Stereo power and phase meter

Power output measurements from 1 mW to 400W in a variable load

by C. T. Hodgson

A twin meter instrument for simultaneous output power and phase measurements on the two channels of an audio frequency stereo system. Power measurements in the range 1 mW to 400 watts per channel can be made by feeding switched internal resistances. The instrument is easily calibrated using either a.c. or d.c. For sinusoidal inputs the meter readings are accurately related to mean power.

OUTPUT POWER is generally one of the first specifications of an audio system to be looked for by the average hi-fi enthusiast. Power levels of 100 watts per channel, and more, are commonplace in present-day hi-fi systems. But there are many variations in power rating quoted in descriptions of audio amplifiers; for example, average power, peak power, music power, continuous power, mean power, and another power rating that is being increasingly used nowadays called r.m.s. power. This is absolute nonsense, of course, like talking about a miniature watt, and a number of authorities, for example Baxandall[1], have aired their strong objections to its continued use. It is important, therefore, to state clearly exactly which units of power this instrument actually measures. A moving coil loudspeaker is far from being purely resistive over the whole audio frequency spectrum, if indeed at any frequency but, unless otherwise stated, it is ordinarily understood that the loading of an amplifier under laboratory tests is predominantly resistive.

In a circuit consisting only of a simple resistance the power in watts is given by the expression I^2R where I is the d.c. or r.m.s. value of the current; this is the mean power. This instrument uses an almost pure resistance to load the amplifier under test and the power it indicates is relative to mean power. Some authorities contend that, where peaky signals are involved, such as noise (and music, in general, can be considered as noise by this definition), there is some justification for an alternative standard unit of power. Whilst this may be true in certain very special circumstances, in the author's opinion the specification of mean power in the established way is more valuable and more easily measured for direct

