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HIGH-VOLTAGE TESTING CURRENT MEASUREMENT TECHNIQUES

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16. ABSTRACT

A discussion of the effects of power supply ripple on insulating testing is presented. A meter to overcome these effects is also presented along with equations indicating the ripple effects.

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HIGH-VOLTAGE TESTING CURRENT MEASUREMENT TECHNIQUES

by

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Division of Research
Engineering and Research Center
Denver, Colorado

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UNITED STATES DEPARTMENT OF THE INTERIOR * BUREAU OF RECLAMATION

In May of 1981, the Secretary of the Interior approved changing the Water and Power Resources Service back to its former name, the Bureau of Reclamation. All references in this publication to the Water and Power Resources Service should be considered synonymous with the Bureau of Reclamation.

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INTRODUCTION

One of the main obstacles to overcome in attempting to perform d-c insulation tests on high-voltage insulation is the effect of the high-voltage d-c test set ripple. Many persons believe that d-c testing is impractical because an extremely well regulated test set is required in order to obtain meaningful test data. This conclusion has seriously limited and hindered d-c insulation testing, especially with respect to high-voltage cable insulation testing.

The requirement for extremely well regulated power supplies has not been imposed by some peculiar property or electrical response of the test specimen, but rather as a result of the fact that test set ripple voltage, under most circumstances, will produce a very large ripple current with respect to the direct current that is to be measured. The ripple current can create havoc with conventional metering circuits, thus leading to the conclusion that an extremely well regulated test set is needed in order to eliminate the ripple current. Although this conclusion is valid, it is unrealistic in that an extremely well regulated supply is very difficult to find. There are other less stringent alternatives available to the test engineer.

This report presents an alternative test method that does not require low-ripple-voltage test sets. A test method and measurement scheme is described that can accurately measure low level direct current in the presence of very large ripple current.

CIRCUIT ANALYSIS

Insulation test specimens are largely capacitive in nature and have very high resistance. The direct current to be measured is extremely low, usually not more than 10 microamperes for large specimens and less than 0.01 microampere for small specimens. Because the test specimen is almost always capacitive, very large ripple current, with respect to the direct current component, will be generated. This ripple current can be reduced significantly simply by inserting a 1-megohm resistor in series with the test specimen (refer to fig. 1). This resistor is very small in comparison to the test specimen resistance, and, therefore, has a negligible effect on the direct-current response of the insulation with respect to test voltage. A worse case insulation direct current of 10 microamperes through the 1-megohm resistor produces a d-c voltage drop of only 10 volts. This resistor transforms the test circuit impedance from purely capacitive to mainly resistive. To illustrate this point, consider a 1-μF test specimen which has an impedance of $-$ j2.65 kΩ; by adding the 1-megohm resistor in series, the impedance increases to 1000 $-$ j2.65 kΩ. The net effect is a reduction of ripple current by over two orders of magnitude. This resistor also serves to isolate the specimen from the test set.

Even though reduced by a factor of 380, the ripple current is still large enough to cause problems. Therefore, a special current meter was designed to further reduce the alternating current. The meter input was designed with a 20-kΩ input resistance shunted by a 10-μF nonelectrolytic capacitor. This arrangement creates an alternating current division between the capacitor and meter to reduce the current through the meter by a factor of 75.

An active two-pole filter (fig. 2) was designed into the meter to essentially eliminate the alternating current prior to measuring the direct-current component. The corner frequency is 1.1 Hz. This results in an attenuation of -68 dB at 60 Hz (equivalent circuit gain of 0.0004 at 60 Hz). This corresponds to a reduction of the alternating-current signal by a factor of 2500.

CONCLUSIONS AND RESULTS

This measurement technique has been used successfully to test cable insulation up to 350 kV d.c. with an unregulated test set. Through the use of extensive corona shielding techniques, currents on the order of 0.5 to 1.5 microamperes were successfully measured at the 350-kV level.[1] From calculations similar to those shown in appendix A, it was shown that the a-c component at the measuring terminals (after filtering) was less than 0.1 μA. It is believed that the currents actually measured during the tests were due to a combination of corona, cable leakage, and cable conduction.

[1] Current meter located at cable pothead in order to bypass test set and circuit corona leakage currents.

This same technique has been used for over 5 years to measure stator insulation leakage current, and with slight modification has been used in the laboratory to measure the leakage current of individual stator coils where the current is usually on the order of 10 nanoamperes.

Test set load regulation will influence the output voltage during and shortly after an output voltage transition, but should not affect the metering circuit after the test specimen capacitive component of current decays to zero. However, line regulation does present a problem with respect to an unregulated power supply. If a stable a-c supply bus is not available, which is usually the case, an electronic a-c power line conditioner will be necessary to prevent major fluctuations in the high-voltage direct current.

