# Transformers in audio design

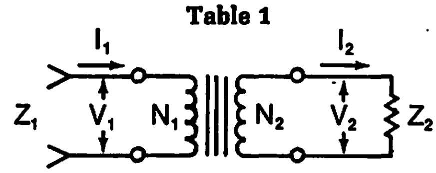
By Bruce E. Hofer

**With proper application, transformers often deliver sonically superior results.**

In 1831, Faraday observed that a changing voltage applied to a coil wound on an iron core would induce a related voltage across a second coil. Transformers couple power from one circuit to another through a common magnetic field. Transformers offer the fundamental advantages of isolation and common-mode rejection between two circuits and thus find application at almost every interface in an audio system.

Table 1 reviews the basic relationships between voltage ratio, impedance ratio and turns ratio. Transformers possess the *unique* property of impedance conversion because the input and output powers must be approximately equal. For example, a 1kΩ resistor connected to the primary of an ideal 1:2 turns ratio (step-up) transformer will electrically look and behave like a 4kΩ resistor at the secondary connections. Transformers are thus attractive devices for coupling signals between circuits with significantly different impedance levels such as a microphone and a low-noise pre-amplifier.

**Table 1**




$$\frac{V_2}{V_1} = \frac{I_1}{I_2} = \frac{N_2}{N_1}$$

$$Z_1 = Z_2\left(\frac{N_1}{N_2}\right)^2$$

*The basic relationship between voltage ratio, impedance ratio and turns ratio.*

The impedance ratio is a common specification of many audio transformers and is equivalent to the square of the turns ratio. For example, a 600/10kΩ transformer will have a 1:4.08 turns ratio and a +12.2dB voltage gain. The impedance ratio generally suggests the nominal values for source and load resistances to obtain the best frequency response. Optimum S/N ratio *also* depends upon maximizing signal power transmission which occurs only when source and load impedances are matched.

Transformers have their share of imperfections with inherent bandpass limitations and non-zero distortion. It is not too surprising that their popularity has declined in the age of transistors and integrated circuits. However, as many engineers and contractors have learned from experience, there are far more audible problems in the *real world* than failing to achieve 0.001% residual distortion specs or dc-to-light frequency response.

### Transformer-equivalent circuit

Figure 1 shows a simplified model of a typical *transformer-coupled* circuit. Note how the secondary elements, including the load impedance, are transformed or *reflected* back into the primary as a function of the turns ratio. Winding resistance is due to the finite conductivity of copper wire. The leakage inductance of a winding is due to the small percentage of flux that is not linked by the other windings. Capacitance exists between the turns of each winding.

High frequency response is limited by the complex interaction of leakage inductance, winding capacitance and the source and load impedances. Computer circuit analysis techniques are generally required to predict exact response. There is a potential high frequency resonance between the inductance and capacitance elements that can cause very audible ringing or *smearing*. Leakage inductance is particularly sensitive to winding assembly and can vary significantly, unit to unit, from a low-quality vendor. Making a consistent high-quality audio transformer is similar to making a fine wine—both involve the careful blending of effects and attention to detail.

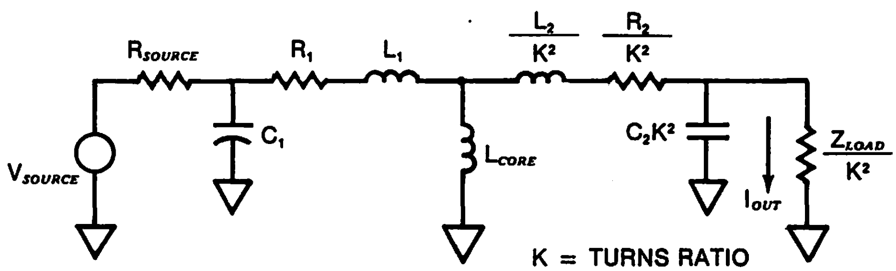



*Figure 1. A simplified model of a typical transformer-coupled circuit. The ac equivalent circuit is seen by the source. $R_1$, $L_1$, $C_1$ and $R_2$, $L_2$, $C_2$ model the primary and secondary windings respectively. Note the secondary impedance sealing due to the turns ratio. $L_{CORE}$ limits low-frequency response and is typically 1Hz to 1,000Hz.*

Small signal, low frequency response is limited by the core inductance seen by the input. (See Figure 1.) This inductance results from the magnetic field established by the source winding. It is roughly proportional to the square of the number of turns ($N^2$) and the *relative permeability* of the core material. (Relative permeability is a measure of the flux concentration property of a material.) Most ferromagnetic alloys exhibit values from 1,000 to 100,000, meaning they can pass that much more flux than empty space with the same cross-sectional area. Transformers would be useless for audio applications without a core. Unfortunately, all core materials *saturate* or exhibit a sharp drop in relative permeability above some critical flux density.

