NATIONAL INSTITUTE OF OCEANOGRAPHY

WORMLEY, GODALMING, SURREY

A Multiple Floating-d.c. Power Supply for an Analogue Computer

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S. ISHIGURO AND A. J. BUNTING

N.I.O. Internal Report No. A.35

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Abstract

Some types of electronic analogue computer require a multiple floating power supply having d.c. outputs whose electrical isolation from each other, from the circuit earth, and other parts can be regarded as perfect with respect to the analogy. Since such a power supply operated from a power line is not commercially available so far, this has been developed for the purpose. Noise voltage both between output terminals and between output terminals and earth is less than 200 μV p-p. Each output is 10·00 V with a stability of $< \pm$ 0·03% against line voltage (± 10%), and load current (0 to 60 mA), and a temperature stability of 0·01% per °C. The output impedance is less than 0·05 ohm from d.c. to 10 kHz. A short-circuit protection and remote-error-voltage-sensing terminals have been prepared for each unit. The number of output units is unlimited in principle, with a flexibility in electrical and physical arrangement. The cost of the power supply is comparable to that of battery operations.

1. Introduction

An electronic analogue model, designed by Ishiguro at the National Institute of Oceanography for analysing storm surges in the North Sea, has been operated successfully several years. This consists of a number of transistor circuits whose power supplies cannot be common and should be isolated electrically from earth. These are operated at the moment by individual dry batteries for simplicity of arrangement, although these have several disadvantages such as relatively high output impedance, voltage changes with time, and necessity of quite frequent replacements.

A power supply for this application should satisfy the following conditions at least:

(1) The input power should be supplied from a 240 V rms ± 10%, 50 Hz ± 1% line, and the d.c. output should be divided into a considerable number of units, say 200. The cost per unit should be reasonable compared with that of the main part of the apparatus.

(2) The d.c. outputs should be isolated electrically from each other, from the power line and from earth, with a high impedance, say >100 M ohms. However, a small capacity, say <500 pF with a stability of ± 1%, can be permitted between each d.c. output and earth, if the capacitance is uniform throughout all the units.

(3) Noise voltage, including a.c. components, between each d.c. output and earth should be small, say <0·5 mV p-p.

(4) Each d.c. output voltage should be highly stable, say ± 0·05%, against changes of the line voltage (± 10%), frequency (± 1%), load current (0 to 60 mA), and normal environmental temperature change (0° to +40°C). Noise voltage, including a.c. components, contained in each d.c. output should be small, say 0·5 mV p-p.

(5) The impedance of each d.c. output should be low, say 0·05 ohm, from d.c. to 10 kHz.

(6) Other items usually required for precision power supplies, such as fast recovery time and small over-shoot voltage, short warm-up time, short-circuit protection, and remote-error-sensing terminals, are also preferable.

No commercial product which satisfies all the conditions above is available so far; only one commercial type satisfies Condition (3) but does not satisfy Condition (1). Therefore, we have decided to develope a power supply especially for this purpose.

The aims of the design are as follows: (A) A principle which requires a minimum of non-standard components has been chosen. (B) The electronic circuit and its physical construction have been designed to be as simple as possible, and to have optimum performance. (C) All the components have been selected from inexpensive versions due to mass production and not due to low quality. (D) In order to minimize costs no special efforts have been made to miniaturize the equipment.

2. Noise-voltage reduction between outputs and earth

To satisfy Conditions (2) and (3) at the same time is the most important requirement for this apparatus, and careful consideration is necessary.

Fig. 1 shows a conventional arrangement of typical a.c. operated d.c. power supply, with its a.c. equivalent. For conventional uses, one of the d.c. output terminals is earthed so that Z_{E1} = zero and e = zero. The impedance between Terminals 1 and 2 is usually very low so that Terminal 2 is also practically earthed. Therefore no problem arises with respect to Condition (3), even with large stray capacitances C_{ps} and C_{Es} existing. However, if Z_{E1} is large as specified by Condition (2), both the primary and secondary voltages appear, through these capacitances, between the output terminals and earth. This is the main reason why conventional power supplies cannot be applied for our purpose.

Fig. 2 shows one of the arrangements by which a conventional power supply system can be applied to our purpose with minor alterations. In this arrangement, a double screening is used for the secondary winding and its related parts, in addition to a separate screening for the primary winding. The inner screen of the secondary part is connected to one of the d.c. output terminals, while the rest of the screens are earthed. As shown in a simplified a.c. equivalent circuit, e can be very small if C_{ps} and Z_p are very small which is not difficult to realise. C_{E1} is now the only problem to solve. There are two possible solutions: to make C_{E1} small so that for example $1/\omega C_{E1} = 0{\cdot}01\, Z_{E1}$, or to make C_{E1} relatively small and stable as specified by Condition (2).

The arrangement described in Fig. 2 can eliminate the main part of the noise voltage appearing between the d.c. output terminals and earth, and this arrangement can reduce the noise voltage to about 10^{-5} of the primary voltage (700 V p-p approximately if this is connected directly to a power line). In order to reduce the noise voltage further, other kinds of noise sources should be eliminated.

Noise voltages of 50 Hz component Since C_{ps} (in Fig. 2) cannot be zero, a part of line voltage is introduced to the secondary circuit. In order to reduce this effect and to make the seconday lead wires as short as possible, two kinds of transformers are used between the power line and the rectifier of each unit. The first transformer TC is used in common for a group of units (say 50), and this steps down the line voltage to about 20 V rms. This voltage is supplied to an isolating transformer T1 contained in each unit as shown in Fig. 3. The primary circuit of T1 is earthed through an adjustable potentiometer VR_a so that all 50 Hz component voltages appearing on the d.c. output, through C_a, C_b, C_c, C_{sc} and r_e are cancelled; where C_a, C_b, C_c are leakage capacitances due to the imperfection of the screens, C_{sc} is the capacitance between the primary circuit of T1 and its screen, r_c is the resistance of lead wires, and r_e is the resistance between the two earth points.

Noise voltage generated in the rectifier circuit Fig. 4 shows voltage and current waveforms in the rectifier circuit (see Fig. 3 for symbols). Since E_1 is kept almost constant all the time, the rectifier current i_{as} can flow only when the secondary voltage of T1, e_{gs}, becomes higher than E_1 so that i_{as} takes a square-pulse like waveform. At the start of each pulse, voltages rise with a relatively large time constant since the circuit is loaded. At the end of each pulse, voltages fall with a very small time constant since there is practically no load. This gives a voltage waveform as shown e_{as} in Fig. 4. This voltage contains many high frequency components as well as 50 Hz.

After the rectified voltage has passed the filter consisting of C_1, R_1, C_2, it has almost only a 100 Hz component with amplitudes of 600 mV p-p across C_1, and 20 mV p-p across C_2.

These voltages and voltage e_{as} described previously appear between the d.c. output and earth, even if the impedance between the output terminals is zero, unless electrostatic coupling between these parts and earth is eliminated. Therefore, all these parts should be contained within the inner screen. Imperfection of the inner screen

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which is represented by C_c in Fig. 3 will produce a noise voltage, but low frequency components such as 50 and 100 Hz are attenuated more effectively than high frequency components since C_c is very small, so that the residual noise voltage becomes a waveform such as shown by e in Fig. 4. This voltage will be less than 0·2 mV p-p if the screens are arranged carefully.

Noise voltage due to resistance in conductors Several electronic components of the secondary circuit are connected to a common conductor shown by a thick line in Fig. 3. It can be regarded, for most cases, that such a conductor has a uniform electric potential everywhere. Compared with the noise-voltage level specified for this power supply, however, irregularity in voltage distribution on the conductor is appreciable. For example, a current of 100 mA p-p through a conductor which has resistance of 0·01 ohm produces 1 mV p-p. In particular a part of the conductor by which the filter current is carried produces a considerable voltage containing 100 Hz and high frequency components. If physical positions of electronic components on the conductor are not correct such a voltage would appear between the d.c. output terminals and between the terminals and earth. The worst arrangement is that the output terminal is connected near the lead wire of C_1 and at the same time the error-voltage sensing circuit is connected to the further end of the conductor. The best arrangement is to connect the components, including the inner screen, to the conductor in the same order as shown in Fig. 3.

Noise voltages due to magnetic coupling from T1 Conductors, such as screen and lead wires, in the magnetic field of Transformer T1 produce voltages depending on both the primary and secondary currents of the transformer and conditions of coupling. For example, one turn of conductor around the full flux will produce approximately 50 mV p-p of 50 Hz component from the primary, and approximately 100 mV p-p of pulsed voltage from the secondary, if the conductor has no load.

The electro-static screen for the secondary winding has the most serious effect, since this has a complete turn around the full magnetic flux and is electrically isolated from earth. Fig. 5(a) shows the geometric relationship of the screen and the core. Fig. 5(b) shows an equivalent circuit of electromotive force induced in the screen and its stray capacitance. The stray capacitance per unit surface-area of the screen at bc and ef is approximately twice that of the rest of the screen, while the electromotive force is distributed along the screen. Fig. 5(c) shows a simplified equivalent of the previous circuit. When the two ends of a and b are kept open, almost no voltage will appear between d and E, since the currents passing through the main stray capacitances cancel each other. Therefore, d is the best position to connect the lead wire of the screen; ab and fg are the worst areas to do so since induced voltages will appear directly between the d.c. output and earth. The lead wires of the secondary winding of T1 should also be screened, and the end of the screen should be kept open.

The screen of the primary winding of T1 has the same effect, but induced voltages do not appear between the output terminals and earth, even if the lead wire is connected to any position, since the screen is earthed.

The rest of the components should be arranged as far from the magnetic flux as possible, although the coupling effect on them is relatively small. It should be noted that a magnetic screening would not be worth applying since this has no effect on the electrostatic screen of the secondary winding.