APPENDIX A - RIPPLE CURRENT NOTES AND CALCULATIONS

Following are several notes and a typical computation pertaining to proper ripple current suppression and filtering techniques. Refer to figure 1.

1. If necessary, the series resistor (R_1) can be increased to 10 megohms, and in some cases where low meter current is expected, it can be increased to 100 megohms. Example, $100\ M\Omega \times 10\ \mu A = 1\ kV$ (too high); however, $100\ M\Omega \times 1\ \mu A = 100$ volts (acceptable).

2. The current meter shunt capacitor (C_2) should be nonelectrolytic and of high quality (high insulation resistance) to prevent shunting direct current around the meter. Capacitance values between 1 and 10 μF are practical. A capacitor smaller than 1 μF will not help much, and one larger than 10 μF is expensive and too awkward to handle.

3. The current meter input impedence (R_{in}) can also be changed to vary the alternating current division between the shunt capacitor and meter. The resistance should not be decreased much below 10 or 20 kΩ or the effect of the shunt capacitor will be lost. The input resistance should not be increased above 1 megohm, without serious consideration given to the redesign of the meter circuit described in appendix B. Above 1 megohm, the d-c voltage developed across the resistor may cause the protective zener diode and/or neon lamp to conduct, and thereby create a direct-current bypass path around the meter.

4. The filter circuit can be modified to increase or decrease the a-c rejection factor by shifting the corner frequency (fig. 2). Halfing the corner frequency essentially adds an additional 12 dB of attenuation. The corner frequency should not be reduced too much or the low-frequency response of the meter will suffer.

5. In figure 1, the current meter has been inserted between ground and the test set ground current return lead. This is acceptable for testing below 50 or 100 kV, but above these voltages, the meter should be placed in the high-voltage lead as close to the test specimen as possible. This will elminate test circuit corona and leakage currents from being measured. When testing high-voltage cables (sometimes as high as 400 kV d.c.), we use 100-mm (4-in) PVC Pipe to corona shield the high-voltage test lead that connects the high-voltage supply to

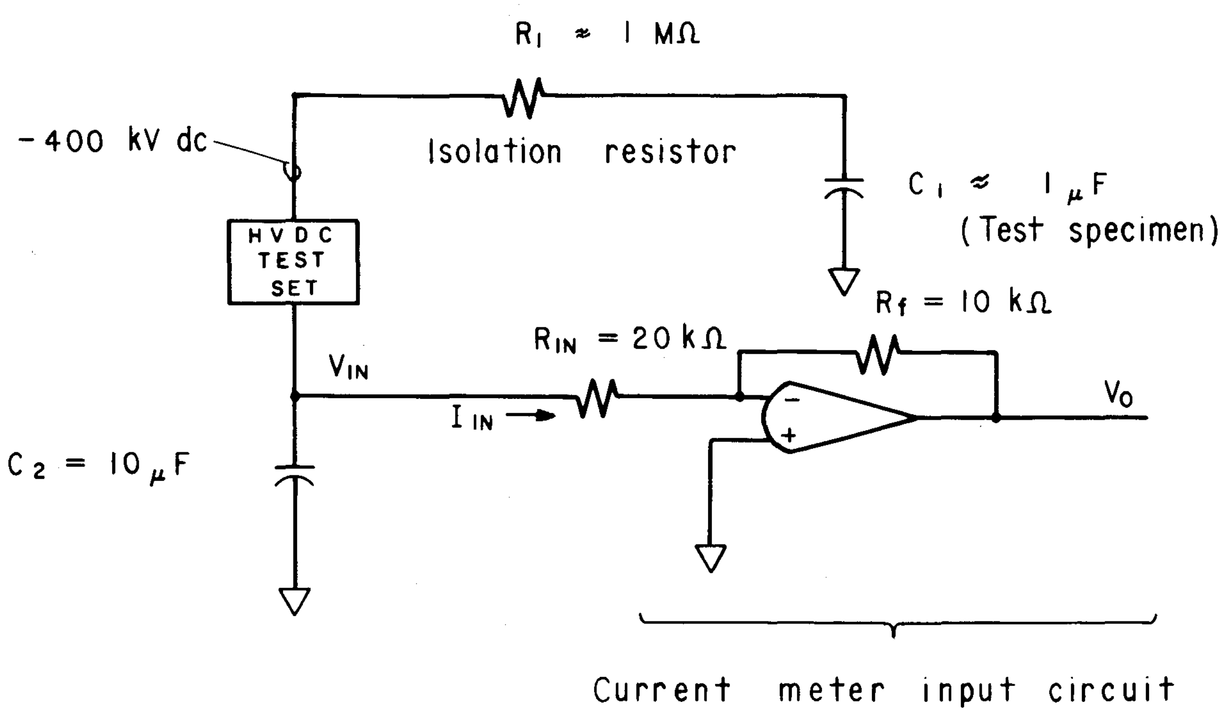

Figure 1.—High-voltage circuit.