A basic audio transformer rating is the maximum signal level it can pass without gross distortion. This is typically specified at 20Hz and 1% to 3% THD. Figure 2 shows how the flux generated in a core is phase shifted with respect to the applied voltage and its relationship to signal frequency. Because the peak flux level is *inversely* proportional to signal frequen-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cy, the maximum allowable signal level decreases to zero at 0Hz. When saturation occurs, the large shunting inductance and the *reflected* secondary elements in the equivalent circuit of Figure 1 almost disappear. The transformer input impedance drops, limited only by the resistance and leakage inductance of the primary winding, potentially provoking current limiting or other disastrous effects in the source.

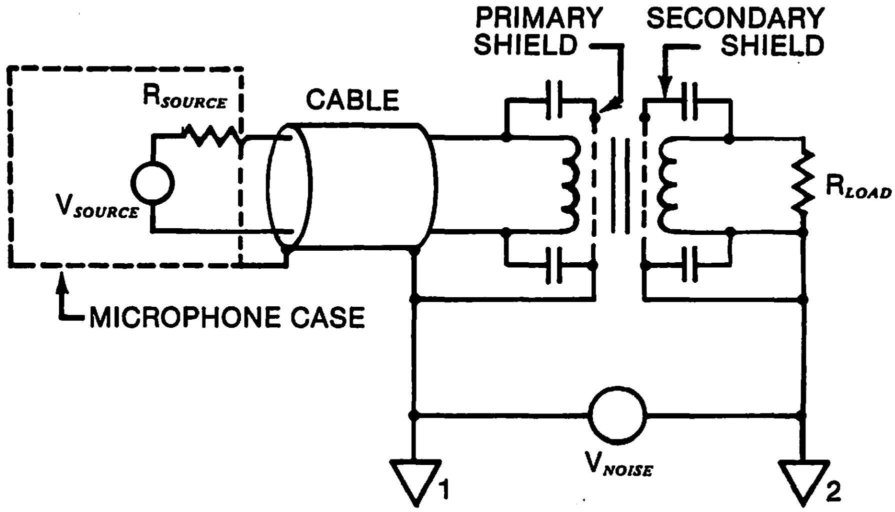
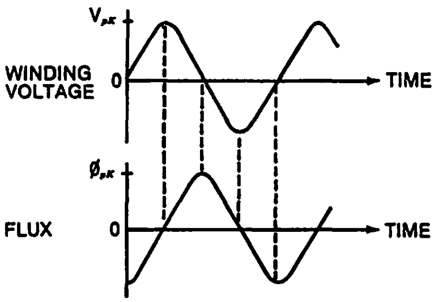



*Figure 3. Faraday shields break up the winding to winding capacitances and substantially improve isolation from $V_{NOISE}$. A 130dB common-mode rejection at 60Hz is possible. Without shields, a fraction of $V_{NOISE}$ would couple into $R_{LOAD}$ or access the input due to slight mismatching in cable capacitance.*




$$\phi_{pk} = \frac{V_{pk}}{2\pi f N}$$

**Figure 2.** *The winding voltage is proportional to the flux rate-of-change. Peak flux is inversely proportional to signal frequency and number of turns in the winding. Note the 90-degree phase shift between flux and voltage.*

### Input transformers

Input transformers are optimized for isolation and common-mode rejection. They come in two basic *flavors* depending upon signal level. Low-level versions are intended for coupling a microphone or other *low-impedance, low-output* transducer to a preamplifier and provide voltage step-up ratios of 1:2 to 1:10 (+6dB to +20dB). Maximum input signal ratings are typically −10dBu to +8dBu (0dBu = 0.776Vrms). High-level versions can take up to +30dBu and are intended for coupling line sources with unity gain or even modest attenuation factors such as 2:1.

Input transformers usually contain one or more *Faraday shields* to improve isolation and common-mode rejection. A Faraday shield is a grounded conductor placed between primary and secondary windings to break up the capacitance often present between them. It can be made of fine wire mesh, metal foil, or simply a single layer winding. Figure 3 shows how such a shield splits the capacitance between the input and output windings preventing common-mode signals from coupling into the source of load. Two Faraday shields give the best performance with each connected to their respective input and output circuit commons. As a bonus, the grounded capacitance of the shields interact with the transformer's leakage inductance to form an effective RFI (radio frequency interference) filter.

