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Transformers

Here, you will find out what transformers are and what they do. And you will discover how one manufacturer designs and tests their transformers.

An interesting approach to transformer operation is to start with a generator driving an ideal iron-core inductance. An ideal inductance has two important characteristics. First, the coefficient of coupling is unity. This means the magnetic flux due to the electrical current is totally linked to all the turns through the magnetic core material. In a real inductance there is less than 100 per cent flux linkage. Second, in the ideal inductance, it takes zero current to magnetize the core. In all *but ideal* conductances, it takes some small amount of current to magnetize the core. As expected, the generator will see an inductive load, see FIGURE 1(A). By connecting the generator from the center tap to one end, and a resistor from the center tap to the other end, see FIGURE 1(B), we convert the iductance to a transformer. The inductive current in each half of the inductance is out of phase and cancelled. The generator will see a purely resistive load if the coupling coefficient is unity and an ideal core material is used. Later on we shall see the effect of less than unity coupling and a less than ideal core material. The electrical connection at the center tap need not be made, see FIGURE 1(C), leaving only the magnetic coupling between the two windings. FIGURE 1(D) shows the transformer in its more conventional representation.

IMPEDANCE, VOLTAGE, AND CURRENT TRANSFORMATION

Transformers in audio signal circuits are used for a variety of purposes, including isolation, impedance matching, voltage transformation, and current transformation. Voltage, current, and impedance changes are a function of the turns ratio, but in all cases the power in the primary circuit equals the power in the secondary. We therefore have the well known transformer equations:

$$E_pI_p = P_p = P_s = E_sI_s$$

$$\frac{N_p}{N_s} = \frac{E_p}{E_s} = \frac{I_s}{I_p} = \sqrt{\frac{\xi_p}{\xi_s}}$$

P = Power
N = Turns
E = Voltage
I = Current
ξ = Impedance
subscript$_p$ = primary
subscript$_s$ = secondary

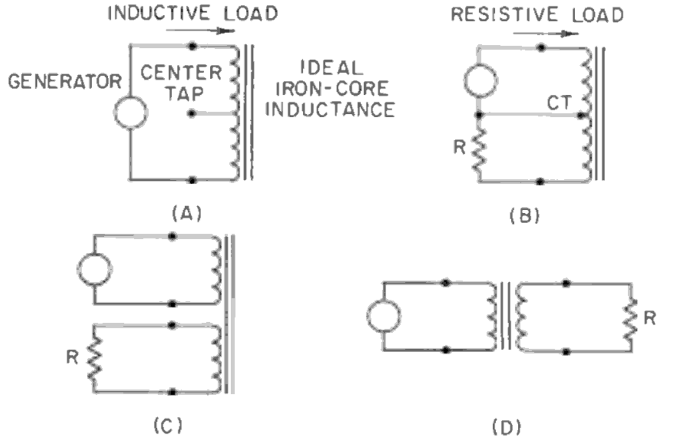

Figure 1. An ideal iron-core inductance connected as a transformer. At (A) a generator driving an inductive load is seen. (B) shows a generator driving a resistive load. At (C) the electrical connection is eliminated, while at (D) a conventional transformer representation is shown.

These equations are set down in the form of a nomograph (FIGURE 2) which can be used more easily to determine the ratios of primary to secondary turns, impedance, voltage, and current. The current and voltage ratios are expressed in dB. Very often a transformer or circuit specification will only list one of these items, but with the nomograph of FIGURE 2 we can determine the remaining primary and secondary relationships. Take the case of a transformer used to match a 150-ohm line (primary) to a 600-ohm line. The impedance ratio is 4:1. We enter the

