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Ac losses in Prototype Multistrand Conductors for Warm Dielectric Cable Designs

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***Abstract*— We report on multiphase ac losses in four-layer prototype multi-strand conductors (PMCs) wound from HTS tape provided by American Superconductor Corporation. These conductors are prototypes warm dielectric cable designs, such as for the US Dept. of Energy's Superconductivity Partnership Initiative Project at Detroit Edison. We report on single phase "two phase"(no current in the PMC but with an external ac magnetic field generated by the two normal conductors arranged at the remaining corners of an equilateral triangle forming a three-phase configuration) ,and balanced three phase losses. Losses were also measured using a set of saddle coils to apply an ac magnetic field to the PMC. The losses were measured as a function of temperature, frequency, and current. We compare the losses for three PMCs, one (4LA) wound conventionally with equal pitch angles for all layers and the two others (4LB and 4LC) wound to achieve equal current distribution (UCD) among the layers, and thus lower single-phase losses in the operating region. In addition, 4LC was wound with a newer generation tape having a higher critical current. The PMC 4LC was found to have the lowest single, two-phase, and three-phase losses.**

***Index Terms*— Superconducting power transmission lines, alternating current losses, multiphase losses, high temperature superconductors.**

I. INTRODUCTION

SUPERCONDUCTING power transmission lines are being considered by the electric utility industry as a replacement and upgrade for existing oil-cooled copper underground-transmission lines in urban areas. In these areas, increasing loads require more current carrying capability. Because superconducting transmission lines can carry two to three times as much current as existing copper lines and can be retrofitted into the same conduits, they offer a significant economic advantage in that they require no expensive new construction.

One of the most important issues in superconducting transmission line engineering design and application is the ac losses these conductors incur at power-line frequencies, both from the self magnetic field of the conductor, and, in certain designs, from the ac magnetic fields generated by the other two phases of a balanced three-phase line.

We report here on both the single phase and on multiphase ac losses resulting from the magnetic field of the other two phases of a three-phase superconducting power transmission line on the phase under test. There are several designs for retrofitting underground power transmission lines with high temperature superconductor (HTS) cables. In the "cold dielectric" design each superconducting phase is surrounded by a superconducting shield. Outside of the shield, therefore, there is no net magnetic field, so that there is no influence of one phase on the others. In the "warm dielectric" design there is no coaxial shield around each phase, thus reducing the use of HTS material significantly, but at the expense of interaction among the phases. The project led by NKT in Denmark employs a cable of the warm dielectric design [1]. If the conductors are relatively far apart, e.g., 20 to 30 cm or more, there is little effect of the fields from the other phase conductors [2]. This was the design of the Detroit Edison - Superconductivity Partnership Initiative (SPI) cable retrofit project sponsored by the U.S. Department of Energy. Here, the major loss component is the single-phase loss with transport current flowing only in the PMC. However, for installations where space is at a premium, typically all three phase conductors are installed in a single conduit with conductor spacing on the order of 10 cm, and the influence of the other phases does need to be considered.

We have measured the ac losses of three prototype multistrand conductors (PMCs) constructed as designs for retrofit cable projects. The cable is designed to carry 2400 Arms. The PMCs tested differ in tape critical current and in winding design. We will compare and contrast the performance of the conductor designs.

II. EXPERIMENTAL

A. Experimental Apparatus and Procedure

Voltage measurements have been used by a number of

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groups to measure the single-phase ac losses of power transmission line prototypes. However, complications arise as to placement of voltage contacts and interpretation of data when a PMC is subjected to external magnetic fields that may drive currents in circular paths that do not cause a voltage to appear at the contacts but do result in losses. This is in particular the case when the multiphase losses are to be measured in a PMC of the warm dielectric design.

