Current ripple effect on superconductive d.c. critical current measurements*

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The effect of current ripple or noise on d.c. critical current measurements was systematically studied. Measurements were made on multifilamentary Nb–Ti superconductor. A low-noise, battery-powered current supply was required in this study in order to make the pure d.c. critical current measurements. Also, an electronic circuit that stimulates a superconductor's general current–voltage characteristic was developed and used as an analysis tool. In order to make critical current measurements in which current ripple was present, the battery supply was modified to allow the introduction of controlled amounts of a.c. ripple. In general, ripple in a current supply becomes more significant in current supplies rated above 500 A because effective filtering is difficult. The effect of current ripple is a reduction in the measured d.c. critical current; however, ripple of sufficient amplitude can result in arbitrary measurement results. The results of this work are general and quantitatively applicable to the evaluation of critical current data and measurement systems. A theoretical model was developed to further support and explain the ripple effect. An unexpected benefit of this work was a more precise method for general critical current data acquisition. Problems common to all large conductor critical current measurements are discussed.

Keywords: critical currents; superconductors; Nb–Ti

The presence of current ripple (any periodic departure from d.c. output level) reduces the measured d.c. critical current, I_c (see Reference 1). In addition to quantifying this effect, an attempt was made to determine its source. Several possibilities are discussed. A recent literature search indicates that this is the first documented study of this type. The I_c measurements reported here were made using a straight sample geometry and a radial-access magnet.

Experimental apparatus and procedure

Battery powered current supply

A battery current supply was modified to allow the creation of current ripple with variable frequency and amplitude[2]. The maximum d.c. output of this supply is 1000 A. The maximum tested frequency, a.c. amplitude, and d.c. bias for this supply are 10 kHz, 170 A, and 400 A, respectively (these values were not achieved simultaneously). The performance of the supply as a source of a.c. current at several frequencies was evaluated by measuring the peak amplitude and RMS values of the output current. To judge the shapes of the waveform, the ratio of the peak amplitude to the RMS value was compared to the theoretical value for the given waveform (1.73 for a triangular wave and 1.41 for a sinusoid). For both waveforms and all frequencies (60 Hz triangle; 60, 360, and 1000 Hz sinusoids) the variation between the theoretical and measured ratios increased with increasing a.c. amplitude. For I_c measurements at 8 T, this variation was nearly independent of frequency and had a maximum value of less than 12% at the maximum tested a.c. amplitude of 70 A. At amplitudes below 40 A, the maximum variation was less than 5%.

Sample and instrumentation

The sample measured in this experiment was a commercial multifilamentary Nb–Ti superconductor with a diameter of 0.65 mm. The filament twist pitch was 0.8 twist cm^{-1}. There were 6006, 5 μm diameter filaments with a Nb diffusion barrier around each of the filaments. The sample was contacted with several sets of twisted-pair voltage taps. This allowed simultaneous acquisition of data with several voltmeters to determine any variation in the observed effect, any difference in voltmeters, and any effect due to voltage-tap geometry. One voltage-tap pair was connected to the sample in such a way that the mutual inductance between the voltage-tap pair and sample was enhanced. It spanned the same segment of the sample as another lower mutual-inductance pair. Two other voltage-tap pairs had their wires connected near the sample, and only one of the wires was connected to the sample (referred to as null tap pairs). This provided

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pairs that should not have any non-inductive voltage. One of these pairs had low and the other had high mutual inductance. This allowed for a determination of how the voltmeters measure a purely inductive voltage.

The sample voltage has several components. For this work, the intrinsic d.c. transport *V–I* characteristic of the superconductor was assumed to have the voltage proportional to the current raised to the power *n*, where *n* for the tested sample was about 30 (see Reference 1). There might be a slight current transfer voltage but otherwise the non-inductive component of the voltage should be zero, within measurement limits, until the current approaches the I_c. Here, the highly current dependent flux–flow voltage occurs. The unavoidable loop made by the pair of voltage taps and the segment of the sample between them, will give an inductive voltage proportional to the time derivative of the sample current. There will be a highly asymmetric voltage signal due to periodic entry of the peak current into the flux–flow region of the superconductor at high enough bias currents.

