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POWER ELECTRONIC DEVICES BASED ON PIEZOELECTRIC ELEMENTS: CURRENT STATE AND PERSPECTIVES

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Summary. *The analysis of existing designs of piezoelectric elements, methods of calculation and electrical circuits connecting held systematizing technical solutions in the design and use of power electronics devices based on them are given.*

A comparative analysis indicated the advantages and disadvantages of structures and noted the priority and promising areas of development in electronics, fundamental circuits operate the piezoelectric element in optimal conditions.

Based on analysis of information sources there was given a list of applications of piezoelectric transducers and their advantages compared to traditional technical solutions.

Keywords: *piezoceramic, piezoelectric transducer, piezoelectric transformer, piezo-semiconductors management, Start-control electronic apparatuses.*

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Problem setting. Modern demands to electro-technical devices according to energy-saving requirements, miniaturization and interoperation with controlling computer systems require interaction with piezoceramic producers to search for technical decisions in the sphere of electronic devices on the basis of piezoceramic and ferroelectric materials.

Currently piezoceramics are used in the ultrasonic diagnostic equipment in medicine, air and train transport, power engineering, oil and gas rigs; power piezoceramics are also used in the ultrasonic welding, surface refinement, coating, and mechanic processing of materials etc.

As the result of scientific and research work there appear new piezoceramic types, already known constructions of piezoceramic elements and components are being created and upgraded.

The mentioned-above facts require the systematization of techniques in the area of piezoelectric components application, identification of their development trends, prospect directions of scientific and engineering innovations in this sphere.

Analysis of available piezotransformers' design. Peculiar attention is paid today to the piezoceramic transformers (PT) and actuators (piezodrives particularly), whose operation principles are as follows.

While feeding at input electrode (actuator) of changing voltage PT by means of reverse piezoeffect in piezoelement, the mechanic vibrations appear with the frequency of applied stress, and on the output electrodes (generator) PT by means of direct piezoeffect the AC voltage emerges. The connection between activator and generator is mechanical. PT operation frequency is determined by its geometric dimensions, and also by parameters of piezomaterial itself.

The piezotransformer includes not less than three electrodes with the thickness 10…20 μm on the piezoelectric plate surface.

An input electrode is assigned to feed the voltage with the frequency of PT mechanic resonance.

There are mainly used PT, constructions of which are shown on figure 1, and their design – on figure 2.

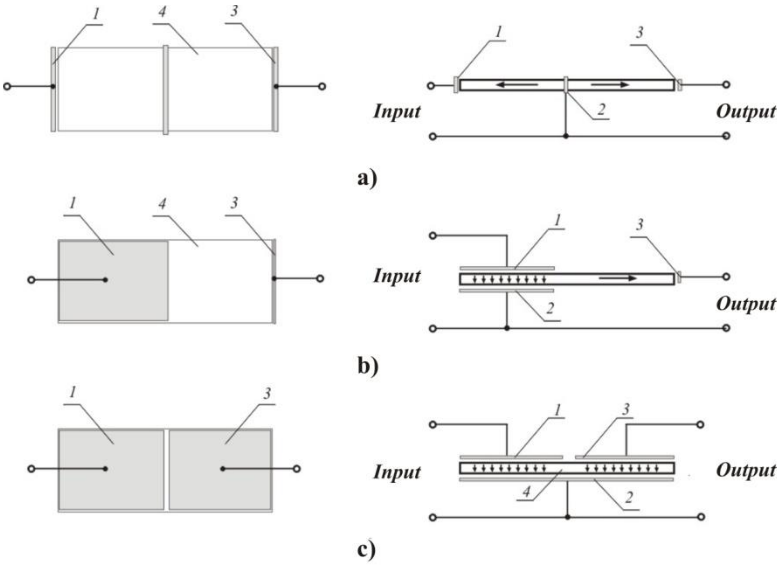

Figure 1. Piezoelectric transformer structures: a) longitudinal - longitudinal type b) transversely - longitudinal type, c) transversely – transversal type

The PT with the lengthwise type generator (fig.1, a) is called voltage piezotransformer (VPT), transformation voltage coefficient for which exceeds 1000.

