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ELECTRONICALLY BALANCED ANALOGUE-LINE INTERFACES

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1. INTRODUCTION

Professional audio equipment generally uses balanced-line interconnection between individual units. The balanced lines are twisted-pair cables. By "balanced", we mean that the wanted signal is transmitted in such a way that the instantaneous signal voltage with respect to ground on one wire of the line is equal and opposite to the signal voltage on the other wire. The wanted signal is recovered by a receiving device which is responsive only to the differential voltage between the two wires of the line.

Discrimination against unwanted interfering signals induced onto the line by stray electrostatic, magnetic, or electromagnetic fields is on the basis that interfering voltages on each wire of the line will be equal, but not opposite: these are "common-mode" signals.

By reciprocity, the wanted signal does not radiate from a balanced line, and does not crosstalk into adjacent circuits. We have now stated the main purpose of balanced interconnections which is to minimise interference and crosstalk. Anything which disturbs the symmetry of the balanced system converts common-mode signals into differential signals and vice-versa; and so degrades the performance.

In order to allow maximum flexibility and to permit several pieces of equipment to be fed from a common source, it has become customary not to terminate the line ends in their characteristic impedance Z_o, (except for very long "external" lines). Optimally the sending end source impedance is about 45 Ω in this case, and the bridging impedance of receiving equipment is 50 - 100 kΩ.

In this situation the line appears as a capacitance when, as is usually the case, the length of line is short compared to a wavelength of the highest frequency, 20 kHz. It used to be the case that transformers were always used at the sending and receiving ends of the line.

Historically, they also performed an impedance matching function, when thermionic valves were used. These matching functions are not required with semiconductor electronics, and so in a sense the transformers represent additional components. The question is, do they enhance or degrade the overall system performance? Because of their bulk and cost, they have begun disappearing from line equipment, as they have already disappeared from the majority of audio power amplifiers.

Meanwhile, the standard of high quality sound is continually rising, as are the number of potential sources of interference. Interference sources now include many which are unrelated to mains frequency; and quite a few in the 15 - 200 kHz frequency range, such as switch-mode power supplies and video equipment. The AES/EBU digital audio interface is a video-like signal of about 6 MHz bandwidth, frequently fed along improperly terminated twisted pairs in close proximity to analogue cables. It is prudent therefore to pay attention to the performance of balanced circuits at radio frequencies.

In the next section, we shall review established practice in transformer-coupled line circuits, and then examine typical performance characteristics compared with electronically balanced interfaces.

2. REVIEW OF BASIC TRANSFORMER PRACTICE

Figure 1 shows a typical transformer-coupled line circuit. Line sending amplifier As feeds the primary of transformer T1. An electrostatic screen scr 1 is interposed between primary and secondary windings. This may consist of a single layer winding connected to ground at one end, with the other end left open circuit. The floating secondary winding is connected to the line, which exhibits capacitance to ground, shown as C1 and C2. At the receiving end, at the right of the diagram, there is a complementary arrangement, where T2 couples to the input of the receiving amplifier Ar.

Floating the line in this way saves the cost and technical difficulty of providing accurately-centre-tapped windings, not just in terms of equal turns each side of centre, but in respect of winding resistance and stray capacitance equality. In a line of moderate length, the equal line capacitances C1 and C2 are dominant in establishing the balanced condition. With very short lines, a metre or so long, the degree of line balance is strongly influenced by internal capacitances within the transformer.

By reason of the floating nature of the line, induced common-mode voltages can be very high. Postulating a line with 1 nF total capacitance to ground, and 10 pF capacitance to an adjacent 240 V mains cable; the common-mode voltage would then be 2.4 V rms.

The transformers T1 and T2 very often have mu-metal screens to mitigate the influence of ambient magnetic fields: even so variable orientation may be needed to achieve low hum levels. At a given signal level, the working flux density in the transformer core is inversely proportional to frequency, and so transformers show increasing harmonic distortion at low frequencies. A large shunt inductance is required to maintain response at low frequencies. Low leakage inductance is required to maintain response at high frequencies. Unfortunately these two requirements are mutually incompatible.

Floating circuits of this kind have versatility in that they can be operated unbalanced by grounding either side of the line. This facility is useful in test instruments, but usually it has no relevance in audio systems designed for balanced operation.