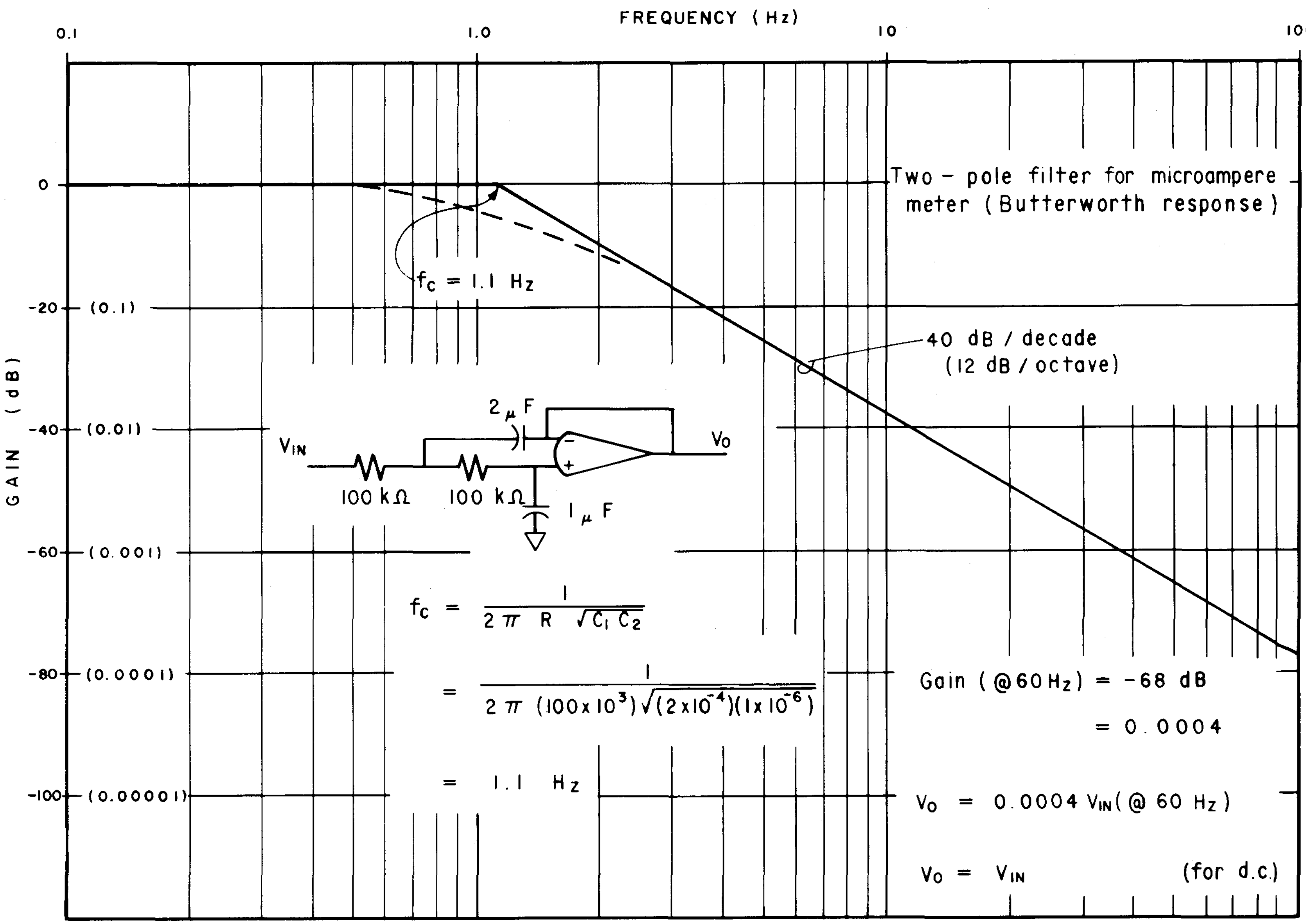

Figure 2.—Meter filtering circuit.

the test specimen. A current meter was built inside a 300-mm (12-in) section of the 100-mm PVC pipe. The meter is installed at the pothead end of the pipe corona shield. The meter enclosure and pipe assembly is an extremely efficient corona shield.

