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Thermally induced EMF in unirradiated MI cables

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Abstract

Radiation and temperature induced currents and voltages in mineral insulated (MI) cables, (generally termed RIEMF and TIEMF, respectively) have recently been the object of discussion and study. The problem is due to a possible electromagnetic force (EMF) generated along the centre conductor of ITER magnetic diagnostic coils in a radiation field, and the difficulty of separating radiation and temperature effects from the required signal. Previous work has shown the importance of temperature gradient effects. To address this problem further, studies of TIEMF have been carried out on an MI cable across the ends of the centre conductor at temperatures up to 550 °C, making point-by-point measurements, as well as annealing tests. It has been confirmed that voltage maxima appear in well-localized regions of the cable, indicating that some inhomogeneity is present. No geometric variations were observed by X-ray imaging of the cable.
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1. Introduction

The extensive use of mineral insulated (MI) cables in ITER, together with the low voltage signals that must be carried in some cases, implies that a careful analysis of all the possible sources of noise and off-set voltages is of paramount importance. An example of MI cable use for a critical device of particular concern is the equilibrium pick-up diagnostic coils [1]. The coil output signal is fed to an integrator, so any electromagnetic force (EMF) induced by radiation (RIEMF) and/or thermal effects (TIEMF) along the central conductor is added to the real signal, and moreover can rapidly saturate the integrator if too high. Because thermal gradients are inherent in all irradiation experiments, measurements on RIEMF for candidate MI cables during gamma and neutron irradiation have included both radiation and thermal effects, making the results difficult to explain. More recent work has indicated the important role of thermal gradients along the cable [1–5]. In particular, work on four different MI cables has shown that TIEMF voltages >1 μV can be generated for temperature differences as low as 30 °C [4]. It was found that MI cables with Cu, or Cu alloy centre conductors were far worse than those with stainless steel conductors; however, comparable bare copper wires did not generate any measurable TIEMF. The most important finding of this previous study was the localization of the thermally sensitive regions in the MI cable, as illustrated in Fig. 1. The positive, negative, and zero voltages generated on moving the heating source along the MI cable are perfectly reproducible, and strongly suggest local inhomogeneities. In the work presented here, one of the candidate MI cables for

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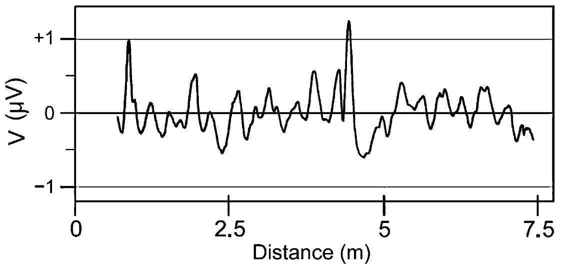

Fig. 1. Value of EMF measured in the cable core while moving the heating source (at 48 °C) at a continuous rate of 0.025 m/s. Horizontal scale indicates the distance between the heated point and the cable connector box.

use in ITER has been further examined for TIEMF without radiation, thus separating thermal effects from RIEMF and enabling one to assess the consequences for MI cables and coils. The work has concentrated on the localized regions, studying the effect of high temperature and examining the geometrical symmetry of the cable.

2. Experimental procedure

The MI cable examined (Thermocoax 1C CAc 10 Si), consists of a central Cu conductor, SiO_2 insulation, and a Cu lined 304L stainless steel sheath, outside diameter 1 mm [3,4]. The conductor and sheath facing the insulator are both Cu to avoid any electro-chemical effects, and the conductor is of very low resistivity, a requirement for magnetic coil applications. The high TIEMF observed in this cable enables thermal effects to be readily detected and localized. Voltage across the ends of the MI cable central conductor was measured with a Keithley 148 nanovoltmeter with a resolution of less than 1 nV for the most sensitive range. To ensure highest accuracy and lowest possible noise, the full maintenance routine for the Keithley 148 nV was carried out and all the internal circuits were checked and adjusted to fulfil the specifications. Finally a low thermal EMF shorting plug was used to measure noise and long term drift of the instrument alone. Under these ideal conditions, noise was less than 1 nV and long term drift $= \pm 5$ nV, well within the specifications. In order to separate the effect of possible drift and offset due to the nanovoltmeter itself from a real signal caused by TIEMF, a two-pole inverting 'make before break' wafer switch was mounted at the input of the nanovoltmeter in an electrically shielded box to enable the polarity of the cable ends to be changed. The 'make before break' switching sequence shorts the two conductor ends and instrument input when passing from one polarity to the other, thus avoiding large spurious voltages due to open circuits and charge build-up.