The transformation coefficient according to the voltage in PT of cross diametrical transversal type (fig. 1, c) during operation mode does not exceed 10, but they can work at considerable load currents (up to several amperes), that's why they are called current piezotransformers [1].

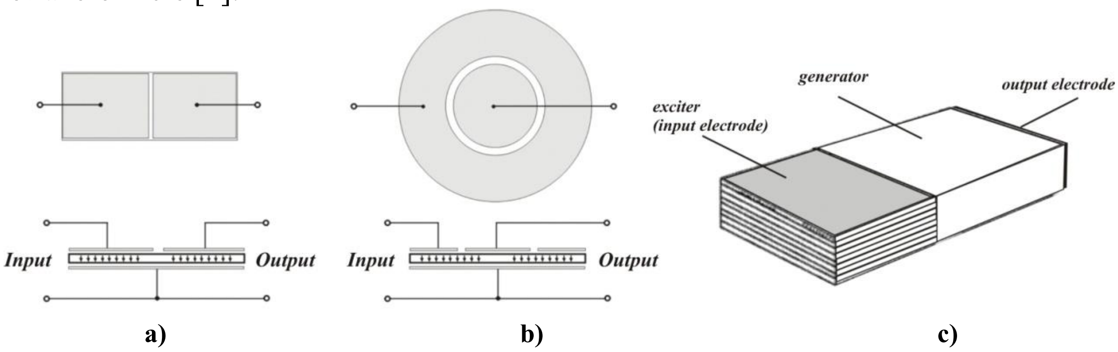

Figure 2. The piezoelectric transformer forms: **single-layer** (rectangular or square plate (a) disc-type with electrodes in the form of concentric circles (b)); **multilayer** (multilayer piezoelectric transformer of voltage (c))

A disk-type piezotransformers are mainly used as impedance transducers, measuring of physical values or as current transformers.

One-layer PTs are the devices of rectangular or round shape, in which input and output sections are polarized in terms of thickness, and which use vibrations of the 2nd or 3rd mode. Their power specific capacity maximum is 0,5-1,0 W/cm^2, and the PT power load under optimal weight and dimensions of transducer don't exceed 20 W. Such piezotransformer thickness is 1…1,5 mm, and, as the result, the long-term modes that are close to open circuit operation and electrical fault can result in its fracture due to considerable mechanic stresses in the piezotransformer plate. This appreciably limits the operation area of one-layer PT according to the power and operation conditions [2].

Lately the industry manufactures principally new piezotransformers – **multi-layer** ones. The construction of multi-layer voltage piezotransformers includes several thin piezoceramic layers with the thickness 100-200 microns, and also platinum or platinum-palladium electrodes (fig. 2, c), which creates PT entering section (actuator). The activator plates are polarized on thickness, and outputs are connected to its verge electrodes where input voltage is loaded. From electrodes of PT input section, which is polarized longitudinally, the output voltage is measured. Such construction provides higher power specific capacity up to 40-50 W/cm^2, that allows decreasing the piezotransformer dimensions in 3-5 times in comparison with their one-layer constructions.

The piezotransformer input section design in form of the multi-layer structure allows increasing the inducement coefficient according to the voltage to the values of several dozen units with the efficiency output $\eta > 90\%$. Here, multilayered piezotransformer's input resistance is decreasing to dozens of Oms; it facilitates the transmission of considerable power from piezotransformer input to output at little value of input voltage amplitude. Taking into consideration these advantages, multilayered (9 layers) PT of piezoceramic materials CTBS-8, with dimensions (mm) 35x5x2 and 20x4x2 are already produced in series [3].

The main advantage of multilayered piezotransformers in comparison with one-layer ones, as they say, is their smaller size (especially thickness) and higher efficiency output.

