A SUPERCONDUCTING MODULATOR FOR EXTREMELY SENSITIVE VOLTAGE MEASUREMENTS ACROSS MULTIFILAMENTARY SUPERCONDUCTING WIRES

F. van Overbeeke, H.H.J. ten Kate and L.J.M. van de Klundert,
Twente University, Dept. of Applied Physics,
P.O. Box 217, 7500 AE Enschede, the Netherlands.

Abstract

In this paper we describe a superconducting chopper amplifier used as an instrument to measure the V(I) curve of multifilamentary superconductors. Experimental results are presented.

Introduction

For a number of reasons interest has emerged in sensitive and accurate measurement of the V(I) curve of multifilamentary superconducting wires. On one hand, information can be obtained from it regarding the quality of the superconducting material and the production process, by calculating the distribution function of the critical current from it [1]; on the other hand, superconducting wires that will be used in highly stable magnet system which are operated in the persistent mode, have a maximum current that is not determined by the usual criterion of $\rho = 10^{-14}$ Ωm, but by a much more conservative value like 10^{-18} Ωm. If we take a practical wire, for example one with a diameter of 0.6 mm operating at 200 A, this means that a voltage across the wire of the order of 1 nV/m should be detectable.

At room temperature DC voltages of this order of magnitude can be measured only with very expensive equipment. Furthermore, the thermovoltages experienced in the connection lines between the sample and the instrument are probably much greater, unless the experiment is performed on very long samples. For this reason, a measurement system is preferred of which the first stage of amplification is located at the temperature level at which the experiment is performed, usually 4.2 K.

An elegant but also rather expensive solution to this problem is the use of a SQUID sensor. However, apart from the high cost, this instrument needs to be located in an electromagnetically "clean" environment, especially in a weak magnetic field. It was decided not to accept the latter condition beforehand and to build the measurement system as cheap as possible and therefore the principle of a chopper amplifier with a superconducting modulator was adopted.

The Instrument

History

The concept of a superconducting chopper amplifier was already developed in the 1950's independently by Templeton [2] and de Vroomen et al. [3]. Their modulators were tantalum or thallium wires, switched in and out of the superconducting state by means of an oscillating magnetic field. In order to operate such a system in the high stray field of a magnet, Edwards [4] built a similar system with a thermally switched NbZr modulator. Each of the referenced instruments was claimed to have a noise level of less than 10 pV after low-pass filtering with a time constant of less than 1 second.

Description

The lay-out of the instrument in its essential form is sketched in Fig. 1. The taps between which a voltage has to be measured are connected to the low-impedance side of a transformer via the superconducting modulator. By switching the latter between the resistive and superconducting states, an AC voltage is generated on the transformer's primary side, of which the amplitude is proportional to the DC voltage U_i. If the transformer has a ferromagnetic core, as is the case in our instrument, it will behave as a relatively high impedance. However in the case of an air-core transformer, which we still plan to apply because it should be usable in high magnetic fields, care should be taken that the effective input impedance of the system does not become too low. The transformer has a high winding ratio (10^2-10^3) and is followed at room temperature by an AC amplifier, filter and phase-sensitive detector. Because the resistive transition of the modulator is independent of the sign of the modulating current, in thermally as well as magnetically activated devices, half the reference frequency f_s can be used as the modulating frequency. As a result, the system is not sensitive to interference of the modulating signal, provided that it contains no even harmonics of $f_s/2$.

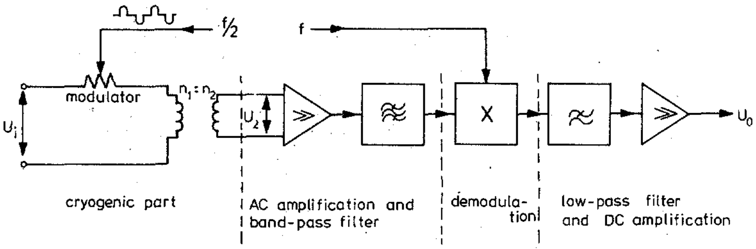

Figure 1. Basic concept of a superconducting chopper amplifier.

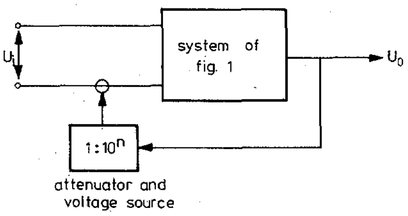

Figure 2. S.c. chopper amplifier used as a zero detector in a feedback system.