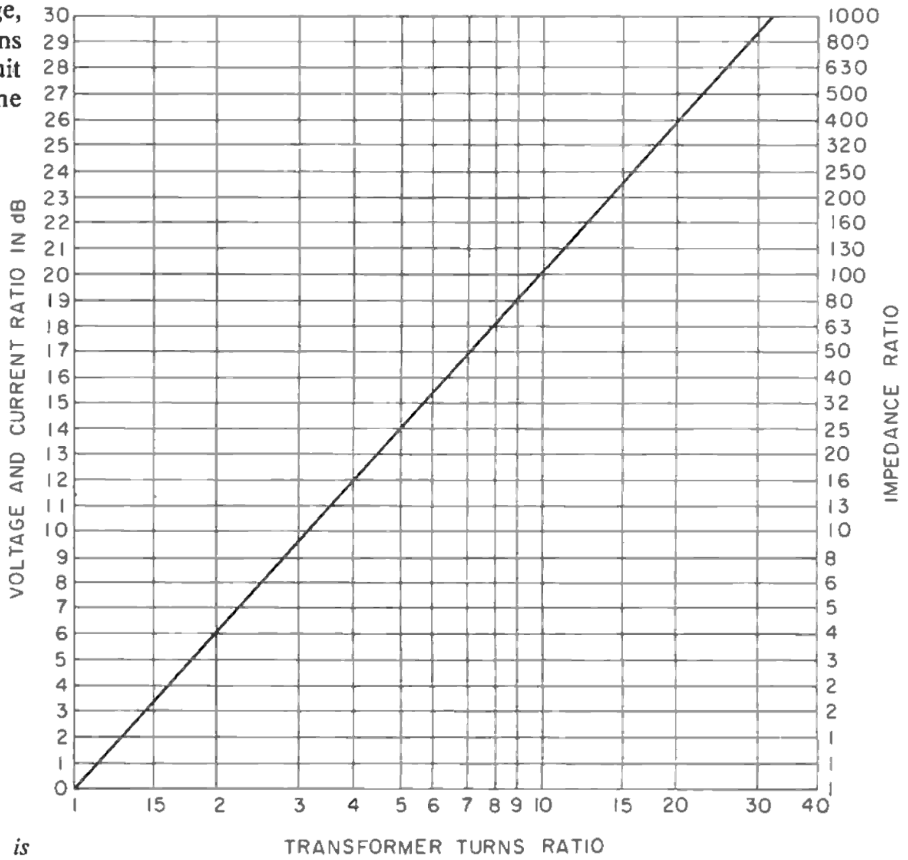

Figure 2. A transformer nomograph.

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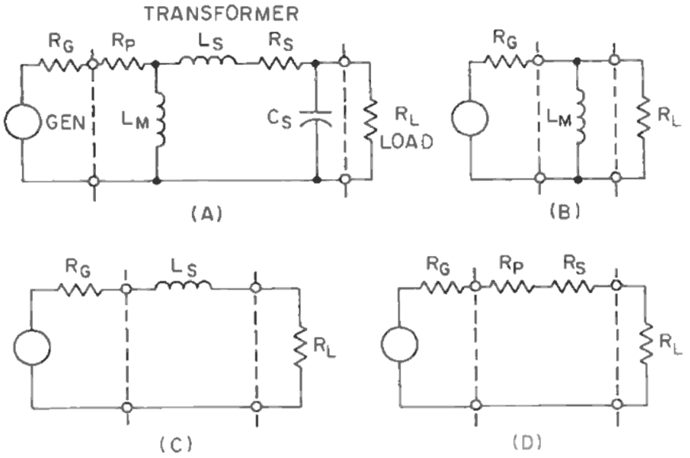

Figure 3. At (A) a simplified equivalent transformer circuit is shown, (B) is a low-frequency equivalent circuit, (C) a high-frequency equivalent circuit, and (D) is an efficiency equivalent circuit.

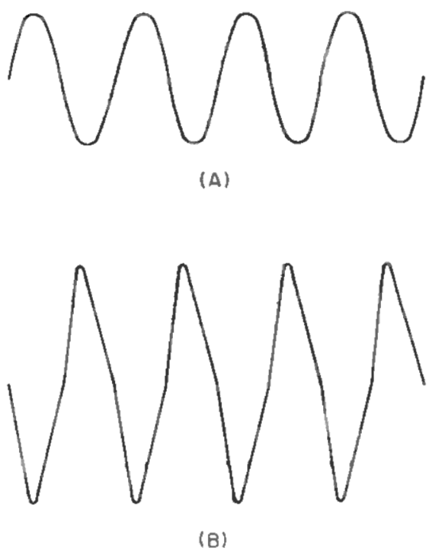

Figure 4. (A) The output waveform below maximum power capability is shown while at (B) we see the output waveform when the core is saturated.

nomograph at the right hand side, where the impedance ratios are shown, at the indicated ratio of 4. Going to the left on that horizontal line, we intersect the voltage ratio scale at 6 dB—which is the voltage gain and also the current loss in the secondary. To find the turns ratio we note where the horizontal 4:1 impedance line intersects the sloping line; we then drop down vertically from that point to the turns-ratio scale at the bottom of the nomograph. We intersect this scale at 2, so that we know the turns ratio is 2:1. The secondary has the larger number of turns since it is a step-up transformer.

As a second example, we can start with a known primary to secondary voltage gain of 10 dB. We enter the nomograph on the left hand side at 10 dB, and going to the right on that horizontal line, we intersect the impedance ratio scale at 10, which means that the secondary impedance is ten times that of the primary. The turns ratio is found as in the first example and is slightly less than 3.2:1 (actually 3.17:1). The nomograph can also be used to convert voltage or current ratios into the dB equivalent.