Superconductor simulator

A simple electronic circuit was designed to simulate the intrinsic *V–I* characteristic of a superconductor. This circuit was used to characterize the response of a nanovoltmeter when the input voltage is a highly asymmetric periodic voltage which results from passing a d.c.-biased a.c. current through a superconductor. A more general application of this circuit had been to aid in the development and testing of critical current data acquisition systems. This circuit was developed based on an idea by Ekin and Brauch of NBS. The original idea used a diode in series with a current sensing resistor. The combination was placed in parallel with a high current shunt resistor. This passive circuit gives a non-linear *V–I* characteristic. Unfortunately, the curve is not very sharp ($n \approx 10$) and it is not adjustable. An active simulator circuit is shown in *Figure 1*. The input of the simulator circuit comes from a large shunt connected in series with the current supply. This input voltage is compared with a bias voltage and then amplified by OA2. The adjustable bias voltage produced by OA1 simulates the I_c. No output occurs until the input voltage has risen above the bias voltage. The gain of the amplifier may be varied and simulates the *n* of a superconductor. The voltage output of this amplifier stage drives the base of transistor T 1. A non-linear current results at the emitter of the transistor. This non-linear current results from the combination of the diode (D1) and output transistor (T1). The current passes through two shunt resistors that provide the circuit's output signals. Typically, the nanovoltmeter to be tested is connected to the 0.01 Ω resistor and a recording instrument is connected to the 100 Ω resistor. Another channel of the recording instrument is connected to the analog output of the nanovoltmeter. These two channels are then compared and the nanovoltmeter may be thus characterized under conditions similar to an I_c measurement. The 0.01 Ω series resistor is externally connected to the remainder of the simulator circuit to allow thermal stabilization of the nanovoltmeter to resistor connection.

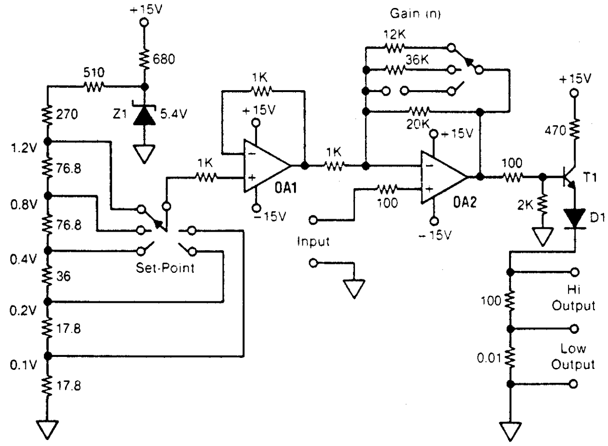

Figure 1 Schematic diagram of an electronic circuit that simulates the intrinsic voltage–current characteristic of a superconductor

Data acquisition

Two types of voltmeter were used to measure the sample voltage. One was an analog nanovoltmeter and the other was a digital nanovoltmeter. Both were direct current meters with an amplified analog output, which was fed to a digital processing oscilloscope. The voltage signal of a current sensing resistor was split, amplified, and fed into two channels of the digital processing oscilloscope. One of these current signals was filtered to give the d.c. component and the other was unfiltered (passed wide band). A total of eight channels (two current and six voltage) were used to acquire data simultaneously.

The sample voltage and current were measured at relatively fixed current ripple and many d.c. bias currents (point method). These points along the voltage–current (*V–I*) curve were analysed to determine the I_c. This procedure is different from the more typical procedure where the current is ramped continuously with time while the voltage and current are recorded. Ramping the current was not an option in this experiment because the a.c. and d.c. components of the current had to be accurately separated and the steady state voltage measured. The point method has some general advantages over the ramp method. The point method allows for a longer time averaged voltage to be measured (if voltage noise is a problem) without greatly increasing the time required for taking a complete *V–I* curve. This is achieved by selecting a distribution of current bias points that results in a more precise measurement. This requires taking a few widely spaced points in the low current portion of the curve to establish the base line and then taking a progressively closer-spaced point distribution as the current increases toward I_c. The point method greatly reduces the effect of inductive voltage and sample motion. The only disadvantages are that it takes longer because the voltage has to settle for each data point and the general shape of the curve has to be known a priori. The I_c was defined as the d.c. current at which the measured electric field strength rose to $0.2\ \mu V\ cm^{-1}$. The precision of the I_c measurement was about ± 1%.