3. Design of the rectifier, filter, and voltage stabilizer

The circuit of one unit is shown in Fig. 6. Components for one unit are listed in Table 1. A shunt-impedance voltage-regulator has been employed since the total power dissipation of this apparatus is not large and no special components are required for short circuit protection. A bridge-connected silicon rectifier has been chosen mainly from an aspect of physical size because this has to be contained in the inner screen. A simple ripple filter, consisting of two 1000 μF capacitors and one 33 Ω resistor, is used by which the ripple voltage can be reduced to 20 mV p-p approximately. Their physical dimensions are again an important factor in choice since they are also contained in the inner screen. A large current rating resistor is used for R3 as well as R2, since these act as the main heat dissipaters when a short circuit is made between the output terminals. A combination of a PNP silicon transistor and a silicon zener diode ($E_z = 6{\cdot}5$ V at $I_z = 5$ mA) has been chosen for the error-voltage sensing circuit so that the combined temperature coefficient becomes very small. A zener diode which has a lower voltage will improve this combined coefficient, but it has a higher dynamic ~~zener~~ impedance so that the voltage stability against current is reduced. Therefore a compromised design has been made for this point. In order to operate the zener diode at a low dynamic zener-impedance by increasing the average zener current, R5 is connected in series to the zener diode from a stabilized voltage. Two NPN silicon transistors, Tr-1 and Tr-2, are used for the main voltage controller and its amplifier.

It has been found that the circuit has a reasonable stability even without Tr-2, but it is not sufficient to obtain a low impedance specified for this apparatus. All the transistors have been chosen from the aspect of low cost subject to these satisfying the technical requirements of the circuit. The chosen types have much higher qualities than required; the main reason seems to be a mass production of these types due to a large demand. Stability and output impedance for high-frequency load-changes are limited only by stray capacitances and inductances of other components. In order to preserve a good frequency characteristic, therefore, a capacitor is used to shunt the output terminals only for preventing a self oscillation of the circuit. In order to make the capacitance between the output and earth uniform throughout all the units, a preset capacitor CV is used which can be adjusted from the outside of the case after each unit is fixed to the computer. A pair of terminals for remote error-voltage sensing is prepared inside the case. For this purpose a four-conductor screened cable should be used. If this is not necessary, a twin-conductor screened cable can be connected so that each error-sensing terminal and one of the output terminals are connected with a part of the conductor respectively.

4. Design of Transformer T1

The electronic circuit shown in Fig. 6 requires 50 Hz 16 V rms, 100 mA to operate at the input terminals of the rectifier. The output voltage of the mains transformer, TC, is 21·5 V rms. Transformer T1 should satisfy these conditions to connect these two parts, as well as conditions required for screening of windings. From the power rating required and the physical dimensions for screening, a Belclere Type KX Unisil core has been chosen. Design factors of the transformer windings are shown in Table 2. This design would be flexible for changes of voltages and current rating of abou ±30%

Screening of the transformer is most important for this application. Several methods of construction of screens have been examined; for example, a metal plated bobbin with a metal-foil side-cover. The most successful method is screening of each winding with a single metal foil without bobbins. The process of constructing windings in such a way is shown in Fig. 7. The dimensions of the primary and secondary windings are shown in Fig. 8. The dimensions of winding formers are shown in Fig. 9.

Some characteristics of a prototype transformer are shown in Fig. 10 and a summary of the characteristics is shown in Table 3.

5. Design of physical arrangement of components

Arrangement of components for one unit is shown in Fig. 11. A standard type aluminium-alloy die cast box with a lid has been chosen for the case which, at the same time, acts as a heat sink, electro-static screen and dust cover as well as a mounting chassis for components. This has been found the most economical way so far, although the size and weight of the case are somewhat too large for this purpose. An aluminium container (originally designed for a desiccator container) is used for the inner screen for the same reason. This is fixed on the inside wall of the case with a metal clamp (originally designed for a large cylindrical capacitor) and two nylon screws by inserting an insulation plate with one surface copper clad (originally designed as printed circuit board). The copper cladding becomes the lid of the inner screen tube and has the effect of screening. The transformer is also fixed inside the case directly, with the input and output lead wires. The rest of the electronic components are mounted on a printed circuit board which is also fixed inside the case. The power transistor Tr-1 is held in thermal contact with the case wall by an electrically insulated heat-sink adaptor with a nylon screw. Two holes have been made for adjusting VR and CR from outside the case, after each unit is installed.

6. Electrical characteristics of a unit

Some electrical characteristics of a prototype unit have been tested which has been designed according to the circuit shown in Fig. 6 and the physical arrangement shown in Fig. 11.

Fig. 12(a) shows changes of a.c. input current, I_{as}, and voltage, E_{as}, at the input of the rectofier with and without an external load on the unit. The impedance at the nominal value of E_{as} = 17 V rms is approximately 170 ohms and is practically constant against the change of load.

Fig. 12(b) shows d.c. voltages across C_1 and C_2, E_1 and E_2 respectively, against E_{as}. At the nominal value of E_{as}, E_1 = 19 V and E_2 = 16 V approximately. E_{as} should not be higher than 20 V rms for the protection of C1 whose working voltage is 25 V.

Fig. 12(c) shows changes of d.c. output voltage E_o, as the parameter of E_{as}, against the output current I_o. For the specified maximum current of I_o = 60 mA, E_{as} can be changed from 15·5 V rms to 18·5 V rms without a serious effect on E_o. (See Fig. 13(b) for detail.)

The circuit cannot be used at a lower value than E_{as} = 15 V rms.

Fig. 12(d) shows output-current cut-off characteristics against output current I_o, which acts as a short-circuit protection. The output voltage is cut off at I_o = 85 mA approximately when E_{as} is the nominal value. This corresponds to +40% of the specified maximum current. However, if E_{as} is changed by ±10%, the cut-off current will be changed by ±23%. See Fig. 13(a) for details.

Fig. 12(c) shows the temperature stability of output voltage in an ambient temperature range of -10°C to +60°C. The temperature coefficient is approximately 0·01% per °C.

Fig. 13(a) shows the same characteristics as shown in Fig. 12(d), but gives details around the nominal value of E_{as} and the full range of I_o. The stability of E_o is ±0·025% for I_o = 0 to 60 mA at E_{as} = 16 V rms ±10%.

Fig. 13(b) shows the same characteristics as shown in Fig. 12(c), but with details around the nominal values of E_{as}.

Fig. 13(c) shows a test circuit used for obtaining data shown in Fig. 13(a) and Fig. 13(b). See Chapter 7.

Fig. 14(a) shows the output impedance, Z_o, against frequency, f, of sinusoidal load current. In this test a standing current of 50% of the maximum specified current was modulated sinusoidally with an amplitude of ±30% of the specified current. Z_o measured at the output terminals (inside the case) is 0·05 ohms from 1 Hz to 10 kHz, and gradually increases up to 0·2 ohms at 100 kHz as shown by A in Fig. 14(a). When lead wires are connected to the terminals, Z_o is affected appreciably depending on the quality and length of wires. As examples, two cases are shown here: C shows an effect of a screened twin-conductor cable without use of the remote error-voltage sensing terminals; and B shows an effect of the same cable with another screened twin-conductor cable for error-voltage sensing at the remote end. These examples suggest that choice of lead wires is quite important.

Fig. 15(a) shows responses of the output voltage to step changes between no load to full load (current = 60 mA). The responses at the output terminals 1-2 show that there is no overshoot or undershoot and both patterns have a time constant of 1·2μs approximately. The stability of E_o is kept within ±0·007%. The output impedance measured by this method which can be regarded as the d.c. resistance, is 0·0234 ohm. When the responses are measured at the ends of the same lead wires, previously described, large peaks appear in both the positive and negative sides.

The positive peak reaches to +0·2% of the nominal value of E_o, and takes about 6 μs to settle down on the nominal value. The negative peak shows almost the same change, but with a slightly lower amplitude. The output impedance measured in this way is affected, of course, by the lead wires. Fig. 15(b) shows the test circuit; see Chapter 7.

Fig. 16(a) shows the response of the output voltage to step changes in line voltage between -10% and +10% of the nominal value. The changes of E_o are kept within +0·1% approximately at both no load and the full load. The time constant is approximately 0·1 sec for both its rise and fall, at both no load and the full load.

Fig. 16(b) shows the response of the output voltage to the 'on' and 'off' conditions of the nominal line voltage. Fig. 16(c) shows details of the same responses near the nominal voltage of E_o. When the line voltage is switched on at no load, E_o reaches -0·1% of the nominal value of E_o within 0·3 sec, and -0·01% within 0·6 sec with no overshoot. When the line is switched on under the full load, E_o reaches -0·1% within 0·4 sec, and -0·01% within 1 sec approximately (not a pure exponential). When the power line is switched off, E_o shows an overshoot which reaches +0·12% of the nominal value at no load, and +0·05% at the full load; in both the cases E_o falls below the nominal value within 0·05 sec. These show that the apparatus is ready to use, with a stability of +0·01%, within 1 sec at the longest after it is switched on; and that actions of switch-off do not make any voltage harmful to the main computer network. Fig. 16(d) shows a test circuit; see Chapter 7.

7. Test methods for units

Since there are a considerable number of units to test, the test methods for some items are specified here. Data described in the former chapter have also been obtained by these methods. VR and VC in each unit should be adjusted before test. All the tests should be carried out under a normal ambient temperature, unless otherwise specified, and the test temperature for each case should be recorded.

7.1 Line and load stabilities of the output voltage

Since the expected output-voltage stability of this apparatus is ±0·01%, at the best, a voltmeter whose accuracy is better than this value is required for testing. If such a voltmeter is available, there is no problem. If not an alternative method suggested here would be useful. This method is based on the assumption that the output-voltage stability does not depend on the preset output voltage if it is set around the nominal value within a very small deviation (say ±0·05%). If the measurement is carried out after such a pre-setting, the stability can be assessed by taking differences between the preset voltage and actual voltages under test conditions. Fig. 13(c) shows such a method: an external voltage is adjusted so that the voltmeter indicates no voltage when the output voltage is preset at a particular level. If it is changed by other conditions, the voltmeter will indicate the difference from the preset value. For this method, a less accurate voltmeter can be used. For the test of the prototype unit described in the former chapter, a digital voltmeter has been used which has a 10 V full scale with ± 5 mV absolute accuracy and 50 M ohm input impedance. The stability of the external voltage should be checked.