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It can be shown [5] that the maximum RMS value of the f_S-component of the signal U_2 is given by:

$$(U_{2,RMS}/U_i)_{max} = \sqrt{2}\; n_2/n_1 \quad (1)$$

In practice the gain of the system can be a factor 2 smaller which is the price of stable operation of the modulator.

This gain being neither accurately known, nor in practice very constant as a function of the time, it is more convenient to use the instrument as a zero detector in a feedback system, as is shown in Fig. 2. In order to realize an acceptable performance, different parameters have to be weighed against each other.

The feedback system of Fig. 2 is stable only if the open-loop gain meets the well-known criteria from the theory of control systems, like the Nyquist criterion. Because the low-pass filter already introduces a phase shift of 90°, the phase shift of modulated low-frequency signals in the band-pass filter should be very limited in the relevant frequency range.

For example, it was chosen to have $f_S = 85$ Hz and to have an open-loop gain of 0 dB at $\omega = 10$ (s^{-1}) (see Fig. 3). An extra phase shift due to the band-pass filter at $\omega_S \pm 10$ of 30° was considered acceptable, with $\omega_S = 2\pi \cdot f_S$. Because the system should be operated in an electromagnetically rather noisy environment, an attenuation for 50 Hz signals of 60 dB was also specified. This results in a 4th order Chebyshev filter with -3 dB points at $\omega_S \pm 25$ (s^{-1}). The problem is now that cross-products of 85 Hz and 50 Hz, for example 170·250 or 255·350, experience only a small attenuation and especially the former one is clearly observed if the system is switched to a high gain such as $U_0/U_i = 10^9$ (see Fig. 2).

The price for smaller cross-products is thus a smaller bandwidth of the filter which implies that 0 dB open-loop gain has to be chosen at a lower frequency, with the result of a longer response time of the overall system.

The realized system

Modulator. The modulator (Fig. 4) consists of monofilament NbTi/Cu wire, of which the copper matrix has been etched away over a length of approximately 5 mm. Close to the etched part a bifilarly wound insulated manganin heater wire is laid. This assembly is mounted between two pieces of anodized aluminium sheet, whereas the remaining space is filled with Stycast resin. In this way a switch is created with short thermal time constants and having a resistance in the heated situation of the order of 0.1-1 Ω, which is high enough for our purpose.

Transformer. It is our final aim to build a system without an iron-core transformer. Because of the ease of manufacturing however, our present model has been provided with a ferrite pot-core, which has been placed at such a distance from the experiment that stray fields of the magnet have no observed influence. It appears to behave satisfactorily at cryogenic temperatures. The numbers of windings are $n_1 = 5$ and $n_2 = 10{,}000$. Both the primary and the secondary circuit have been wound with superconducting wire. It may be advisable to wind the secondary coil from a resistive conductor in order to damp oscillations due to parasitic capacitances. The natural frequency of this transformer is about 4 kHz and has been damped with a parallel resistor on the secondary side of 10 kΩ. This resistor however is transformed to the primary side with a factor $4 \cdot 10^6$, which means that the transformer behaves as a resistor of 2.5 mΩ, which effectively reduces the gain given in eq. (1) by a factor 2.

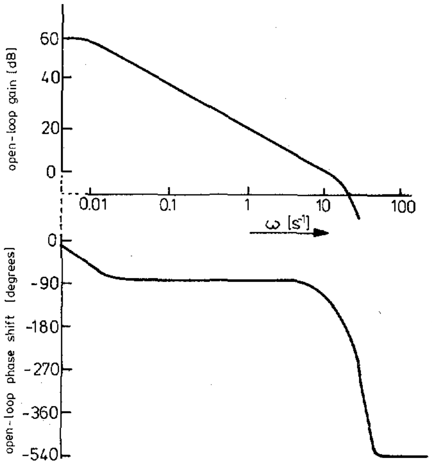

Figure 3. Amplitude and phase diagrams of the open-loop transfer function.

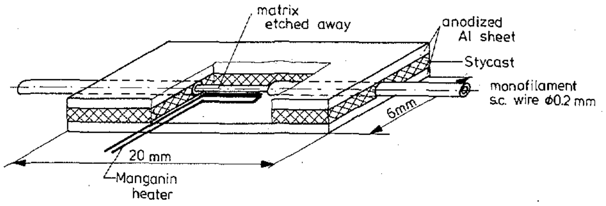

Figure 4. Lay-out of the superconducting modulator.