Results

Voltmeter tests

In order to develop a quantitative understanding of the nanovoltmeter's input–output relationship for a.c. voltage inputs and thus determine the effect on the measured I_c, two a.c. tests were conducted on both the digital and analog nanovoltmeters. The first test (symmetric test) consisted of applying sinusoidal voltage signals of various amplitudes and frequencies to the nanovoltmeter input and measuring the resulting output signal. A.c. signals of appropriate amplitudes were obtained by dividing the output voltage of an a.c. signal generator. The objective of the second test (asymmetric test) was to determine the response of the nanovoltmeters to the highly asymmetric a.c. voltage that is characteristic of a superconductor carrying a sinusoidal current. The superconductor simulator circuit was employed to generate the required asymmetric nanovoltmeter input signals.

The results of the symmetric tests were considerably different for the digital and analog meters. In both cases, the d.c. output of the meters increased with increasing a.c. input amplitude. However, the output signal from the analog meter was approximately an order of magnitude greater than that of the digital meter for a given a.c. input. Defining the a.c. rejection (ACR) of the nanovoltmeter as 1 minus the ratio of the d.c. output voltage to the peak a.c. input voltage provides a useful measure of a meter's relative tolerance of a.c. input voltages. This is not the common mode rejection ratio (CMRR)[3]. For the analog meter, a 60 Hz, 500 μV peak a.c. signal resulted in a d.c. output of 5.2 μV, or an ACR of 99.0%. The same input signal applied to the digital meter resulted in a d.c. output of 0.66 μV, or an ACR of 99.9%. This input signal was on the high end of those encountered in this ripple experiment, indicating that a detectable artificial voltage may be observed for the analog meter. For a voltage-tap pair with a 1 cm separation, a typical mutual inductance was about 2 nH (53 μV peak for 60 Hz and 70 A amplitude; 880 μV peak for 1000 Hz and 70 A amplitude). The mutual inductance of the high inductance taps was about 6 nH.

The dependence of the d.c. output on the input signal's frequency (60, 360, and 1000 Hz) was also investigated. Again, there was a significant difference between the response of the analog and digital meters. Although the d.c output of both meters did not show monotonic dependence on the input signal's frequency, the analog meter showed a considerably stronger frequency dependence. For the analog meter, a 250 μV peak a.c. signal at 60, 360, and 1000 Hz resulted in a d.c output of 0.8, 3.5, and 0.5 μV, respectively. The same input signals applied to the digital meter resulted in a d.c. output of 0.14, 0.16, and 0.10 μV, respectively.

In the case of the asymmetric test, the behaviour of the two meters was essentially the same. A broad range of d.c. biased sinusoidal signals was applied to the input of the simulator circuit resulting in a large variety of typical asymmetric nanovoltmeter input signals. As before, three a.c. frequencies (60, 360, and 1000 Hz) were tested. In order to determine the nanovoltmeters' responses to these input signals, the signals were observed and analyses on a digital processing oscilloscope. The peak-to-peak, time-averaged, and RMS values of the input signals were thus determined and compared with the output of the nanovoltmeters. The results were that, regardless of the meter being tested or the character of the input signal (frequency, d.c. bias level, and a.c. amplitude), the nanovolt meter's output signal was always within 5% of the time-averaged (d.c.) value of its input signal. In other words, the nanovoltmeter behaves like a very low frequency, low-pass filter, which results in an output from the nanovoltmeter that is a time average of its input signal. This behaviour is consistent with the symmetric test where the meters were shown to measure the time average of their input signals.

Theoretical results

The motivation for modelling this effect is to help understand what is being measured and how to generalize these results to different samples, ripple, and voltmeters. It will become clear that the shape of the *V–I* curve and the amplitude of the ripple will change the magnitude of this effect. To extend the d.c. I_c criterion to a general current waveform in a way consistent with the design limits of a superconductor application, the measured voltage criterion should reflect the ohmic power loss within the superconductor. Differentiation between voltage and electric field strength criteria will be dropped in this section.

It is instructive to consider the power dissipated in a normal conductor when the conductor is carrying d.c.-biased a.c. current. A normal conductor is similar to a superconductor with an n of 1 and, thus, would have a finite critical current, based on a voltage criterion. The magnitude of the effect of a.c. ripple on the measurement of d.c. I_c can be calculated for this case. For the purpose of this argument, start with the definition of I_c as the RMS value of the total current (a.c. and d.c.) at which the RMS of the total voltage equals some criterion. This would be correct for a normal, ohmic sample because it is analogous to the derivation of a.c. power. For sinusoidal waveforms, the time average of the instantaneous power is the product of the RMS of the current and the RMS of the resistive voltage. However, measurements of this voltage would require a complex voltmeter that could separate the resistive from the inductive voltages and be capable of measuring the RMS of the total (a.c. and d.c.) resistive voltage. Based on this definition of I_c and value of n equal to 1, the measured d.c. I_c would be equal to the square root of: the I_c without ripple squared minus the RMS of the ripple squared. For example, the power of 99.9 A d.c. plus 5 A RMS a.c. is equal to the power of 100 A d.c. [$99.9 = ((100^2 - (5)^2)^{\frac{1}{2}}$]. The two components of current add in quadrature, thus for a low percentage ripple the effect on the d.c value is very small, for $n = 1$.