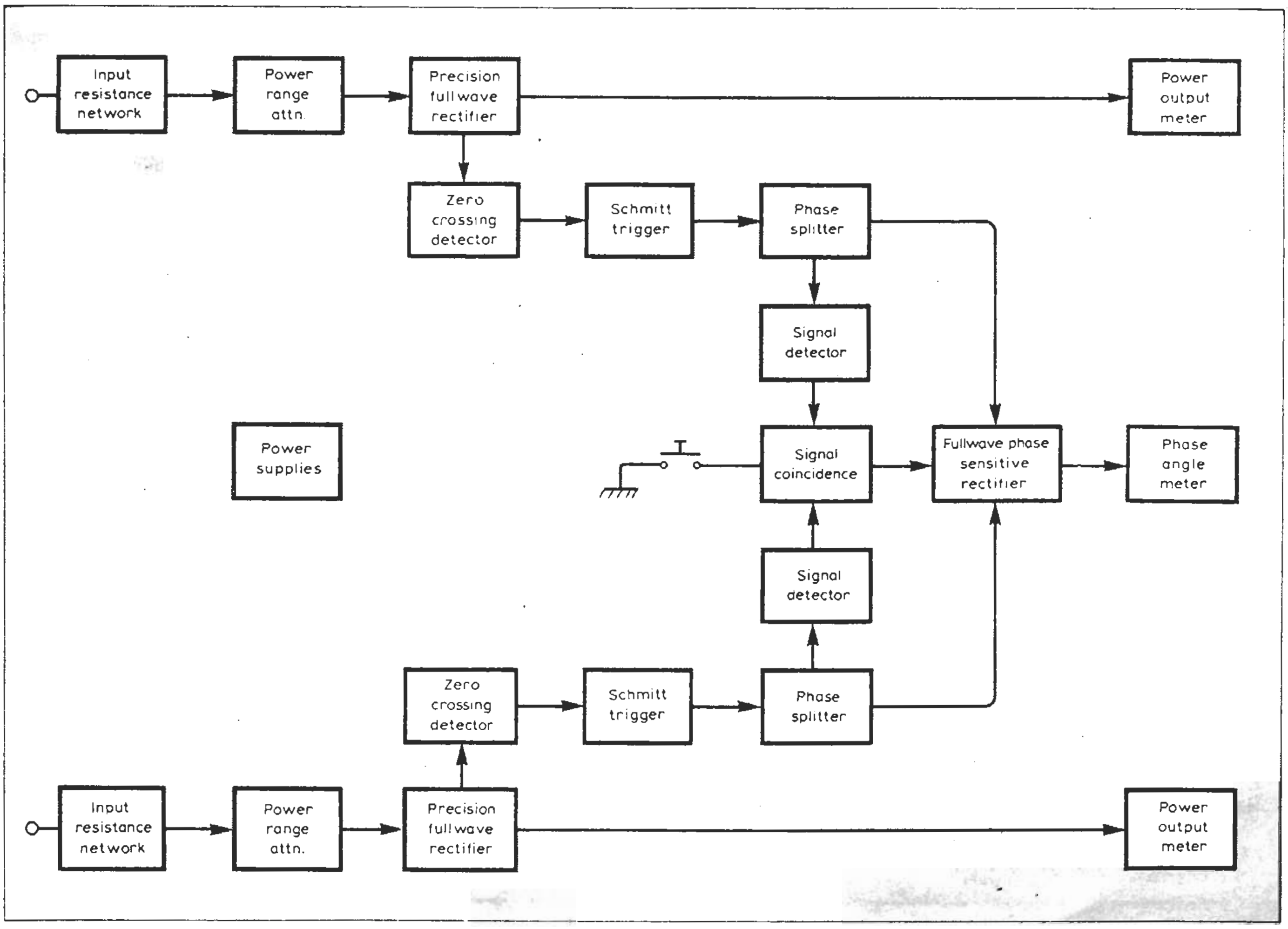


Fig. 1. *Block diagram of complete instrument.*

comparison of systems. Measurement of absolute power by the classical method of determining its thermal or chemical effect is inconvenient in audio engineering practice to say the least.

In this instrument the value of the load resistance is first selected by a switch from a range of built-in commonly used values. The same switch unit selects a tap on the resistor such that the voltage output at the tapping point is the same for the five values of load resistance. This voltage is applied to a precision rectifier circuit through an attenuator calibrated in mean power: 1mW to 100 watts in six decade steps. The rectifier therefore works only over a restricted range of voltages. After rectification the unidirectional half sine-waves are applied directly to a moving coil volt-meter which reads the average value, $2/\pi$ times the maximum value. The meter is actually calibrated in dB, where 0dB is at the centre of the scale and corresponds to the selected value of power on the power range selector switch. A standard VU meter could also be used since these are calibrated in a similar way; the only difference is the percentage f.s.d. for a given power level. This is far from being an absolute method of power measurement, but the accuracy on pure sine-waves or square-waves (and d.c. of course) is excellent and the presentation of power is direct and extremely convenient. It is subject to some degree of error in the presence of waveform distortion and figures are given in the text for values of 2nd and 3rd harmonic distortion up to 50%. Errors for more realistic values of distortion are too small to read on the meters.

The 3dB bandwidth of the amplifier extends to over 200 kHz and is flat from zero to around 30kHz. The twin-channel capability, like that of a double-beam oscilloscope, enables direct comparison of stereo amplifier channel characteristics such as frequency response and output power, etc., to be observed over the whole range of audio frequencies. The inclusion of a precision phase meter is primarily for circuit research and development work. The phase relationship between the two channels from 5Hz to 50kHz is continuously presented in direct form, and the combination of three panel meters is useful for setting-up stereo and quadrophonic systems and for the purpose of demonstration.