For changing the line voltage or the load current, an a.c. voltage adjuster or a variable load resistor, operated manually, is used. For measuring these voltages or currents conventional laboratory meters can be used.

7.2 Response of the output voltage to step changes of load

Fig. 15(b) shows a measuring method of the output-voltage response to step changes between no load and full load. This test gives transient waveforms and a difference of two d.c. voltage levels. In order to obtain accurate results in waveforms, an extremely careful arrangement is necessary because of a small rise time (of the order of 1 μs) and a small voltage (of the order of 1 mV).

A fixed resistor representing the specified full load (167 ohms) is connected to the output terminals of a unit under test, through a reed switch controlled by a transistor switching circuit for making the 'off-resistance' as large as possible. The reeds of the switch and its lead wires are electrostatically shielded. The magnetic coupling between these parts and the magnetic coil of the relay is avoided by balancing the physical positions of the components; this adjustment can be done by checking the circuit without external current. An oscilloscope is used for recording the responses, together with an a.c.-balanced differential amplifier whose lead wires are also checked.

7.3 Output impedance

This should be measured in two ways: (A) d.c. resistance, and (B) impedance for a frequency range of 1 Hz to 100 kHz.

For (A), the value of a d.c. voltage-level difference obtained by the method described in 7.2 can be used; $Z_o = \Delta E/I_o$, where ΔE is the voltage-level difference, and I_o is the output current.

For (B), a measuring method is shown in Fig. 14(b). In this method a power transistor is used for an electronic load which is modulated by an external oscillator. The amplitude of the modulation is adjusted by an attenuator built into the oscillator, and the mean level of the modulation is adjusted by a potentiometer connected to the base of the transistor. The load and the oscillator are floated from earth through a 0·1 ohm ±1% non-inductive resistor for current measurement. The output voltages E_v and E_i are measured by an oscilloscope with a differential amplifier (1 mV/cm scale). The 0·1 ohm resistor should be connected near to one of the output terminals. The output impedance at a particular frequency is given by $Z_o = (E_v / E_i) \times 0{\cdot}1$ ohm.

7.4 Output voltage responses to step line-voltage changes

Fig 16(d) shows a measuring method. A similar method to that described in Fig. 13(c) is used, but an oscilloscope with a d.c. differential amplifier instead of a digital voltmeter, because the responses take 0·1 sec to a few seconds. The line voltage is changed from -10% of the nominal value to +10% or from zero to the nominal value, by operating SW2 or SW1 respectively. In order to obtain these voltages a voltage adjuster and VR are adjusted at static conditions. All the responses are measured both with and without the full load, by operating SW3.

7·5 Insulation between the output and earth

This should be higher than 500 M ohms. High voltages (more than 150 V for example) are not desirable for use in measurements. The test should be done when a unit is not connected to a power line or to a load. A suggested method is as follows:- dry batteries of E_s (say 100 V) are connected, through a high resistor R_s (say 100 K ohms ±1%), between the terminals and earth (the case of a unit). The voltage drop E of the 100 K resistor is measured by an adequate voltmeter (e.g. input impedance 50 M ohms, accuracy ± 5 mV). Insulation resistance is given by

$$\frac{1}{\frac{E_s}{E} - 1} R_s \qquad \text{or approximately } (E/E_s)\, R_s \quad \text{when } E_s \gg E$$

7·6 Temperature coefficient

A complete unit should be put into a temperature regulated refrigerator and a laboratory oven which cover a temperature range of -5°C to $+60^{\circ}$C. A motor fan is necessary to make a uniform temperature distribution over a unit. The power line and load should be controlled during the test. The output voltage can be measured by the same method described in 7.1 but the stability of an external voltage used for this method should be checked frequently since the test period is long.

7·7 Noise voltage between the output terminals, and between these terminals and earth

Noise voltage between the output terminals can be measured by an oscilloscope with a high gain amplifier (1 mV/cm at least). Its input impedance is not critical since the output impedance of a unit under test is very low.

Noise voltage between the output terminals and earth, however, should be measured more carefully, since a high impedance is involved. When VC of each unit is adjusted, including lead wires, if they exist, to be 500 pF, the impedance between these points is 6 M ohms approximately for the lowest frequency (50 Hz), since the insulation resistance existing in parallel with this is higher than 500 M ohms. In order to measure the noise voltage across this impedance, the input impedance of a measuring apparatus should be higher than 120 M ohms for the accuracy of ±5%. The sensitivity of the apparatus should be of the order of 100 μV. These conditions are not always available for most conventional oscilloscopes. If the noise voltage as measured by a normal oscilloscope is e'_m, the real noise voltage e should be calculated by as follows:

$$e = \frac{1 + Z_s/Z}{1 + Z_s/Z_L} e'_m$$

where

$$Z = \frac{Z_L Z_m}{Z_L + Z_m} \qquad Z' = \frac{Z_L Z'_m}{Z_L + Z'_m}$$

$$Z_s = \frac{Z Z' \left(1 - \frac{e}{e'_m}\right)}{(e/e'_m) Z' - Z}$$

e_s	Noise voltage at a source (not known)
Z_s	Source impedance of the noise voltage (not known)
Z_L	Impedance between the d.c. output and earth (measurable)
e	Noise voltage across Z_L (to measure)
Z_m	Input impedance of a measuring apparatus (known)
Z'_m	Reduced impedance of the measuring apparatus by shunting with an external resistance (known)
e_m	Value of e, when Z_m is applied (measurable)
e'_m	Value of e, when Z'_m is applied (measurable)

8. Arrangement of common parts for all the units

Common parts for all the units are shown in Fig. 17. A common step-down transformer, TC, is used for every 50 units. The secondary of this transformer is earthed through near the electrical centre of VRB for balancing all the undesirable voltages of 50 Hz component appearing at the outputs. The primary of this transformer can be operated directly from a power line of 240 V rms ± 10%, if the stability of the output voltage is not required to be higher than ±0·1%. However, a stabilization of the primary voltage has many advantages in addition to an improvement of the output voltage stability by one order. Therefore, a solid-state a.c. voltage stabilizer which has ±0·2% stability including line frequency fluctuations has been used in common for all the step-down transformers. This can cover up to 8 transformers (400 output units) at the maximum, but is usually used with 4 transformers (200 output units), the rest of the power being used for other apparatus. This arrangement makes the whole system flexible, and the cost per unit becomes most economical.

9. Conclusion

The overall characteristics of the whole system are summarized in Table 5. These satisfy all the conditions described in Chapter 1.

Acknowledgements

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Construction of the actual apparatus has been carried out by Mr. G.H. Balchin.

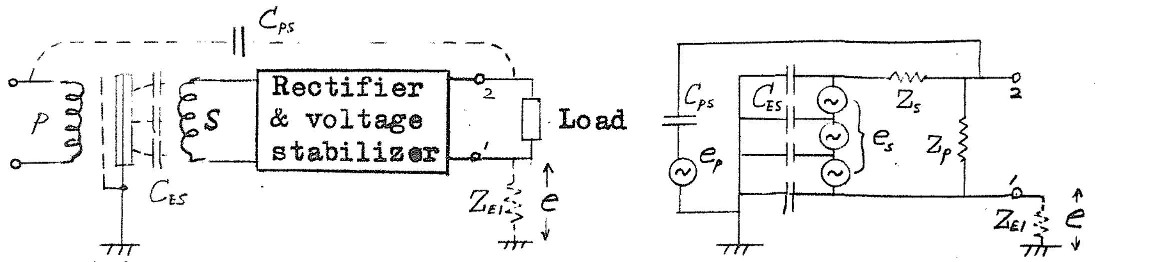


Fig. 1(a) A conventional arrangement. (b) Simplified a.c. equivalent.

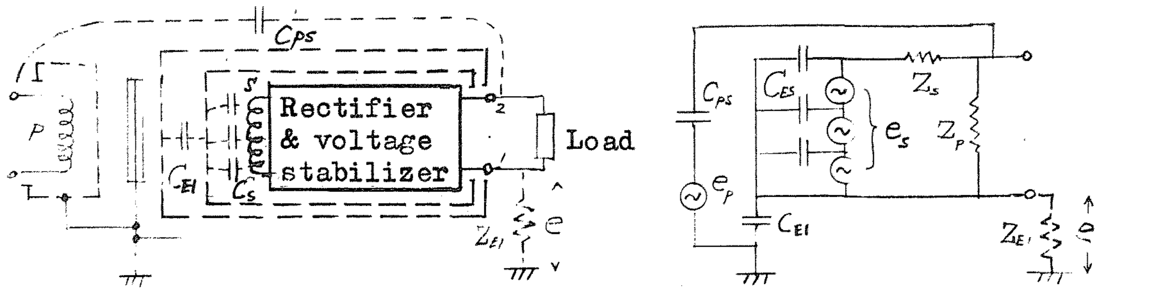


Fig. 2(a) Double screened arrangement. (b) Simplified a.c. equivalent.

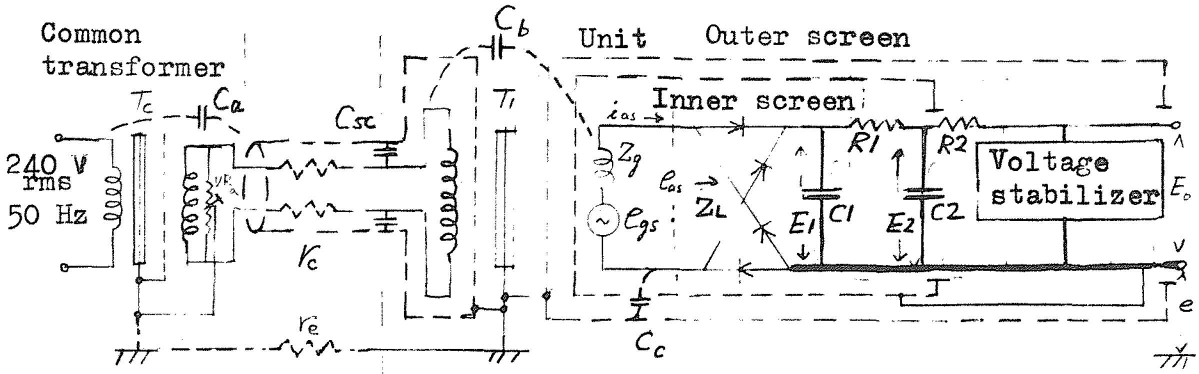


Fig. 3 An equivalent circuit for noise voltages.

