how it works

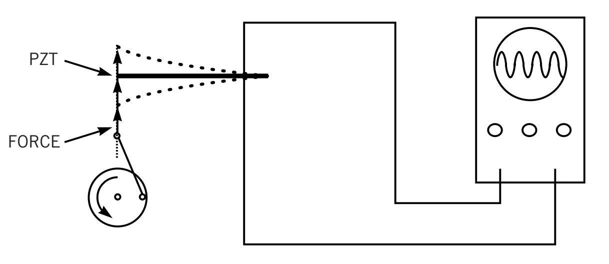
PIEZOELECTRIC "TRANSFORMERS" CONVERT ELECTRICAL ENERGY TO MECHANICAL ENERGY, AND VICE VERSA, TO PRODUCE HIGH-VOLTAGE AC AND DC OUTPUTS. DESPITE THEIR SMALL SIZE, THESE TRANSFORMERS PRODUCE VOLTAGES AS HIGH AS 7000V DC FROM A 5.5 TO 7V INPUT.

Piezoelectric transformers make good vibrations

Jim Phillips, CTS Wireless Components

A SOMEWHAT ARCANE AND little-known technology that relies on the piezoelectric effect is adding a welcome design alternative to the art of generating high voltages. The idea of a piezoelectric "transformer" is not a new one, but the complicated nature of the design, which requires some knowledge of electronics, mechanics, and materials, has taken 43 years to get right (**Reference 1**). The advantages of piezoelectric transformers are many: small size, no windings and thus no short-circuit capability between the windings, and the ability to generate a wide range of high-voltage ac or dc outputs. One immediate application of these transformers is for generating the high voltage that's necessary to run the cold-cathode fluorescent lamp of an LCD (see "A svelte beast cuts high voltage down to size" on pg 93).

Piezoelectric transformers are, in fact, not transformers. They have no wires or magnetic fields. A better analogy is that they are dynamos. The piezoelectric transformer works like a motor that is mechanically coupled to a generator. Understanding this concept requires a basic understanding of piezoelectricity.



NOTE: PZT=LEAD-ZIRCONATE-LEAD-TITANATE.

Figure 1

In the direct piezoelectric effect, an applied force or vibration results in an output voltage.

PIEZOWHAT?

Many materials, such as quartz, lithium niobate, and lead-zirconate-lead-titanate (PZT) exhibit some form of the piezoelectric effect. The piezoelectric transformer uses PZT, hence, it is a PZT transformer. Two piezoelectric effects exist: the direct effect and the inverse effect. With the direct effect, placing a force or vibration (stress) on the piezoelectric element generates a charge (**Figure 1**). The polarity of this charge depends on the orientation of the stress compared with the direction of polarization in the piezoelectric element. During the manufacturing process, poling, or applying a high dc field in the range of 45 kV/cm to the PZT transformer, sets the polarization direction.

The inverse piezoelectric effect is, as the name implies, the opposite of the direct effect (**Figure 2**). Applying an electric field, or voltage, to the piezoelectric element results in a dimensional change, or strain. The direction of the change is likewise linked to the polarization direction. Applying a field at the same polarity of the element results in a dimensional increase, and fields of opposite polarity result in a decrease. An increase in one dimension in a structure results in a decrease in the other two through Poisson's coupling, or the fact that lateral strain results in longitudinal strain at Poisson's ratio. This phenomenon is an important factor in the operation of the transformer.

The piezoelectric transformer uses both the direct and inverse effects to create high-voltage step-up ratios (**Figure 3**). A sine-wave voltage drives the input portion of the transformer, which causes it to vibrate. This operation is the inverse, or motor, effect. The vibration couples through the structure to the output to generate an output voltage, which is the direct, or generator, effect.

ALCHEMY AND BLACK MAGIC

The piezoelectric transformer is constructed of PZT ceramic, but more precisely it is a multilayer ceramic. The manufacturing of the transformer is similar to the manufacturing of ceramic chip capacitors. The process prints layers of flexible, unfired PZT-ceramic tape with metallic patterns, then aligns and stacks the layers to form the required structure. The next step involves pressing, dicing, and firing the stacks to create the final ceramic device.