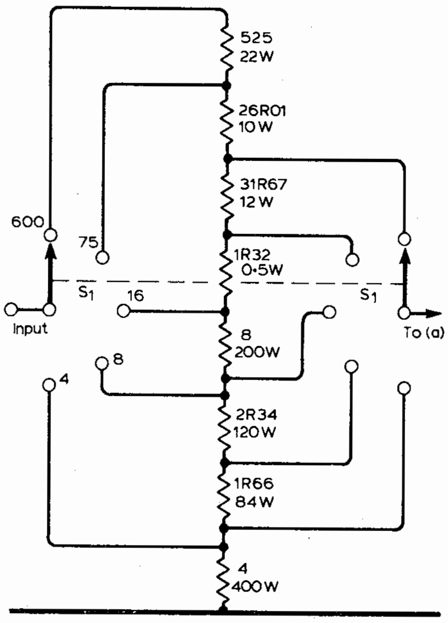


Fig. 2. *Input resistance switching arrangement in its basic form.*

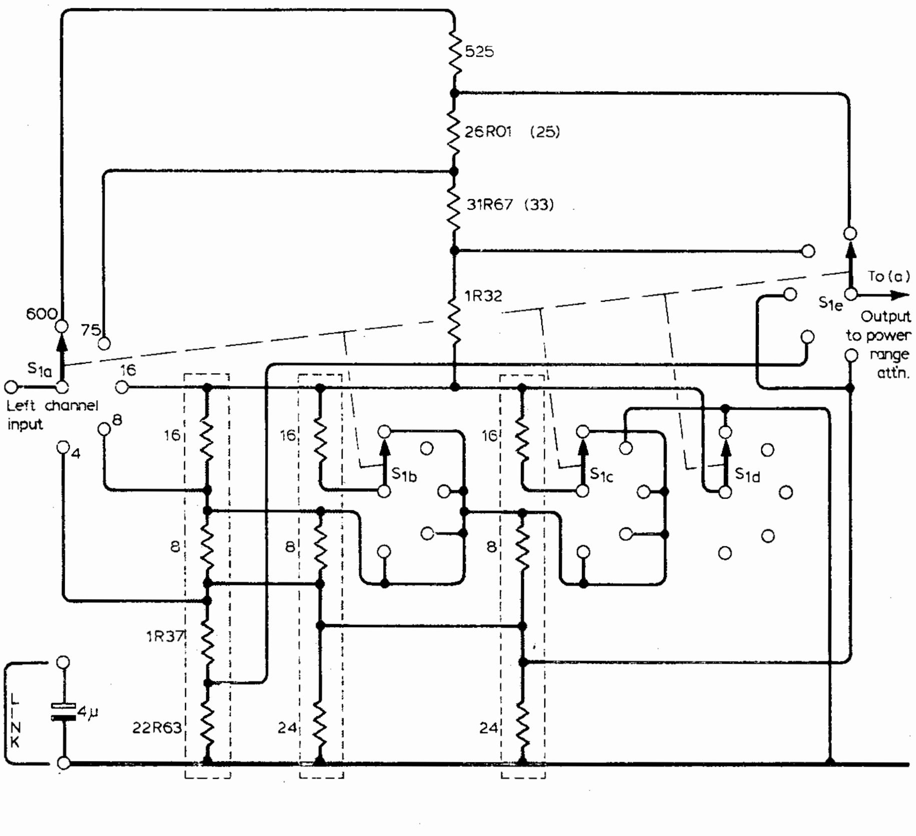


Fig. 3. *Practical arrangement for switching input resistance.*

Circuit design

Load selector. There are five fixed values of input resistance, 4, 8, 16, 75 and 600 ohms. The three lower values are those most commonly used in audio equipment for the British market as well as many other countries whilst the other two are well established values for attenuating networks and source impedances for test gear. The input impedance selector switch has three separate functions apart from the twin channel function; firstly it selects the desired value of load resistance, secondly it controls the distribution of power within the load and thirdly it taps the load network to provide the same output voltage, for a given output power, for any of the five load resistances.

The basic resistance network is shown in Fig. 2. The high-power loads for the three lower resistance values are constructed from commercially available electric fire elements. This is a very cheap and practical method of constructing high-wattage resistors, since any non-standard value can be wound and power can be spread evenly over a large area. The length/diameter ratio of the resistance coils is such that the inductance is small. The switching arrangement of the sections and the close screening provided by the heat sink and mounting rods all help to minimise the inductive reactance. There are three 1kW bars for each channel, making six in all. The heat sink is a prefabricated structure of aluminium alloy.

1kW bar elements, for a 240V supply, have a nominal resistance of 55 ohms. They are rewound, with the original wire, to a value of 48 ohms, in three sections of 8, 16 and 24 ohms. One element in each triple has an additional tap on the 24 ohm section, but all bars could incorporate this tap, if desired for the purpose of standardization. It is unimportant which bar is additionally tapped: indeed all three taps could be connected together in the interests of symmetry. The input impedance selector switch connects the sections in various series-parallel arrangements. For example, each 4 ohm load consists of six parallel paths of 24 ohms, as in Fig. 3, so that the heat generated is evenly spread within the heat sink. Each bar is supported on a 0.25in diameter aluminium alloy rod which effectively conducts heat to the cabinet metalwork. The effectiveness of this arrangement is such that the temperature rise inside the cabinet is approximately 0.12°C/watt; this could be further improved by anodising the sink black, but this has not been done on the prototype. On the two higher resistance ranges (75 and 600 ohms) the power handling capacity is rather lower: using the components specified, 25 watts can be safely handled on both of these ranges.