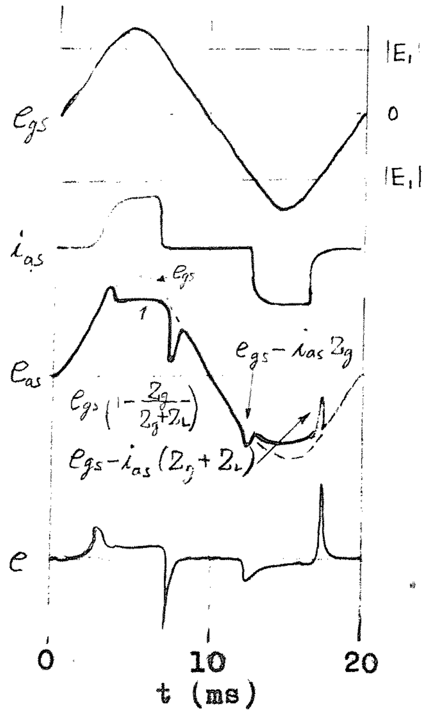


Fig. 4 Some waveforms in the circuit shown in Fig. 3

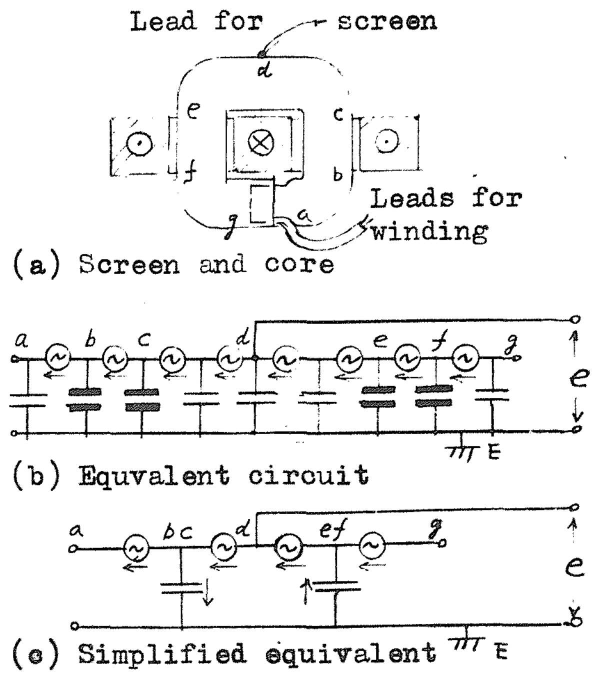


Fig. 5 Voltages induced in the screen of the secondary winding.

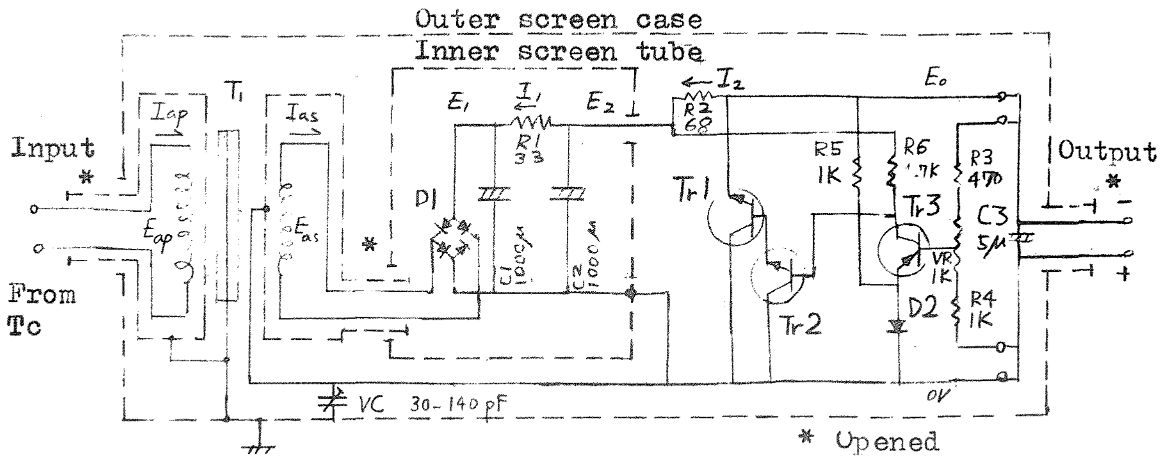


Fig. 6 Circuit of one unit

Table 1. List of components for one unit

Component		Manufacturer	Cost per unit Q'y = 1 (s)	(d)	100 (s)	(d)
Tr 1	BFY51 NPN, silicon, 0·8W	Mullard	12.	6	3.	9
Tr 2	2N3702 NPN, silicon, 0·3W	Texas	4.	7	3.	6
Tr 3	2N2925 PNP, silicon, 0·2W	G.E.	4.	8	4.	8
D1	CSK B80C400 Bridge, 0·4A	Semikron	10.	3	9.	3
D2	0AZ244 Zener, 6·8V, 0·27W	Mullard	4.	8	3.	7
C1	1000 μF 25V MEF 109A1	Hunts	4.	2	2.	2
C2	1000 μF 25V MEF 109A1	Hunts	4.	2	2.	2
C3	10 μF 15V Sub-min.	R.S.	1.	3	1.	3
VC	30-140 pF 500V S1401 30/140	Wingrove		9		8
R1	33 Ω 1·5W 70°C F23 5%ST	Welwyn	3.	1	1.	9
R2	68 Ω 1·5W 70°C F23 5%ST	Welwyn	3.	1	1.	9
R3	470 Ω 0·5W 70°C MR5 5%ST	Welwyn	2.	0		10
R4	1K Ω 0·5W 70°C MR5 5%ST	Welwyn	2.	0		10
R5	1K Ω 0·5W 70°C MR5 5%ST	Welwyn	2.	0		10
R6	4·7K Ω 0·5W 70°C MR5 5%ST	Welwyn	2.	0		10
VR	1K Ω 0·25W 55°C MP-Dealer, lin	Plessey	2.	8	1.	8
Transformer:						
core and clamp	KX, Unisil	Belclere	7.	6	7.	0
self-bonding wire	29SWG, 1200"	LEWC		6		6
self-bonding wire	31SWG, 1200"	LEWC		6		6
aluminium foil	0·001"T			3		3
insulation tape				6		4
Copper clad for p.c.b.	0·625"T	Formica		6		4
Copper clad for screen	0·625"T	Formica		5		3
Outer screen case	6908P	Eddystone	7.	6	6.	9
Inner screen tube	Cont. for SA3	Silicagel	1.	6	1.	6
Clamp for tube	CE45402/007	Plessey		7		7
Heat-sink adapter	1004	Jermyn	3.	3	3.	3
Input lead wire, Output lead wire, 2 4BA nylon screws, 2 4BA brass screws, 8 4BA nuts, 2 Grommets and 2 clips, Bracket for p.c.b.			3.	0	3.	0

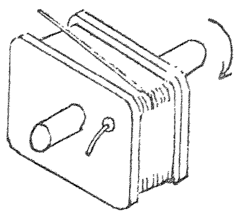
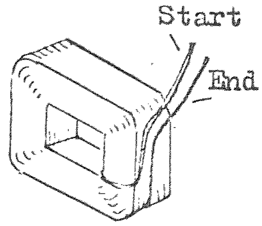
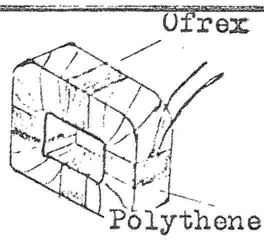
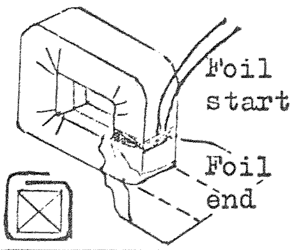
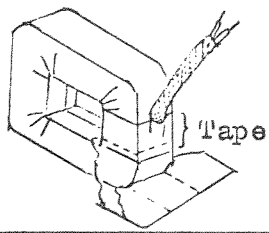
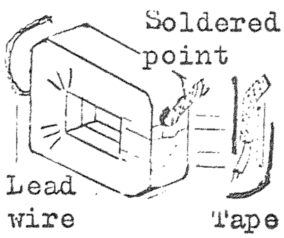
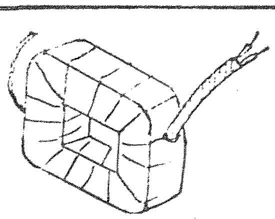
Process			Remark	Prim.	Second.
	1	Wind a coil on a former, using 'Lewmexbond' self-bonding wire.	SWG No.	29	31
			Turns	460	460
			Former 'A'	0.43"	0.34"
	2	Connect N units of coils in series to 240 V power line for t sec. so that the coils are sealed by heating.	N	4	3
			t	10 - 12	5 - 8
	3	Bind the coil at four parts with Ofrex. Coat the coil with polythene and seal its end with Ofrex.	Ofrex : 0.25" x 2" x 0.001" Polythene : 0.25" x 24" x 0.001"		
	4	Wrap the coil with an aluminium foil except the end part.	Aluminium foil : 4.8" x 2" x 0.001"		
	5	Put a flexible sleeve on each lead wire, and put a screen tube on them. Fix them to the coil with p.v.c. tape.	Sleeving : 2 " x 0.08" (dia.) Screen tube : 1.5" x 0.15" (dia.)		
	6	Complete the aluminium foil screen. Solder the screen tube and the lead wire to the foil.	Screen should not make a closed circuit around the magnetic flux. Lead wire : 7/40 p.v.c. coverd, 4"		
	7	Wrap the coil with a p.v.c. tape.	P.v.c. tape : 12" x 0.4" 0.005"		

Fig. 7. Process of constructing transformer windings.

