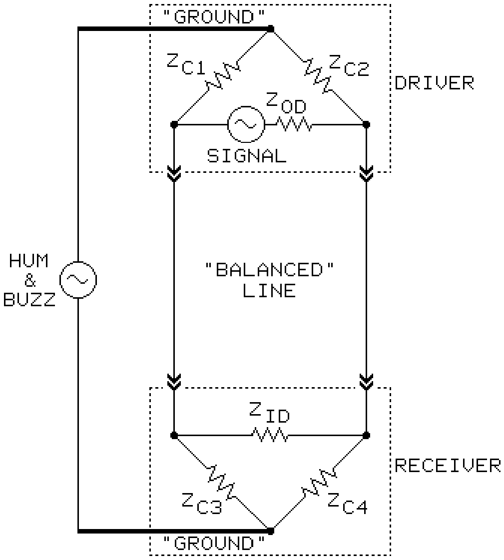
Jensen AN-002

ANSWERS TO COMMON QUESTIONS ABOUT AUDIO TRANSFORMERS

by Bill Whitlock

WHAT DOES "BALANCED" REALLY MEAN ?

The purpose of a balanced line is to transfer a "signal" from one place to another while rejecting "ground noise", which is *not* white noise or hiss, but power line related hum and buzz. To accomplish this noise rejection, two signal lines are used and the ***IMPEDANCE* of the two lines to ground must be equal** or "balanced". Since anything connected to the line affects its impedance, always consider the "system" consisting of the driver, the line itself, and the receiver. It is a popular belief that the signals must have opposing polarity and equal amplitudes, or symmetry. **Signal symmetry has NOTHING to do with noise rejection**. The system must reject noise even when there is no signal and, in fact, this is usually how system noise testing is done. Illustrated below is a generalized balanced system schematic, rearranged to show that it takes the familiar form of a Wheatstone bridge.



"**Balanced**" **System as Wheatstone Bridge**

A Wheatstone bridge has a "generator", four impedance "arms", and a "detector". In our schematic, the "generator" is the ground noise, the "arms" are the common-mode impedances of the driver outputs Z_{C1} and Z_{C2} and receiver inputs Z_{C3} and Z_{C4}, while the "detector" is the receiver itself, which is sensitive only to the voltage *between* the two lines.

If the ratio of Z_{C1} to Z_{C3} is precisely the same as the ratio of Z_{C2} to Z_{C4}, the bridge is said to be "nulled". In this ideal condition, none of the ground noise will appear at the receiver no matter how large the noise is. In the real world, however, all kinds of mass-produced equipment will be interconnected and exact matching of these impedances at inputs and outputs cannot be reasonably expected. Equipment designers can minimize the effects of these mismatches or "unbalances" through judicious choices of input and output stage circuit topologies and common-mode impedances.

The Wheatstone bridge is most sensitive to small fractional impedance changes in one of its arms when all the arms are the same impedance. It is least sensitive when one pair of arms is very low impedance and the other pair is very high (we change the impedance of *pairs* because the ratios of the two sides must match in order to null the bridge). Therefore, we can minimize the sensitivity of our balanced system (bridge) to impedance unbalances by making common-mode impedances very low at one end of our line and very high at the other.

To deliver the maximum ***signal*** *voltage* from driver to receiver, the differential impedance must be low at the driver and high at the receiver. Most line drivers with low differential output impedance will also have inherently low common-mode output impedances, so the low impedance arms of the bridge are almost always at the driver. Generally, in professional audio, low impedance means under 100 Ω and high impedance means over 10 kΩ.

Active circuits having high *differential* input impedance (sometimes called "bridging" since several can be bridged across a line with minimal level loss) are widely used, but the importance of the ***common-mode*** input impedances of these circuits has long been ignored by most designers. Almost all such "electronically balanced" inputs have common-mode input impedances in the 5 kΩ to 20 kΩ range, which seriously degrades their performance as a balanced line receiver. The common-mode input impedances of an input transformer are inherently about 1000 times that of most "actively balanced" inputs, ***giving the transformer about 60 dB better ground noise rejection*** in the real world, where significant source impedance unbalances almost always exist.

WHAT'S THE DIFFERENCE BETWEEN "OUTPUT" AND "INPUT" TRANSFORMERS ?

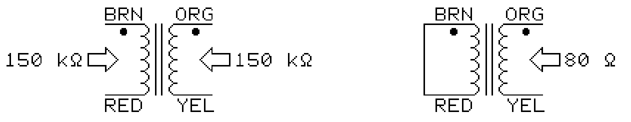
Most simply stated, *output* transformers are used at the *low* impedance or driven end of a balanced line and *input* transformers are used at the *high* impedance or receiving end. The technical requirements, and as a result, the designs and physical constructions, of the two transformer types are **very different**.

An OUTPUT transformer is driven by an amplifier and typically loaded by several thousand pF of cable capacitance plus the 20 kΩ of a "bridging" line receiver. At high frequencies, most of the driver output current is used charging the cable capacitance. Occasionally, and usually because someone mistakenly thinks they must "terminate" a cable, a real 150 Ω or 600 Ω load must be driven, requiring even more driver output current. Therefore, an output transformer must have a low output impedance, especially at high frequencies. This requires **low DC resistance windings** and **very tight magnetic coupling**, since the sum of the winding resistances and the "leakage inductance" resulting from imperfect coupling are effectively placed in series between amplifier and load. To maintain the impedance balance of the output line, the transformer must also have **balanced output capacitances**. This requires a uniform distribution of primary to secondary capacitance across the windings. All these goals can be met in high performance output transformers built using bifilar (primary and secondary wound as if they were a single wire) designs and precision winding techniques.

