50 Years of Piezoelectric Transformers. Trends In The Technology

Alfredo Vázquez Carazo
Department of R&D Engineering, Face Electronics, LC
427 W. 35th Street, Norfolk, Virginia 23508, U.S.A

ABSTRACT

The initial concept of a piezoelectric transformer (PT) was proposed by C.A. Rosen, K. Fish, and H.C. Rothenberg and is described in the U.S. Patent 2,830,274, applied for in 1954. Fifty years later, this technology has become one of the most promising alternatives for replacing the magnetic transformers in a wide range of applications. Piezoelectric transformers convert electrical energy into electrical energy by using acoustic energy. These devices are typically manufactured using piezoelectric ceramic materials that vibrate in resonance. With appropriate designs it is possible to step-up and step-down the voltage between the input and output of the piezoelectric transformer, without making use of wires or any magnetic materials.

This technology did not reach commercial success until early the 90s. During this period, several companies, mainly in Japan, decided to introduce PTs for applications requiring small size, high step-up voltages, and low electromagnetic interference (EMI) signature. These PTs were developed based on optimizations of the initial Rosen concept, and thus typically referred to as "Rosen-type PTs". Today's, PTs are used for backlighting LCD displays in notebook computers, PDAs, and other handheld devices. The PT yearly sales estimate was about over 20 millions in 2000 and industry sources report that production of piezoelectric transformers in Japan is growing steadily at a rate of 10% annually. The reliability achieved in LCD applications and the advances in the related technologies (materials, driving circuitry, housing and manufacturing) have currently spurred enormous interest and confidence in expanding this technology to other fields of application. This, consequently, is expanding the business opportunities for PTs.

Currently, the industry trend is moving in two directions: low-cost product market and value-added product market. Prices of PTs have been declining in recent years, and this trend is expected to continue. Soon (if not already), this technology will become a serious candidate for replacing the magnetic transformers in cost-sensitive applications. Currently, leading makers are reportedly focusing on more value-added products. Two of the key value-added areas are miniaturization and higher output power.

Piezoelectric transformers for power applications require lower output impedances, high power capabilities and high efficiency under step-down conditions. Among the different PT designs proposed as alternatives to the classical Rosen configuration, Transoner laminated radial PT has been demonstrated as the most promising technology for achieving high power levels. Higher powers than 100W, with power densities in the range of 30-40 W/cm2 have been demonstrated.

Micro-PTs are currently being developed with sizes of less than 5mm diameter and 1mm thickness allowing up to 0.5W power transfer and up to 50 times gain. Smaller sizes could be in the future integrated to power MEMs systems. This paper summarizes the state of the art on the PT technology and introduces the current trends of this industry.

HISTORICAL INTRODUCTION

It has been 50 years since the development of piezoelectric ceramic transformers began. The first invention on piezoelectric transformers (PTs) has been traditionally associated with the patent of Charles A. Rosen et *al.*, which was disclosed on January 4, 1954 and finally granted on April 8, 1958 [1]. Briefly after this first application, on September 17, 1956, H.Jaffe and Don A. Berlincourt, on behalf of the Clevite Companies, applied for the second patent on PT technology, which was granted on Jan. 24, 1961 [2]. Since then, the PT technology has been growing simultaneously with the progress in piezoceramic technology as well as with the electronics in general. Currently, it is estimated that 25-30 millions of PTs are annually sold commercially for different applications. Thus, the growth of the technology is promising and is expected to expand to many other areas as an alternative to magnetic transformers.

In attempt to be historically accurate, it is required to mention that the first studies on PTs initially took place in the late 20s and early 30s. Based on the research of the author of this paper, Alexander McLean Nicolson has the honor of being the first researcher to consider the idea of a piezoelectric transformer. In his patent US1829234 titled "Piezo-electric crystal transformer" [3], Nicolson describes the first research in this field. The work of Nicolson on piezoelectric transformers, recognized in several other patents [4], was limited to the use of piezoelectric crystals with obvious limitations in performance, design and applicability as compared to the later developed piezoceramic materials.

Piezoelectric transformers (from now on referred to as piezoelectric ceramic transformers), like magnetic devices, are basically energy converters. A magnetic transformer operates by converting electrical input to magnetic energy and then reconverting that magnetic energy back to electrical output. A PT has an analogous operating mechanism. It converts an electrical input into mechanical energy and subsequently reconverts this mechanical energy back to an electrical output. This mechanical conversion is achieved by a standing wave vibrating at a frequency equal to a multiple of the mechanical resonance frequency of the transformer body, which is typically in the range of 50 to 150 kHz. Recently, PTs operating at 1MHz and higher have also been proposed.

