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Current supply for high-T_c superconductor testing

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Abstract. Precise and accurate measurements of the DC critical current of high-T_c superconductors often require a current supply that has high input-to-output isolation, high isolation from ground and low output ripple. Also, to ensure precise current control, the supply should have low current drift and its input–output characteristic should be linear. A design for a simple and inexpensive current supply that has these characteristics is presented. The primary power source is a 12 V wet-cell battery and the typical operating range is from 10 mA to 10 A. The supply's current ripple is <0.4 mA RMS over this operating range. At an output current of 5 A the current drift is $<2\%$ h^{-1} without a warm-up period. The maximum variation of the supply's output from linearity, over its full operating range is $<5\%$.

1. Introduction

The development of high-critical-temperature (high-T_c) superconductors has resulted in a great increase in the number of reseach laboratories that are manufacturing and testing superconductors. The measurement of the voltage–current characteristic of a superconductor yields a key performance parameter, the critical current. Consequently, there is a growing demand for instruments and methods for accurately measuring the critical current of these materials. A major component of a critical-current measurement system is the current supply (Goodrich and Fickett 1982). The current supply described here was adapted from an earlier design that is being used predominantly for testing conventional (low-critical-temperature) superconductors (Bray *et al* 1989). This new current supply is a simple and inexpensive instrument that has been used extensively to measure the DC critical current of high-T_c superconductors (Moreland and Goodrich 1988) as well as the resistivity of electrical contacts (Ekin *et al* 1988) for these materials. The supply incorporates the characteristics of low output ripple (periodic and random departure from the DC current level), high input-to-output isolation, high isolation from ground, low current drift and a linear response. These characteristics allow very sensitive measurements of the superconducting specimen's voltage as a function of the applied current (Goodrich and Bray 1990).

2. Circuit design

The basic circuit is a voltage-controlled current source (see figure 1) consisting of three main stages: input, control and power. The principal power source for the supply is a 63 A h, 12 V wet-cell battery. This battery is a deep-cycle marine/recreational-vehicle battery. A deep-cycle battery is used because, unlike an automobile battery, it is designed to tolerate repeated discharges without a reduction in its service life.

2.1. Input stage

The main function of the input stage is to provide electrical isolation between the input signal-generator and the supply circuit in order to avoid ground-loops (Goodrich *et al* 1987, Morrison 1977). This isolation is achieved through the use of an optical isolator or an optocoupler (0C1, figure 1)). An operational amplifier (0A1) is used to compare the input signal with a feedback signal in order to achieve a more linear response from the input stage. The capacitor that is connected between the inverting input and the output of 0A1 reduces its AC gain and, thus, it increases the stability of the feedback circuit. The output signal from 0A1 is amplified by a transistor (T1), and the output current from this transistor is then applied to the input of 0C1.

The feedback signal is supplied by a second optocoupler, 0C2, which is in series with 0C1. The feedback signal is taken from the output of 0C2, rather than from 0C1, to preserve the isolation boundary (vertical broken line in circuit diagram). The function of 0C2 is to imitate 0C1; consequently, they must be selected so that their input–output characteristics are well matched.

The feed-forward optocoupler, 0C1, was found to be a significant source of current ripple because of an unused base terminal which was picking up 60 Hz noise. This problem was greatly reduced by connecting the base

