and \(H\) is magnetic field, is developed as equation (5);

\[
\nabla \cdot (E \times H) = H \cdot \nabla \times E - E \cdot \nabla \times H
\]

Rotation of electrical field and magnetic field in the right term is modified by Maxwell equations, and the both terms are arranged after volume integral in arbitrary closed volume \(V\). The result becomes equation 6.

\[
- \int_S (E \times H) dS = \int_V E \cdot J dV + \int_V E \cdot \frac{\partial D}{\partial t} dV + \int_V H \cdot \frac{\partial B}{\partial t} dV
\]

, where \(J\), \(D\), and \(B\) are respectively density of current, density of electrical flux, and density of magnetic flux. These values has relationship by equation 7, and equation 8, using permittivity \(\varepsilon\) and permeability \(\mu\),

\[
D = \varepsilon E
\]

\[
B = \mu H
\]

The AC loss is obtained from equation 6, where the Poynting vector is surface-integrated on the closed area \((S)\) enclosed the volume \((V)\) and furthermore time-integrated for one period of AC. In the case of the volume doesn’t have ferromagnetic material and ferroelectric material, equation 6 becomes equation 9. The AC loss is derived from the Poynting vector.

\[
Q = - \int_T dt \int_S (E \times H) dS = - \int_T dt \int_V E \cdot J dV
\]

4.2. AC loss measurement of conductor without shield layer

HTS cable consisted of only conductor without shield is simulated as figure 5, which shows a cylindrical conductor of radius \((R_c)\).

Figure 5. AC loss analysing model of a HTS conductor without a shield layer.
The magnetic field \((H_c)\) and the electrical field \((E_c)\) are provided from equation 8 in uniform magnetic field and electrical field along circumferential direction and axial direction. Since some actual HTS cables consist of HTS tapes wound spirally around a former, there is longitudinal magnetic field along axial direction. We neglected the longitudinal field in the basic analysis, because we simplified the model. This model is realized by non-winding tape on the conductor.

\[
H_c = \frac{l}{2\pi R} , \quad E_c = \frac{V_c}{l} \tag{8}
\]

, where \(I\) is cable current, \(V_c\) is voltage between voltage taps, and \(l\) is distance between the taps. The equation 7 that is substituted equation 8 for is surface-integrated on S-surface. The AC loss per unit length is shown as equation 9, and equation 9 shows that the AC loss is derived by using the current and the voltage in the conductor.

\[
Q = \frac{1}{l} \int_0^T dt \frac{l}{2\pi R} \frac{V_c}{l} \int_S ds = \frac{1}{l} \int_0^T dt \left( \frac{2\pi l V_c}{l} \right) = \frac{1}{l} \int_0^T V_c l dt \tag{9}
\]

4.3. AC loss measurement of conductor with shield layer

Divergence of Poynting vector on a shield layer is considered as in and out of the Poynting vector from a coaxial cylinder surface enclosed by surface of inside of shield and surface of outside of the shield. Counter direction current against the conductor current flows in the shield in the condition of Figure. 2, the magnetic field in outside of the shield is zero. The Poynting vector in the outside is zero. The AC loss from the Poynting vector inside the shield is indicated by equation 10 as figure 6.

\[
Q = \frac{1}{l} \int_T dt \int S E_S \cdot H_S ds \tag{10}
\]

![Figure 6 AC loss analysing model of a HTS conductor with a shield layer.](image)

The electrical field and the magnetic field is provided from equation 11 in uniform along circumferential direction and axial direction like the conductor examination and shield current in the closed surface enclosed by the shield inside surface. We neglected it the same as the conductor without shield layer in section 4.2.
The AC loss per unit length of the shield layer is derived by using the current and the voltage in the conductor as same as the conductor. In the case of actual shield layer, the voltage taps is not put on inside surface of the shield in the structure. The voltages of the inside surface and the outside surface are same, because multi-layer shields is gather at cable end with solder and any cross section of shield has the same potential of voltage along the axis.

5. Summary
AC loss is important parameter for realization of HTS cables, and many researchers have been developing AC reduction technologies for long time. AC loss measurement that can be used in common wide currency is required, and the international standard will be requested for the merchandize. A lot of experiences and data is needed for establish of the standard. The proposal of the AC loss measurement in the paper has two objectives; one is that all researchers will test by the same method for accumulating data, and the other is that discussion about AC loss measurements will start. In this progress, the standard will be established under international agreements.

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