Piezoelectric transformers were initially considered as high voltage transformer devices. Two different designs driving the initial steps in the development on these "conventional" PTs were, the so-called Rosen-type PT designs and the contour extensional mode uni-poled PTs. Until early in 90s, the technology evolution was based on improvements in these two basic designs.

Although Rosen proposed several types of PT embodiments in his patents and publications, the name of "Rosen-type PT" currently refers to those PTs representing an evolution on the initial rectangular design idea proposed by C. Rosen in 1954, as shown in Figure 1.

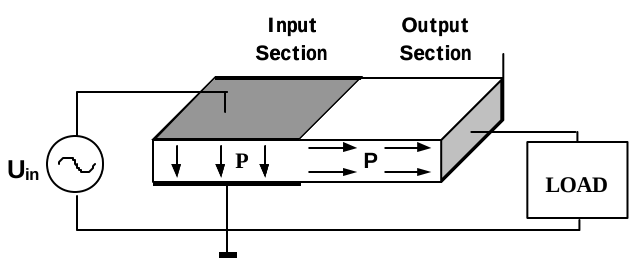

Figure 1. Basic structure of a "Rosen-type" piezoelectric transformer [1].

Thus, the "Rosen-type" piezoelectric transformers are step-up piezoelectric transformers vibrating in the longitudinal mode having thickness polarization in the input section and longitudinal polarization in the output section [5,6,7,8]. The Rosen-PT operates when an input electrical voltage having a frequency near to the resonance frequency of the PT. The deformation of the body in resonance also affects the output section, which it will develop a proportional voltage between the output electrodes. In Rosen's initial proposal, the PT consisted of a single ceramic body having input and output electrodes with thickness and longitudinal polarization directions. Currently, most PTs are manufactured using multiple layers co-fired together for the input section (multilayer input section), in order to reduce the operational voltage.

Coming to the next design, the unipoled circular PT vibrating in the contour extensional mode is based on the Jaffe and Berlincourt idea [2]. Figure 2 shows (left and center) shows two basic designs of these PTs. Other embodiments on this idea were proposed by Berlincourt in 1973 [9] and in other additional works [10]. Recently, work on unipoled PTs for high voltage application has been also carried out by Laoratanakul et *al*. [12].

Although initially designed for step-up voltages, the contour type PT has been recently reconsidered for step-down applications also, by using the low input impedance section as the output section. This will be discussed later in this paper.

During the 70s, PTs were considered as potential replacement for magnetic transformers in commercial applications. Several US and Japanese companies, like RCA Corporation [13], Motorola [14], Denki Onkyo Limited [15], and Matsushita [16], used PTs for generating high voltage required by the cathode-ray tube in black and white television receivers. Several attempts were also reported for using piezoelectric transformers as igniter in gas-based stoves (Matsushita [17]), in small engine applications (Briggs & Straton [18]) and in automobiles (Nippon Soken [19]. In the 80s, Siemens [20] and General Electric, were among other companies, which worked on the application of PTs for triggering power switch gates such as triacs, thyristors, Mosfets, etc, with galvanic decoupling.

Initially, these PT applications suffered from serious instability and device failure problems related to: (i) *immature materials fabrication technology*, (ii) *mechanical reliability problems in the nodal point* (iii) under developed *driving circuits*. Because of these problems, none of the above-mentioned applications achieved success and several additional years were required until the ceramic technology and electronic components were ready to provide reliable solutions using PTs.