6. Worse case test set ripple (specified at rated load current) is used in the calculations presented. In some instances this is a very conservative approach in that the actual ripple voltage decreases as the load current decreases. At the higher test voltage levels, corona and leakage currents from the test set and circuit leads can actually load the test set to the rated output current level. In this case, the specified ripple voltage is a realistic figure to use in the calculations presented.

Calculations

Assume 5-percent test set ripple (worst case at rated load current) and 60-Hz square wave ripple waveform.

$V_{Ripple} = 5\%$ of 400 kV d.c. = 20 kV

$X_{C_1} = -\ j2.65$

$X_{C_2} = -\ j0.265$

$$I_{Ripple} = \frac{V_{Ripple}}{R_{Load}} = \frac{20\ \text{kV}}{1.0 - j0.0029\ \text{M}\Omega}$$

Neglect the effect of R_{in} and

$-\ j2.9\ \text{k}\Omega\ (X_{C_1} + X_{C_2})$,

therefore,

$1.0 - j0.0029\ \text{M}\Omega \approx 1.0\ \text{M}\Omega$

$I_{Ripple} = 20\ \text{kV}/1.0\ \text{M}\Omega = 20\ \text{mA}$

$$V_{in} = I_{Ripple} \cdot X_{C_2}$$
$$= 20\ \text{mA}\ (-\ j0.265\ \text{k}\Omega) = -\ j5.3\ \text{V}$$

$$I_{in} = \frac{V_{in}}{R_{in}} = \frac{5.3\ \text{V}}{20\ \text{k}\Omega} = 265\ \mu\text{A}$$

$$V_o = \frac{R_f}{R_{in}} \cdot V_{in} = \frac{10\ \text{k}\Omega}{20\ \text{k}\Omega}\ (5.3\ \text{V})$$
$$= 2.65\ \text{V @ 60 Hz}$$

$$V_{Out\ of\ filter} = V \times G_f$$
(filter input) (filter gain)

From figure 2, G_f at 60 Hz = −68 dB or 0.0004

$V_o = 2.65$ volts $\times\ 0.0004 \approx 1$ millivolt

Switching circuit has a gain of 1 or 10;
for a gain of 10, $V_o = 10$ millivolts = 0.01 volt

$I_{Meter} = V_o / R_L$

V_o = output of switching circuit

R_L = load resistor

$$I_{Meter} = \frac{0.010\ \text{volt}}{1\ \text{k}\Omega} = 0.01\ \text{mA}$$

full scale meter = 1 mA

$$\text{Percent error due to ripple} = \frac{0.01 \times 100}{1} = 1\ \text{percent;}$$

1 percent of 10 μA (meter calibration) = 0.1 μA or roughly one order of magnitude below the level of current to be measured.

APPENDIX B — TEST METER CIRCUIT DESCRIPTION

Please refer to figure 3. The front end of the metering circuit has a resistor-capacitor network (the 10-μF capacitor and 10-kΩ resistor, R_2) to divert a large portion of the alternating current around the meter. The remainder of the input circuitry serves to protect the meter electronics from transients and surges.

The input amplifier is an inverting operational amplifier that has a d-c voltage gain of 1. However, because the test specimen has an extremely high resistance, the input amplifier circuit functions as a current-to-voltage converter with a gain or transfer function equal to 10 mV/μA. The next stage consists of a low-pass, two-pole filter. The d-c gain is equal to 1. The corner frequency is set at 1.1 Hz. For the component values shown, the frequency response is critically damped, i.e., a butterworth filter response. The meter amplifier has an FET switch to change the circuit voltage gain from 1 to 10. The mechanical current meter has been placed inside the feedback loop along with a full-wave bridge so that the meter will accurately register the correct current magnitude regardless of polarity. The meter amplifier transfer function is:

A. FET on, thereby shorting the 90-kΩ resistor. The voltage gain is equal to 10; however, the actual transfer function is: meter current / input voltage = 10 μA/mV.

B. FET off, 90-kΩ resistor is in the circuit. The voltage gain is equal to 1; however, the actual transfer function is: meter current / input voltage = 1 μA/mV.

The remainder of the circuitry consists of an absolute value amplifier, comparator and FET driver. The overall circuit provides the meter with an autoranging function. Full scale meter registration is 10 μA on the low range and 100 μA on the high range. A bipolar voltage meter connected to the output of the comparator is used to indicate the current meter scale. A three-position switch has been provided to select the high scale, low scale, or the autoranging mode of operation.