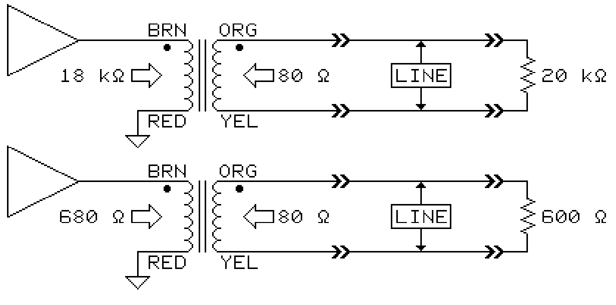
An INPUT transformer is driven by the balanced line and is typically loaded by the input of an amplifier stage. Its primary must have a high impedance to the differential voltage between the lines and this requires more turns of smaller wire producing relatively **higher resistance windings**. The transformer must also suppress any response to the common-mode voltage. A **Faraday shield**, connected to ground, is used to prevent capacitive coupling of the common-mode voltage from primary to secondary. Placing this thin copper foil between windings also reduces magnetic coupling, resulting in **increased** "**leakage inductance**". To maintain impedance balance of the input line, the capacitance of the primary to the Faraday shield must be uniformly distributed across the winding. Because of its generally higher impedances and relatively high leakage inductance, ***the secondary load on an input transformer must be carefully controlled***. The recommended load resistance and/or RC network must be used and load capacitance kept to a minimum. Generally, this means physically placing the input transformer as close as possible to the input amplifier stage. For example, the capacitance of 2 feet of shielded cable, about 100 pF, on the secondary of some input transformers will degrade bandwidth and transient response.

WHAT'S THE "IMPEDANCE" OF A TRANSFORMER ?

The "impedance" specification of audio transformers seems to confuse many engineers. Although they tend to produce optimum results when used with specified external impedances, ***the transformer itself has no intrinsic impedance***. It simply reflects impedances, modified by the square of the turns ratio, from one winding to another. Keeping in mind that input and output *power* are equal, some simple application of Ohm's law will prove this.
The confusion probably stems from the fact that ***transformers can simultaneously reflect two different impedances***. One is the impedance of the driving source, as seen from the secondary, and the other is the impedance of the load, as seen from the primary. An example of ***output*** transformer properties is shown below.



"OPEN CIRCUIT" "SHORT CIRCUIT"

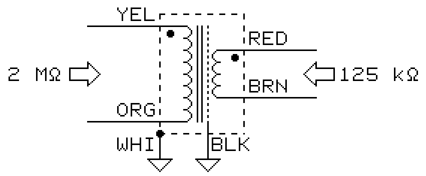


LINE DRIVER APPLICATIONS

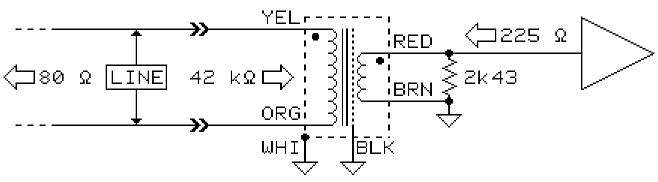
Jensen JT-11-DM 1:1 Output Transformer

The open circuit impedance, at 1 kHz, of either winding is about 150 kΩ. Since the DC resistance is about 40 Ω per winding, if the primary is short circuited, the secondary impedance will be 80 Ω. If we place the transformer between an amplifier and a load, the amplifier will "see" the load through the transformer and the load will "see" the amplifier output impedance (generally tenths of an ohm for amplifiers with negative feedback) through the transformer. In our example, the amplifier would "look like" 80 Ω to the output line or load and the 600 Ω load would "look like" 680 Ω to the amplifier. If the load were 20 kΩ, it would "look like" slightly less than 20 kΩ because the open circuit transformer impedance is effectively in parallel with it. For most loads, this effect is negligible.

An example of ***input*** transformer properties is shown below.



"OPEN CIRCUIT"



LINE RECEIVER APPLICATION

Jensen JT-10KB-D 4:1 Input Transformer

The open circuit impedance, at 1 kHz, of the primary is about 2 MΩ. Because this transformer has a 4:1 turns ratio, therefore 16:1 impedance ratio, the secondary open circuit impedance is about 125 kΩ. The DC resistances are about 2.5 kΩ for the primary and 92 Ω for the secondary. Since this is an input transformer, it must be used with the specified secondary load resistance of 2.43 kΩ for proper frequency and time domain responses. We can calculate that this load will "look like" about 42 kΩ at the primary, which certainly makes it suitable for a "bridging" input stage. To minimize the noise contribution of the amplifier stage, we need to know what the transformer secondary "looks like", impedance wise, to the amplifier. If we assume that the primary is driven from the line in our previous output transformer example with its 80 Ω source impedance, we can calculate that the secondary will "look like" about 225 Ω to the amplifier input.

REFERENCES:

B. Whitlock, "Balanced Lines in Audio - Fact, Fiction, and Transformers", Journal of the AES, Vol 43, No 6, June, 1995.

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