In the literature sources there also is available the information about **cylindrical piezoelectric transformers** with two sections of generator electrodes and two pairs of activator electrodes, every of which is in-fed with electric signal with its frequency and electrical angle [4].

The outer and inner cylinder surfaces have sputtered electrodes. An inner electrode are common, and on the other hand, the outer one is divided in axial direction by cuts into electrically unbound parts (fig. 3). Such piezotransformer generator electrodes (θ_0; $-\theta_0$), (φ_0; $-\varphi_0$) are connected to electronic device with perpetual (few dozen MΩ) input resistance ("open circuit operation" mode).

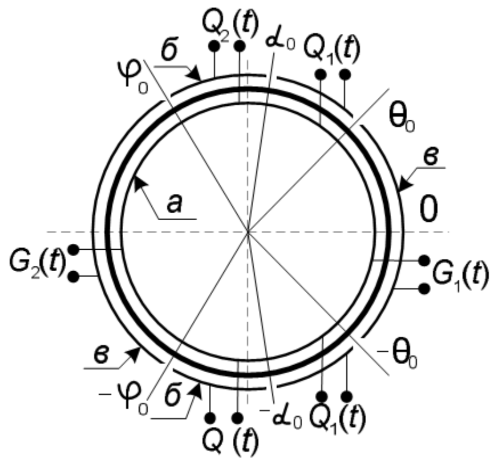

Figure 3. Location of electrodes on cylindrical piezoelectric transformer (end view), a – internal bond electrode; b – exciter electrodes; c – the oscillator electrodes

The cylindrical piezotransformers are used in the hydro acoustic transducer constructions, they are oscillation system, which works in the frequency wide range from hundreds Hz to several MHz.

In some issues the description and calculation of PT **of hybrid multilayered structure magnetic piezoelectric** were made [1], the construction of which is shown on fig. 4.

Such construction is a piezotransformer with input sections of ME-composite (PMNPT and Tergenol-D) and output section of mono-crystal PMN-PT. The input section length is marked as *l*, *l'* – the output section length, h_m, h_p – section thickness, *W* – section width, *H* – the direction of applied magnetic field stress (fig. 4).

A magnetic field, that is created by coil around primary section, produces mechanic stress in the magnetostriction's component and in primary piezoelectric section. Later, acoustic vibrations are transmitted into secondary section via front surface of input section PMN-PT. In the latter, as the result of direct piezoeffect, voltage is generated. The outputs of input section (L-T- regime) are joined and ME-stress on the primary section doesn't appear [5]. The polarization direction of input and discharge sections is marked as P.

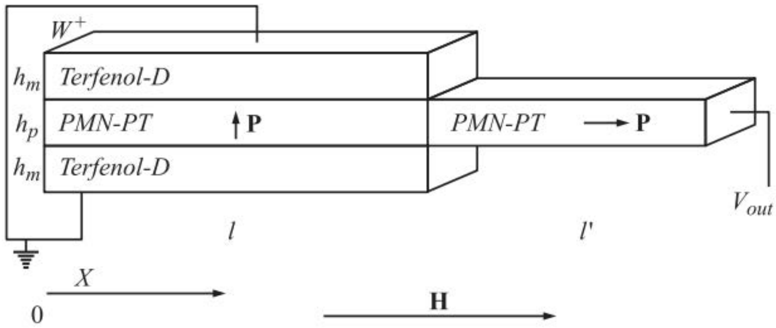

Figure 4. The design of the ME-piezoelectric transformer

Device parameters, that are described above, can be adjusted with magnetized field due to magnetostriction primary section properties. The identification of piezomagnetism in the primary section is carried out faster than polarization processes or piezo module changes under the electric field action that is used for the properties adjustment in standard piezotransformers [1, 2]. These things open new possibilities for changing of ME-properties of device, the achievement of the biggest directed ME-coefficient and the voltage amplification in the wide boundaries.