A d.c. voltmeter will measure the time average of the voltage, which is close to the correct quantity to measure for a superconductor with finite n. Consider the case where the d.c. bias current is well below the flux–flow region and the a.c. amplitude is just large enough to put the total current into the flux–flow region. The instantaneous voltage signal will be zero except at the peak of the current when it will look like a periodic delta function. Considering the a.c. power analogy, the current is fairly constant for the period of non-zero voltage and the time average power becomes the product of the time average of the two. Thus the d.c. voltmeter is the proper instrument to use based on the definition of I_c that relates to the average power. It can be shown that for $n = 2$ and a sinusoidal waveform, the time average of the voltage gives the same d.c. value of I_c as the time-averaged power for the case where $n = 1$. In general, the difference between the time-averaged voltage and the time average power is a difference of 1 in the exponent. For an n of infinity, the d.c. voltmeter will give a reduction in the measured I_c that is equal to the a.c. amplitude. This sets the limits for the effect and these are consistent with the experimental data. Current ripple should be considered as a percentage of I_c and this in combination with n can be used to estimate the effect.

Calculating the time average of the instantaneous, resistive voltage would model the measurement of d.c. critical current with ripple. This can be done by starting with the approximate voltage–current relationship.

$$V = V_0(I/I_0)^n$$

where: I_0 is a reference critical current at a voltage criterion of V_0: V is the instantaneous voltage: I is the instantaneous current: and n reflects the shape of the curve with typical values from 20 to 60 (a higher number is a sharper transition). The time average of this voltage, V_{ta}, is

$$V_{ta} = [V_0/(I_0)^n] \int_0^1 I^n \, dt$$

where the period was set to 1 s ($\omega = 2\pi\ \mathrm{s}^{-1}$) in general. For a sinusoidal and d.c. current, the instantaneous current can be expressed as

$$I^n = [i + a \sin(2\pi t)]^n = i^n[1 + (a/i) \sin(2\pi t)]^n$$

where i is the d.c. component of the current and a is the amplitude of the sinusoidal component. Thus, the time-averaged voltage becomes

$$V_{ta} = V_0[i/I_0]^n \int_0^1 [1 + (a/i) \sin(2\pi t)]^n \, dt$$

or

$$V_{ta} = V_0[i/I_0]^n G$$

where G is defined as the value of the integral and $V_{ta} = V_0$ when $I_0^n = i^n G$. Also, if a d.c. instrument is used to measure the sample current, i will always be the measured quantity regardless of the a.c. and the d.c. current levels. Based on these definitions, I_0 is the d.c. critical current without ripple and the value of i, where the sample voltage equals the I_c criterion, is the measured d.c. critical current with ripple present, i_c. In order to keep the equations based on measured quantities instead of theoretical quantities, such as I_0, the percent difference, D, is defined as the difference between I_0 and i_c normalized to i_c

$$D = 100\,(I_0 - i_c)/i_c = 100\,(G^{[1/n]} - 1)$$

This definition is consistent with a/i_c ratio in the integral (the ripple is relative to the measured quantity i_c).

The integral G was determined by numerical integration for a number of values of n and a/i_c ratios. These results are shown for two different ranges of current ripple in *Figures 2* and *3*. The x axis is percent ripple amplitude (percent of a/i_c) and the y axis is the percent reduction in measured critical current, D. The line of I_c reduction equal to the a.c. amplitude was predicted as the limit as n approaches infinity, and these plots are consistent with this limit. Consider the physical meaning of a point on this limit line where the ripple amplitude is 100%; at this point, the I_c reduction is 100%. The amplitude of the ripple is equal to the measured d.c. critical current with ripple present ($a = i_c$) and $I_0 = 2i_c$.