TRANSFORMER FREQUENCY RESPONSE

Up to this point, we have assumed a perfect transformer. Since the perfect transformer does not exist, we have to consider how the actual transformer deviates from the ideal, and how this affects the circuits in which we employ it. The simplified equivalent circuit of an actual transformer with a 1:1 turns ratio is shown in FIGURE 3(A). Resistors R_p and R_s represent the d.c. resistance of the primary and secondary winding, respectively. L_m is a shunt inductance which is present due to the magnetizing current, i.e. that current which is required to produce flux in the core. This small amount of current needed to magnetize the core is 90 degrees out of phase with the load current, which is why it appears as a shunt inductance. The smaller the magnetizing current, the higher the value of L_m. L_s, or leakage reactance, is there because the coupling coefficient is less than unity, and represents the imperfect cancellation of inductive currents discussed above in reference to FIGURE 1(B). L_s is in series with the load current. The shunt capacitance C_s represents the stray capacity existing between the windings. The quantities R_p, R_s, L_m, and C_s, in conjunction with the source and load impedance, determine the band width of the transformer.

LOW FREQUENCY

If we consider the low frequency end of the band, we can further simplify the circuit by eliminating L_s, whose series reactance at these frequencies is negligible, and C_s, whose shunt reactance at these frequencies is very high. If we lump R_p and R_s with the generator and load resistance respectively, we have the circuit shown in FIGURE 3(B). The low frequency limit of the transformer response is determined by the following formula:

$$F_{LC} = \frac{\dfrac{R_G R_L}{R_G + R_L}}{2\pi L_M}$$

F_{LC} is the low frequency cut off where the response is the 3 dB down. At frequencies below the 3 dB point, the response rolls off at 6 dB per octave. As the generator or load impedance is increased, the low-frequency cutoff will increase and the low frequency response will be attenuated further.

If the transformer is to go down to very low frequencies with a given source and load impedance, then the core material must require as little magnetizing current as possible, which is equivalent to increasing L_m. The larger L_m, the lower the low frequency cut off.

HIGH FREQUENCY

At high frequencies, the reactance of L_m is large and we can ignore it in the transformer high frequency equivalent circuit. We also make the simplifying assumption that C_s is small enough to ignore so that we arrive at the high frequency equivalent circuit of FIGURE 3(C). The high frequency limit of the transformer is determined by the following formula:

$$F_{hf} = \frac{R_G + R_s + R_p + R_L}{2\pi L_s}$$

F_{hf} is the high frequency cutoff and the response is 3 dB down at this point. At frequencies above the 3 dB downpoint, the response rolls off at 6 dB per octave. In this circuit, as the generator or load impedance decreases, the

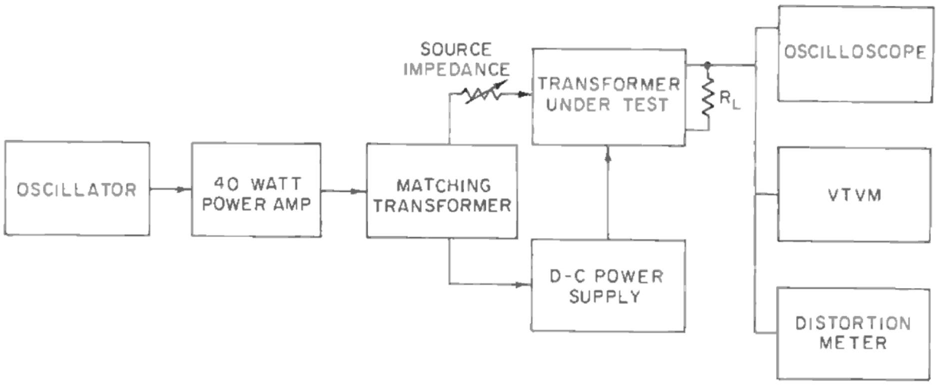

Figure 5. The transformer test setup as used at United Transformer Company.

high frequency cutoff will decrease and the high frequency response will be attenuated further.

TRANSFORMER EFFICIENCY

The effect of the primary and secondary d.c. resistance is to lower the transformer efficiency. FIGURE 3(D) shows the equivalent circuit as it relates to input/output efficiency in the midband. Part of the power intended for the load is dissipated in resistors R_p and R_s. When source or load impedance is below the rated value, efficiency will drop. Engineers at the United Transformer Company (UTC), one of the leading manufacturers of transformers, explained to me during a visit there that typical losses in a well designed transformer amount to about 1 to 1½ dB —or we can say that transformer efficiency is about 90 to 85 per cent. UTC design engineers stated that it is well within the state-of-the-art to build transformers with higher efficiencies, but that size and other economies dictate a compromise design with moderate losses.