The piezoelectric availability in the sections gives the ability to adjust both the transformer properties and the electric field.

The objectives of the article are:

- to generalize the calculation methods of piezoelectric transformers;
- to systematize the construction design of high frequency electric transducer similarly to piezotransformer base;
- to determine priority and perspective directions of their development and application.

Task setting. To accomplish the given task is necessary:

- to analyze and estimate the accuracy of the piezotransformer calculation methods taking into account their constructive peculiarities;
- to determine PT operation modes parameters and scheme peculiarities to regulate the high frequency transformers' operations;
- to systematize constructive peculiarities of output cascades of piezo-semiconducting operation circuits;
-to estimate the prospects of power electronic devices on the basis of PT in the real technical systems.

The methods of piezotransformer calculation analysis

The piezoelectric transformer is a thermodynamic system with split parameters where the processes are described by the system of electro-mechanic equations that was suggested in [1, 2].

A immobile modes of harmonic oscillations with the frequency being close to the electro-mechanic resonance frequency can be described with the equation system in one of the next options:

$$S=s^{E}T + d_{t}E; \qquad D=dT + \varepsilon^{T}E; \tag{1}$$

$$S=s^{D}T - g_{t}D; \qquad E=-gT + \beta^{T}D,$$

and also with the wave equation

$$\rho_n \left(\partial\zeta^2/\,\partial t^2\right) = \partial t/\partial x, \tag{2}$$

which determines the dependence between forces and oscillation velocity in the elementary volume of piezotransformer. Here:

T – mechanical stress;
E,D – electro-magnetic field voltage and induction, correspondingly;
S – elastic strains;
β^{T}, ε^{S} –dielectric steels;
s^{E},s^{D} – elasticity modules;
ζ – particles' displacement in piezoplate body;
ρ_n – piezo-material density;
x – coordinate.

The steady-state modes' parameters of harmonic oscillations in the area of PT electro-mechanic resonance are received after integration of equations (1) and (2) taking into account marginal conditions under the harmonic signal action on PT. To simplify the calculations the assumption about constants independency is made that are included into equation (1) starting from the level of input voltage and single-module character of plate mechanic vibrations mode.

This allows eliminating them to the linear equations and building of electro-mechanic PT substitution on the basis of electro-mechanic analog method.

The electro-mechanic analog method

The basis of the method [1, 2] is the statement about the analogy between the components of mechanic and electric systems, when the transition from the analysis of thermodynamic system with split parameters to electric circuit with focused parameters *R, L, C* occurs. The last ones are determined via piezotransformer's dimensions and the piezo-material's constant. There was also imposed the supposition about the electric circuit parameters' independence from the frequency in the narrow area of resonance frequencies.

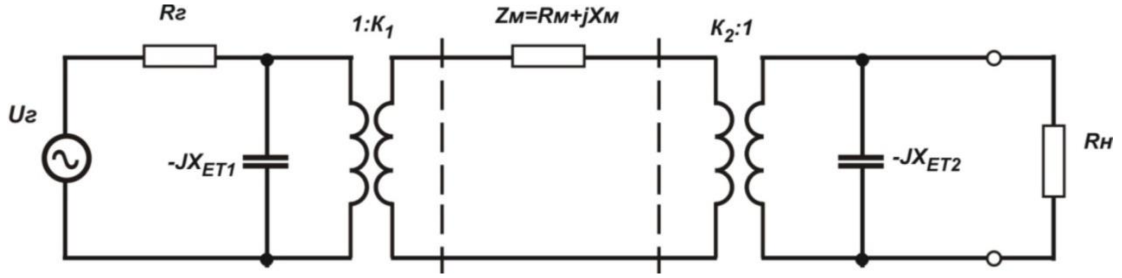

Figure 5. PT equivalent circuit of transversely – transversal type

The circuit contains input electro-mechanic transducer, which includes capacitive resistance of PT input section (actuator) X_{ET1}, ideal transformer with the coefficient of transformation K_1, mechanic transducer MT that is mechanic node of the circuit, as well as mechanic-electric converter, which includes capacitive resistance of PT output section (generator) X_{ET2} and ideal transformer with the transformation coefficient K_2.