Room-temperature electronics. The characteristics of the band-pass filter have been outlined in a previous section. The amplifiers and demodulating circuit are all built with commercially available low-noise components to ensure that the sensitivity and accuracy of the system are completely determined by the cryogenic part. The output voltage is transferred to the feedback attenuator via an isolation amplifier, so that there is no galvanic contact between electronic system and sample. The attenuator is a current source feeding a current proportional to the output voltage to a resistor of 1 mΩ that has been mounted in the cryostat in series with the primary circuit of the transformer. The gain of the whole system can be set to $U_0/U_i = 10^5, 10^6, 10^7, 10^8$ or 10^9. The output signal is filtered with a time constant that can be chosen from 0.1 to 10 seconds and is then recorded by a computer, a plotter, or another device.

Application for V(I) Measurement

Experimental implications

The use of a high-sensitivity instrument implies that our measurements will also be very sensitive to noise that is generated by the other equipment involved in the experiment. Furthermore, the steepness of the V(I) curve has important experimental implications.

Voltages are measured along 1 m of wire. Even if the potential wires are laid very close to the sample conductor, an induction coefficient of less than 0.2 μH is hardly attainable. This means that low-frequency ripple of the sample current with a derivative of

$dI/dt = 0.01$ A/s is measured as a voltage of at least 2 nV. Raising the current with a constant ramp, as is frequently done in I_c-measurements, is therefore impractical because of the small dI/dt that would be allowed. The most appropriate way is to adjust the current successively to a number of pre-chosen values and to measure the resulting voltage with each value. The current source should be able to maintain the current at a constant value with a high precision (better than 10^{-4} over several minutes). Apart from this, the high-frequency ripple (remnants of the power frequency) should be as small as possible. Although the system is theoretically not sensitive for these signals, they may result in overloaded amplifiers, thus affecting their linearity.

The slope of the V(I) curve is much higher than the ratio V/I. In the current interval where the relation $V = I^N$ applies, the difference is a factor N, which means that a current drift of q% is experienced as a voltage drift of N·q%. As above, we conclude that use of a high-precision current source is imperative.

If the sample wire is subjected to a magnetic field, a similar reasoning applies to the magnetic-field control. Drifting of the magnetic field can be interpreted as a changing I/I_c. This will not be mathematically worked out here for reasons of limited space, but obviously leads to the conclusion that either the magnet should be fed by a high-precision current source as well, or it should be operated in the persistent mode. The latter solution was chosen in our experiments.

Lay-out of the experiment

The experimental set-up is shown schematically in Fig. 5. The measurements are performed on an MCA wire, 367 fil. NbTi:Cu=1:1.25, having a diameter of 0.2 mm. The wire is wound on a bobbin with a diameter of 60 mm, which fits in a small Maxwell-type magnet generating a maximum magnetic field of approximately 2.2 T. The potential wires are connected to the sample at a distance of 1 metre from each other and are wound carefully on the bobbin together with the sample. The compensation resistor is a narrow strip made of brass sheet with a resistance between the measurement contacts of 1 mΩ at 4.2 K. All wiring in the measurement circuit, including the primary coil of the transformer, is made with NbTi/Cu monofilament superconducting wire having a diameter of 0.2 mm. In order to reduce the 50 Hz ripple of the sample current, a low-pass filter is realized with a resistor of 10 mΩ and an inductance of 0.6 mH (see Fig. 5).

Performance of the instrument

The "dirty" electromagnetic environment in which the instrument is used severely deteriorates its performance. Due to the relatively high number of joints in the primary circuit an offset voltage of several nanovolts and a low-frequency drift voltage of 200 pV peak, after filtering at $\tau = 1$ s, is not exceptional. As soon as the power supplies of sample and magnet are switched on, the latter increases by at least a factor 10. This is mainly due to the current source of the magnet, which has a relatively high drift. Closing of the persistent-mode switch eliminates the effect of this drift.

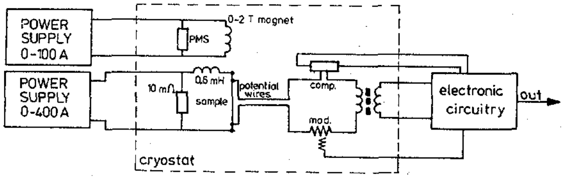

Figure 5. Experimental lay-out for the measurement of V(I) curves.