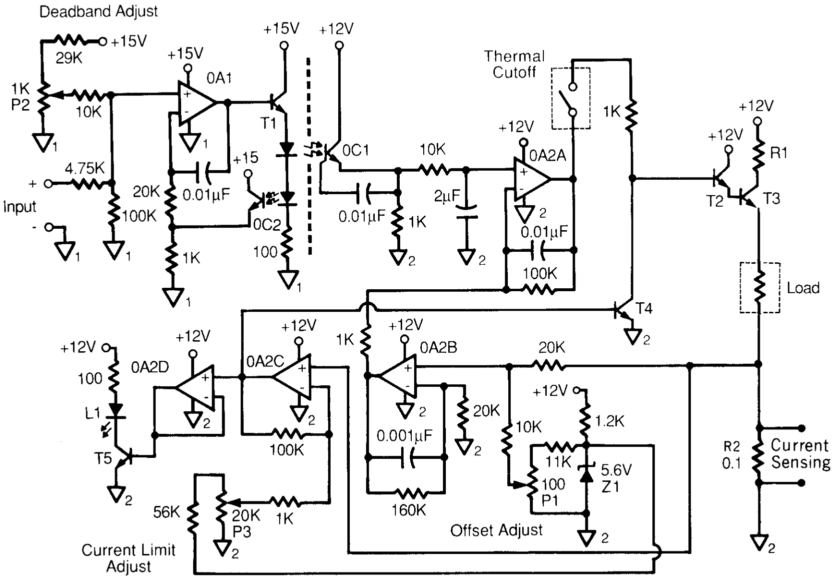

Figure 1. Circuit diagram of battery-powered current supply.

terminal to the emitter terminal with a 0.1 μF capacitor. The addition of a capacitor to the feedback optocoupler, 0C2, resulted in oscillation; consequently, the capacitor was omitted.

2.2. Control stage

The control stage of the circuit is based on an operational amplifier (0A2A) that compares the signal from the input stage with a current-proportional feedback signal in order to compensate for the non-linearity of the Darlington transistor pair in the supply's output stage. The feedback signal originates from a 0.1 Ω precision (R2) resistor that is in series with the load. This resistor is also used for monitoring the load current. Another operational amplifier (0A2B) is used in the feedback path, in a non-inverting configuration, to amplify the feedback signal. The gain of this second amplifier can be adjusted to change the transconductance gain (the ratio of the current output to voltage input) of the supply by changing its feedback resistor.

The feedback capacitors across 0A2A and 0A2B reduce their AC gain and, thus, stabilise the circuit. The 100 kΩ feedback resistor across 0A2A and the 1 kΩ resistor at the output of 0A2B also reduce the gain for increased stability. The use of a resistor between the output of 0A2B and the input of 0A2A is not ideal because it attenuates the feedback signal and, therefore, may cause a slight decrease in the linearity of the supply's response. However, depending upon the load, the omission of this resistor can result in oscillation.

2.3. Power stage

The power stage contains two transistors, T2 and T3, that are combined to form a Darlington pair. T2 and T3 are, respectively, 3 A and 25 A power transistors. The output of the control circuit is connected to the base of T2 and the load is connected to the emitter of T3. The output is terminated at the 0.1 Ω precision resistor which is connected between the load and common. The purpose of the collector resistor, R1, is to dissipate excess power. The appropriate collector resistance depends on the resistance of the load; however, it should be selected so that the total output resistance (the collector resistor, the precision resistor and the load resistance) drops the majority of the supply voltage at maximum output current, thus minimising dissipation at T3.

2.4. Quiescent point adjustment

Two potentiometers are used to adjust the quiescent operating point of the circuit. The offset adjustment, P1, is used to create a slight initial offset voltage at the output of the feedback amplifier. This is necessary because the amplifier exhibits a slight non-linearity when its output is near the limits of its supply voltage (0 V in this case). Since this non-linearity is introduced in the feedback loop, it is translated into a non-linearity in the supply's response. The offset voltage brings the quiescent point of the amplifier into its linear region. The Zener diode, Z1, compensate for variations in the battery voltage and regulate the voltage across P1.

An undesirable effect of the offset voltage is that it creates an initial dead-band region in the supply's response. The offset voltage creates an input voltage threshold that must be exceeded for the supply to generate current. This results because the offset voltage is applied to the inverting input of the feed-forward amplifier, 0A2A, and, as a consequence, the output of the control stage remains negative until a voltage that is equal to the offset voltage is applied to 0A2A's non-inverting input. The dead-band region can be reduced to a negligible level by adding a bias voltage to the supply's input signal. The bias voltage is adjusted with potentiometer P2 after the offset voltage has been adjusted for maximum linearity. A small amount of dead-band is desirable to ensure that the output from the current supply is zero when the input voltage is zero.

2.5. Protection

The output transistor, T3, is protected by limiting its operating temperature and its maximum output current. The temperature is limited by a manually resettable thermal cut-off switch that disconnects the base of T2 from the output of 0A2A. The cut-off switch is bonded to the case of the output transistor with a high-temperature epoxy adhesive. The thermal cut-off point is 93 °C. At this case temperature, the transistor can operate with a continuous power dissipation of 120 W; however, a high capacity heat sink is required to hold the case temperature below 93 °C at this power dissipation. Consequently, the supply can operate with a continuous output current of 10 A and a collector–emitter voltage of 12 V. This assumes that the entire 12 V supply voltage is dropped across T3. In practice, some of the supply voltage is dropped across the output resistance, and the current can be increased with an upper limit of 25 A, the transistor's maximum continuous operating current.