The calculation results according to the electro-mechanic analog method are rather approximate with deviation around 15 % only at minor input signals (to 5W) and insignificant (not more than 15%) alterations of load resistance.

Experimental & analytical method

For the PT basis devices, which works under strong influences, the mentioned above calculation method is inefficient. For example, PT loading and frequency characteristics in the real ranges of load alterations within the operation systems cannot be obtained analytically by the transformations from the equivalent circuits.

So far there is no available information about analytical presentation of the processes in PT under strong influences stipulated both by the complicated problem (PT is likely to be a nonlinear system with split parameters and mobile properties) and by its insufficient research from the point of view of physics. Thus, the experimental and analytic methods to investigate the PT characteristics are used [2].

The methodological basis of these researches is the ideas of IT "grey" and "black" boxes.

The behavior of "black box" is influenced via inputs X_i (factors) with the help of determined values (levels) factors with outputs Y_i, (reactions) that are connected with the factors though the feedback function, which is composed on the basis of experiments tables of discrete values X_{in}, Y_{in} (*n* – number of experiments) or mathematical planning. The PT was represented in the form of multi-dimension operation object with three input factors X_i (PT actuator voltage components – by amplitude, frequency and electrical angle) and with three outputs coordinates Y_i, (and the same compounds of PT output voltage).

On the fig. 6, except for the impacts of input and output voltages components, the external impact $f_k(t)$ was shown (alterations of stress, temperature, mechanic and other external impacts), as well as internal influences *fi (t)* (noises, fatiguing and so on).

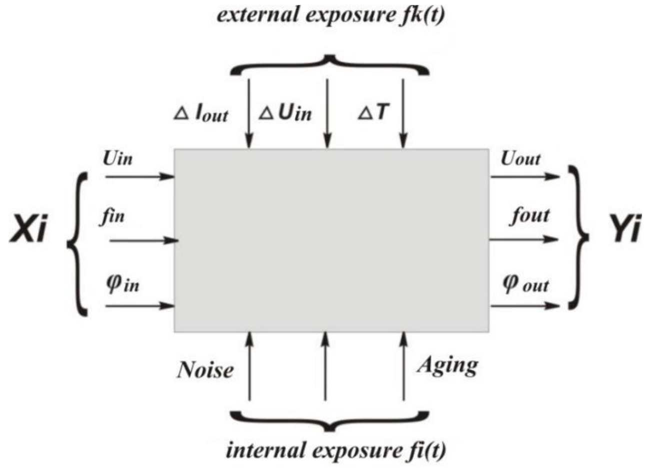

Figure 6. The PT as the object of influence of various factors

The PT parameters are unchangeable only in the weak electric fields under the minimum loadings. With the input electric field voltage growth A_{en} PT parameters firstly are being changed linearly, and under considerable A_{en} =10...15 V/mm have nonlinear dependency and can be accompanied by the PT body fracturing. That's why the PT diversification rate in each of its modes must not exceed nominal diversification rate $\Delta P_{nm} <= \Delta P_{nm.perm}$.

The alteration of environmental temperature *T* results in considerable impact on the main PT parameters.

The dependence of PT parameters upon external mechanic impacts as well as outer magnetic fields isn't considerable and doesn't exceed 1 %, and in designing the device, as a rule, this change is neglected.

High-frequency PT design

The PT simple construction needs very complicated operation system, which is stipulated by the narrowness of resonance AFC, by the high steepness of PFC at the mechanic resonance frequency, transformation coefficient dependency and PT efficiency on the input voltage frequency and other actuating impacts [2]. So, for the PT calculation parameters reserving under the load or medium temperature changing, it is necessary to hold the input voltage frequency equal to the PT mechanic resonance frequency.