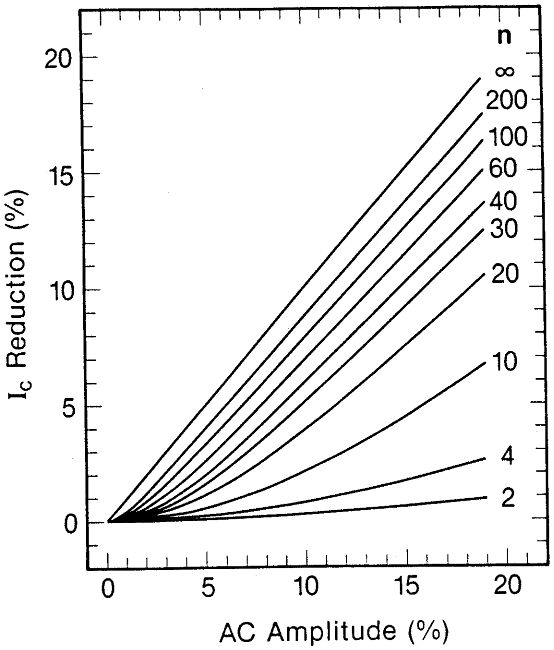

Figure 2 Model curves of the percent I_c reduction *versus* the percent a.c. amplitude for several values of n

Comparison on model and experimental data

The I_c for increasing d.c. bias current was measured as a function of a.c. amplitude and frequency using the two

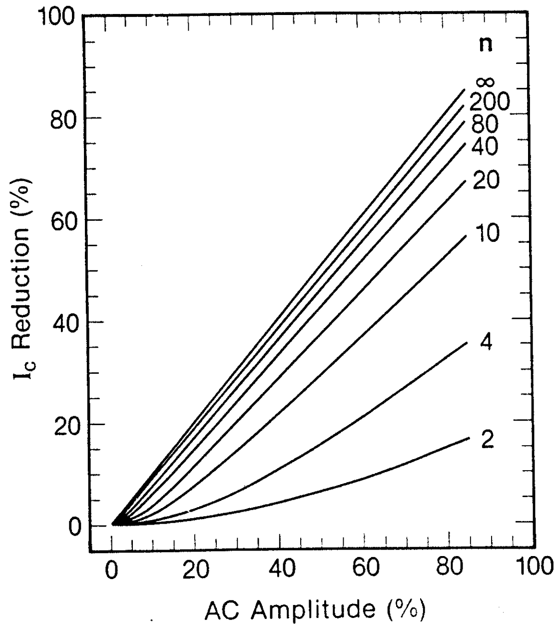

Figure 3 Model curves of the percent I_c reduction *versus* the percent a.c. amplitude for several values of n

different types of voltmeters and various pairs of voltage taps. The reduction in the measured d.c. I_c *versus* a.c. amplitude is shown in *Figures 4, 5, 6* and *7*. These data were taken with a magnetic field of 8 T where the I_c without ripple was 140 A. The symbols indicate actual data points and the solid lines are the model curves. The a.c. amplitude is the peak value of the a.c. component of the current waveform (not peak-to-peak or peak of total current). A reference line ($n = \infty$) was drawn for an I_c reduction equal to the a.c. amplitude. For all frequencies and waveforms, these data are just below this reference line indicating that the effect is to reduce the measured I_c by slightly less than the a.c. amplitude. The −60 Hz frequency was labelled negative to indicate that it was a triangular waveform at 60 Hz rather than a sinusoidal waveform. At all of the other frequencies, the waveform was sinusoidal with very little distortion. The zero frequency data had only the intrinsic ripple of the supply, which was about 0.3 A in this operation. The triangular waveform was tested to determine whether the detailed shape of the ripple and the relationship of RMS to peak changed the measured values. For cases where the comparison of two different current waveforms is based on their having equal amplitudes rather than equal RMS values, these data suggest that the detailed shape does not significantly effect the measured I_c. The a.c. amplitude is the relevant quantity for scaling the effect on the measured d.c. I_c.

The data shown in *Figures 4* and *5* were taken using the analog nanovoltmeter while the data shown in *Figures 6* and *7* were taken using the digital meter. The 60 Hz data of *Figures 6* and *7* were measured on the identical pair of voltage taps as the 60 Hz data of *Figures 4* and *5*. The digital meter data, at frequencies other than 60 Hz, were measured simultaneously with the corresponding analog meter data but with another pair of voltage taps that spanned the same segment of the sample. This other pair of voltage taps had a higher mutual inductance but the results for both pairs of taps were within the experimental limits. The results measured by the two voltmeters were very close. This indicates that the measured d.c.