3. PERFORMANCE COMPARISONS BETWEEN TRANSFORMER-COUPLED AND ELECTRONICALLY BALANCED INTERFACE CIRCUITS

We shall compare the three principal aspects of performance: Frequency response, distortion, and common-mode rejection. In the succeeding figures 2 - 5, "X" denotes the transformer curve, relating to <u>one</u> transformer only. The transformer's inter-winding screen and mu-metal housing were grounded.

3.1. Frequency Response

Figure 2 represents the short-line case, where the load is 100 kΩ, (resistive only). We see that both sending circuits achieve a frequency response within 0.5 dB to 20 kHz, but may note that the transformer response is heading towards a leakage inductance resonance above the 50 kHz frequency span of the graph.

We may now look in Figure 3 at the frequency response at the far end of a 500 m line, terminated in 100 kΩ, and note significant differences. The transformer circuit shows a peak of +2 dB at 9.5 kHz and is -6 dB at 18 kHz whereas with the electronically balanced sending amplifier the response has gently rolled off to -1 dB at this frequency.

The response difference is audible. We may conclude that the electronically balanced sending amplifier is relatively immune to variations caused by the connection of indeterminate lengths of line, whereas the transformer-coupled amplifier is sensitive to line loading.

3.2. Distortion

Figure 4 compares THD performance versus frequency at the nominal peak programme level +8 $dB_{0.775}$, of electronically balanced sending and receiving amplifiers in cascade: with and without the connection of one transformer in the line. It can be seen that the transformer starts to introduce distortion below about 200 Hz. If two transformers are used, one at each end of the line, distortion is doubled. The rise in distortion between 1 and 10 kHz is caused by falling loop gain in the amplifiers, and the apparent fall beyond 10 kHz is due to the limited bandwidth of the measuring system. A target THD level of -80 dB (0.01%) is compatible with the performance of 14-bit digital systems such as NICAM (REF 1).

The frequency response and distortion specifications of send and receive circuits are tight - envisaging cascaded connection of several such circuits in operational practice.

3.3. Common-mode Rejection

Figure 5 compares the common-mode rejection of a transformer with a preferred electronically balanced line receiver (to be described in section 4.2. below). The measurements were made with a common-mode voltage of +20 $dB_{0.775}$ (22 V peak-to-peak). The transformer has very good common-mode rejection in excess of 100 dB at low frequencies: and needs to have this because of the very high common-mode impedance to ground and the associated likelihood of high common-mode voltages.

The electronically balanced circuit has 88 dB common-mode rejection at low frequencies and this degrades to 50 dB at 20 kHz. There is a crossover frequency at about 100 kHz, above which the transformer gives less common-mode rejection than the electronically balanced circuit. At HF and VHF frequencies the common-mode transmission through the transformer is via a complex network of distributed inter-winding capacitances interacting with the inductance of the screen and its lead-out wires. The common-mode input filter largely determines the performance of the electronically balanced circuit at these frequencies.

4. EXAMPLES OF ELECTRONICALLY BALANCED CIRCUITS

A criterion is that these shall be compatible with transformer-coupled circuits.

4.1. Line Sending Circuits

Figure 6a shows a quite widely-used circuit which emulates the floating source provided by a transformer, and so it will also operate in an unbalanced mode with one side of the line grounded. The permitted voltage excursion on the line is limited to less than the supply rail voltage. The often relatively high common-mode impedance to ground may encourage a relatively high common-mode voltage and care has to be taken that this does not push the amplifier into voltage overload. The configuration uses 10 precision-tracking resistors.

Figure 6b shows the circuit of a much simpler balanced line driver which only needs one defined-ratio resistor pair. This line driver was used to obtain the measurement given in the previous section. The differential source impedance is 2RS = 44 ohms. The common-mode impedance is RS/2 = 11 ohms. Previously we considered the common-mode voltage induced onto a floating line by 10 pF capacitance to a 240 V mains cable, and saw that in the example given it was 2.4 volts. By substituting a source of 11 ohms impedance, the common-mode voltage is reduced from 2.4 volts to 8 μV.

In practical application, protection circuits and common-mode RF filtering are added at the output of the amplifier. These will be discussed later. The output dc offset is normally trimmed to less than 1 mV.