Table 2. Design factors of transformer windings

	Secondary	Primary
Wire ('Lewmexbond')	31 SWG	29 SWG
Max. current rate	0·127 A	0·174 A
Actual nominal current	0·10 A rms	0·11 A rms
Number of turns	460	460
Turns per layer	22	27
Number of layers (0·3")	21	17
Total length of wire	1200" approx.	1200" approx.
Resistance (theoretical)	7·3 ohms	5·3 ohms
Voltage drop at nominal current (theoretical)	0·91 V rms	0·95 V rms

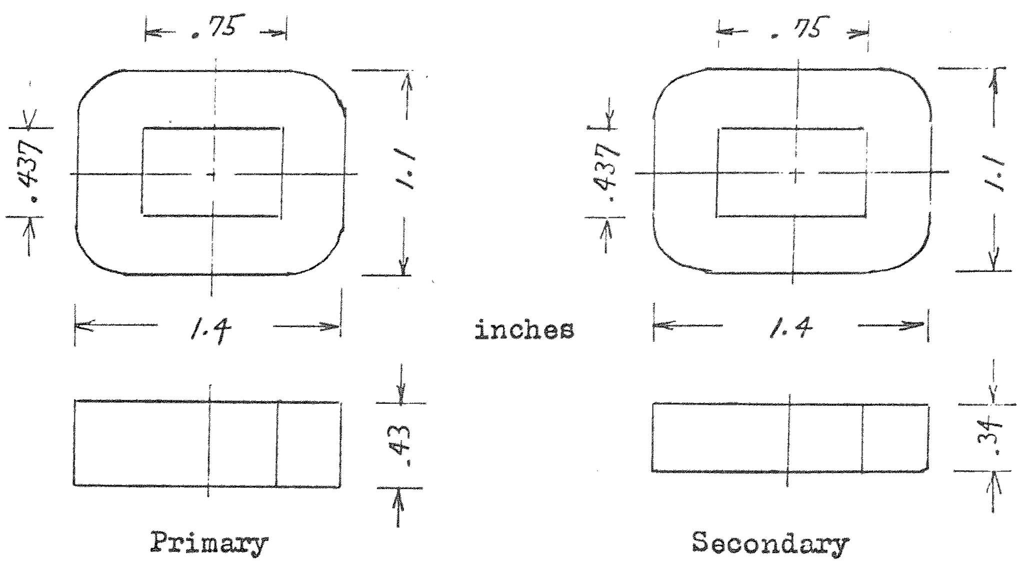


Fig. 8 Dimensions of windings of T1

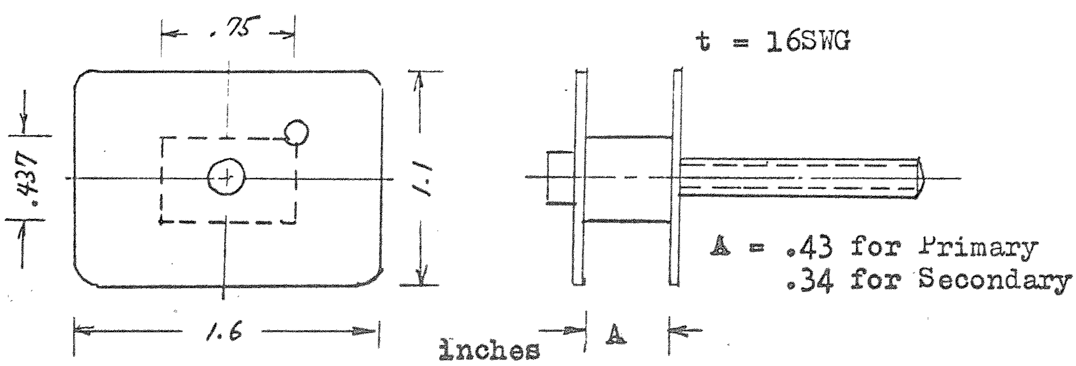


Fig. 9 Dimensions of winding formers of T1

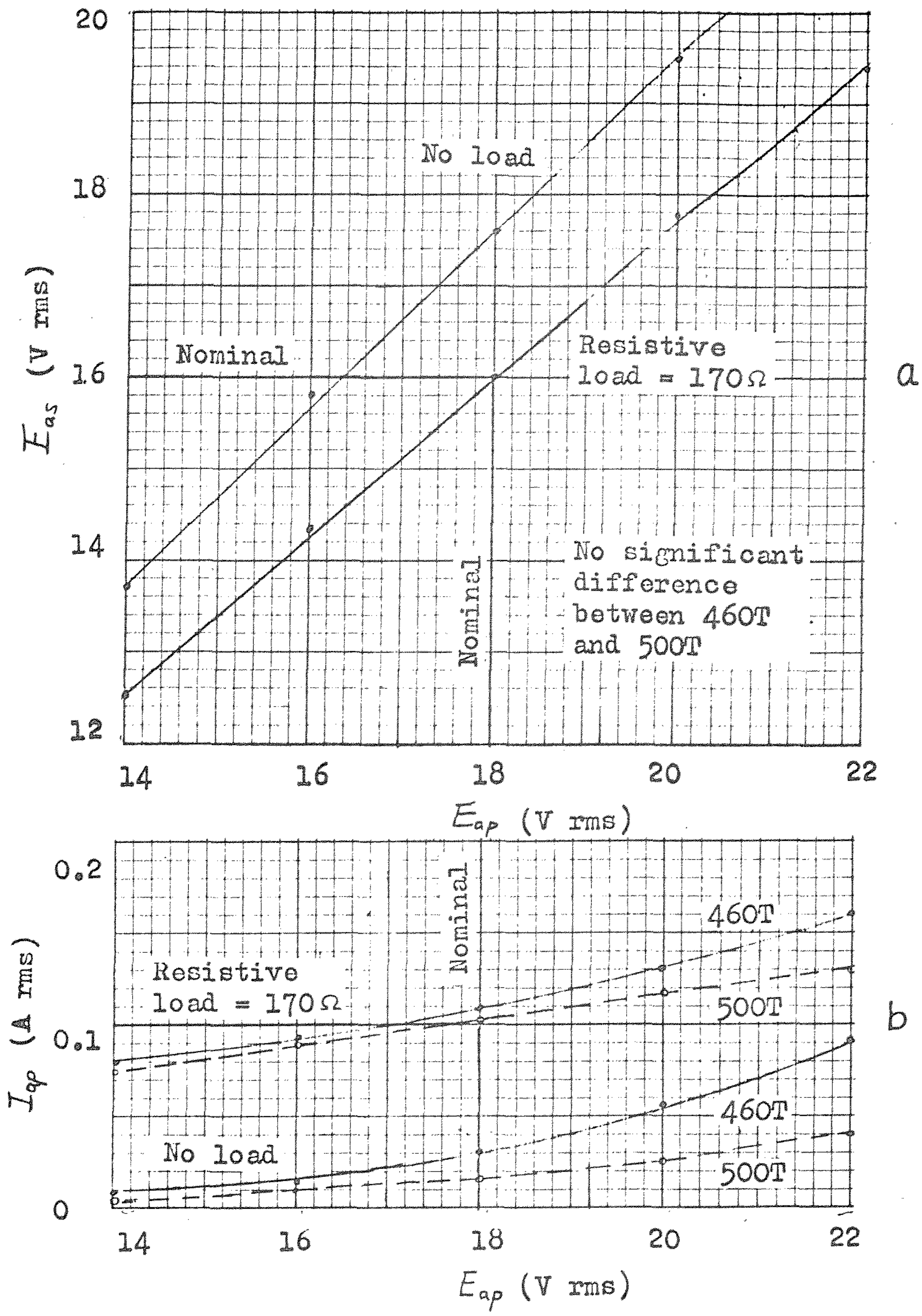


Fig. 10 Characteristics of Transformer T1.

Table 3. Characteristics of Transformer T1.

Primary	voltage current power	E_{ap} I_{ap} P_{ap}	18.0 V rms 0.11 A rms 1.98 W rms	Inductance Resistance	0.27 H 7 Ω
Secondary	voltage current power	E_{as} I_{as} P_{as}	16.0 V rms 0.10 A rms 1.60 W rms	Inductance Resistance	0.29 H 10 Ω
Efficiency		ϵ	81 %		