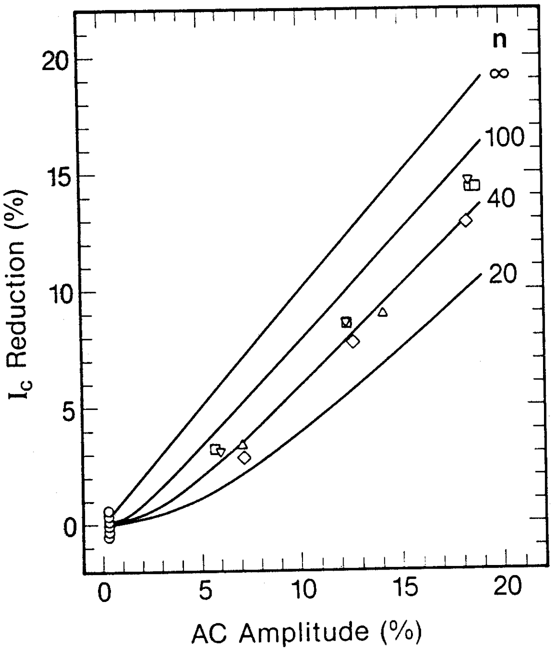

Figure 4 Percentage I_c reduction *versus* the percentage a.c. amplitude. Model curves are shown for several values of *n*. Experimental data taken with an analog voltmeter are shown at several frequencies. The −60 Hz frequency was labelled negative to indicate that it was a triangular waveform at 60 Hz rather than a sinusoidal waveform. Frequency (Hz): ○, 0; □, 60; △, −60; ▽, 360; ◇, 1000

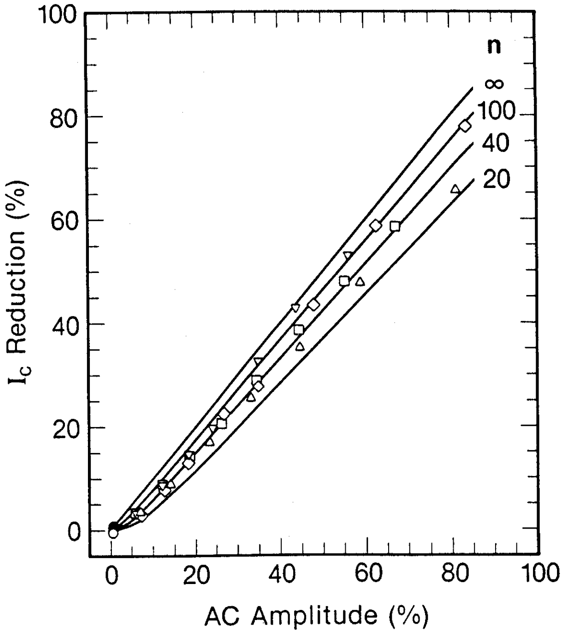

Figure 5 Percentage I_c reduction *versus* the percentage a.c. amplitude. Model curves are shown for several values of *n*. Experimental data taken with an analog voltmeter are shown at several frequencies. For key to symbols, see *Figure 4* caption

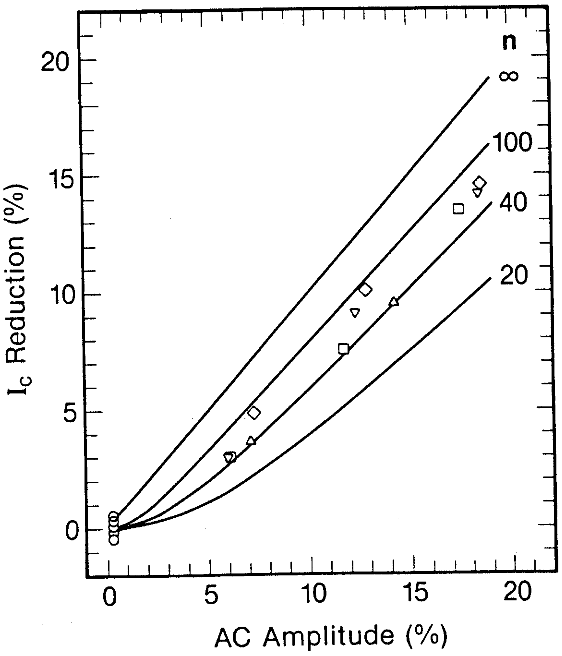

Figure 6 Percentage I_c reduction *versus* the percentage a.c. amplitude. Model curves are shown for several values of *n*. Experimental data taken with a digital voltmeter are shown at several frequencies. For key to symbols, see *Figure 4* caption