Most of transistor transducers, which use piezotransformers that were designed with the purpose to create secondary in-feeding sources for devices with limited overall dimensions, are, mainly, control systems to lever the output voltage on loading. Remarkably, multiplied strain resistance can vary within wide ranges.

Main reasons, which are required for rather simple PT control system, are:

- narrow resonance amplitude-frequency characteristics (AFC);
- high steepness of electrical phase-frequency characteristics (PFC), which are approximated to the mechanic resonance frequency;
- transformation coefficient dependent on voltage K_u and piezotransformer efficiency output on input voltage frequency;
- mechanic resonance frequency dependent ω_p on environmental temperature *T*;
- dependence of dielectric penetration ε_{33}^T of piezoelectric ceramics from temperature *T*, that causes the dependency of input and output PT capacitive resistance on temperature;
- output voltage dependency U_{in} on mechanic resonance frequency ω_p at different fixed values of load resistance R_l .

To retain PT calculation parameters under conditions of load alteration or environmental temperature *T,* it is necessary to keep the input voltage frequency equal to the frequency of own PT mechanic resonance, and the voltage on loading – on the given value level, using the reverse connections system or systems, which monitor the changing of several PT parameters simultaneously.

The solid-state control system with piezotransformer

The solid-state control systems with piezotransformer (SSCSP), that depend on the mode of operation and the number of control channels are divided into three main groups: single-dimensional. two-dimensional and multidimensional.

A single-dimensional control systems are based on the circuits, which provide the alteration of acting value of working harmonics of PT input voltage U_{in} to sustain of PT output voltage Uex at the given level.

Circuits, which are associated with single-dimensional control systems, characterizes of simplicity, reliability and provide instability of output voltage within 2% (at insignificant temperature fluctuations).

An autonomous generator control circuits are mostly used by control systems with frequency-depend element in contour of positive feedback (it is conventionally associated with single-dimensional control systems, because it compensates the influence on the output voltage both with AFC drift and by PFC drifts, i.e. the amplitude-frequency control is applied, however, in this case the influence in the amplitude channel is determined as the main one).

Their main disadvantages are:

- being apt to self-actuation on stray harmonics (it is discarded by selection of optimal location of reverse connection section on the PT surface);
- possible collapse of autonomous oscillation and deviation from the resonance frequency as result of significant alteration of input voltage or PT temperature.

Two-dimensional control systems have advantages of single-dimensional ones, and, practically, are deprived of disadvantages of the latter.

The PT output voltage stabilization in such circuits is secured simultaneously by two channels influence.

For example, at amplitude-frequency mode the amplitude and frequency correcting signals are imposed, which influence on the frequency ω and input voltage amplitude U. However, such SSCSP contain a large number of functional nodes and have more difficult construction. Besides, in the case of efficient changes of load resistance R l, the operation breakdown is possible as result of working point transition from the working right slope to the opposite one of PT AFC. This causes stabilization breakdown, because the working point has to be chosen on the right AFC slope being close to resonance frequency.

Multi-dimensional control systems are based on the interaction at all main operation channels.

One of the ways intrinsic to this system is the carrying out of operational impacts of SSCSP when simultaneously with the impact on the frequency it provides the influence on the amplitude of PT input voltage in the function from operational electric angle signal.

The multi-dimensional method that PT control system provides the control and influence on the input voltage amplitude, input current, input voltage frequency, electric angle shift between input or output voltage and input PT current.

Output cascades of piezo-semiconductor control systems

Main circuits of output power transistors cascades SSCSP are illustrated on fig.7 [1,2].

In the fig. 7 are shown the circuit of single-pulse power amplifier (PA) with inductance $L_к$ in transistor VT1 collector circle, on fig.7,b – push-pull amplifier with compensation inductance $L_к$ (half-bridge circuit), on fig.7,c – bridge amplifier, designed without compensation's inductance.

At small values of input PT capacity (below 50 nF) use half-bridge or bridge amplifier without induction $L_к$, because losses for transistors switching in this case are minor.