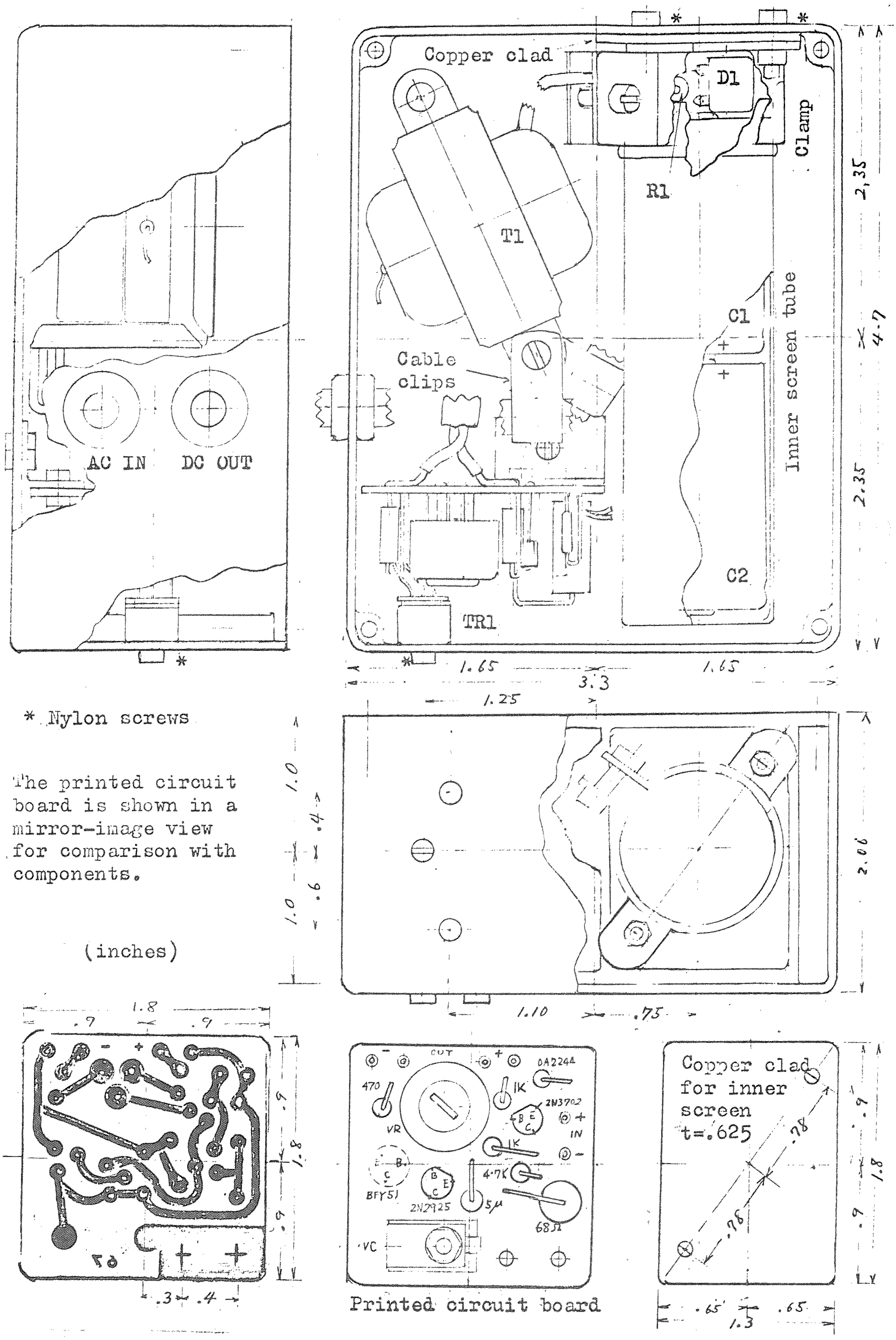


Fig. 11 Arrangement of components

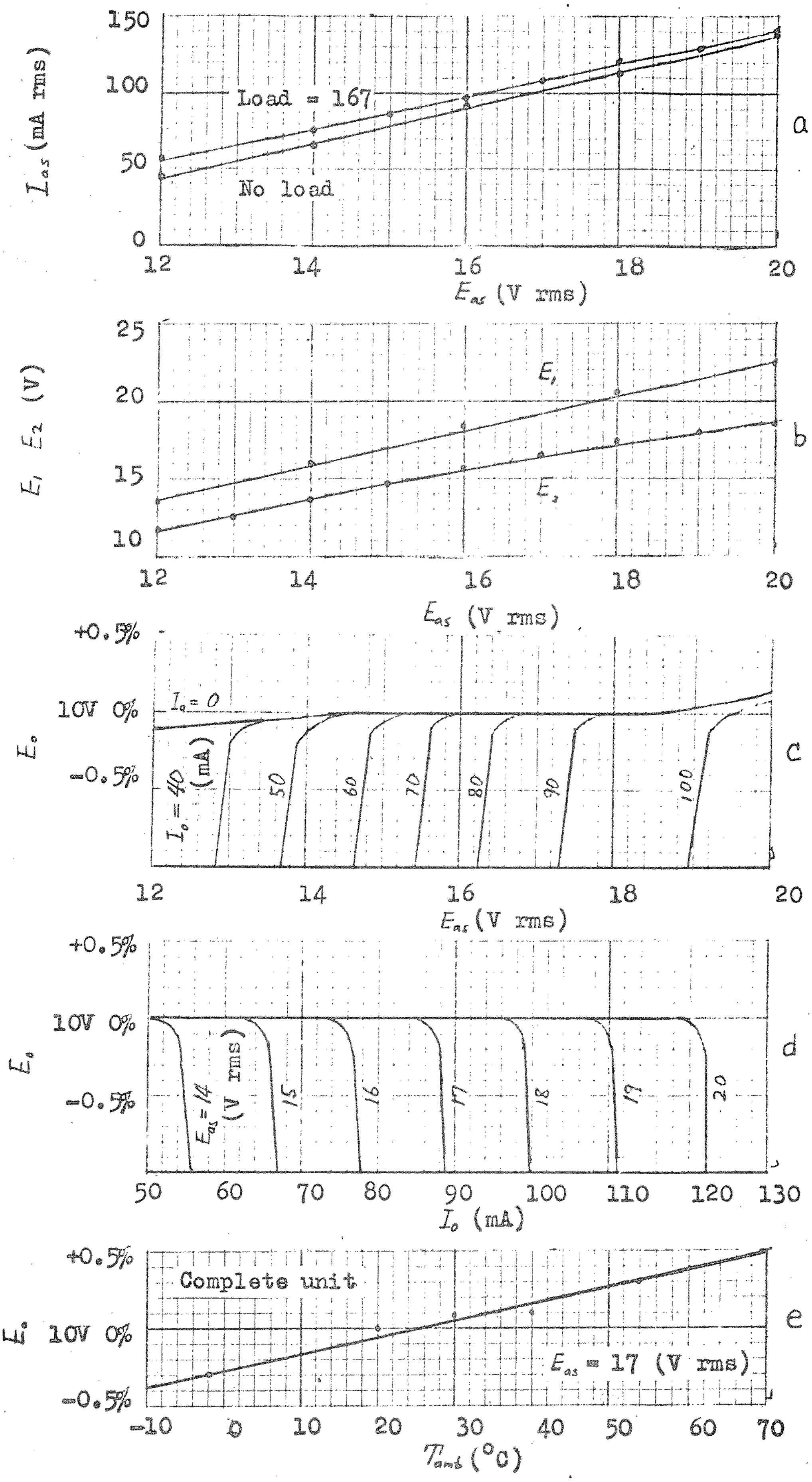
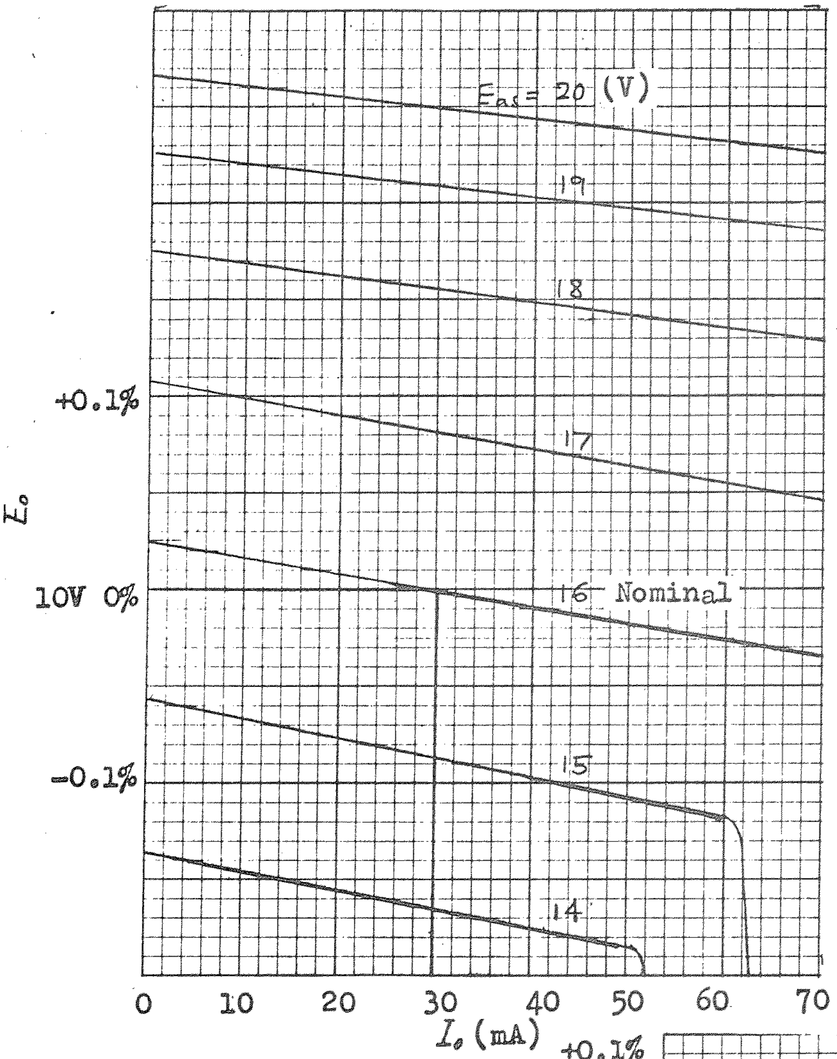
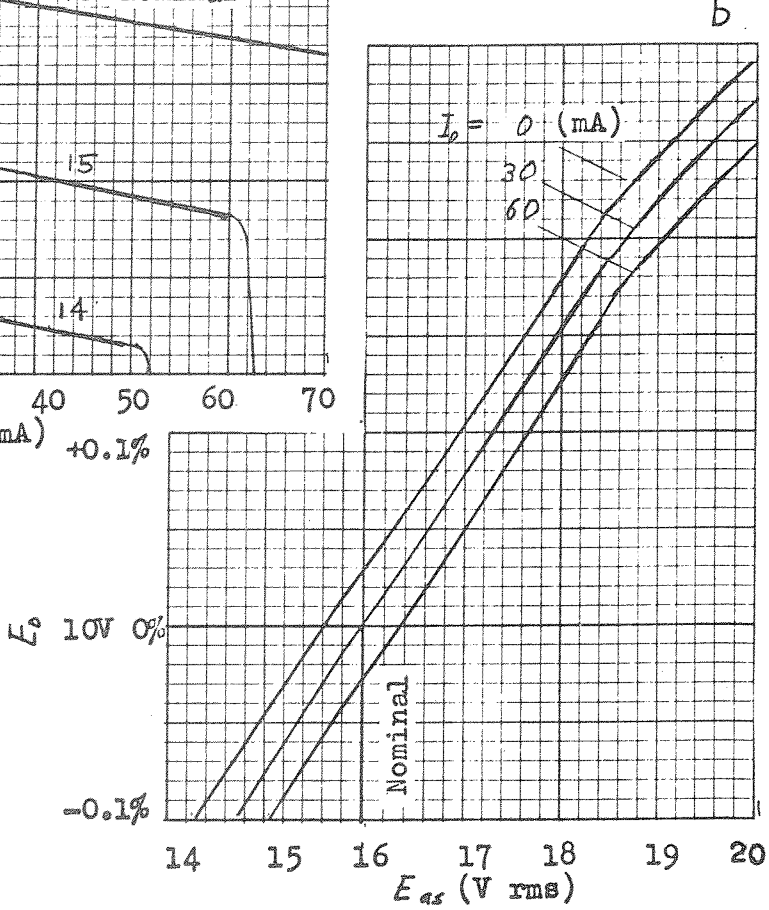


Fig. 12 Electrical characteristics of a unit



Average values are taken from several data.