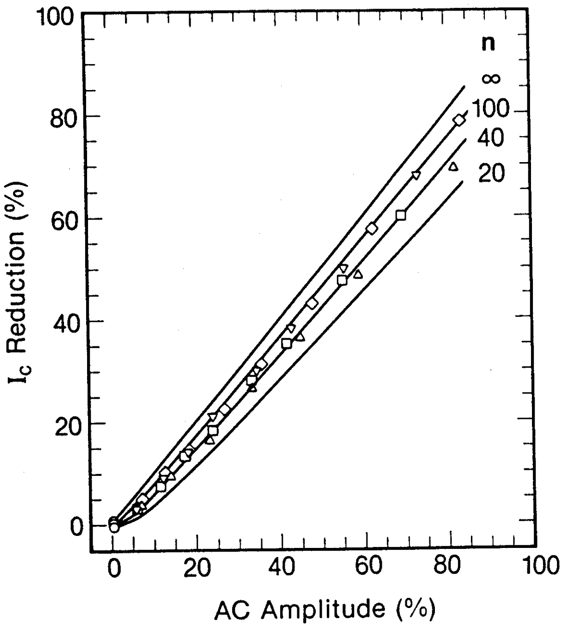

Figure 7 Percentage I_c reduction *versus* the percentage a.c. amplitude. Model curves are shown for several values of n. Experimental data taken with a digital voltmeter are shown at several frequencies. For key to symbols, see *Figure 4* caption

value of I_c does not depend on the voltmeter used. There were, however, other differences between these two voltmeters that will be discussed later. The effect of current ripple was measured for a number of sample segments and each segment gave similar results.

The experimental data fall between the $n = 20$ and the $n = 100$ model curves, within experimental error. The measured value of n was about 30. A model curve with $n = 30$ would be a lower limit to the effect. These experimental values indicate that the effective n may be higher because of the range of electric fields that occur during the peak current (n is a weak function of E) or because sample heating increases the value of n. The model and data are in close agreement, within ±2% for ripple below 20% and within ±10% for ripple up to 80% using $n = 30$.

The model curves can be used to estimate the effect of current ripple on the measured d.c. critical current. For approximating the effect of commercial power-supply ripple on critical current measurements, the curves of *Figures 4* and *6* may be the most useful because of their lower range. Both ripple and the reduction in critical current can be generalized to a percentage effect. Heating through a.c. losses may increase the size of this effect at higher amplitudes depending upon the sample geometry. Voltmeter effects will also become more significant at higher amplitudes.

Discussion

Artificial current transfer voltage

The analysed data from both the digital and the analog voltmeters gave the same values of I_c. However, some I_c data taken with the analog nanovoltmeter indicated the presence of a current transfer voltage[1]. This was not true of the data with the digital meter. It is believed that this behaviour is simply an artifact of the measurement system and not the result of a true current transfer voltage. Two characteristics of the measurement system may explain this effect. One concerns the sample current supply and the other concerns the nanovoltmeter. First, at high a.c. amplitudes the sample current supply's a.c. amplitude increases with increasing d.c. bias level which results in an increasing inductive voltage at the sample voltage taps. Second, as was determined in the symmetric voltage test, the nanovoltmeters have a small d.c. voltage output when subjected to an a.c. input, and this d.c. voltage increases with increasing a.c. amplitude. Consequently, during a cycle of data acquisition, the nanovoltmeter has an increasing d.c. voltage output which is interpreted by the data analysis program as current transfer voltage. The digital meter does not indicate this artificial current transfer voltage because of its considerably greater rejection of symmetric input signals. Finally, good agreement between the data taken by the two meters is achieved by simply subtracting the artificial voltage from the analog meter data. When this current transfer correction is large, significant errors in the determination of the I_c can result. This is probably the reason that the high amplitude analog voltmeter data at 360 Hz (worst case ACR) was out of line with the other frequency data.

A.c. voltage threshold

Although both analog and digital nanovoltmeters have demonstrated predictable input–output behaviour with respect to low amplitude a.c. input signals, there is an apparent a.c. amplitude threshold above which their behaviour becomes erratic. This erratic behaviour varied from a random output to a very low frequency (less than 1 Hz) and high amplitude output. These outputs could be positive or negative. Both meters display this erratic behaviour but the a.c. amplitude threshold for the digital meter is approximately 10 mV, whereas the threshold for the analog meter is approximately 1 mV. These results are similar to the symmetric test where the digital meter was shown to have a considerably greater tolerance for a.c. input signals.