Power range selector. There are six preselected values of output power, from 1mW to 100W in 10dB steps, for which the output meter reads 0dB. If the power meter has 0dB as its centre calibration, the full scale deflection on the highest range is +6dB, corresponding to 400 watts per channel. If standard VU meters are used then full scale deflection will be restricted to 200 watts per channel. Using external loads as power shunts in addition to the internal chain of switched resistors can extend the range of power measurements to any desired value.

The power range selector takes the form of a switched attenuator, connected across the output terminals of the input load resistance, see Fig. 4. The total resistance value of the attenuator is 68.89kΩ, so that errors in power measurement and input resistance caused through circuit loading by the attenuator are negligible. For simplicity, only single, standard 1% values of resistance in the E12 range are used in the attenuator, but the errors in attenuation are sufficiently small to make this a most practical arrangement. Output loading in this application is the impedance of the non-inverting input of an operational amplifier and it is sufficiently high to cause negligible error.

Precision rectifier. A number of circuit configurations have been published for minimising the effect of non-linearity of diode I_a/V_a characteristics by incorporating them in the feedback path of a high-gain amplifier. One basic arrangement is simply to connect a diode bridge rectifier in the feedback loop of an operational amplifier and feed a moving-coil meter directly from the common-polarity terminals. Such an arrangement works extremely well in practice, its main drawback being that neither of the meter terminals can be grounded. Alternative arrangements, using an additional operational amplifier to deal with the positive and negative halves of the input waveform separately, do not have this defect. There is little difference in the performance of any one of them but the arrangement described by Mann[2] is used in this instrument because it is probably the simplest to construct and very easily balanced, an important feature in the present application. The output impedance is low, it has one output terminal grounded and therefore it can be used to drive external recording instruments if desired.

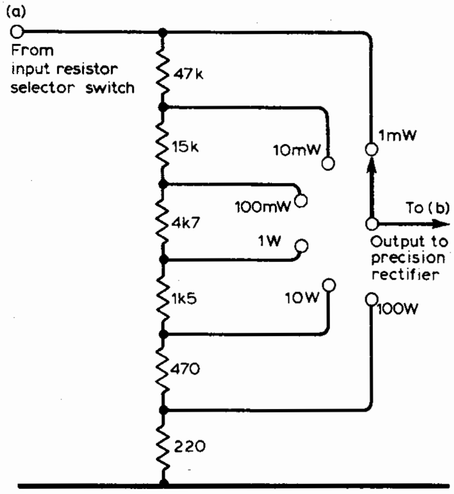


Fig. 4. *Range switch, preferably using 1% resistors.*

The circuit diagram of the complete rectifier is shown in Fig. 5. For sine-wave input, the output waveform consists of almost perfect, unidirectional, half sine-waves. The average value of the output voltage is therefore 0.637 times the peak value. A moving-coil voltmeter responds linearly to the average voltage but the scale can be calibrated in any desired units, and in this application the units are dB referred to any one of the six standard power values selected by the power range selector. Thus, on the lowest range 0dB corresponds to 1mW in any of the selected values of load resistance, and on the highest power range it corresponds to 100 watts. The performance figures of an amplifier are so much more easily compared with the specification by this type of presentation. It is not intended as a substitute for an oscilloscope but rather to enable one to reserve the oscilloscope for examination of waveforms in other parts of the circuit whilst continuously monitoring the output power.