The biggest step in achieving commercial success was taken in the late 80s. Several Japanese companies, including NEC, Tokin, Tamura, Matsushita, and others, made a revision to the concept of PTs, taking advantage of the improvements of novel piezoelectric materials, more reliable manufacturing technology including multilayer co-fired processes, new concepts on

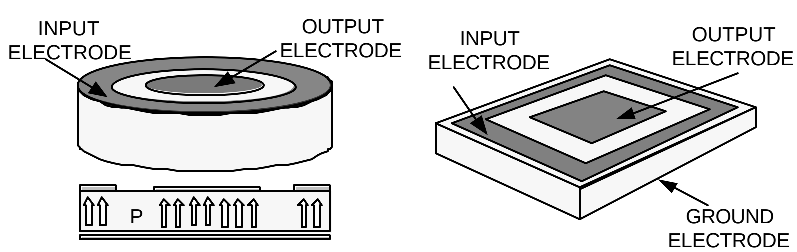

Figure 2. Contour extensional – unipoled - piezoelectric transformers [2,10]

integrated circuits, and housing solutions. The target of these companies was to develop a low-profile product as an alternative to electromagnetic transformers for customer applications requiring high voltage and low power. The main application was focused on transformers for backlighting CCFLs (cold cathode fluorescent lamps) for liquid crystal displays (LCD). During the 90s, CCFL technology enjoyed a significant boom as the preferred technology for compact, portable devices. Piezoelectric transformers started then to become preferential technology to provide a very compact solution to backlight the LCD displays. This stirred the market outlook on PTswith the market expansion of lap top computers and similar LCD display using portable devices such as PDA, digital cameras, camcorders, and other.

During this period many patents were issued on modifications of the initial concept of C.A.Rosen, including driving circuits, mounting solutions, and novel materials to enhance the performance of these devices. From a commercial standpoint, unipoled piezoelectric transformers did not succeed in high voltage LCD applications due to the larger operational area related to its design, thus larger space required. Additionally, step-up voltage levels obtained with this type of PT was lower compared to the longitudinal Rosen-PT. This was due to the better form-factor of the Rosen-PTs which allows for a long and thin PT for the CCFL inverter.

Currently, many Japanese laptop manufacturers, including Toshiba, NEC, Hitachi, Panasonic, and others, are using this technology. In these applications the choice of transformer depends on several factors including cost, size, and efficiency. Piezoelectric transformers can be thinner, lighter, and more efficient than magnetic transformers. Additionally, PTs have the advantage of inherent sinusoidal operation, high strike voltage, non-flammability, and no electromagnetic noise. Consequently, PTs offers a more compact alternative to magnetic transformers in many commercial applications. Figure 3 shows some commercial piezoelectric inverters for CCFL.

The significant evolution in the know-how on the PT technology in the last decade has inspired research on many applications related to this technology. The trends in the technology are now toward the use of PTs for power applications. In the last decade, different types of power PTs designs have been reported mainly under the efforts of two companies: NEC in Japan and Face Electronics in U.S. Other groups in Europe and Korea, with alternative proposals, seem to be following these tendencies toward power applications.

The features of PTs have recently gained the interests of space and military agencies, such as NASA and DARPA, which currently are supporting research to apply PTs to the new generation of small satellite.

This paper provides an overview of the different aspects of this technology that have driven this evolution and summarizes the trends of the technology based on the latest developments in this area.

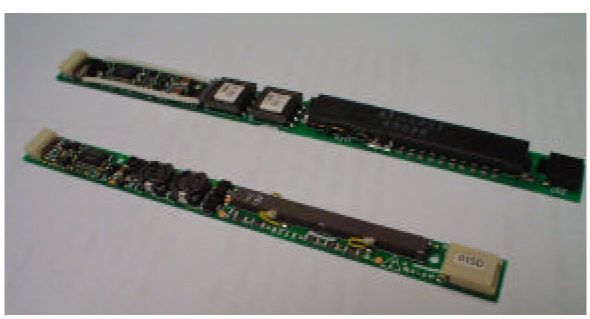

Figure 3. Commercially available piezoelectric inverters for CCFL applications.

TRENDS IN THE PIEZOELECTRIC TRANSFORMER TECHNOLOGY

Development of Driving Techniques for PTs

Piezoelectric transformers are narrow band devices that have to be operated close to the resonance frequency. In this operation, the driving circuit design must take into account that PTs are frequency and load dependent devices. Under these conditions, the PT operates in a window having the higher efficiency condition. Practically, the selected driving frequency is chosen slightly higher than the resonant frequency. There are two reasons for this selection: (i) the maximum efficiency is achieved at a frequency slightly higher than the resonant frequency and (ii) the control of the transformer is easier in the inductive window (above resonance).