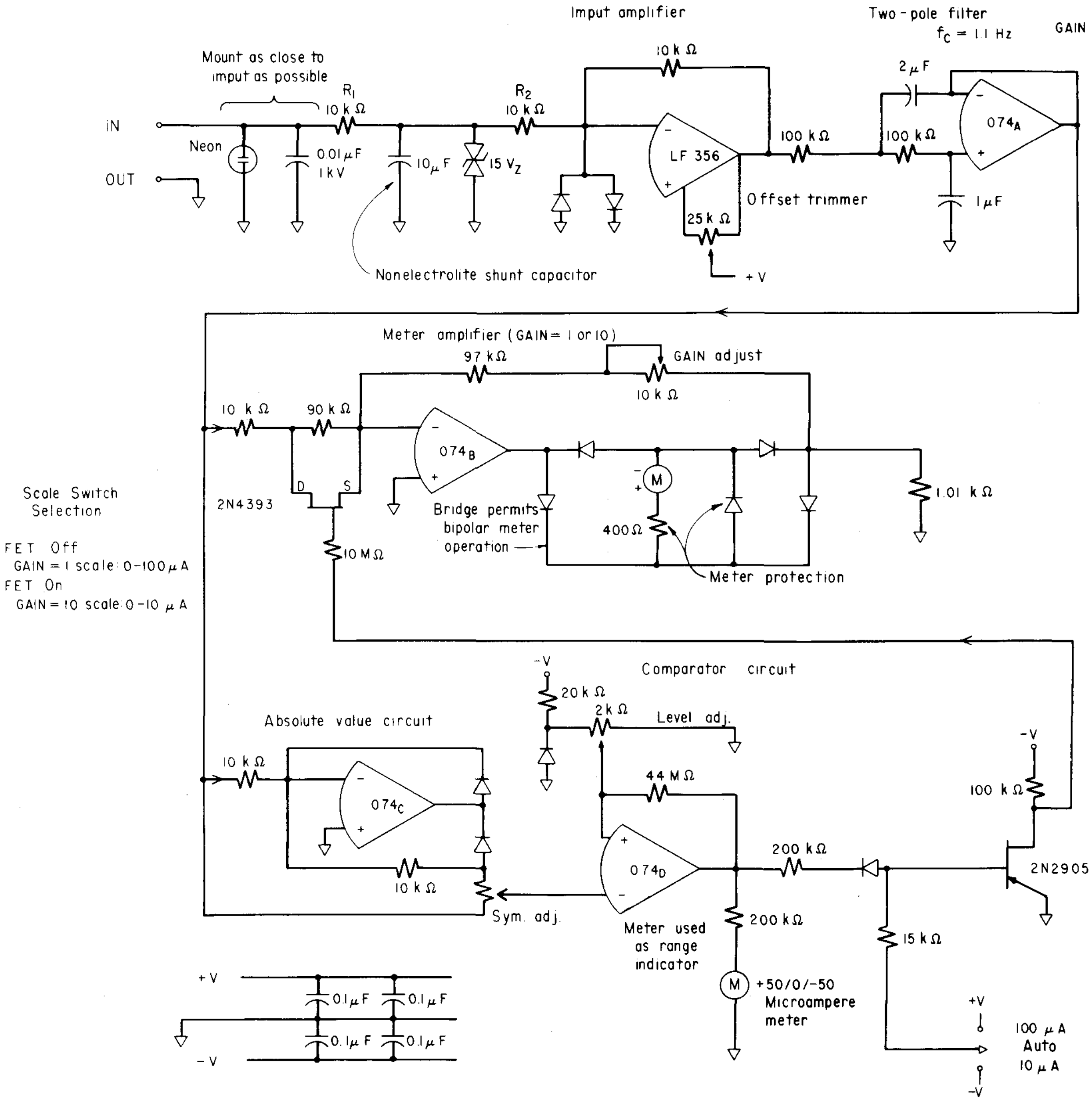

Figure 3.—Current meter for high-voltage insulation testing.

NOTES:

1. Power supply ± 15 V dc or ± 9-V battery.
2. All diodes IN484A.
3. Meter bridge is optional.
4. Auto range function optional. The lower two operational amplifiers and the FET, and the transistor circuits can be eliminated if auto range is not desired.
5. The 10-μF front end capacitor must be a nonelectrolite type.
6. Filter circuit is required.
7. Suddenly discharging the cable may damage the meter circuits.

ALINEMENT:

1. Adjust offset to null meter.
2. Adjust GAIN for full scale meter deflection with proper imput current.
3. Adjust level to about 55 mV at trimmer wiper.
4. Adjust symmetry to 60 mV at trimmer wiper with +0.1 V at the output of the filter amplifier.
5. Readjust level as necessary for proper scale switching in auto range position.

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