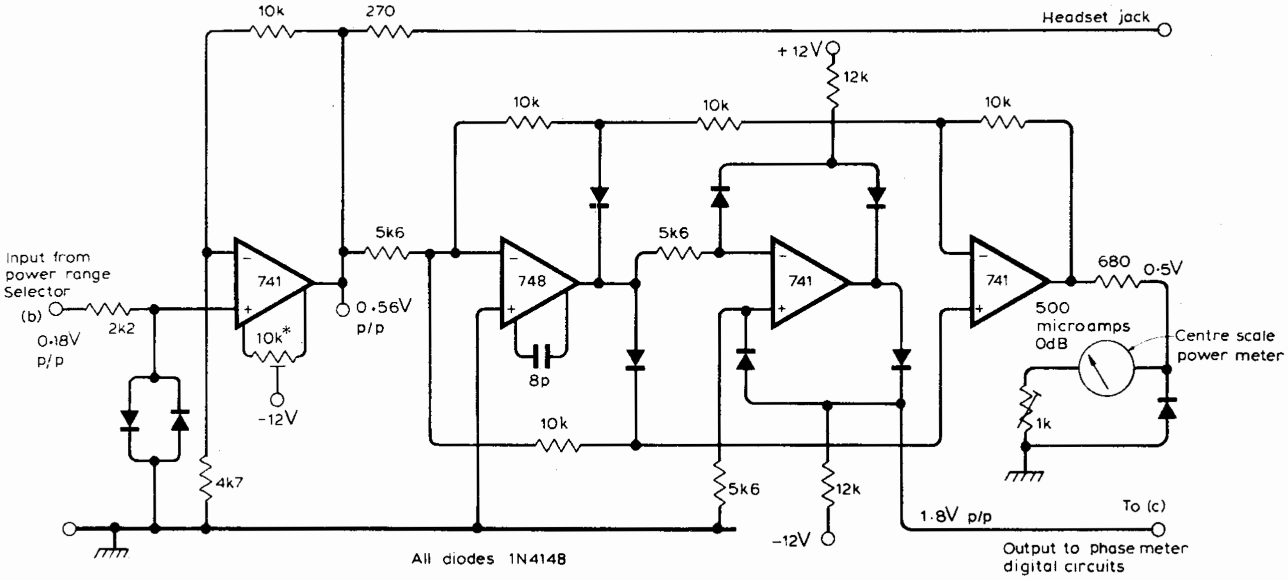


Fig.5. *Precision full-wave rectifier circuit (748) and zero-crossing detector. The nulling pot. on the first 741 sets the correct balance in the rectifier for meter zero (power).*

Phase-angle meter. Like the full wave rectifier the phase meter, seen in Fig. 6, is also a precision circuit. The principle of operation is well known but the circuit arrangement used in this instrument embodies a number of novel features. The two input signals are first converted into square waves, paying particular attention to the preservation of the 1:1 mark-space ratio over the range of input levels. If the square-waves are simply added by a NAND gate, the output consists of a varying duty-cycle pulse of constant amplitude. The average d.c. output is directly proportional to the duty-cycle ratio, and hence phase angle, but in this simple arrangement the duty-cycle is only 25% for a 90° phase angle. Considerable smoothing is needed to obtain a steady meter indication at low audio frequencies.

The circuit used in this instrument operates in push-pull and full-wave addition is employed. In this way the output for signals in-phase or out-of-phase is d.c. and can be used down to fractional cycle signals. At 90° phase difference the output is a square wave