4.2. Line Receiving Circuits

Let us start with the simplest differential receiver based on a single operational amplifier and a precision 4-resistor network. This is shown in Figure 7a. By inspection, it is seen that common-mode rejection is provided, and that the common-mode voltage excursion at the input terminals (±) of the amplifier is one half the line common-mode voltage.

Thus common-mode voltages approaching twice the amplifier supply rail voltage can be accommodated. For simplicity, a floating dc signal source is shown. In accordance with classical OP-amp theory, we assume there is no voltage between the OP-amp input terminals, and so may visualise these joined together. Clearly, the differential input resistance is 2R, and so the differential input current I_{in} is $V_{in}/2R$. Where does this current actually flow?

It flows from ground, via a total resistance 2R to the lower wire of the line, L_b. Therefore the potential of this node with respect to ground is - V_{in}. The potential of the upper wire of the line, node L_a is zero! One side of the line is virtually grounded. This immediately suggests the logic of driving the line from an unbalanced source, as shown in Figure 7b. Rejection of common-mode interference is good, but crosstalk may now be a problem because of the unbalanced system. There may also be a compatibility problem when this receiver is connected to a balanced system, eg, where the sending-end source is visualised as centre-tapped to ground. The signal current flowing in the centre tap ground path, I_{ct} is $V_{in}/2R$ and the currents in the two wires of the line differ by a factor of 3.

Balance may be restored by preceeding the differential amplifier with two voltage followers, which gives us the classical "Instrumentation Amplifier" configuration, Figure 7c. Unfortunately, the common-mode input impedance is now very high, and the permitted common-mode voltage (compliance as it is called) is now limited to less than the supply rails, ie, is halved in comparison with the former case.

A preferred line receiver topology which has been successfully used by the BBC since 1978 (including use at transmitter sites with high field strengths) is shown in Figure 8. This is fully symmetrical and perfectly balanced. It has a moderate common-mode input resistance of 25 kΩ. Using our previous example of 10 pF coupling to 240 V, 25 kΩ reduces the common-mode voltage from 2.4 volts to 19 mV.

Common-mode voltages approaching twice the supply rail voltage can be accommodated. Implementation is now greatly facilitated by the availability of packages which include four resistors, laser-trimmed to better than 0.01% ratio, which track within 2 ppm over the temperature range; along with the OP-amp. Unadjusted common-mode rejection figures of 80 dB can be achieved.

A typical distortion figure is -100 dB (0.001%) at frequencies up to 1 kHz, relative to +8 dB$_{.,,,}$ line level, and so this line receiver goes quite well with 16-bit digital systems. Note that no capacitors are fitted in series with the inputs: there is generally no need. If they were fitted, close matching would be needed to avoid degrading the common-mode rejection at low frequencies.

4.3. RFI Suppression and Protection

The need to consider common-mode rejection at radio frequencies and to ensure adequate performance has already been mentioned. This is easily accomplished by a bifilar wound common-mode filter, the topology of which closely resembles a standard mains filter. Filtering is applied at both the sending and receiving ends of the line, and this does not influence in any way the wanted differential-mode transmission.

Apparently simpler filtering which adds resistance to each leg of the line is prone to seriously degrade common-mode rejection unless precision components are used.

In a complex broadcasting environment the probability of a line sending or receiving amplifier being accidentally mis-connected (in the stress of the moment) to the output of a 100 W amplifier, or telephone ringing tone, or 50 V dc, or simply being short circuited, is real! BBC designed equipment incorporates appropriate protection circuitry.

It is important to realise that the equipment must also be protected when it is switched off. Figure 9 shows a line receiver front-end by way of example. RF filtering is provided by the second-order low-pass filter L1, C1, R1. Power supplies to the operational amplifier(s) are shunt regulated by the current-fed zener diodes D1, D2 at typically ±15 V. (The current sources CS1, CS2, prevent "hash" currents from being dumped into the analogue ground plane.)

Clamping potentials at ±30 V (twice the supply rails) are established by further zener diodes D3, D4. The incoming line is connected to the ±30 V clamps via the bridge rectifier, which is non-conducting in normal operation. In the event of excessive over voltage on the line, the line voltage is clamped at ±30 V, and the PTC resistors PTC1 and PTC2 (which act as self re-setting fuses) protect the clamping diodes. In the event that the line receiver is not switched on, line voltages in excess of 15 V "pump up" the OP-amp supply rails to prevent damage.