Single-pulse output amplifier circuits (Figure 7,a) are used only at small values of feeding voltage (approximately 0,3U PT).

The compensation induction usage $L_к$ increases U_{in} up to (1,8…1,9)U_f, where U_f – feeding voltage, and the first harmonics amplitude can reach the value of 2,5U_f [2].

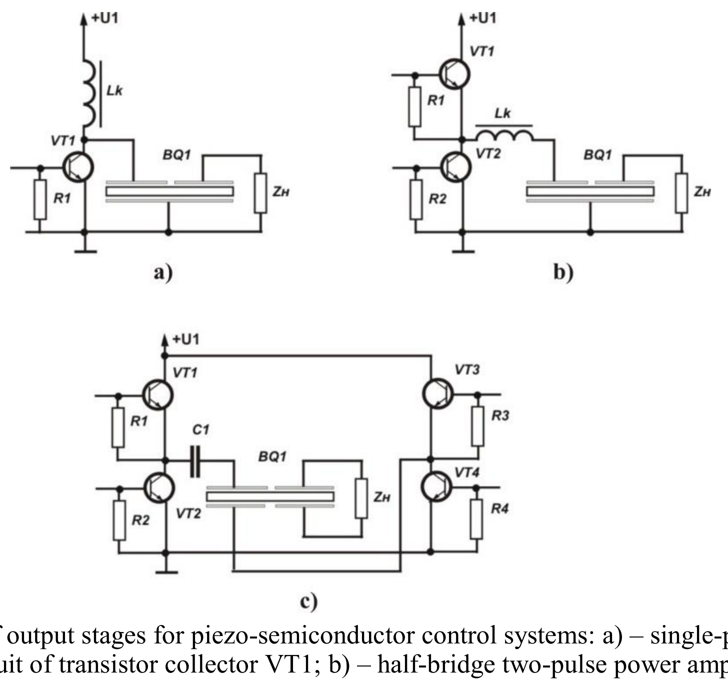

Figure 7. Schemes of output stages for piezo-semiconductor control systems: a) – single-pulse amplifier with induction L_k in circuit of transistor collector VT1; b) – half-bridge two-pulse power amplifier circuit with induction L_k; c) – bridge circuit of two-pulse power amplifier without induction L_k

In other cases half-bridge or bridge amplifier are used, because they efficiency output higher and they easy in use.

Usage a piezotransformers' with households and industrial gas-discharge lamps

The main demand to the converters constructions is the minimal geometric dimensions that allow fixing them in the lamp cap. For this purpose the most perspective trend is the usage of multi layer piezoelectric transformers.

Piezoelectric transformers are used for the control and current stabilization of gas-discharge lamps

Unlike power supply based on piezotransformers [1, 2], which provide the output voltage stabilization, electronic ballast (EB) for the ignition and current stabilization of the fluorescent lamps (FL) basis on PT are working in the mode of current stabilization [3,6,7].

The electronic ballast circuits differ from classic SSCSP circuits by the absence of additional capacitor of resonance contour (it is turned on simultaneously to loading), which function in EB the capacitance of PT input section plays.

The PT usage gives electronic ballast some advantages, such as:

- high voltage for the ignition of lamp on at the first trying [7];
- sinusoidal form of the lamp current with working of output EB cascade at the switch mode;
- the value of amplitude coefficient of lamp current, that doesn't exceed $\sqrt{2}$.

Some electronic ballast's circuit [4,5] are made for permanent preheat electrodes of the fluorescent lamps. In this case piezotransformer is used for three lamp regulations: FL electrodes heating, FL ignition on by high voltage of PT and the stabilization of lamp current in the normal mode operating with maximum efficiency of PT.

The typical construction of the electronic ballast [7] should comprise: voltage transformer (frequency), the protection device, appointed for switching off in the prolonged regulations of idle motion or lamp electrodes preliminary heating, electronic starter (for starter type's electronic ballast).