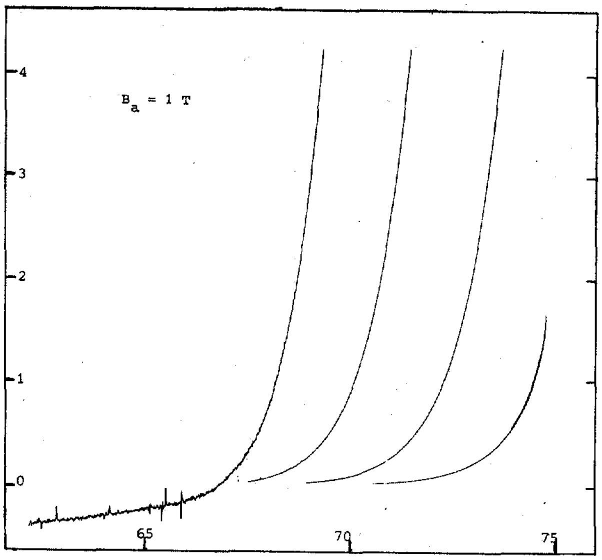

Figure 6. Measured voltage across the MCA wire as a function of the current. Horizontal scale: Sample current (A); Vertical scales for the curves from left to right: 10 nV/div; 100 nV/div; 1 μV/div; 10 μV/div.

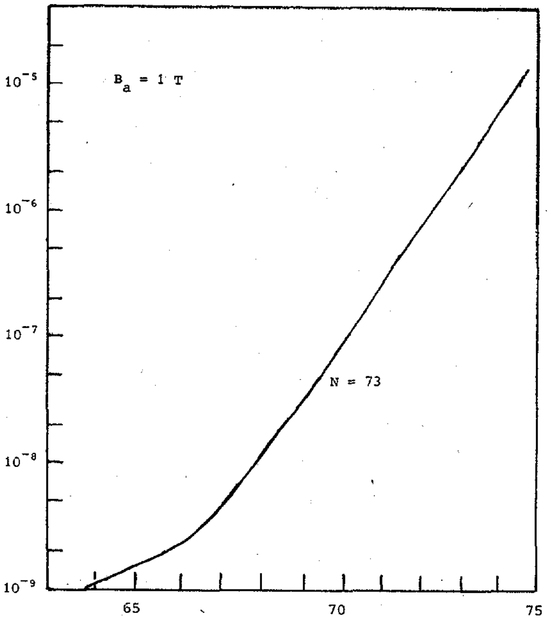

Figure 7. V(I) curve of the MCA wire on a logarithmic scale. Horizontal scale: Sample current (A); Vertical scale: Voltage across the sample (V).

Results

A typical example of a V(I) curve that is measured in this configuration is given in Fig. 6. The applied DC field B_a was set to 1 T and the voltage across the sample wire was measured over 4 decades. The measurement system showed an offset voltage of -6 nV, whereas the offset due to induction by the current derivative was about +2 nV.

The two curves for the smallest voltages were measured with an output low-pass time constant of 1 second, whereas the two others were obtained with $\tau < 0.1$ s. The big spikes on the leftmost curve are due to movement of furniture near the cryostat.

If these curves are plotted in a logarithmic graph such as Fig. 7, it is seen that over several decades in the voltage we have $V \propto I^N$ with $N \approx 73$. This curve exhibits a smaller N value for lower currents. Although this may be due partly to incorrect compensation for offsets, the error introduced by this compensation is not big enough to completely account for a smaller N. There are however indications that the occurrence of a smaller N in the low-resistivity range should be expected from theoretical considerations.

The distribution function of the critical current of this wire can not be completely determined because of the poor cooling of the sample, which results in quenching at a current that is smaller than $I_c(10^{-14}\ \Omega m)$. At 1 T, this I_c is 75.2 A.

The distribution function is proportional to d^2V/dI^2 and is steeply increasing in the interval that we have covered with measurements, as is shown by Fig. 8. A dip in this curve below I_c, as was sometimes observed by Warnes et al. [1], does obviously not occur. Future experiments will show what happens for higher currents in a better-cooled configuration.

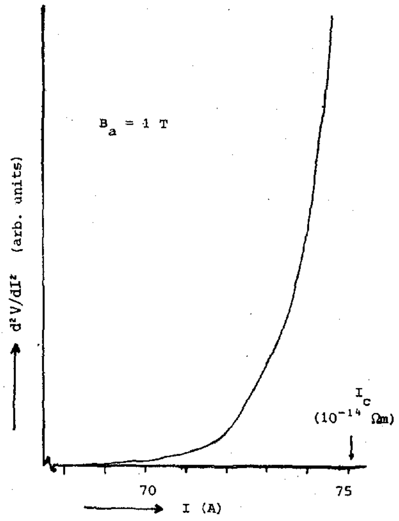

Figure 8. The distribution curve of the critical current at 1 T.

Conclusions

A superconducting chopper amplifier is a useful instrument to obtain V(I) curves of superconducting wires over many decades of the voltage. A sensitivity of less than 1 nV can be attained, if noise coming from the high-current sources that are involved is sufficiently eliminated. Considering results that were obtained earlier with a similar instrument, the sensitivity limit may be brought down one or two decades more.

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