The supply's maximum output is adjusted with the current limit potentiometer, P3. The potentiometer voltage is compared with the voltage across R2 by 0A2C. The output of 0A2C is applied to the base of the current-limit transistor, T4. When the output current exceeds the selected maximum level, T4 diverts the power-stage input current and, thus, limits the supply's output current. When this happens, the output current oscillates about a slightly reduced DC bias level. A slight variation of this current-limiting scheme, where the current-limit transistor (T4) is replaced by a silicon-controlled rectifier (SCR), has also been used. In this case, the SCR is switched on when the output current reaches its maximum value, which results in the output current being reduced to zero and oscillation is avoided. The SCR can be reset, and normal operation can be resumed by reducing the input control signal to zero. The output signal from 0A2C is also applied to the base of another transistor, T5, through a buffer, 0A2D. T5 controls a light-emitting diode, L1, which indicates a current limit condition.

3. Performance

The typical operating range of the supply is, depending upon the load and collector resistances and the output transistor cooling, approximately 10 mA to 10 A; however, satisfactory operation in the 0.2 mA range has been demonstrated and, with increased output resistance, operation up to 25 A is possible.

The measured current ripple for this supply is <0.4 mA RMS over a DC output range of 10 mA to 10 A and a ripple-frequency range up to 300 kHz. The ripple may actually be significantly less than this because the residual noise of the instrumentation is comparable to the measured signal. Regardless, this measured current ripple is still typically an order of magnitude lower than for comparable AC-powered current supplies.

The linearity of the current supply's output was measured over an operating range of 0 A to 10 A. This was achieved by taking the difference between the measured output current and the current predicted by a linear-fit equation. The linear-fit equation was derived from the meaured output current versus input voltage. The maximum deviation is less than 5%.

The current drift of the supply was measured by setting the input voltage at a selected level and then monitoring it along with the output current for periods up to one hour. For these tests the total output reistance was approximately 1.2 Ω. At a nominal current of 5 A, the one-hour current drift is $<2\%$; at 1 A, $<0.9\%$; and at 0.1 A, $<0.5\%$. The short-term drift was measured for a period of 5 min and a period of 30 s. For the 5 min test, the drift was $<1.4\%$ at a current of 5 A, $<0.45\%$ at 1 A and $<0.37\%$ at 0.1 A. In the case of the 30 s test, the drift was $<0.28\%$ at 5 A, $<0.09\%$ at 1 A and $<0.09\%$ at 0.1 A.

Drift measurements are often made following a warm-up period. The supply is set at the nominal output level and allowed to stabilise prior to the beginning of the drift measurement (a 30 min warm-up period is common). This type of meaurement is not particularly relevant with respect to critical-current measurements where the current is not held constant for significant lengths of time. The drift-measurement data presented above represent the worst possible situation because the supply was not allowed a warm-up period prior to the meaurement. Other data demonstrate that the drift is substantially lower when the supply is allowed a warm-up period. In any event, the short-term stability of the supply has proven to be more than adequate for measuring critical currents.

4. Discussion

The two principal benefits of a battery-powered current supply over an AC-powered supply, for testing superconductors, are low current ripple and high isolation from ground. The presence of an AC component of the test current, or ripple, systematically reduces the measured critical current of superconductors. Also, current ripple can cause false voltage indications that vary in character and magnitude depending on the amount of ripple (Goodrich and Bray 1988). With regard to current ripple, a battery-powered supply—a purely DC device—is inherently superior to an AC-powered supply, which relies on rectification and filtering to produce its DC output current.

The extremely low voltages that must be detected in order to determine the critical current render the measurement particularly susceptible to errors caused by the spurious signals that can result from ground-loops. A battery-powered supply reduces the overall measurement systems's susceptibility to this source of error because of its extremely high ground isolation. The optically coupled input stage is equally important for avoiding ground-loops. The input-to-output resistance of the optocouplers is approximately 100 GΩ. The actual input-to-output isolation of the supply is probably less than this (the resistance is greater than our measurement capability); however, it is much greater than that of typical commercially available AC-powered supplies (of the order of 10 MΩ).