This frequency and load dependence can be easily evaluated by plotting the output voltage against frequency curves for different output loads, as shown in Figure 4, where also is represented the inductive window above resonance where maximum efficiency is achieved. Due to this double dependence, transformer ratio and efficiency are strongly dependent on frequency control, load fluctuation and input voltage variations. Consequently, in order to ensure stable operation of the PT, the driving circuit has to correct the influences of these electrical variables. The implementation of a compact and reliable controlling circuit using discrete components is complex and, thus has discouraged many researchers from entering this field.

Two major developments have been introduced in the driving techniques for PTs in the last decade which have significantly enhanced the commercial success of PTs: (i) use of resonant converters topologies for driving the PTs, (ii) use of integrated IC circuits providing a compact set of control features for the PT application.

Resonant converters were originally considered in the early 90s as an extension of the general approach undertaken in Power Electronics to use high frequency switching circuits to minimize the size of dc-dc and ac-dc converters. Numerous efforts were undertaken in this area mainly with magnetic components [21]. In general, to drive a PT, either a sine wave or a square wave voltage can be used. In general, a sine wave voltage is preferred for minimizing the circulating energy through the shunt input capacitance Cd1 characteristic of the input of PT. However, generating a sine wave requires more reactive components in the converter than generating a square wave. With resonant converters, the sine input waveform is generated by using a square wave voltage in combination with some technique to minimize the switching loss. Such a combination is the so-called Zero Voltage Switching, ZVS [22]. The combination of the ZVS techniques and the PT can reduce the capacitive turn-on loss due to the input capacitance Cd1 of the PT, and achieve high efficiency. Figure 5 shows some of the standard topologies currently used to drive PTs, including push-pull, half-bridge and Class-E. From all of them, the standard approach used for step-up applications has been the push-pull topology, since it allows higher step-up ratios than half-bridge and, also has a simpler driving control circuit for the transistors' gates. However, half-bridge and Class-E are currently being evaluated for PT for power applications.

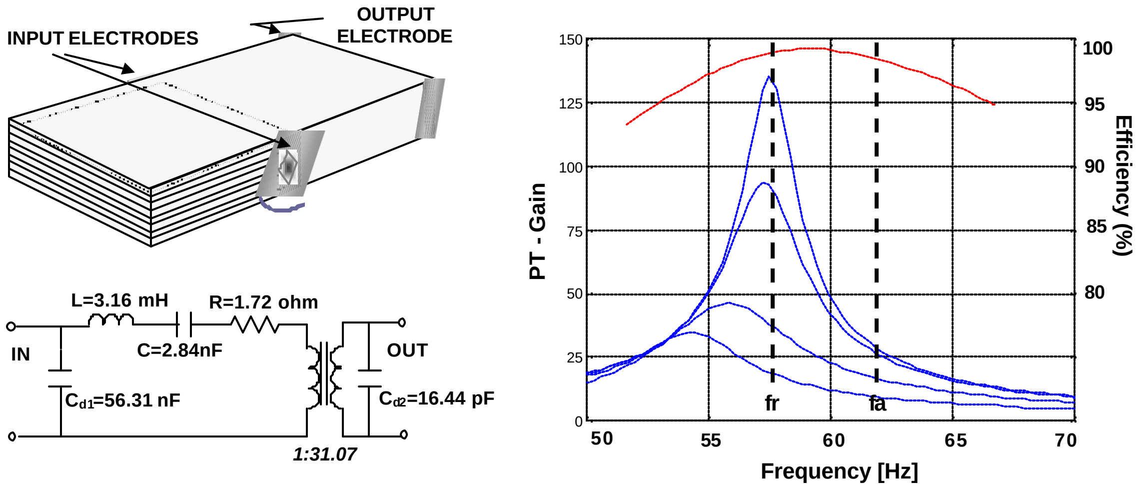

Figure 4. Equivalent circuit for a PT and frequency and load behavior.

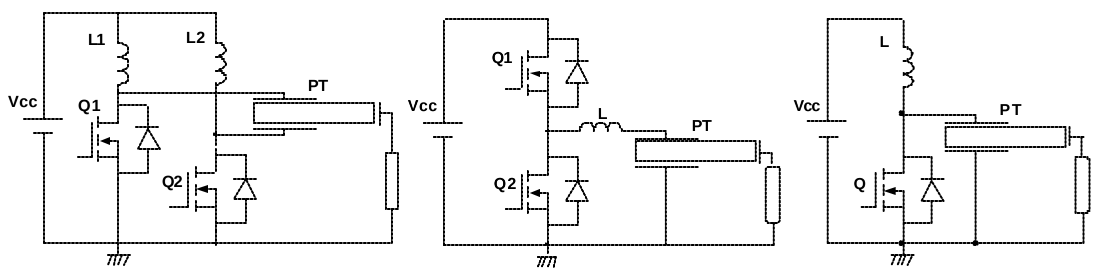

Figure 5. Piezoelectric transformer driven using push-pull (left) and half-bridge (center) and Class-E (right) topologies