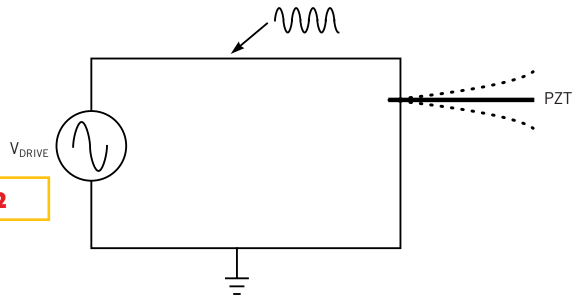
The input section of the transformer has a multilayer ceramic-capacitor structure (**Figure 4**). The pattern of the metal electrodes creates an interdigitated plate configuration. The output section of the transformer has no electrode plates between the ceramic layers, so firing produces a single ceramic output structure. Conductive material, which forms the output electrode for the transformer, coats the end of the output section.

The next construction step establishes the polarization directions for the two halves of the transformer. Poling of the input section across the interdigitated electrodes results in a polarization direction that aligns vertically to the thickness. Poling of the output section creates a horizontal or length-oriented polarization direction. Operating the transformer drives the input in thickness mode, which means that an applied voltage between the parallel plates of the input causes the input section to become thicker and thinner on alternate halves of the sine wave. The change in input thickness couples through to the output section, causing it to lengthen and shorten and thereby generating the output voltage. The resulting voltage step-up ratio is proportional to the ratio of the output length and the thickness of the input layers.

THE FUN PART

The equivalent circuit model for the piezoelectric transformer looks identical to that of its series-resonant magnetic counterpart (**Figure 5**). The differences, however, extend past the nominal values to the physical representation of the various components. The input and output capacitances are simply the result of having a dielectric between two metal plates. The effective dielectric constant of PZT material is 400 to 5000, depending on composition. At this point, unfortunately, basic electronics ends. The rest

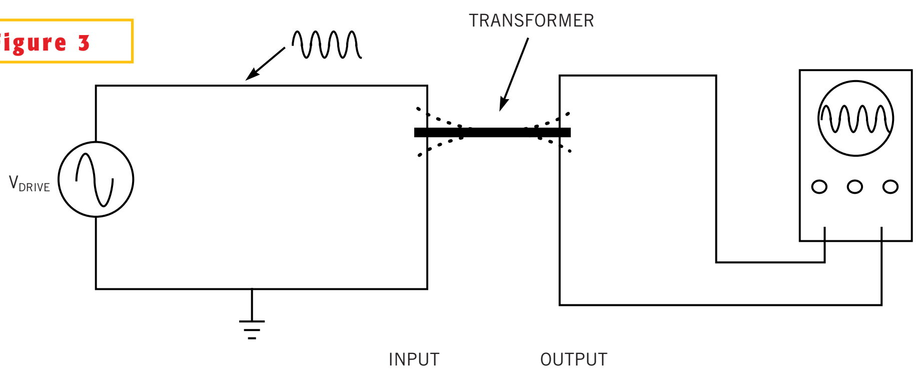
Figure 2



NOTE: PZT=LEAD-ZIRCONATE-LEAD-TITANATE.

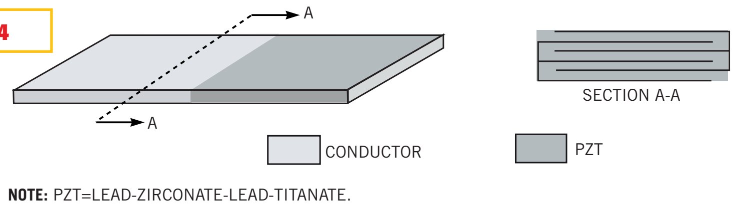
In the inverse piezoelectric effect, an applied voltage results in vibration or movement.

Figure 3



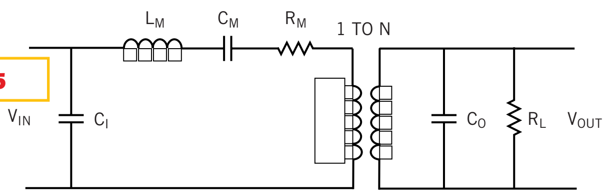
The piezoelectric transformer uses both the direct and indirect piezoelectric effects; an applied voltage results in vibration, which in turn generates the output voltage.