A 25 m length of the MI cable, 'U' bent into two parallel 12.5 m arms and joined to the switch box, was laid in open standard PVC cable trunking to avoid mechanical oscillations during testing. All cable heating was carried out at between 2 m and 12 m from the switch box and nanovoltmeter to avoid thermal or electrical noise in the measuring system. A 'hot air gun' with electronic control allows heating up to 550 °C of a small 20 mm portion of the cable. To measure the temperature in the MI cable, a thermocouple type K was located in the heated region (attached to the heater and kept

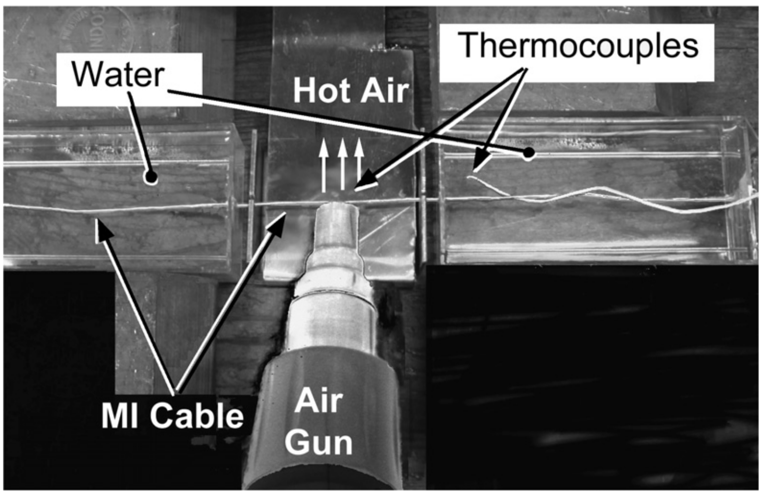

Fig. 2. Experimental set-up for measurement of thermoelectric EMF in a small section of the MI cable.

very close to the MI cable so temperature was almost the same). An initial scanning at about 70 °C was made over the cable to identify the zones of maximum and minimum TIEMF sensitivity.

To examine the identified zones at higher temperature, the corresponding portion of the cable was mounted between two water reservoirs. The cable passes through sealed holes in each reservoir where it is immersed in the room temperature water, hence reducing the propagation of heat along the central conductor. A thermocouple monitors the water temperature. Another thermocouple follows the same path along the water reservoir and seal and reaches the heating point very close to the cable (less than 1 mm) just by rigidity (but not welded to the MI cable). To isolate the heated section of cable even more and to avoid radiation of heat to the water, a U-shaped copper piece with two slits for the cable was mounted between the reservoirs. The separation between water reservoirs was around 8 cm. A photograph of the set-up can be seen in Fig. 2.

Finally, X-ray photographs were taken of the all the identified zones, two photographs at 90° for each zone being taken to examine the cable symmetry.

3. Results and discussion

In order to quantify and study the TIEMF effect along the cable, the whole length was initially examined by moving the hot air gun (at 70 °C) along the cable in a continuous way (at a constant speed around 1 cm/s). The EMF was recorded as a function of position along the cable, with very similar results to those shown in Fig. 1 being obtained. The critical points where TIEMF was maximum (positive and negative) or zero were identified and marked for fuller analysis. As in previous measurements, these critical points were well defined and repeated scans produced the same results. During the scan, the temperature gradient changes both in time and position, so the exact location of the critical points was determined by several static measurements in the region around each point. These were made heating points close to the observed maximum during a fixed time (normally 1 min) to record thermal EMF. After cooling (so voltage drop to zero) the heated point is moved (with a small step of 5 to 10 mm) and process is repeated until the critical point is well located.

Once located, each critical point was positioned in turn between the water reservoirs, and then heated in steps to record the variation of EMF with temperature up to 500 °C. With each temperature step, the voltage also showed a step increase and then quickly stabilized (time constant depends on the point but it is around 3–10 s typically). Fig. 3 shows the results of TIEMF as a function of temperature for two sequential heatings of a positive maximum critical point. It can be seen that the effect is reproducible and the thermoelectric voltage is linear up to about 220 °C, up to this temperature, TIEMF will be directly proportional to the thermal gradients present in the reactor. By about 450 °C, the TIEMF saturates (27 μV). The saturation may in part be due to diffusion of the thermal gradient, but the temperature of water at both sides of the cable did not increase more than 1 °C, suggesting something intrinsic to the cable. To check this, the cable was also heated rapidly to 500 °C to minimize diffusion of the thermal gradient, and the same value of 27 μV was obtained. This value gives an indication of the order of magnitude that can be expected for in-reactor experiments, and is in agreement with observed values of microvolts for MI cables so far assumed to be a radiation effect [1,6]. In contrast to the large voltages generated on heating the maximum critical points, measurement at a zero point produced an almost undetectable voltage up to 200 °C and values only slightly above the noise at higher temperatures, probably due to thermal diffusion along the cable.

