ISCE

The Institute of Sound and
Communications Engineers

Engineering Note 18.1

Balanced circuits and differential amplifiers

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1. Balanced circuits

1.1 Explanation of terms

Consider Figure 1, in which a piece of twin figure-8 cable running in earthed metal conduit is next to a wire carrying mains voltage . What voltage appears on each conductor of the twin cable?

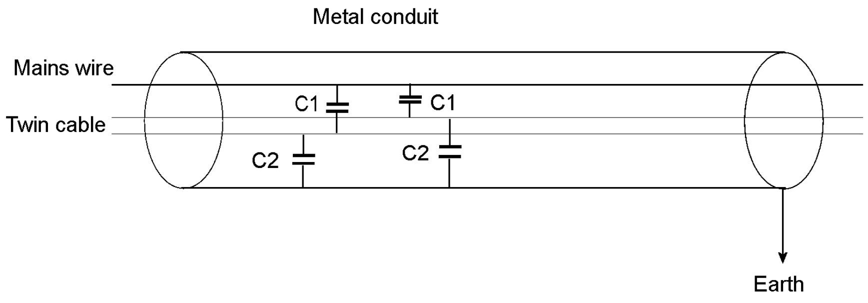

Figure 1 Twin cable exposed to mains interference

Each conductor in the twin cable has a capacitance C1 to the wire and a capacitance C2 to the earthed conduit. Assuming for the moment that any leakage resistance is so high as to be negligible, the voltage on each conductor, *with respect to the earthed conduit,* depends on the impedances of the capacitors, which are inversely proportional to the capacitances. So, if the capacitances of each conductor to the wire and the capacitances of each conductor to the conduit are equal, *the voltages induced on the conductors by the electric field of the wire are equal and in phase*. Such a signal on two (or more) conductors is called a '*common-mode signal*'.

In using balanced connections, wanted signals are put on the two conductors as equal signals of opposite polarity (incorrectly called '180° out of phase'). However, it is important to realise that *balance itself has nothing to do with the equal in magnitude but opposite in polarity signal voltages on the conductors.* Balance still exists even when the signal is absent. There may, however, be other reasons why equal signal voltages (with respect to 'earth') present an advantage.

An isolated cable in an electric field is not of much practical significance. In a real situation, we have a balanced output stage feeding the cable, which is connected to a balanced input. Figure 2 shows this configuration ,and it can be seen that if the resistors Ro are exactly equal and the resistors Ri are exactly equal, the bridge is balanced and no voltage due to Vcm, the common-mode disturbance voltage, appears at the terminals. Remember that V1 and V2 have zero internal impedance, so they can be replaced by short-circuits to see the balanced bridge formed by the four resistors more clearly.

In practice, of course, the resistor values will not be exactly equal. The effect of this is least when the ratio of Ri to Ro is either very large or very small (the latter being rare in practice). However, for other reasons that we shall see later, some compromise on that 'very' may give a better overall result.