In order to ensure the ZVS conditions and to maintain the stability of the converter under load and input voltage fluctuation, strategies for controlling the PTs have been developed since 1995. Initially, the first control circuits were designed as fixed frequency oscillators near the resonant frequency. However, due to the high Q of the PT changes in the resonant frequency due to aging, temperature, load variation, or input voltage cannot be compensated. This, of course, affect negatively the performance of the PT. Currently, the control of the PT is accomplished by using feedback tracking circuits which ensure the stability of the output voltage or current as well as high transformation efficiency under fluctuations of load or variations of input voltage. The natural way to control the operation of the PT is to vary the frequency accordingly to load changes or the input voltage. This control is called "frequency control". The frequency control requires one or several feedback loops which provide information about the output and how the output voltage (or current) is changing so it can be appropriately corrected. There are several possibilities that have been proposed:

i) frequency control by measuring the output voltage
ii) frequency control by measuring the output current (Figure 6, left)
iii) frequency control by measuring the Phase Difference between input voltage and current
iv) frequency control by measuring the input to output phase difference (Figure 6, right).

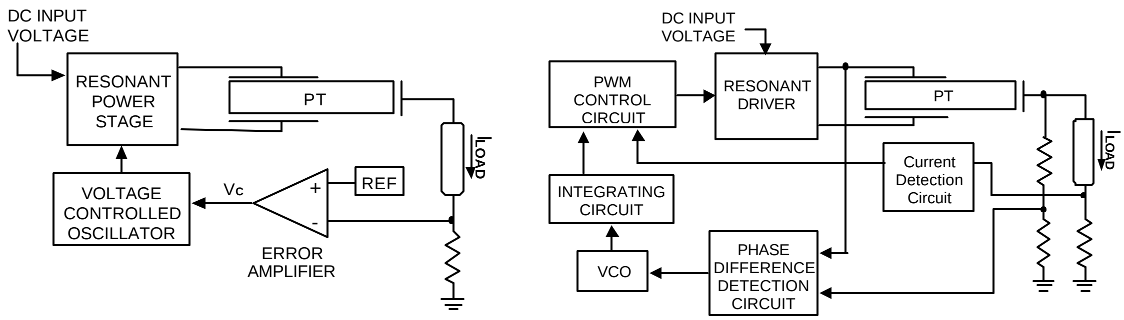

Figure 6. Different tracking control schemes for piezoelectric transformers: (right) based on measuring the output current; (left) based on the input to output phase difference.

The use of a single frequency loop cannot ensure the perfect control of the PT under big variations of input voltage and/or load fluctuations. When this happens the frequency shift required in the transformer to adjust the output conditions may be so large that the efficiency of the PT is significantly affected or/and that the correct transformation ratio to achieve the expected values is not possible. In order to overcome these limitations, a second voltage feedback loop control has been typically added in the latest driving control strategies. The voltage feedback has been implemented in two basic ways. One alternative that has been proposed controls the duty cycle of the driving circuit signal of the transistor gates. The second alternative includes the control of the input DC voltage by using a chopper circuit controlled at much lower frequency than the PT (for instance 100Hz), which switches the input voltage to the switching transistor.

These control strategies have been implemented in a compact integrated ICs also including dimming control, over-voltage, and short-circuit protection capabilities. Nowadays, different companies such as Rohm (BA9802 [23]), Sanyo (LA5663V), Texas Instrument (UCC3975 [24]) among others have commercial ICs ready to fully control PTs. The existence of ICs which allow the design engineer to more simply and reliably control the PTs will increase the number of applications in this area.