Figure 4



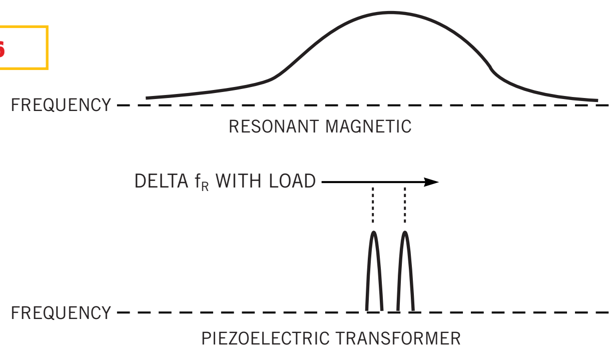
The piezoelectric transformer is a multilayer device consisting of PZT (lead-zirconate-lead-titanate) material.

Figure 5



The equivalent circuit model of the piezoelectric transformer looks like its magnetic counterpart, but many significant differences exist.

Figure 6



The bandwidth of a piezoelectric transformer is much narrower than that of a magnetic transformer.

of the components are more complicated. The inductance, L_M, is the mass of the transformer. The capacitance, C_M, is the compliance of the material, or the inverse of spring rate. Calculating the compliance requires using the applicable generalized beam equation and Young's modulus, which is a constant that expresses the ratio of unit stress to unit deformation. The resistor, R_M, represents the combination of dielectric loss and the mechanical Q of the transformer.

The acoustic, as opposed to the electrical, resonant frequency is related to the product of the capacitance, C_M, and inductance, L_M. The transformer operates in length resonance, and the associated motions are identical to those of a vibrating string. The major difference between a PZT transformer and a vibrating string is that the PZT transformer's frequencies are in the ultrasonic range and vary, by design, from 50 kHz to 2 MHz. Like the string, the transformer has displacement nodes and antinodes. Mechanically clamping a node prevents vibration, which reduces efficiency in the best case and prevents operation in the worst. Mounting the transformer is crucial; you simply can't reflow solder the device to a pc board.

The final element in **Figure 5**'s model is the "ideal" transformer with ratio N. This transformer represents three separate transformations. The first is the transformation of electrical energy into mechanical vibration. This transformation is a function of the piezoelectric constant, which is the electric field divided by stress, the stress area, and the electric-field length. The second transformation is the transfer of the mechanical energy from the input section to the output section and is a function of Poisson's ratio, or the ratio of lateral to longitudinal strain, for the material. The final transformation is the transfer of mechanical energy back into electrical energy, and the calculations are similar to those for the input side.

A RESONANT PERSONALITY

Resonant magnetic high-voltage transformers have an electrical Q of 20 to 30. The equivalent for the piezoelectric transformer is its mechanical Q, which exceeds 1500. This high Q is both good and bad. The ultimate efficiency can be very high, but the usable bandwidth of the transformer is only 2.5% that of the magnetic type. The resonant frequency depends on the compliance of the material, which, in turn, is a function of Young's modulus. An unusual property of piezoelectric materials is that Young's modulus changes with electrical load. In most, if not all, cases, the shift in resonant frequency over rated load is greater than the usable bandwidth (**Figure 6**). Thus, the piezoelectric transformer must operate at resonance to maintain efficiency and stability. The near-resonance designs for magnetic transformers work poorly, if at all, with piezoelectric transformers. Having tracking oscillators is a requirement.□

Reference

1. Rosen, CA, "Ceramic Transformers and Filters," Proceedings of the Electronic Components Symposium, 1956, pg 205.

Authors' Biography

Jim Phillips is a senior member of the technical staff at CTS Wireless Components (Albuquerque, NM). He has worked for the company for 23 years. In his current job, he directs piezoelectric research, development, and design. He has a BSEE from the Illinois Institute of Technology (Chicago). His spare-time interests include photography and antique cars.