MAXIMUM POWER AND DISTORTION

An important limitation on transformer operation is the allowable maximum power level. FIGURE 4(A) shows the output waveforms of an audio transformer in the midband at a level below its maximum capability. When the power level of the transformer is exceeded, the core will saturate (the change in flux is not directly proportional to changes in current) and cause distortion. For a given power level, the flux density increases proportionally as the frequency decreases, so that core saturation is more of a problem at the low end of the transformer pass band. FIGURE 4(B) shows the output waveform of the same transformer when the core is driven into saturation, and severe waveform distortion is evident. Therefore, as power level requirements increase, the amount of core material must increase. Very small transformers can only handle moderate power levels, while larger transformers generally are capable of larger power handling capacities.

TRANSFORMER TESTING

At UTC, a standard laboratory transformer test setup is maintained to check the quality of production items and to evaluate new designs. A block diagram of this test setup, which is used to measure response and distortion, is shown in FIGURE 5. An oscillator is the signal source, and the 40-watt amplifier provides power gain. The matching transformer is also used as a d.c. return path for the power supply which is available for those transformers operating with unbalanced d.c. A variable resistor provides the correct source impedance. Output measuring devices include an oscilloscope, a distortion meter, and vtvm.

A well designed transformer, that is, one designed with a sufficiently wide frequency range, operated below core saturation and properly shielded from hum pick-up, will provide smooth frequency response (equivalent to a high quality amplifier) and extremely low distortion.

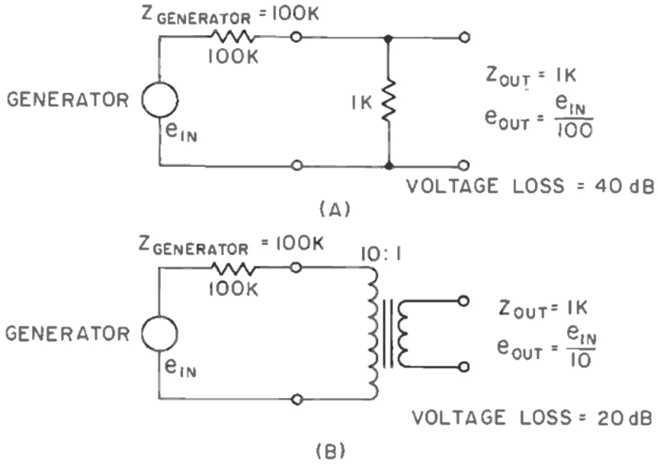

Figure 6. Impedance matching. At (A) a resistive network, and at (B) a transformer.

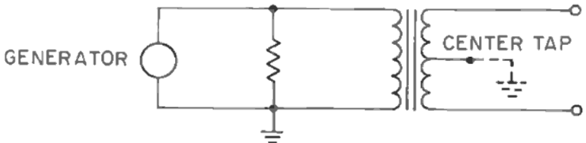

Figure 7. A transformer used for isolation.

EXAMPLES OF TRANSFORMER CIRCUIT APPLICATIONS

Gain. One of the most common uses of transformers is to step up voltage in a circuit. For example, some types of microphones have low output voltage and low output impedance. By using a step-up transformer, one having a primary-to-secondary turns ratio of 3.17:1, we can provide a 10 dB voltage gain. The secondary impedance will increase to ten times that of the primary impedance.

Impedance Transformation. Very often we wish to go from a high impedance circuit to a low impedance circuit. A transformer will accomplish this with the minimum possible loss. If we want to reduce the output impedance of the circuit shown in FIGURE 6(A) from 100 k to 1 k by means of a resistance network, the ouput voltage will be 40 dB down from the generator voltage. If we use a transformer with a primary-to-secondary turns ratio of 10:1 to change the impedance, then the output voltage will be down only 20 dB from the generator voltage (FIGURE 6(B)). By using a transformer for impedance transformation, we provide minimum voltage loss, and actually no power loss, at the low impedance output terminals.

Isolation. If we wish to isolate a circuit or a transmission line from ground, then the transformer, because it employs magnetic coupling, is an excellent choice. In the circuit of FIGURE 7 we have a signal source with respect to ground. If we wish to eliminate the ground reference, then a 1:1 isolation transformer is used. If we wish to provide a source which is balanced with respect to ground, then we can ground the center tap of the secondary. ■