A very similar filter and clamp arrangement is used with line sending amplifiers, but the clamps then appropriately operate at ± Vcc.

5. CONCLUSION

Transformerless electronically-balanced line interface circuits offer a reduction in cost, weight, bulk, and susceptibility to local magnetic fields and as we have seen offer an all round, general improvement in performance. Their tolerance to common-mode line voltage is a function of supply voltage, and is much lower than that of transformers.

Therefore circuit topologies which provide a moderate or low common-mode impedance to ground are preferred.

The importance of good performance at frequencies above the audio band has been stressed, and common-mode RF filtering is recommended (even with transformers).

Circuit arrangements which protect against unintentional abuse have been described. The viability of transformerless interface circuits is greatly enhanced by the advent of low-cost integrated packages incorporating the requisite resistor networks with excellent ratio tolerance, and temperature tracking.

Transformers or other galvanic isolators will continue to be required in a few specific instances, eg, where there could otherwise be a potential safety hazard.

6. ACKNOWLEDGEMENTS

The Author wishes to thank the BBC's Director of Engineering for permission to publish this paper.

7. REFERENCES

REF 1 DTI: NICAM 728: Specification for two additional sound channels with System I television.

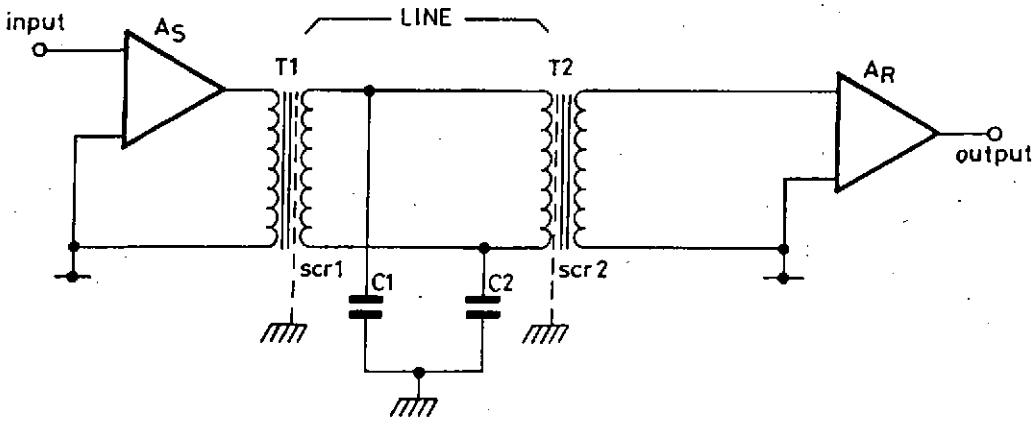

FIG.1

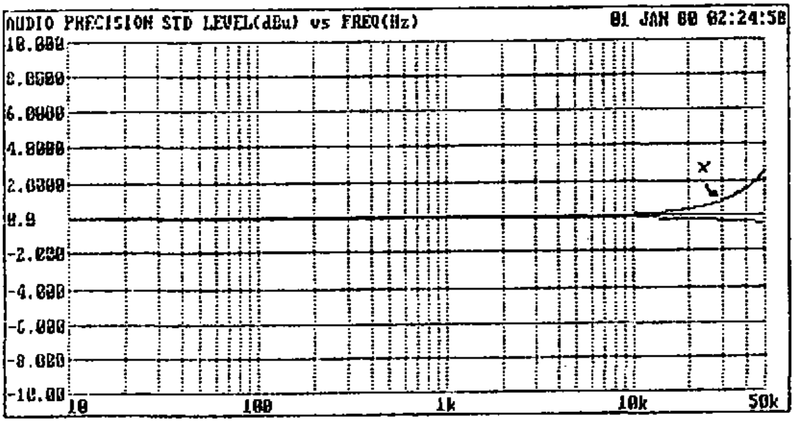

FIG. 2 100kΩ LOAD

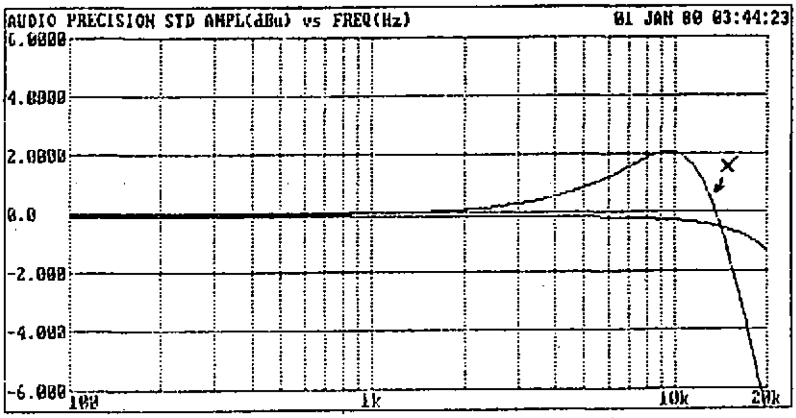

FIG.3 FAR END RESPONSE: 500m LINE

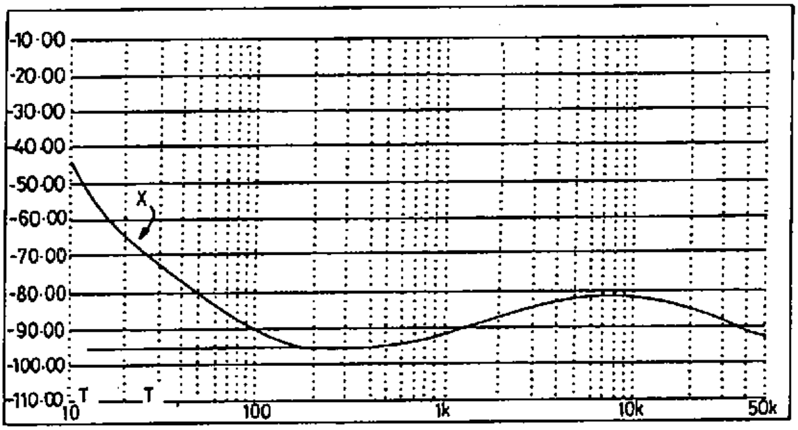

FIG. 4 DISTORTION AT $+8dB_{0.775V}$