A well-designed input transformer with Faraday shielding can't be beat for the rejection of common-mode interference. Typical rejections of 130dB at 60Hz, to 80dB at 20kHz exceed the maximum performance of many practical transformerless input circuits. A transformer-coupled input also does not have the common-mode range limitations characteristic of transformerless designs.

The high frequency response of *low level* input transformers is particularly sensitive to source and load impedances, especially source resistance and load capacitance because of their step-up ratio. Some manufacturers may also recommend a secondary RC compensation network to obtain best response. Cabling adds significant amounts of capacitance and should always be done on the *low impedance side* of an input transformer to avoid excessive high-frequency rolloff.

Input transformers are packaged inside magnetically shielded enclosures to prevent interference from stray fields. The shielding material is typically a nickel-iron alloy that has undergone a special heat treatment to enhance its properties. Soldering to the case, tapping mounting screw holes, or other physical stressing should be avoided to prevent a loss in its shielding effectiveness.

### Output transformers

Output transformers, not the old power amp variety, are optimized for line driving applications. The most important rating of an output transformer is its maximum output level. A maximum output rating will usually specify the source and load impedances because they influence low-frequency distortion. (See the sidebar "Transformer Distortion.")

Output transformers differ significantly from input transformers both in construction and performance. To preserve high-frequency bandwidth with both low impedance sources and loads, it is necessary to minimize leakage inductance. To obtain low inductance, output transformers are commonly wound in a *multifilar* fashion. This gives near perfect magnetic coupling between windings at the expense of a much higher winding to winding capacitance. The resultant compromise in high-frequency isolation is usually acceptable because of the relatively high-output line levels.

*Bifilar, trifilar* and *quadfilar* are terms describing the number of wires wound simultaneously. Step-up or step-down applications require series or parallel connection of multiple

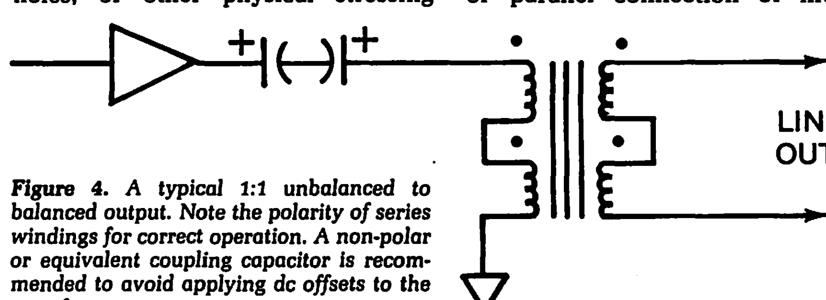



*Figure 4. A typical 1:1 unbalanced to balanced output. Note the polarity of series windings for correct operation. A non-polar or equivalent coupling capacitor is recommended to avoid applying dc offsets to the transformer.*

windings because all the windings have the same number of turns. Quadfilar output transformers are among the most popular because of their flexibility permitting 3:1, 2:1, 1:1, 1:2 or 1:3 configurations.

Figure 4 shows a typical 1:1 application for a quadfilar output transformer interfacing a low impedance unbalanced amplifier to a balanced load or line. Figure 4 also shows recommended capacitive coupling between the amplifier and transformer primary. The flux in the core is magnetically offset by dc winding currents, resulting in a reduction of signal handling capability and an increase in low frequency distortion. Small offset voltages can cause problems because of the relatively low winding resistances of output transformers.

Figure 5 shows how a combination of output and input transformers can solve a tough real world interface problem. In this example, the output from a portable mixing console is cabled to the input of another system 1,000 feet away. The ac power sources are on different circuits with as much as 10V of common-mode ground noise between them. It is hard to imagine a *workable* solution without the use of transformers.

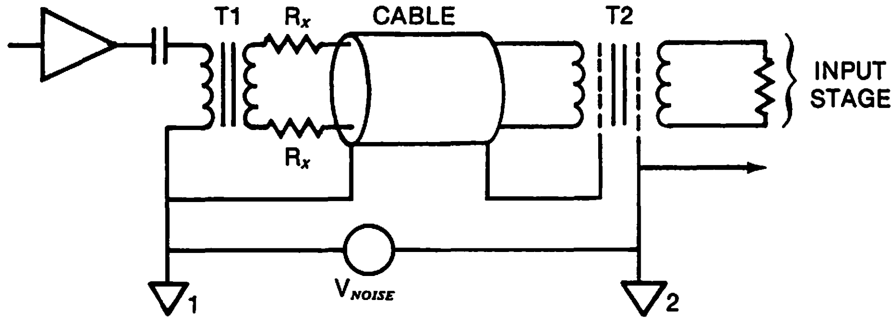



**Figure 5.** *Two transformers can solve tough interface problems where $V_{NOISE}$ can be many volts. T1 is an output type and T2 is a line level input type. Note the recommended grounding of the cable shield. Typical values for $R_x$ are 10Ω to 47Ω depending upon cable length and capacitance.*