For this reason, we chose to use a calorimetric technique for measuring the ac losses. Reference [3] contains substantial detail about the calorimeter construction and operation. Briefly, in this technique, the PMC is thermally isolated except at the two ends. Heat generated uniformly in the conductor results in a parabolic temperature profile along the conductor length. This profile is measured with platinum resistance thermometers and fitted to the equation:

$$q_L = 8kA\Delta T_m/L^2, \quad (1)$$

where q_L is the heat generation (loss) per unit length of the conductor, k is the effective thermal conductivity along the length of the PMC, A is the conductor cross-sectional area, ΔT_m is the temperature difference between the ends and the midpoint of the conductor, and L is the conductor length. The factor kA is determined independently by measuring the temperature gradient along the conductor when a known amount of power is generated by a bifilarly wound heater located at the midpoint. Because the determination of the ac-power loss is independent of the temperatures of the conductor ends, Joule heating at the normal/superconductor junction, which raises the temperature of the ends of the PMC, has little effect on the accuracy of the measurement. The loss is corrected for the temperature variation along the PMC [2].

The PMC is contained in a G-10 (glass epoxy) vacuum jacket with the ends (the current leads) cooled by the surrounding liquid nitrogen. The other two phases in the three-phase configuration are normal copper conductors, with the three phases arranged at the vertices of an equilateral triangle 10 or 20 cm on a side. Because the vacuum jacket of the PMC is a nonconductor, the PMC is affected by the magnetic field generated by the other two phases, similar to the environment present in a warm dielectric three-phase cable. The temperature of the liquid nitrogen bath can be varied from about 75 K to 64 K by controlling the pressure of the bath using a vacuum pump and pressure regulator.

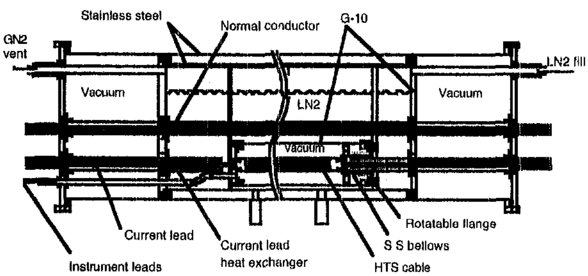

Fig.1. Schematic cross section of cable calorimeter.

TABLE I.
PMC PARAMETERS

PMC	Tape I_c (A)	Cable I_c (A)	Gap (mm)	Winding Angle
4LA	60-85	6000	0.1	±30°
4LB	60-85	5200	0.1	variable
4LC	90-100	4800	1.5	variable

Ac current is supplied by a standard, industrial-type 20 kW ac induction-motor drive modified for use as a variable-frequency power source. The output of the variable frequency source is connected to a 480 V / 5 V, 41.7 A / 4000 A, three-phase, step-down transformer connected in a delta/wye configuration. The power supply is typically operated over the frequency range of about 10 Hz to 180 Hz. It can supply currents up to 3000 Arms near 60 Hz, but is limited to lower levels (~1000 Arms) at low frequency by transformer core saturation and at high frequency by the transformer impedance. The current source performs well both under single-phase and balanced three-phase operation.

In the single-phase loss measurement configuration, ac current flows in the PMC, and the return path is a large distance (>0.3 m) from the PMC. In the "two-phase" configuration, current flows in the two normal phase conductors, generating a magnetic field at the location of the PMC, which carries no current. In the "three phase" configuration, balance, three-phase current flows in the two normal conductors and the PMC. Thus the PMC both carries a transport current and is subjected to a (rotating) magnetic field from the two other phase conductors.

B. Cable

The four layer prototype multistrand conductors (PMCs) were each wound by Pirelli from Bi-2223/Ag sheath multifilamentary tape manufactured by American Superconductor Corporation. PMC 4LA was wound conventionally with equal and opposite pitch angles in alternate layers of about 20 tapes each. PMCs 4LB and 4LC were wound to achieve the same inductance for each layer by adjustment of the pitch angle for each layer. This method was first proposed by the group at Siemens [4]. The result of this winding technique is to achieve uniform current distribution (UCD) among the layers of the PMC. PMC 4LC was wound using tape-to-tape spacing comparable to that achievable with commercial winding equipment and using a later generation, higher performance tape than was used in winding 4LA and 4LB. Each PMC is 1 m long and is wound on a 30 mm diameter core. Other parameters of the PMCs are listed in Table I. The critical current I_c values were measured at 77 K.