The possibility that high temperature annealing may reduce the TIEMF effect has been examined, as this would be a useful treatment to obtain improved cables. Sections identified as having a

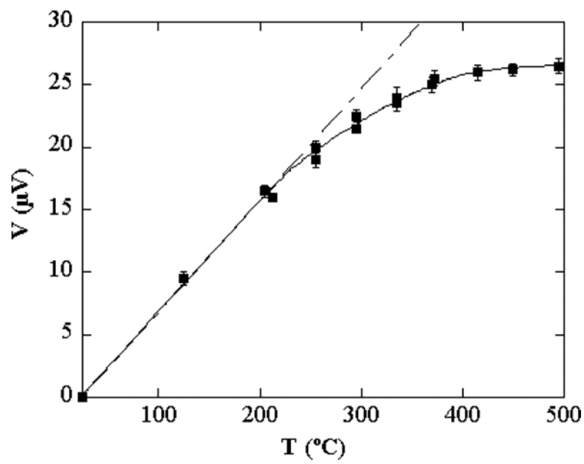

Fig. 3. EMF as a function of temperature for a point in the MI cable where the effect is maximum. Two reproducible heatings are shown. (Lines are only to guide the eyes).

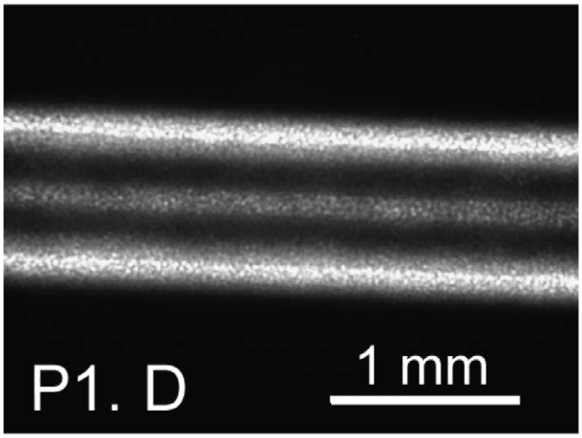

Fig. 4. X-Ray micro-photography of a portion of the MI cable that presents a maximum TIEMF effect.

high TIEMF were now heated up to the maximum temperature of 550 °C and maintained for 10 min. As this extended heating did change the thermal distribution along the cable, the whole cable section was allowed to cool to room temperature before remeasuring the TIEMF values. The results clearly show that no changes occur in the points checked in the MI cable after annealing, and therefore the cause of TIEMF cannot be eliminated by this treatment.

One of the reasons suggested for the thermal EMF is a possible geometric non-uniformity in the MI cable. To examine this possibility, X-ray photographs covering several centimetres on either side of each identified critical point (positive and negative maxima, and points where almost no effect was observed), were taken to obtain an image of the inner cable structure. For each point, two photographs were obtained by rotating the cable by 90° in order to observe any deviation from concentric geometry. The images were carefully analysed by means of an optical microscope. Typical results corresponding to a maximum EMF point are shown in Fig. 4, where the central core and sheath are clearly visible. No observable deviations from concentricity were found for any of the points examined, indicating that geometrical non-uniformity is not the cause of TIEMF. From these results, the possibility that TIEMF is due to variations in the thermoelectric power coefficient along the centre conductor must be considered. These variations may be due to some contamination during manufacture; for example, small amounts (0.1%) of Ni or Fe in the Cu conductor may sufficiently modify the thermoelectric power [1]. Pieces of the MI cable from each of the critical points have been cut and are being prepared for impurity analysis.

4. Conclusions

It has been confirmed that the TIEMF value varies considerably with position along the MI cable and these variations are highly reproducible. The TIEMF sensitivity cannot be annealed out nor reduced by heating up to 550 °C. X-ray examination of the cable eliminated geometric irregularities or non-concentricity of the central conductor as possible causes. Previous in-reactor results on radiation-induced voltages along the central conductor of MI cables are most probably caused by thermal gradients.

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References

[1] T. Nishitani, G. Vayakis, M. Yamauchi, T. Sugie, T. Kondoh, T. Shikama, E. Ishitsuka, H. Kawashima, J. Nucl. Mater. 329–333 (2004) 1461.

[2] T. Nishitani (Ed.), Report of the 13th IEA workshop on radiation effects in ceramic insulators, JAERI-Review 2004-004, March 2004.

[3] R. Vila, E.R. Hodgson, J. Nucl. Mater. 329–333 (2004) 1524.

[4] R. Vila, E.R. Hodgson, Report on thermally generated voltage/current for selected MI cable coils, Euratom EFDA TW4-TPDC-IRRCER final report, December 2004.

[5] L. Vermeeren, Report on thermal effects on RIEMF for selected MI cable coils, Euratom EFDA TW4-TPDC-IRR-CER final report, October 2005.

[6] T. Nishitani, T. Shikama, M. Fukao, R. Reichle, T. Sugie, T. Kakuta, S. Kasai, R. Snider, S. Yamamoto, Fusion Eng. Des. 56&57 (2001) 905.