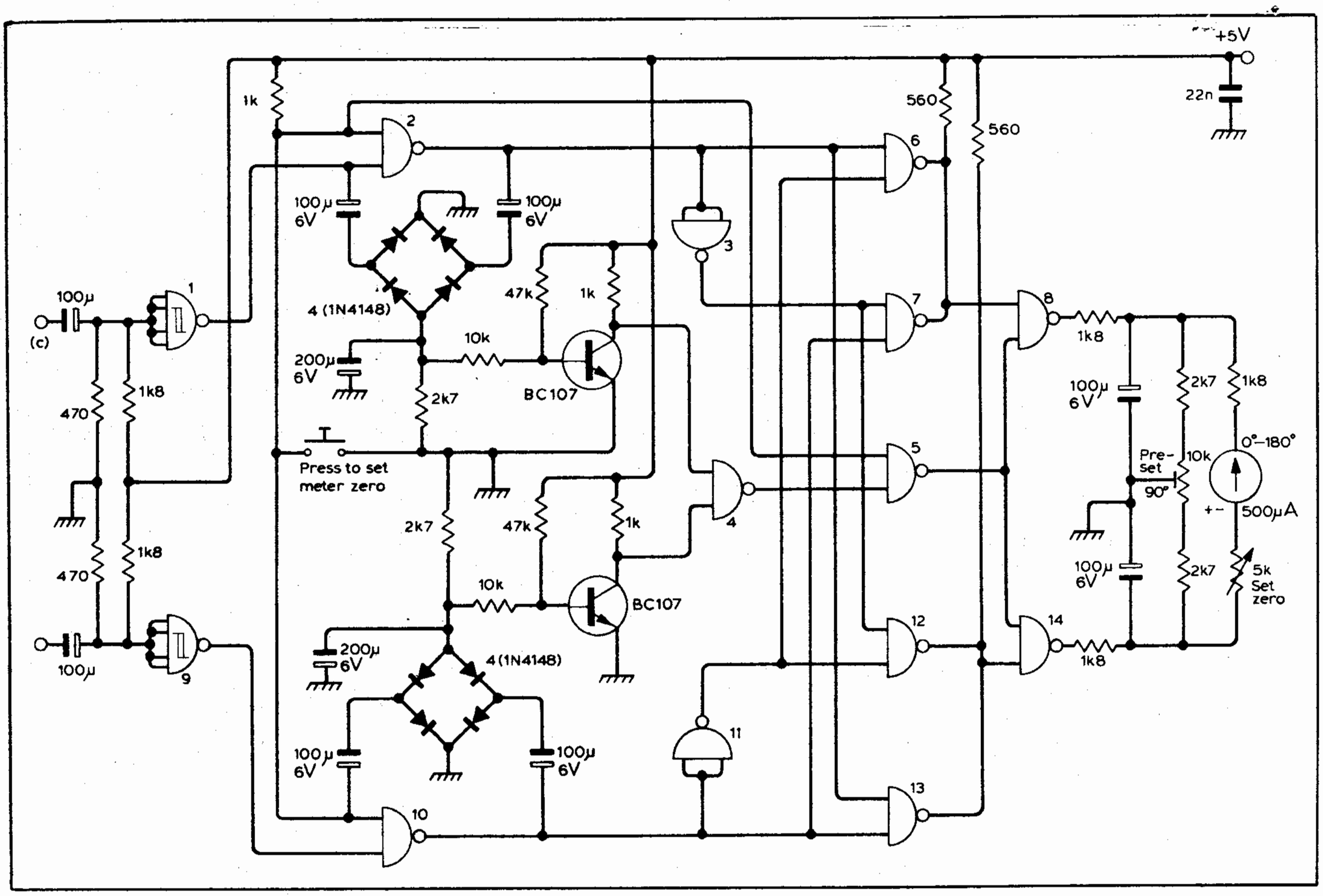


Fig. 6. *Phase meter, fed by zero-crossing detector in Fig. 5.*

at twice the frequency of the input waveform. This is the worst condition and, with a modest degree of smoothing, the system is very effective at frequencies well below 10Hz. The precision depends entirely on the effectiveness of the squaring circuits. Signals from the power range selector switch are in the range 0.057 to 0.36 volts peak/peak (corresponding to 0.18 volts −10dB and +6dB respectively) and perfect squaring has to be achieved only over this restricted range. There are three stages in this operation; firstly the open loop gain of the 748 precision full wave rectifier is used as the first stage of a zero crossing detector. This is followed by a second zero crossing detector designed to drive an integrated-circuit Schmitt trigger, IC_1 in Fig. 6. A NAND gate, IC_2, provides phase-inverted square waves to that, after full-wave rectification, d.c. is obtained. The d.c. output from each signal detector is fed to a NAND gate, IC_4, which switches on the phase sensitive rectifier only when two signals are present.

A second NAND gate in each channel, IC_3 and IC_{11}, provides the bi-phase drive to the phase-conscious rectifier, which uses four open-collector NAND gates connected in push-pull pairs; one pair for each channel sharing a common load resistance. The electronic switching of the meter circuit enables a test condition for 0° to be generated, so that the meter series resistance (5k Ω) can be adjusted to make the directly calibrated meter read accordingly. A simple method of checking that the phase meter is operating correctly is to inject a signal into one channel using the 600 ohm range and to feed the other channel through a capacitor of known value. The input frequency for any phase angle can then be calculated—tan $\theta = X_c/R$ and for a 45° check, $\omega RC = 1$. Using a $0.1\mu F$ capacitor, 45° corresponds to a frequency of 2653Hz. The same test condition can be used to verify the independence of the indicated phase angle on the input power over the range f.s.d. to −30dB on the output power meters.