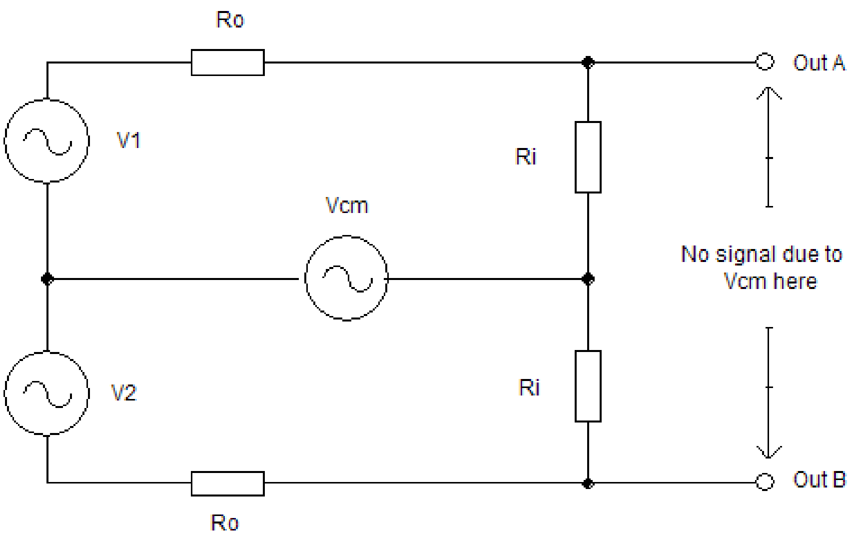

Figure 2 A balanced circuit is a balanced bridge

The bridge is balanced whether or not the signal voltages V1 and V2 are equal, and even if one or both is zero. Note also that there is no specific 'earth' point in this circuit: it works wherever a single earth is connected.

1.2 Differential amplifiers

The basic differential amplifier using an op-amp is shown in Figure 3. The resistor values R are initially taken as all equal, but there are other possibilities. X is a switch, for exploring different circuit configurations. V1 + V2 is the total signal voltage V, and V1 = V2 (in amplitude, but not in polarity with respect to point G).

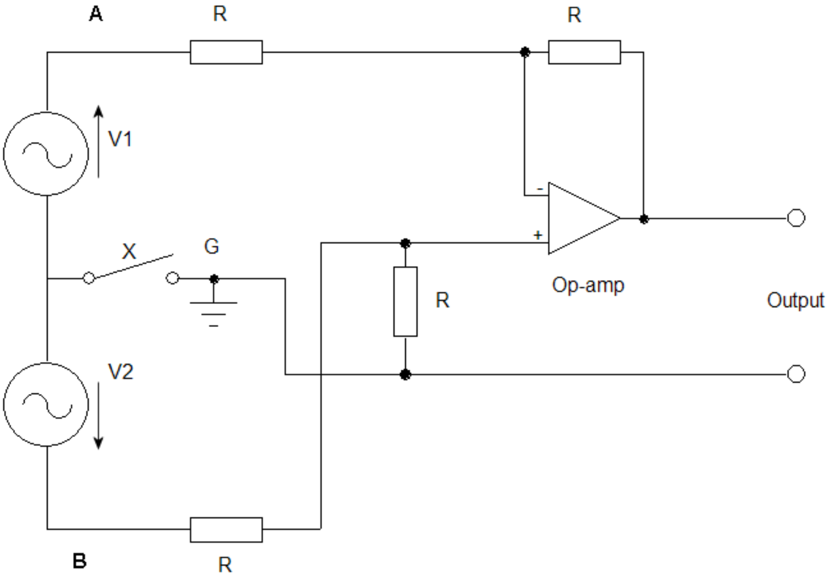

Figure 3 Basic differential amplifier circuit for analysis

If X is closed, we have the circuit condition 'balanced, centre-tap earthed', while with X open, it is 'balanced, floating'. In a balanced floating circuit, there might not be any connection to earth, G, at all.

When analysing op-amp circuits, the main points to bear in mind are that, while the op-amp is operating as an amplifier, *the inputs draw negligible signal current, the – input is a zero-impedance point ('virtual earth') and there is virtually no signal voltage between the + and – inputs, because the open-loop voltage gain is very large.* Note that there may be signal voltage at the – input, even though it is a 'virtual earth' point.

It depends which point one is considering the voltage with respect to.

In the 'balanced, centre-tap earthed' condition, the analysis is apparently straightforward. The two lower resistors make the voltage at the + input V/4, and the voltage at the – input must be the same. However, because of the way they are connected, V1 is of the opposite polarity to V2, so we have to treat its output as equal to –V/2. The voltage across the resistor next to A is thus –V/2 – V/4 = –3 V/4. The current through that resistor is then -3V/4R, and the only place this can go is through the feedback resistor. The voltage across the feedback resistor is thus 3V/4, which makes the output voltage equal to V.