Power Piezoelectric Transformers

In the last decade, the interest in PTs has moved toward a second group of applications beyond the use in CCFL backlighting. Companies in U.S, Japan, and Europe are now investigating the use of PTs for power applications, including battery chargers, linear and compact fluorescent ballasts, DC/DC converter, power supplies, automotive applications, and others. In these applications it is not sufficient to improve single components, but also the overall system, including manufacturing, EMI issues, flatness, overall size, efficiency and functionality. In these applications, compared to the CCFL, the requirements include i) step-down transformers, ii) high power transformers, iii) high efficiency power conversion, iv) low output impedance, v) input to output isolation and v) low content of EMI. New topologies of PTs have been proposed to address higher levels of power conversion than those available with the classical Rosen type PTs (typically use for 5-8W with power densities of about 5-10W/cm^3).

One of the first research efforts on power PTs was undertaken in 1966 by O.M.Stuetzer [25] of Sandia Laboratory. In his publication Stuetzer analyzed the power capabilities of a PT consisting of two thin piezoelectric discs bonded to opposite sides of a metal wall and operating in the thickness mode. In spite of this earlier and mainly theoretical study, PTs were not seriously considered again for power applications until the 90s. The reasons could be the same as mentioned earlier, lack of electronics for driving these applications, lack of appropriate manufacturing techniques for developing such a PTs, etc.

Early in the 90s intense work was re-initiated in Japan by NEC on the same concept of thickness mode PTs (Table I.a) and its applications for power applications. Some of the proposed designs included a 1 to 2 mm thickness discs having a input and output multilayer section and operating at very high frequencies on the order of 1MHz or higher [26-28]. T. Inoue, O. Ohnishi and Yasuhiro Sasaki, among others, hold several of the patents on thickness mode PT [29, 30] designs recently proposed. Simultaneously with the development and improvement in the PT designs for power applications, work was published on circuit strategies to drive the PTs on power applications up to 20W. This is the case for the work performed by Zaitsu and Lin [31,32], also from NEC.

Late in the 90s, NEC switched the research on power PTs to a different type of PT. The reason was the low efficiency levels achieved with the thickness mode PT due to the power loss generated by circulating current. A different alternative to power PTs was proposed a few years later also by NEC as illustrated in Table I.b and I.c. The longitudinal vibration mode transformer [33, 34] operates typically at frequencies in the range of 100 kHz. However, the efficiencies levels shown with this type of PT were also limited.

In 1996, Face Electronics in U.S invented a new concept of power PT based on a radial mode piezoelectric transformer (Table I.f), Transoner® (registered name by Face Electronics) [35]. Power density, design flexibility, manufacturing simplicity and toughness of the Transoner have resulted in this design becoming the reference for power applications in many research publications. During the late 90's and early 2000, Face and Virginia Tech applied Transoner to drive linear fluorescent lamps [36]. The outcome of the research project was a new inductor-less concept to drive piezoelectric transformers. With this new driving concept, the requirement of

Table I. Different configurations of power piezoelectric transformers.

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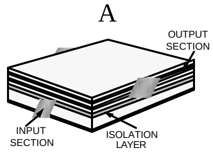
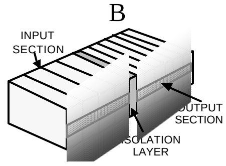
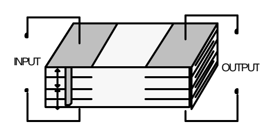
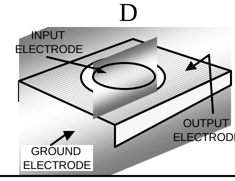
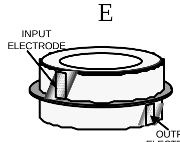
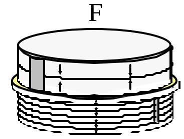
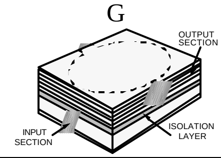
				
Vibration Mode	Thickness	Longitudinal	Longitudinal	Contour
Polarization	Unipoled: Thickness	Unipoled: Longitudinal	Unipoled: Transversal (Thickness)	Thickness
Resonant Freq.	1MHz	50-150kHz	50-150kHz	50-150kHz
Research	Japan, NEC, 1992	Japan, NEC, 1995	Japan, NEC, 1995	Korea

	E	F	G
			
Vibration Mode	Thickness	Radial	Contour
Polarization	Unipoled: Thickness	Unipoled: Thickness	Unipoled: Thickness
Resonant Freq.	400kHz	50-250kHz	50-250kHz
Reseach	Europe, Noliac, 1998	USA, Face, 1996	Japan, NEC, 1997

using magnetic components in series with the PT for achieving Zero Voltage switching conditions was eliminated. Other authors have been working on this idea and several papers have been published lately. Transoner PTs have demonstrated power capabilities up to 100W and are expected to reach 200W with material and design improvements in the near future. The power density demonstrated for this PTs exceed 40W/cm^3 currently. At this time, Transoner is the only power transformer available commercially.