This does not suggest that good critical-current measurements cannot be made using a commercial AC-powered supply; it depends on the overall measurement system and its susceptibility to the problems that are associated with these current supplies (Goodrich and Bray 1990). The use of an optically coupled battery-powered current supply simply reduces the chance of these problems arising.

A non-technical, yet important, benefit of this simple current supply is its relatively low cost. Our estimated total cost for constructing this supply is < \$500.00, which is approximately one third the cost of a comparable commercial supply.

The operating range of the current supply can be reduced by simply changing the value of the current sensing resistor, R2. Without any other adjustments of the circuit, the supply has been successfully operated over a range of 0.01 mA to 100 mA by increasing the value of R2 from 0.1 Ω to 10 Ω.

The main disavantages of a battery-powered current supply are the slight inconveniences associated with the battery itself. These are the need for periodic recharging and the fact that the battery's considerable bulk makes it more difficult to handle than an AC-powered current supply. The battery also presents the danger of overcharging and acid spillage.

At present, three of these current supplies are in use at NIST, and several others are under construction. The first of these supplies has been used regularly for the past two years with only minor modifications. The benefits of these supplies for high-T_c critical-current measurements are such that they have been used exclusively, rather than AC-powered current supplies, since their development.

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Appendix. Component descriptions

An effort was made to avoid the identification of commercial products by the manufacturer's name or number, but in some cases these products might be indirectly identified. In no instance does this identification imply endorsement by the National Institute of Standards and Technology. Similar products by other manufacturers may work as well or better.

All of the resistors used in this circuit are $\frac{1}{8}$W, 1%, metal film resistors except the 0.1 Ω precision resistor, which is a high current and low temperature-coefficient resistor, and the output transistor's collector resistor, which is simply a twisted pair (low inductance) of #18 insulated copper wires of approximately 0.4 Ω resistance. All the capacitors are ceramic. The 12 V source is a 63 A h, deep-cycle marine/recreational-vehicle battery. The 15 V supply is a 115 V AC input, 25 mA output, commercial supply. 0A1 is a number 3140 operational amplifier; a number LM 324 quad operational amplifier is used for 0A2A, 0A2B, 0A2C and 0A2D. The optical isolators, 0C1 and 0C2, are both number 4N25. T1, T4 and T5 are number 2N3904 transistors; T2 is a number 2N4922 and T3 is a number 2N5886 power transistor. The SCR that has been used in place of T4 is a number 2N4145. The 5.6 V Zener diode, Z1, is a number 1N4734A. P1, P2 and P3 are multiturn precision wirewound potentiometers. The thermal cut-off switch is of the manually resettable metal-disc type with a temperature set-point of 93 °C.

References

Bray S L, Goodrich L F and Dubé W P 1989 Battery-powered current supply for superconductor measurements *Rev. Sci. Instrum.* **60** 261–4

Ekin J W, Larson T M, Bergren N F, Nelson A J, Swartzlander A B, Kazmerski L L, Panson A J and Blankenship B A 1988 High T_c superconductor/noble-metal contacts with surface resistivities in the 10^{-10} Ω cm^2 range *Appl. Phys. Lett.* **52** 1819–21

Goodrich L F and Bray S L 1988 Current ripple effect on superconductive d.c. critical current measurements *Cryogenics* **28** 737–43

—— 1990 Integrity tests for high-T_c and conventional critical-current measurement systems *Adv. Cryo. Eng. Mater.* **36** to be published

Goodrich L F, Bray S L, Dubé W P, Pittman E S and Clark A F 1987 *National Bureau of Standards Internal Report* 87–3066

Goodrich L F and Fickett F R 1982 Critical current measurements: a compendium of experimental results *Cryogenics* **22** 225–40

Moreland J and Goodrich L F 1988 Ag screen contents to sintered YBa$_2$Cu$_3$O$_x$ powder for rapid superconductor characterization *IEEE Trans. Magn.* **MAG-25** 2056–9

Morrison R 1977 *Grounding and Shielding Techniques in Instrumentation* (New York: Wiley)