The usage of multi-layer PT constructions in lighting systems is limited for the fluorescent lamps types like T-5, T-8, lamps with cold electrodes and lamps of glowing discharge [3].

Piezotransformer usage in other power devices

Actuators. The actuators, as fulfilling devices or their active element, that transforms one of the energy kinds (electric, magnetic, thermal, chemical) into another (the most frequently – into mechanic), that causes to the certain action, given by the operational signal are conditionally divided into ***powerful*** (package) and slight ***powerful***, to which belong *flexible* (bimorph and strip) and *axis* activators, produced according to the multi-layer piezo-ceramic technology [8,9].

The **stack activators** (SA) are now applied in the space, laser technique and optic instruments for the aerial and mirrors adjustment with nano-metrical accuracy. They are widely applied in case of importance of developing considerable efforts at minimal transposition or the turning angle.

The **piezo-drivers** of the progressive directions is their usage in precise lathes adjustment. Applying the fixed voltage in electrical angle with spindle rotation, one can get high accuracy of processing.

Vibration dampeners. In the lathe building they plan to use actuator to eliminate the vibration. Unwanted lathe vibration can be compensated by means of multi-layer actuators that work in counter-phase with the vibration fluctuations. This will promote better quality of final production, and also will allow avoiding instrument depreciation and will decrease the lathe noise level.

Hydraulic valve drive. As the example – the latest designs of piezo-ceramic high-speed valves both for the fuel gear of diesel engines of cars and trucks and also gas distributing diesel systems and internal combustion engines.

Flexible actuators are used in the piezoelectric gauges of bending moment, in the electronic systems for the blind reading according to Braille's method as electronic switchers.

Stripe actuators creation sufficiently widens their usage, for example, in the textile industry for the systems of threads supply to jacquard machines operated by computer.

A new piezoelements allow using actuators as sensor switchers and contactors, piezo-drives, noiseless stabilizers in the electronic equipment; micro distributors that close and open the different valves including software dosage of drugs, vacuum valves etc.

The ***axis actuators*** are considered to be perspective in microelectronics, they were elaborated on the basis of technology of multi-layer composite piezoceramic.

The actuators sizes are from units of millimeters to the tenth parts of millimeter.

Conclusions

So, power devices projecting and production on the piezotransformers basis is still actual. New construction of multi-layer voltage and current PT elaboration is progressive that will allow meeting requirements to the convertors of different role – minimal geometric dimensions and high efficiency.

The elaboration and gear creation are carried out, built on the base of hybrid multi-layer structure of magnetic-piezoelectric (ME-piezotransformers).

There are still relevant designs using piezotransformers in the perspective television and computer displays as well as piezo-elements that perform functions of actuators for sensor switches and contactors, piezo-drives in electrical equipment.

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СИЛОВІ ПРИСТРОЇ ЕЛЕКТРОНІКИ НА ОСНОВІ П'ЄЗОЕЛЕКТРИЧНИХ ЕЛЕМЕНТІВ: СУЧАСНИЙ СТАН ТА ПЕРСПЕКТИВИ

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Резюме. *На основі аналізу існуючих конструкцій п'єзоелектричних елементів, методик їх розрахунку та електричних схем підключення проведено систематизацію технічних рішень в області проектування та використання силових пристроїв електроніки на їх основі.*

Дано порівняльний аналіз, вказано переваги і недоліки конструкцій та відзначено пріоритетні і перспективні напрямки розвитку даної галузі електроніки, принципових схем керування роботою п'єзоелектричного елементу в оптимальних режимах.

На основі аналізу джерел інформації дано перелік сфер застосування п'єзоелектричних перетворювачів та їх переваг порівняно з традиційними технічними рішеннями.

Ключові слова: *п'єзокераміка, п'єзоелектричний перетворювач, п'єзотрансформатор, п'єзонапівпровідникові системи управління, електронні пускорегулюючі апарати.*

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