One fact that is not initially obvious emerges from this analysis. The impedance looking into the circuit from point B is 2R. The impedance looking into the circuit from point A is calculated from the applied voltage. -V/2 and the current, -3V/4. This gives the value 2R/3, *lower than the value of the physical resistor R connected to point A.* Odd as this appears at first sight, it is due to the fact that the voltage at the – input is of opposite polarity to that at the A input***. Furthermore, it doesn't matter!*** The balanced bridge that gives a balanced circuit its interference-rejection properties has to be balanced for *common-mode* signals, not the *differential-mode* signals shown in Figure 3. We can change the signal to common-mode by inverting either of the voltage generators, say V1. Then the voltage across the resistor connected to A is V/2 –V/4 = V/4, the same as across the resistor connected to B. *The input impedance for common-mode signals is 2R at each input.*

Modern professional audio interface technique is to use low-impedance line driver outputs (100 Ω) and medium impedance inputs (10 kΩ). The input impedances, even if a bit different, make very little difference to the impedances that interfering signals 'see'. There is one configuration that can be troublesome: floating transformer windings at *both* ends result in very high common-mode impedances (just the stray capacitances) and even a small capacitance from an interfering source results in a high common-mode voltage on the balanced circuit. It still has very good common-mode rejection ratio (CMRR), but it needs that to cope with the high common-mode voltage. It's usually better to settle for a lower common-mode impedance at the sending end, as this takes the pressure off the receiving end CMRR, where the common-mode impedance is most conveniently a mid-range value, for low noise and ease of driving.

2. Actual measurements

There are few things as satisfying as measurements that agree very well with theory! A circuit like Figure 3 was set up with an LF351 op-amp. This is not a special choice of device: the experiment will work with any op-amp suitable for audio. The set-up needed some care, including a battery-operated signal source to prevent mains earth currents disturbing the measurements. The table shows the results obtained from measurements at the points indicated, using a 1 kHz balanced signal as input.

Test point	Balanced, floating, X open			Balanced, centre-tap earthed, X closed		
	Voltage to G	Differential input resistance	Input current	Voltage to G	Differential input resistance	Input current
A	98 mV (90° phase)	10 kΩ	200 μA**	0.98 V	6.7 kΩ	98 μA
B	2.0 V	10 kΩ	200 μA**	0.98 V (opposite polarity)	20 kΩ	
- input	0.98 V*	-	-	0.496 V	-	-
+ input	0.98 V*	-	-	0.496 V (opposite polarity)	-	-

* The difference was about 20 mV, and it, and the 98 mV measured at A, are due to the op-amp open-loop gain not being really huge at 1 kHz (it rolls off at 6 dB/octave from around 10 Hz due to the internal compensation needed to keep it stable).

** These two currents must be equal, because there is no other current path – they are the *same* current.

Note the curious situation in the balanced-floating case; the voltage *to earth* at point A is very small (theoretically zero), while the whole signal voltage appears at point B. This normally doesn't matter at audio frequencies, but if the signal contains fast transients that the cable can radiate, there is no cancellation effect; conductor B radiates just as if it was part of an unbalanced circuit.

3. Real input circuits

A real input circuit requires a lot more than just the basic op-amp and four resistors. It is wide-open to r.f. interference, because the op-amp normally doesn't provide any common-mode rejection above audio frequencies. It needs a common-mode r.f. choke and bypass capacitors to filter out any r.f. picked up on the input cable. It is also vulnerable to d.c. and high audio voltage inputs. To prevent damage due to these, back-to-back silicon diodes may be connected across the input, and zener diodes to the supply rails of the op-amp. There may be an AES standard or report on this subject later.

4. Further reading

AES Journal June 1995 (www.aes.org) has several practically-oriented papers on balanced circuits and earthing (grounding) techniques.