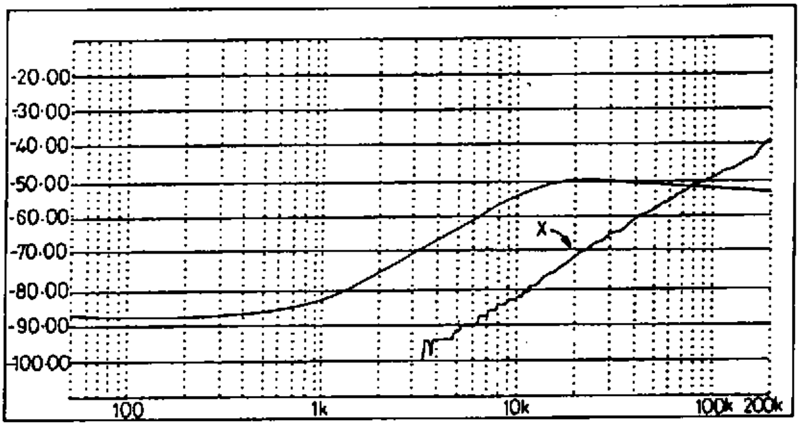

FIG. 5 COMMON-MODE REJECTION

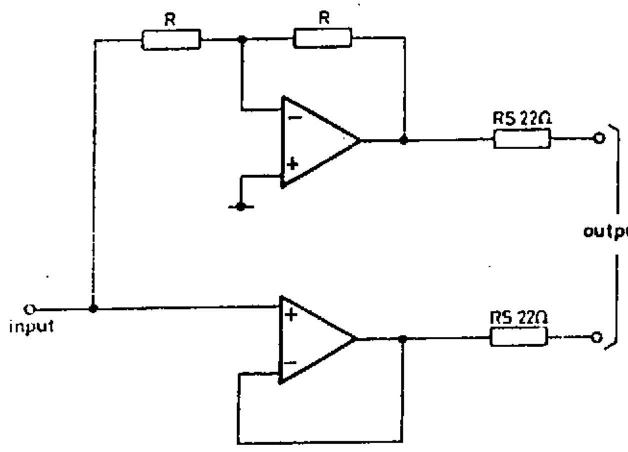

FIG.6b BALANCED SOURCE

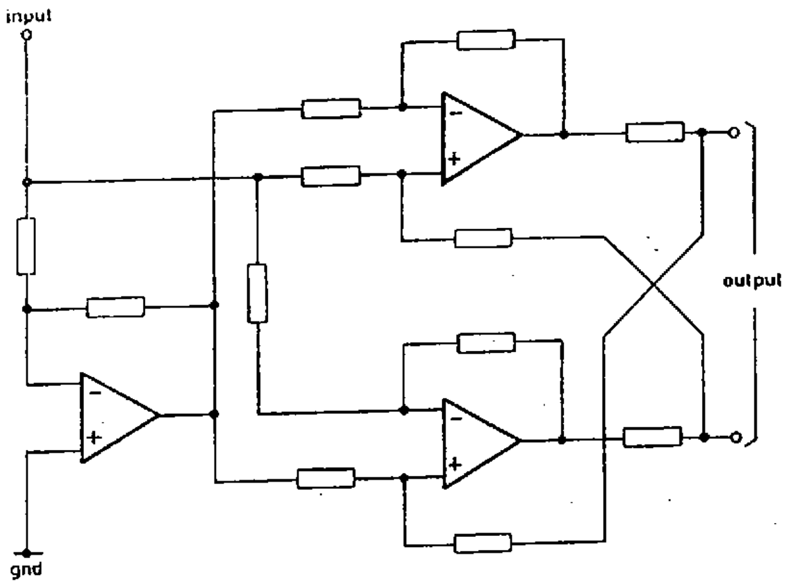

FIG.6a FLOATING SOURCE

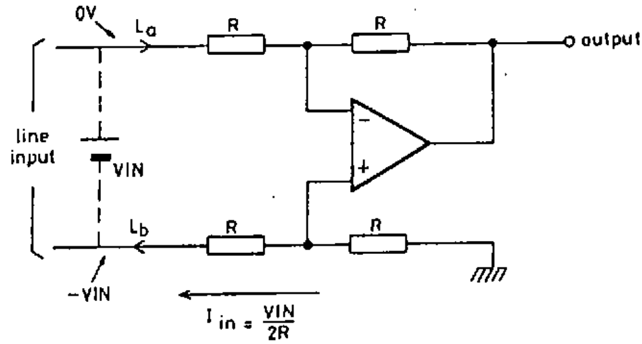

FIG.7a SIMPLE DIFFERENTIAL AMPLIFIER

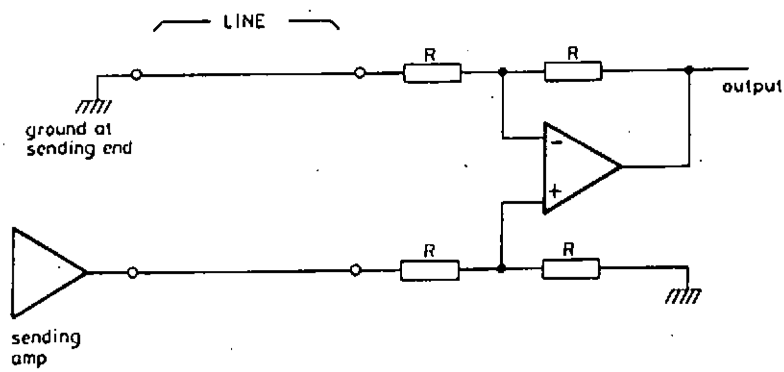

FIG.7b UNBALANCED LINE DRIVER

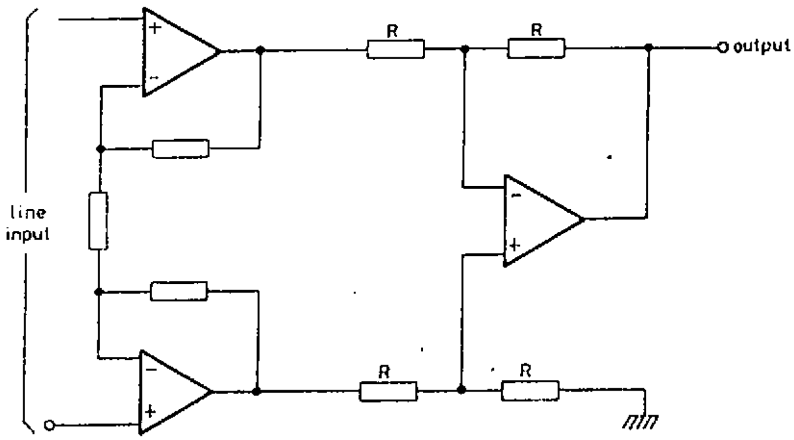

FIG.7c INSTRUMENTATION AMPLIFIER BLOCK

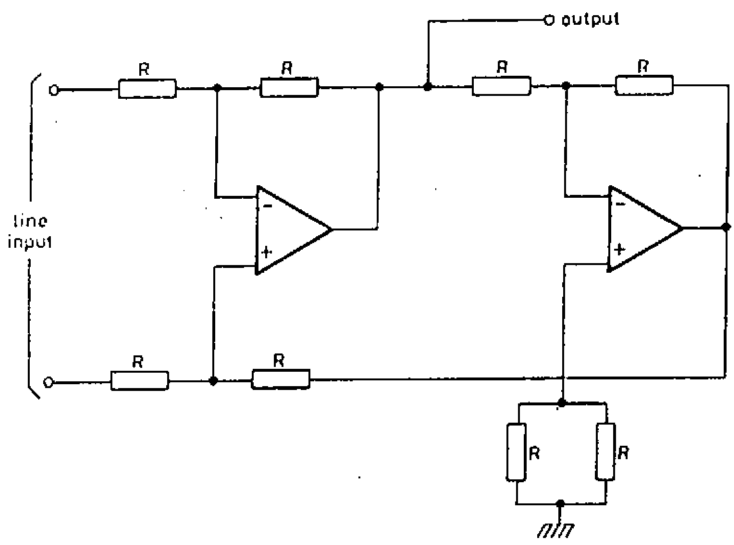

FIG.8 PREFERRED LINE RECEIVER

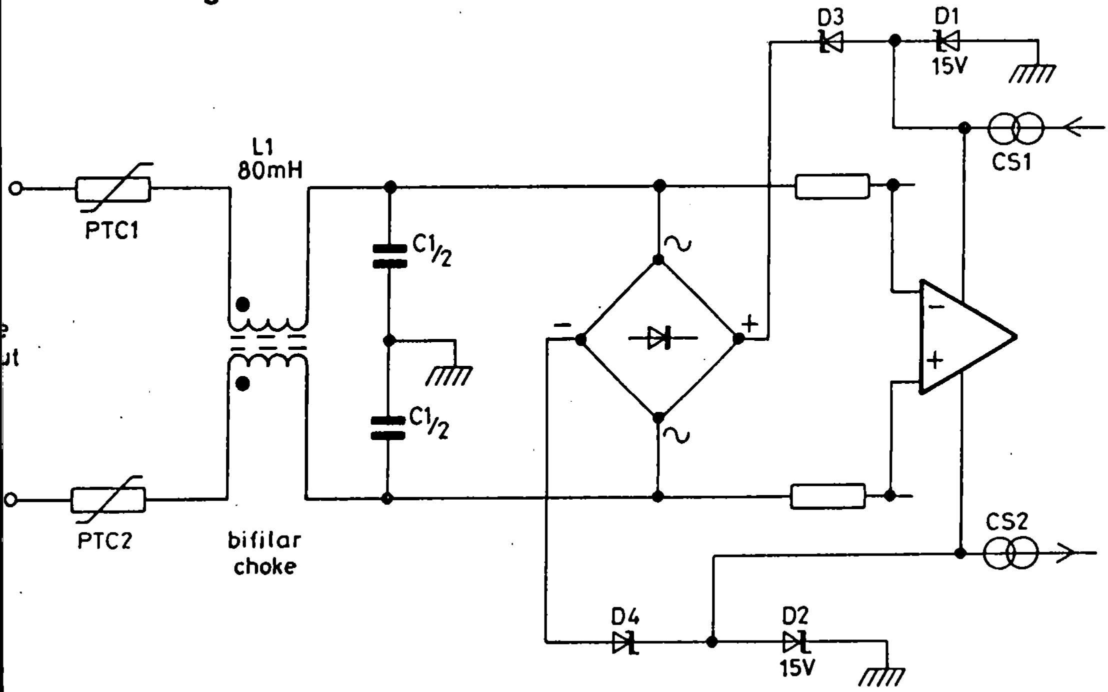

FIG. 9 COMMON-MODE RF FILTER AND PROTECTION CLAMPS