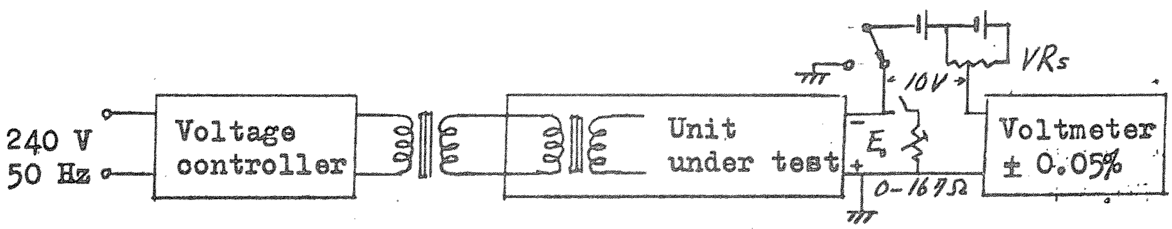


Fig. 13 Line and load stabilities of the output voltage, and a test method

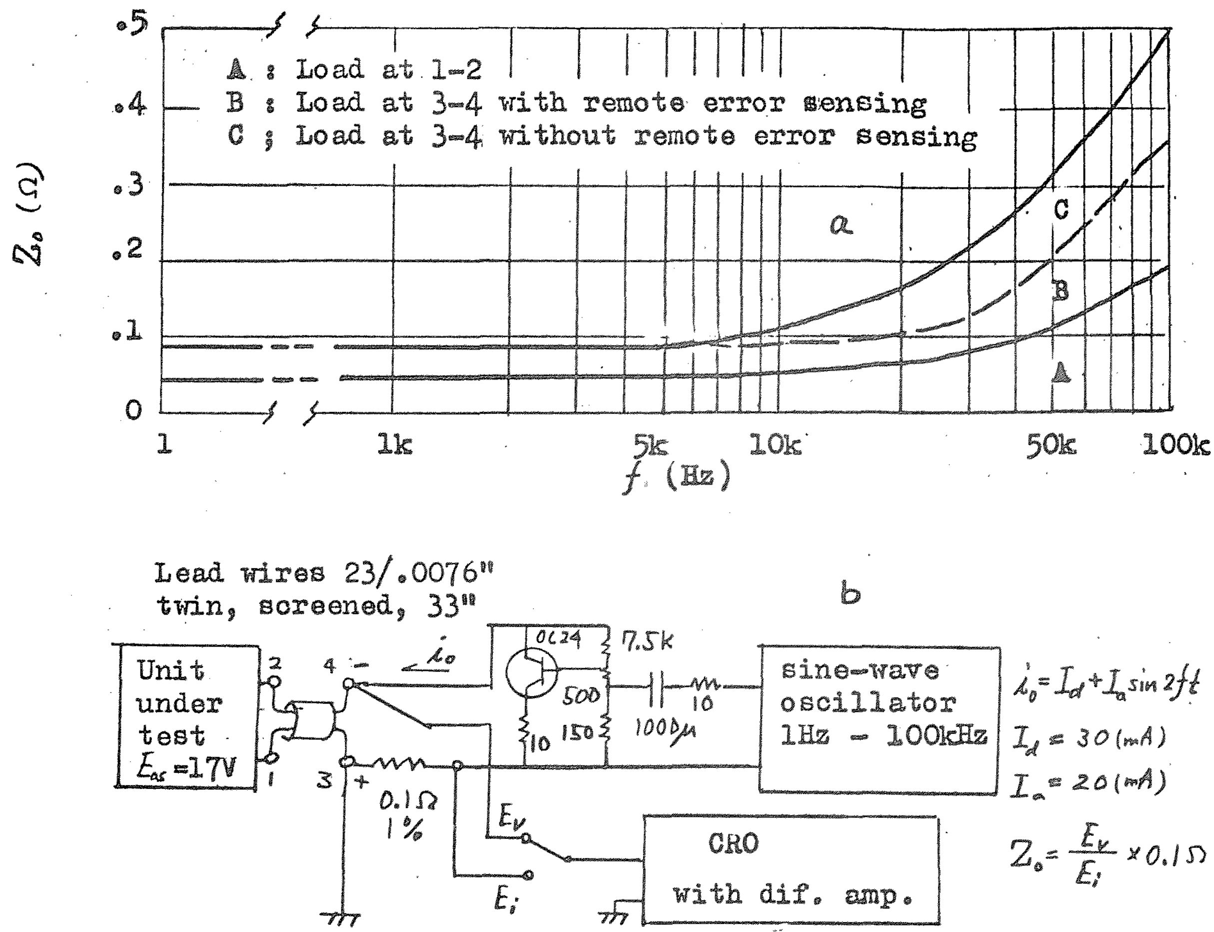


Fig. 14 Output impedance of a unit, and test method.

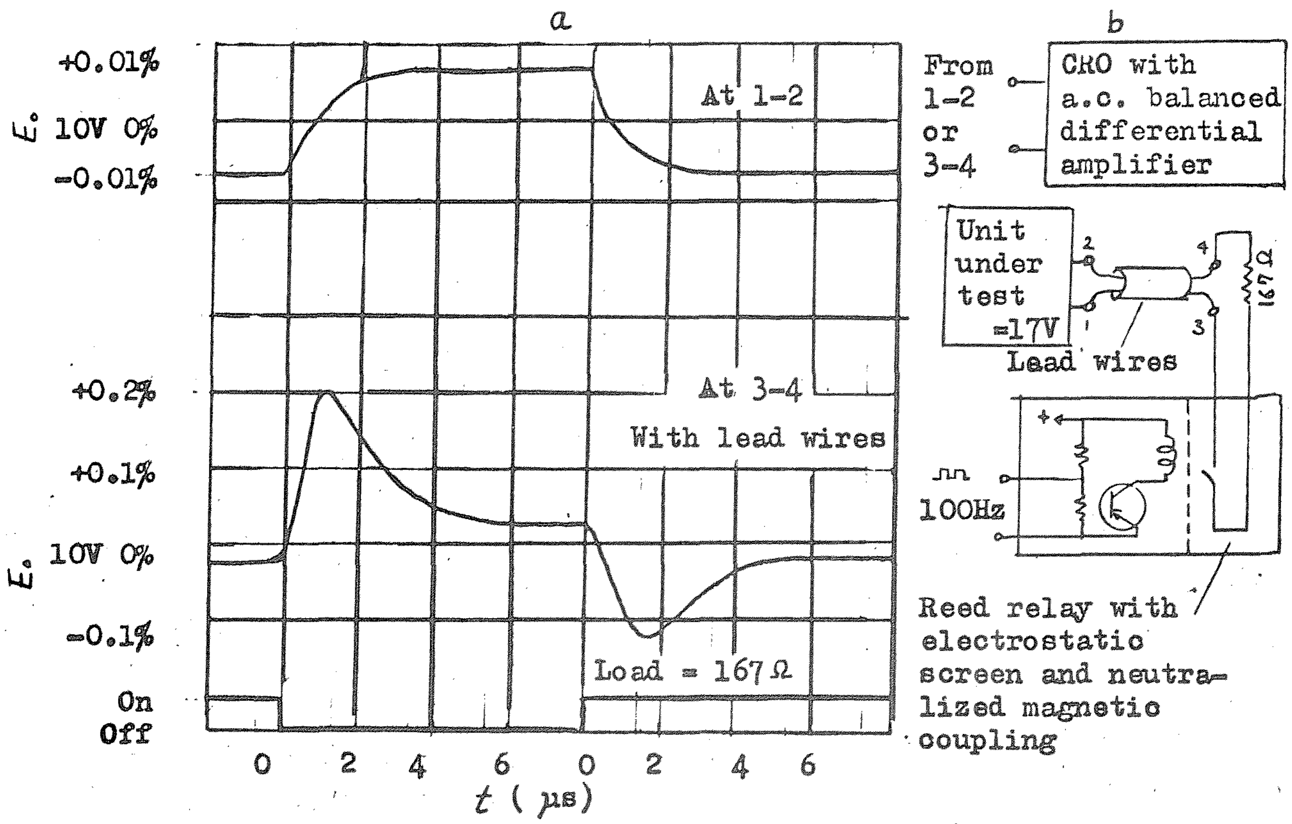


Fig. 15 Output voltage responses to load changes,
and a test method.