III. Results and Discussion

A comparison of the single-phase losses of the PMCs at 76 K and 60 Hz is shown in Fig. 2. The losses depend on the current as a power law with an exponent n near 3. According to the uniform current distribution (UCD) model, magnetic flux penetrates into each of the four layers of PMCs 4LB and 4LC even at the lowest currents. In contrast, the monoblock model predicts that at low currents, flux will only penetrate the outer layers of PMC 4LA. Thus, the losses are lower for than 30°, the unbalanced area is larger than for 4LA. However, these two PMCs show both larger (4LB) and smaller (4LC) two-phase losses than for 4LA. This mechanism would also generate current flow in the end connectors, but there was no significant evidence of excess heating and temperature rise in those components. Thus, although the lack of systematic behavior among the PMCs suggests that this mechanism is not a major component of the two-phase losses, the presence of such an extrinsic effect cannot be ruled out.

Saddle-shaped magnetic field coils, which can apply a transverse magnetic field to the PMC, were added to the calorimeter system to extend the range and controllability of an applied field on the losses in the PMC. This effectively allows simulating a continuously varying spacing of the phase conductors. It was found in every case that the two-phase losses correlate directly with the strength of the applied ac magnetic field.

The balanced three phase losses of 4LC were also measured as a function of temperature, frequency, and spacing of the phase conductors. Fig. 5 shows a comparison of the single, two-phase, and balanced three-phase losses under one condition. It is clear that the single and two-phase loss magnitudes are not simply additive; the three-phase loss has a nonlinear dependence on the transport current and the applied magnetic field. All of the PMCs measured in the ac loss calorimeter should a similar nonlinear dependence, and PMC 4LC shows the best performance, i.e., the smallest ratio (three-phase loss/single-phase loss), about 2.7, of any of the four-layer PMCs. Three-phase losses twice as large were observed in many other PMCs correlating roughly with significantly larger two-phase losses. Thus control of the two-phase loss appears to be important to achieve low three-phase losses.

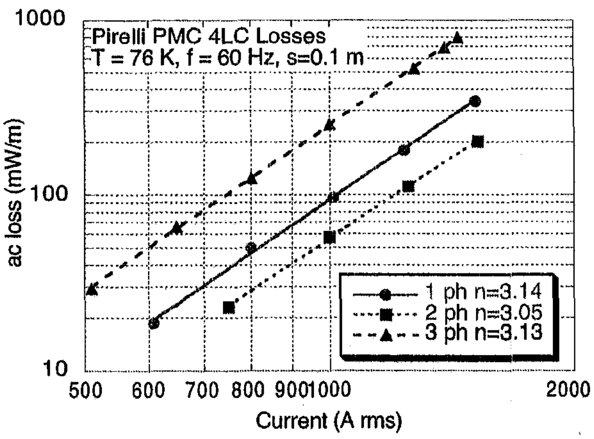

Fig. 5. Single, two-phase, and balanced three-phase losses of PMC 4LC at 76 K, 60 Hz, and 0.1 m phase conductor spacing. The power law exponents *n* are given in the legend.

IV. Conclusions

We have measured the single, two-phase, and balanced three-phase losses of three prototype multistrand conductors for use in warm dielectric cables. The best performance was demonstrated for PMC 4LC, wound with adjusted pitch angles and of higher performance tape and with an inter tape spacing appropriate for machine winding. Single-phase losses at 50 Hz, 77 K, and 2000 A were measured to be 0.69 W/m. The two phase losses were about 0.6 X of this loss, and the three-phase losses, about 2.7 X. This is the best performance of any PMC measured in the ac loss calorimeter, and should be suitable for a warm dielectric cable conductor application.

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