Simultaneously, other designs have been considered as a power PTs. Several research groups in Korea [37] have re-considered the initial uni-poled PT developed by Berlincourt in late 60s (see Historical Introduction) and considered them for step-down applications (Table I.d). Early in 2000, NEC also published work on a piezoelectric-transformer operating in contour-extensional vibration mode (Table I.g). This transformer uses a similar approach as the Face's radial piezoelectric transformer, Transoner. NEC approach uses a square geometry with an internal radial electrode.

In Europe, work has been undertaken on power piezoelectric transformers. Alcatel, Ferroperm and several Spanish universities, collaborated in the development of a piezoelectric AC/DC converter for mobile phone battery chargers. The design is based on a ring-shaped element operating in thickness vibrational mode (Table I.e), where the primary and secondary sections are separated by and isolation layer [38].

Piezoelectric Transformers for Space Applications

On of the most recent fields where the PT technology may have a significant role is in space application. NASA and the DARPA are currently funding three research projects with Face Electronics for developing PTs to be applied in the satellites of the future. The benefits delivered by the PTs include size, weight due to the higher power density compared to magnetic transformers, make of this technology unique for space applications. The areas of development include:

- High voltage piezoelectric-based power supply to drive the main payload of satellite communication systems, the Traveling Wave Tube (NASA) [39].
- Development of a Power Distribution system using piezoelectric transformer technology for small satellite applications (DARPA) [40].
- Development of new integrated ignition systems for small satellite thruster by using piezoelectric transformer technology. These new piezoelectrically controlled igniters will optimize the combustion efficiency while reducing the size as compared to the systems based on magnetic or capacitive ignition (NASA) [41].

Other applications using PTs

Several publications have been recently made for using piezoelectric transformers to isolate feedback circuits [42,43] as well as for driving the gate of MOSFET transistors while providing isolation [44]. This topic was initially considered in the 80s and now is re-gaining interest again with innovative technologies. Piezoelectric transformers provide an excellent isolation means, at the same time provide power and signal transfer to drive the gate of transistors. Figure 7 exemplifies the use of PTs for control of the gate of a MOSFET. In this case, the control gate signal is modulated to the resonance frequency required for driving the PT. In the output of the

PT a demodulator circuit, which may consist of a rectifier circuit, converts the signal back into the input control signal.

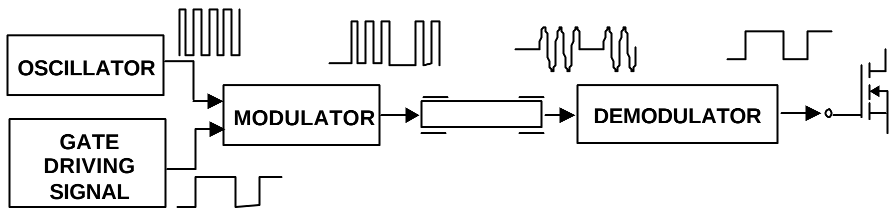


Figure 7. Piezoelectric-based isolated circuit for feedback or Gate driver applications [20,44]

CONCLUSIONS

The total sales per year for PT for CCFL-based applications is estimated to be 25-30 millions, with the maximum production still located mainly in Japan. The growth in PT sales is increasing and novel applications being to be commercially proposed although still in the high voltage field (ozone generator for medical, sanitary and beauty related applications and air cleaners). Manufacturers in China, Taiwan and Korea are beginning to seriously look for a place in this field, which will bring competition and should result in significant reduction in costs.

Simultaneously, new applications for PT are increasing with the commercialization of compact IC driven circuits that provide a valuable tool to the design engineer expert on PTs. This is especially relevant in power electronic applications for portable and compact devices up to 100W. The success of PT as an alternative to magnetic transformers in this field is forecasted in sales at the billion dollar level.

In the U.S the classical magnetic transformer is still the main product used, although interest in PT technology has significantly increased. Laptop computer companies have started to consider this technology in their new models. Also military and space agencies are considering piezoelectric devices as the appropriate technology for power supplies for small satellites of the future.

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