### Other audio transformers

Microphone bridging transformers are used to couple a microphone into several inputs simultaneously. They come in 1:1, 1:1:1 and 1:1:1:1 configurations and have Faraday shields for each winding to provide complete isolation of circuits. It is essential that the shields be connected to their respective circuit commons for best performance.

*Direct-box* transformers are used to couple musical instruments and other high-level sources directly into microphone level inputs. They typically have turns ratios about 10:1 with 20dB or so of attenuation to provide the correct matching between the relative high output impedance and level of such devices and the low impedance of microphone input. Long cables have a negative effect on high frequency response because the cable capacitance *shunts* the high impedance side of the transformer.

Line matching transformers are used to interface remotely located speakers to a *constant voltage* (70.7V) distribution line driven by a centralized power amplifier. This is done to keep the size of the distribution wire and system power losses at a minimum; this is identical in concept to electrical power transmission systems. Line matching transformers often provide primary taps because different speakers may have different efficiencies or may need to be balanced to provide even sound coverage. The most important specification of this type of transformer is its power handling rating and frequency range.

Transformers give the audio system designer the inherent advantages of isolation and common-mode rejection. They do not have the common-mode range limitations of transformerless circuits and are thus the only *practical* solution to many interface problems. The principal disadvantages of transformers include cost, size and weight. Inherent bandpass response and low frequency distortion may be mentioned; however, the hums and buzzes because of inadequate common-mode rejection in a system are usually far more audible than any 50kHz bandwidth limitation or 1% THD at 20Hz. S&VC

## *Transformer distortion*

*Transformer distortion arises from the non-linear magnetic properties (hysteresis) of the core material. This can be modeled with a distortion current source paralleling the winding inductance as shown in Figure 1. In reality the inductance is non-linear, however it is convenient to separate linear and non-linear effects in a model. The distortion current splits between input and output circuits and develops distortion voltages across the various source, load and winding resistances. Note that minimizing source resistance will minimize distortion.*

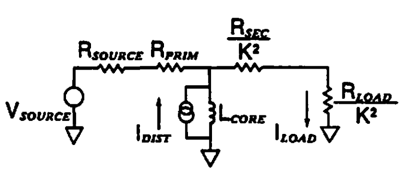



**Figure 1.** *The $I_{DIST}$ models transformer distortion due to non-linear magnetic property of core material. K equals turns ratio. $I_{DIST}$ causes distortion voltages across $R_{SOURCE}$ and $R_{PRIM}$ even when $R_{LOAD}$ is infinite.*

*The selection of core material can have a profound effect on low-frequency distortion characteristics. Figures 2 and 3 show how the measured THD of an output transformer with different cores varies with output level and frequency. Commonly available silicon-steel (M6) offers a high output level before saturation, but exhibits bizarre distortion behavior at very low levels. 80% nickel alloy saturates approximately 8dB lower than silicon-steel but shows little rise in THD at lower signal levels. In all cases the distortion is dominately third-harmonic. Other materials such as 40% nickel alloys, cobalt alloys and ferrites, have different characteristics but find limited applications in audio design.*

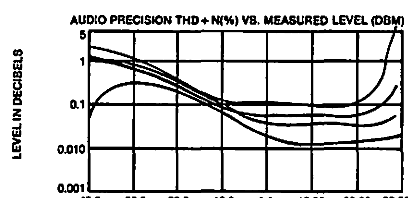



**Figure 2.** *The measured THD of an output transformer with M6 silicon-steel core material. Frequency sweeps are 20Hz, 30Hz, 50Hz and 100Hz, top to bottom. $R_{SOURCE}$ equals 50 and $R_{LOAD}$ equals 600.*

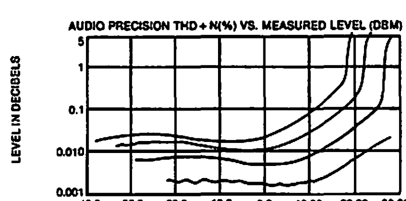



**Figure 3.** *The measured THD of an output transformer with 80% nickel alloy core material. Frequency sweeps are the same as shown in Figure 2 above. $R_{SOURCE}$ equals 50 and $R_{LOAD}$ equals 600.*