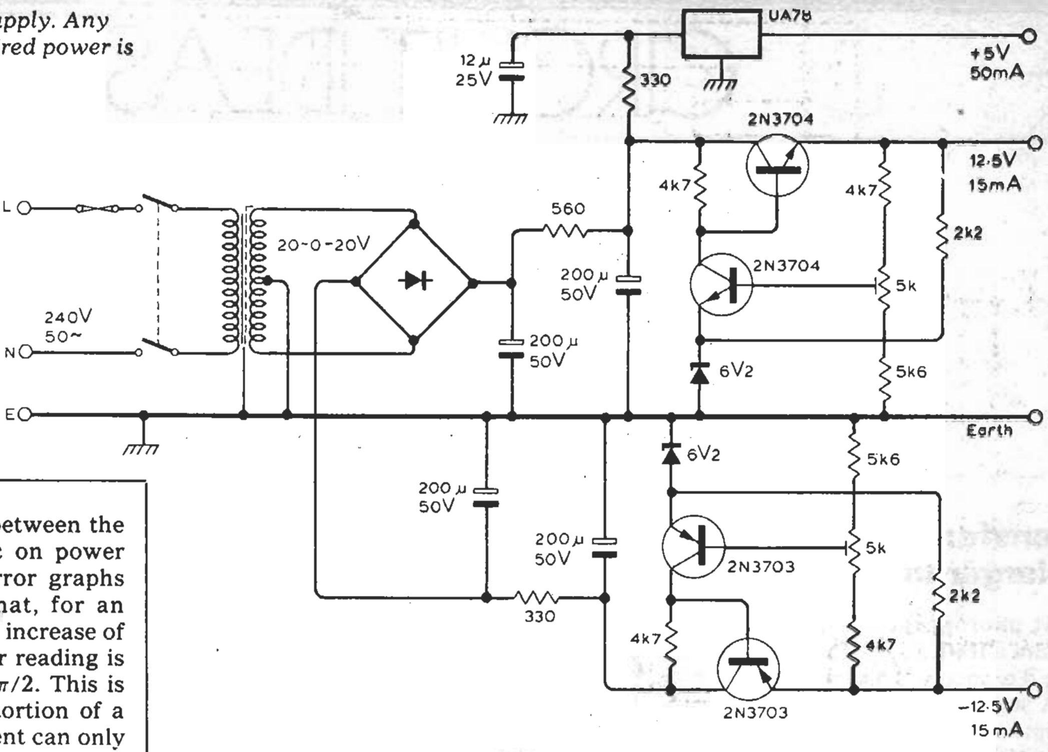
Following education at Hull Technical College and after a brief period as a sea-going wireless operator the author entered the Civil Service, joining Sir Robert Watson-Watt's team at Bawdsey (Radar) research station one year before World War two. Until early 1942 he worked on antennas, receiver installation and calibration of the original chain of radar (CH) stations in the UK. He moved with Telecommunications Research Establishment (TRE, now RSRE) to Malvern in early 1942, where he worked, almost exclusively, on the development of low-noise i.f. amplifiers for radar receivers. After the launch of the first American space satellite, he joined the newly-formed Satellite Tracking Group at Malvern under the direction of Dr. W. A. Scott-Murray, and headed the receiver design team. During the five years prior to retirement he was a Principal Scientific Officer in the Guided Weapons Group at RSRE.

The author now has his own laboratory where he is able actively to continue experimental work in various fields of electronics.

The phase indicating meter is a centre-zero (pointing) movement, actually marked 90° on the scale. A preset potentiometer (10kΩ) connected across the meter circuit enables the circuit d.c. conditions to be balanced at this point. This is an unusual arrangement and may need some clarification. On connexion to a stereo system one wants to know the phasing of the output signals, that is, whether they are in-phase or out-of-phase, and so the meter indication should be unambiguous. A centre zero (reading) meter with full-scale indications of ±90° would be meaningless in this application. For instant verification that a stereo pick-up, microphones or tape recorder heads are correctly phased, two lamp indicators could be used instead of an expensive meter. This is a simple modification since the output at 0° and 180° is d.c. of opposite polarity.

Phase and distortion. It is interesting, especially in view of the volume of correspondence on the effects of phase distortion published in the *Wireless World* recently, to observe (and listen to) sine waveforms with known amounts of harmonic distortion. The illustrations given in Figs. 8 and 9 of 2nd and 3rd harmonic distortion respectively show the horrifying appearance of extreme examples, but the main purpose of these is to illustrate the effect of