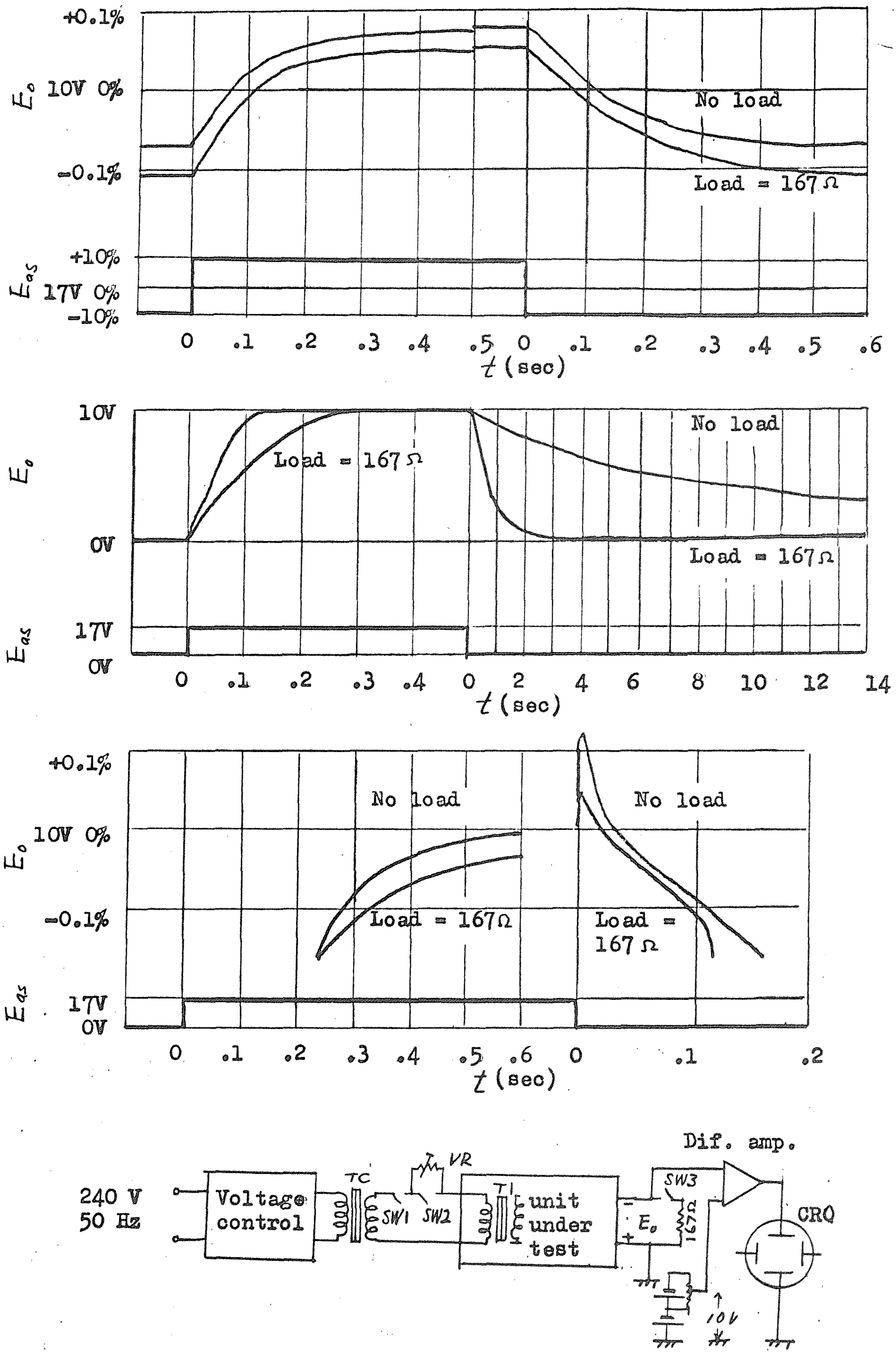


Fig. 16 Output voltage responses to line voltage changes, and a test method.

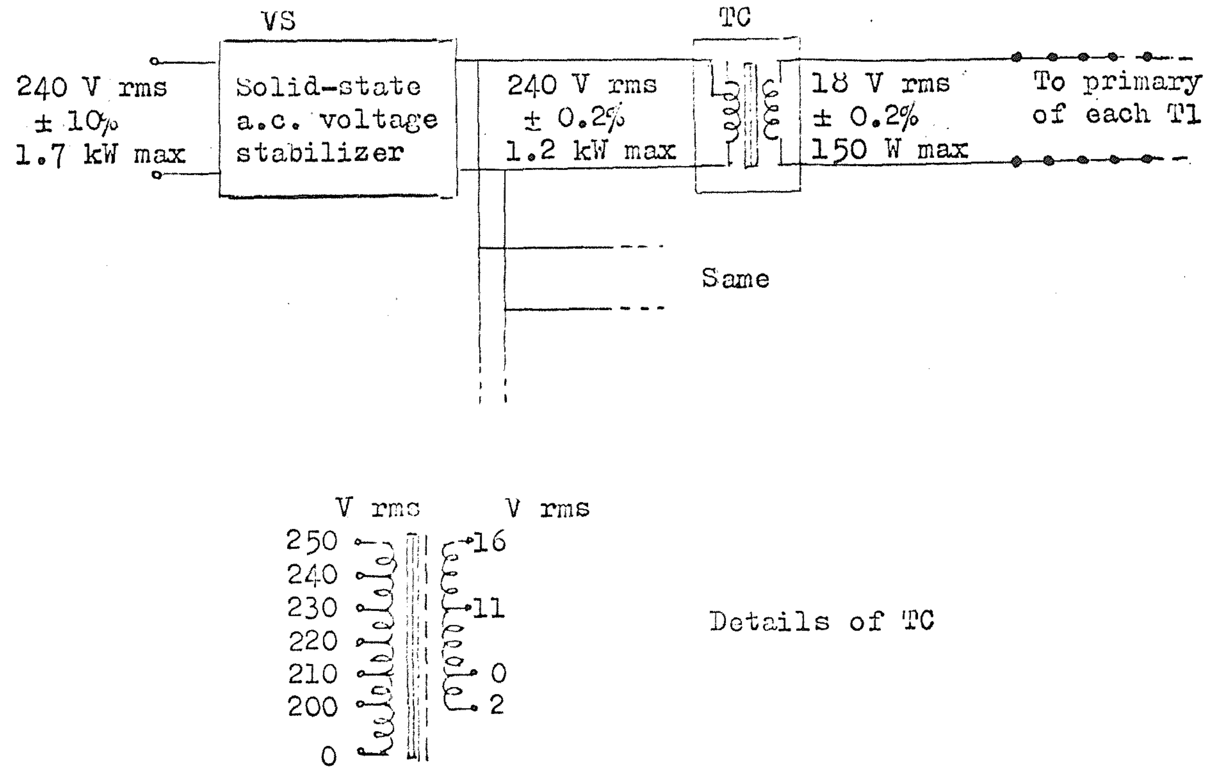


Fig. 17 Common parts for all the units.

Table 4. List of main components for common parts.

	Component	Type	Manufacturer	No.	Unit cost £ s d
VS	Solid-state a.c. voltage stabilizer, input 240 V rms ± 10% output 240 V rms ± 0·2%, 1·2 K W waveform distortion 2%	BTR-5F	Claude Lyons	1	87. 17. 0.
TC	Transformers, input 240 V rms, output 21·5 V rms, 150 W	SH4521 (modified)	Gardners	4*	4. 10. 9.

* As many as required, up to the maximum power rate.

Table 5. Summary of overall characteristics of the system

Input		
Frequency	50	Hz ± 1%
Line voltage	240	V rms ± 10%
Power, each unit	2·7	W approx.
each TC with 50 units	150	W approx.
max. 8 TC, total 400 units*	1·2	KW approx.
max. line power	1·7	KW approx.
Output		
Possible max. number	400	units
Voltage	10.00	V
Current per unit	0 to 60	mA
Cut-off current (s.c. protection)	78	mA approx.
Impedance**		
d.c.	0·042	Ω approx.
1 Hz to 10 kHz	0·05	Ω approx
40 kHz	0·10	Ω approx.
100 kHz	0·20	Ω approx.
Isolation from earth		
Resistance at 100 V d.c.	> 500	MΩ
Capacitance (adjustable)	500	pF ± 1%
minimum	300	pF approx.
Noise voltage (ripple etc.)		
Between output terminals	< 200	μV p-p approx.
Between output terminals and earth	< 200	μV p-p approx.
Stability of output voltage, against		
Line frequency	> ± 0·01 %	
Line voltage	> ± 0·01 %	
Load current	> ± 0·03 %	
Ambient temperature	± 0·01 %	per °C approx.
Recovery time, against		
Step load-current change, 0 to 60 mA		No overshoot
Step line-voltage change, -10% to +10% of nominal value		No undershoot
Warm-up time to reach to -0·01% of nominal output voltage, with full load	1	sec approx. no overshoot
Temperature of:		
Operation	0 to +40	°C
Storage	-20 to +70	°C
Remote error-voltage-sensing terminals		Prepared
Size		
One unit	4·5 x 3·7 x 2·3	inch³
One common transformer for 50 units	4·9 x 3·8 x 4·6	inch³
a.c. stabilizer	15·9 x 9·4 x 9·0	inch³
Weight		
One unit	1·6	lb
One common transformer for 50 units		lb
a.c. stabilizer	70	lb

* Normally 200 units; the rest of the power will be used for other apparatus, since this voltage is stabilized within 0·2%

** Output lead wires are not connected to the output terminals.

Appendix A modified use of the power supply for 4·5 V output

This power supply has been designed to give an output of 10·00 V, but it is possible to modify the output to 4·5 V for the existing computer with a minor alteration of components, although this makes the performance poorer than the original. The alteration is as follows:

(1) Replace the zener diode OAZ244 (6·8 V) with ZF3·3 (3·3 V) made by S.T.C. Limited.

(2) Change the secondary voltage of TC to 12 V rms.

Some characteristics will be changed as follows:

Nominal output voltage	4·5 V
Setting accuracy	± 0·05%
Stability, against	
Frequency change ± 1%	< ± 0·1%
Line voltage change ± 10%	< ± 0·1%
Load current change 0 to 60 mA	< ± 0·1%
Temperature change of 7°C from set temperature	< ± 1%
Output impedance, d.c. to 10 KHz	< 0·2 ohm
Noise voltage, between	
Output terminals	< 0·4 mV p-p
Output terminals and earth	< 0·4 mV p-p

The largest single factor in the stability is now temperature change, i.e. −0·15% per °C; this is due to the negative temperature coefficient of the zener diode used. If another type of zener diode which has a positive temperature coefficient is used, a part of the circuit must be modified since such a diode has a higher zener voltage than the output voltage.