Null taps and passive filtering

Data taken on the null tap pairs (described above) were used to determine the voltmeter's response to the symmetric voltage signals during the experiment. These data were consistent with the symmetric test, the artificial current transfer voltage, and the erratic behaviour, all of which were presented above. This is further evidence for the assertion that these effects are caused by the a.c. inductive voltage. A passive RC filter was inserted at the input of the nanovoltmeter to reduce the a.c. amplitude of the voltage signal. This did reduce the artificial current transfer voltage, and it increased the threshold of the erratic behaviour. However, the passive filter introduced more voltage noise. A passive filter may be an option for some experiments. Another possible method of reducing the inductive voltage is to balance the inductance by opening an opposite area within the twisted pair. This area could be adjusted with a high frequency signal during sample preparation.

Transient losses

The self-field loss is the primary type of transient loss present in the case of sample current ripple for this sample geometry[4]. The only effect of transient loss on the I_c measurement is sample heating, which may raise the temperature of the sample depending upon cooling conditions. The power dissipation is a strong function of frequency, amplitude, and current density. Computed self-field loss (for the 30 cm sample) at 8 T and the highest a.c. current amplitude was 3 mW at 60 Hz (50 mW at 1000 Hz). The effect of current ripple was also measured at 5 T with a.c. amplitudes up to about 170 A. The difference in the power between 5 and 8 T was a factor of 6 for comparable amplitudes and frequencies. There was a slight frequency and amplitude dependence for the 5 T data (higher frequency or amplitude reduced I_c by more), but the results were still at or below the reference line, reduction less than or equal to the a.c. amplitude. The lack of a strong frequency, amplitude, and current density dependence of the measured reduction of I_c indicates that sample heating due to transient losses was not significant for this experiment.

Other sample geometries might have larger transient losses due to current ripple. A change in the sample geometry was made to examine this possibility. The sample was centred in a holder, and four conductors (symmetrically located on a 2 cm diameter circle) were all used for the return current path. This arrangement reduced the effect of the magnetic field from the return current path. I_c data was taken at 5 T with four returns and with one return for various frequencies and a.c. amplitudes. The results with a single return had a slight frequency and amplitude dependence. At 60 Hz (sinusoidal and triangular), these data were within 1% (2 A) of the four-return results. At 360 Hz and 100 A a.c. amplitude, the I_c was reduced by 3% (8 A) as compared to the four-return results. This further reduction is attributed to the additional sample heating due to the transient loss created by the magnetic field of the return current path. For other geometries, such as a coiled sample, this effect could be much larger.

High frequency data

Additional I_c data were taken at higher frequencies (3 and 10 kHz), but experimental difficulties made the results at these frequencies less reliable. Transient losses, inductive voltage, waveform distortion, and reduction in available amplitude all became more significant at higher frequencies. The motivation for investigating higher frequencies was to estimate the effect of frequencies near the range of spikes from silicon-controlled rectifiers (SCR) found in most large power supplies. These data indicated the same trend of reduction in I_c but with more experimental uncertainty. Perhaps a better model of an SCR spike would be a spike rather than a continuous duty-cycle waveform. An extrapolation of the work presented here would indicate that the effect of the spikes would only be to add a finite amount to the time-average of the resistive voltage.

Conclusions

The effect of ripple scales with the percentage of I_c, and the effect depends upon the shape of the *V–I* curve (*n*). For an *n* of 30 or more and large ripple, current ripple reduces the measured d.c. critical current by slightly less than the a.c. amplitude. The effect of ripple is nearly independent of frequency for the range 60–1000 Hz. A d.c. voltmeter measures a relevant quantity, the time average of the voltage. A simple electronic circuit was used to test a d.c. voltmeter's response to an asymmetric waveform that simulates a superconductor's *V–I* characteristic. Reducing the mutual inductance of the voltage taps is important when testing with power supply ripple present.

A large conductor test method has to address the reality of power supply current ripple. Power line frequencies and harmonics (up to three phase, fully rectified) are the dominant frequencies. Current ripple of 1–3% at the maximum current is typical for power supplies in the range 600–6000 A. This ripple is generally a function of output current, but the percentage ripple can be higher for intermediate currents. This can be a significant source of measurement error. The direct effect on the sample voltmeter can also introduce measurement error. Sample heating due to transient losses may also be significant for some sample geometries.

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