Fig. 7. *Suggested power supply. Any similar source of the required power is suitable.*



varying the relative phase between the fundamental and harmonic on power meters of this sort. The error graphs given in Fig. 8(d) show that, for an harmonic content of 50%, an increase of about 0.9 dB in power meter reading is given for a phase angle of $\pi/2$. This is interesting insofar that distortion of a sinewave of voltage or current can only be caused by the addition of "foreign matter" and therefore noise, harmonics or whatever must necessarily add power. At 50% waveform distortion $V_{\text{fundamental}} / V_{\text{harmonic}} = 2$, corresponding to an increase of 25% in power, i.e. + 0.9691 dB. It is perhaps only a matter of academic interest that, because of this, those points on the graph of Fig. 8(d) corresponding to 0 or π which show almost zero error are, in reality, points of maximum error in actual power and that the 0.9dB error shown at $\pi/2$ is, in fact, very nearly the true value. A similar argument for 3rd or any other harmonic also applies but it must be stressed that the power meter errors given in Figs. 8(d) and 9(d) are the practical result of adding measured percentages of harmonic under controlled phase. In a practical situation one seldom knows what constitutes waveform distortion (let alone phase) hence the specification for amplifiers is usually quoted in terms of total harmonic distortion (t.h.d.) and is given as a percentage of the fundamental at certain spot frequencies. For as much as 10% t.h.d. the maximum error given by meters of this sort is of the order of ± 0.2dB. Practically all of this error is caused by 3rd, and, to a lesser extent, other odd harmonics.

The author is indebted to Mr. E. F. Good for helpful discussions and for checking the manuscript and also to Texas Instruments for permission to reprint the circuit of the 'Full Wave Rectifier' (IC_2 and IC_4 in Fig. 5.

References

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2. Richard Mann. Applications of Operational Amplifiers. Semiconductor Circuit Design, Vol. 2, Texas Instruments Ltd.

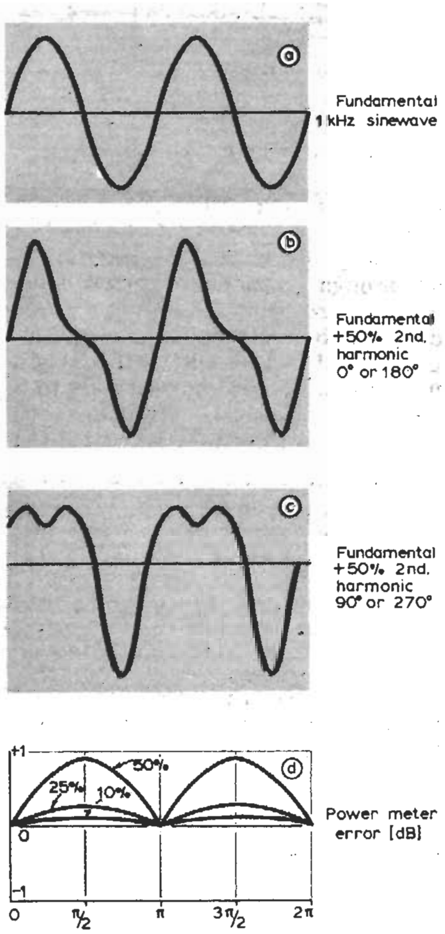

Fig. 8. *Variation of power meter error with change in 2nd harmonic phase relative to zero-crossing of fundamental. Parameters are 10%, 25% and 50% 2nd harmonic.*

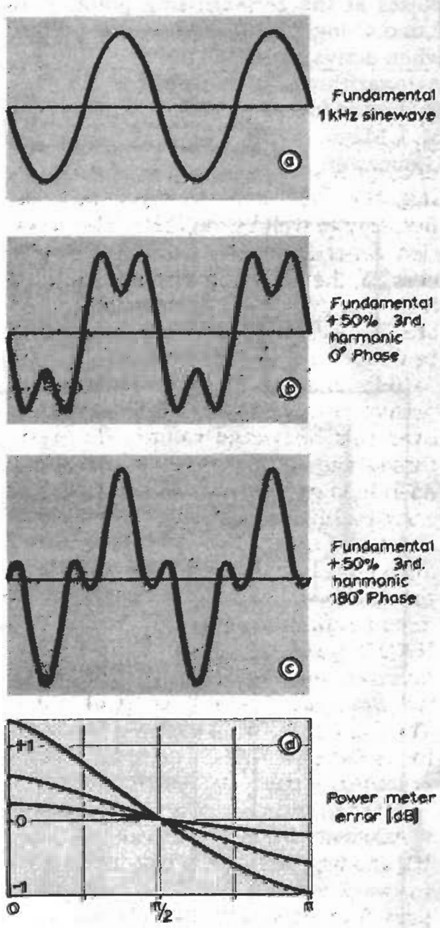

Fig. 9. *Third harmonic distortion and the error caused; the diagrams are similar to those of Fig. 8.*