Journal of the European Ceramic Society **19** (1999) 1275–1279
PII: S0955-2219(98)00419-1

Piezoelectric Non-resonant Transformer to Measure High Voltage

A. Vázquez Carazo* and R. Bosch

Department Enginyeria Eléctrica, Universitat Politécnica Catalunya, A.v. Diagonal 647, 08028 Barcelona, Spain

Abstract

The present paper is based on the research activity carried out at the Polytechnic University of Catalunya on the development of a new instrument transformer to measure voltages in distributing networks. This novel instrument transformer is presented as a future alternative to the classical electromagnetic instrument transformer. Such a solution uses piezoelectric materials working in non-resonance to perform the transformation from high voltage to low voltage. The configuration of piezoelectric instrument transformer of two columns (actuator and sensor columns) was chosen to perform the research. Mechanical, electrical and thermal limits were clearly defined to select the appropriate materials and to determinate the lines of the design to obtain a reliable and precise device. © 1999 Elsevier Science Limited. All rights reserved

Keywords: instrument transformer, piezoelectric properties, PZT, actuators, sensors.

1 Introduction

The use of electromagnetic instrument transformers has been the common technique for years to measure voltages and currents in environments of high voltage. Nevertheless, recently, evolutions in the measurement systems have been required. Reducing costs, improving measure precision and obtaining transformers that satisfy the demands on reliability and safety for installations and staff are some of the causes that are motivating the investigations.

To these typical causes for any evolutive process, others have to be considered motivating the investigation around signal transducers. It concerns the evolution produced in the protection and measuring system (S3 in Fig. 1) connected to the instrument transformer.[1] This is important because it determinates a different conception of the measure transformer technology in comparison to the power technology used at the electromagnetic instrument transformers.

Classically the protection and control instruments were designed based on voltmetric and amperemetric coils (electromechanical technology), which requires a certain excitation power (about 10 VA). This explains why the design of the classic measure transformer was constructed with the capability to satisfy these power requirements (*power* technology).

At present, the protection and control instruments technology tends to electronic technology, being designed with electronic components and microprocessors (that only consume some few mW). This requires a change in the way of designing the measure transducers.

In this paper, the piezoelectric instrument transformer is presented to measure voltage in distribution networks. Then, the most important features and limitations for the design of the transformer and an estimation of its range of application are discussed.

2 The Piezoelectric Transformer to Measure High Voltage

The research activity about piezoelectric voltage transformers started at the end of 1994.[2] Since then the design of the transformer has been modified to adjust its features to the field where it is going to be installed.

The design that finally has been estimated more suitable for its practical introduction was the piezoelectric transformer made of two columns (Fig. 2).

The device consists of two piezoelectric columns, one connected to high voltage and the other to low

---

*To whom correspondence should be addressed. Fax: +34-3-401-66-00; e-mail: vazquez@ee.upc.es voltage. This configuration guarantees the decoupling between the high and low voltage. The high voltage column, called actuator column, is connected to the high voltage to be measured. It generates a mechanical vibration proportional to the electric voltage. The low voltage column, or sensor, receives the vibration and converts it again into an electrical signal. Thus, there is a conversion of electrical energy into mechanical energy followed by a reconversion of the mechanical energy back into electrical energy.

3 Design of the Actuator Column

3.1 Construction

The actuator column is built by piling up a specific number of piezoelectric discs. Commercial PZT disks have been used. The height of the column must stand the specified experimental conditions in terms of dielectric strength.

The discs are piled with all poling vectors aligned in the same direction. Once piled, they are wrapped with a special bandage to give uniformity and stability to the column.

The material chosen within the PZT family has been the PZT-8 ceramic because of its ability to stand high electric fields.

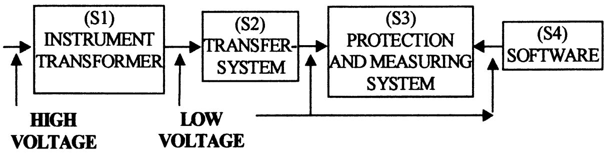

Fig. 1. Systems for protecting the generation and distribution of electric power are composed of four sub-systems. S1: Instrument transformers for measuring currents and voltage; S2: System for transmitting the signals from instrument transformers to protection and control system; S3: Protection and control system; S4: Software for the protection and control system.

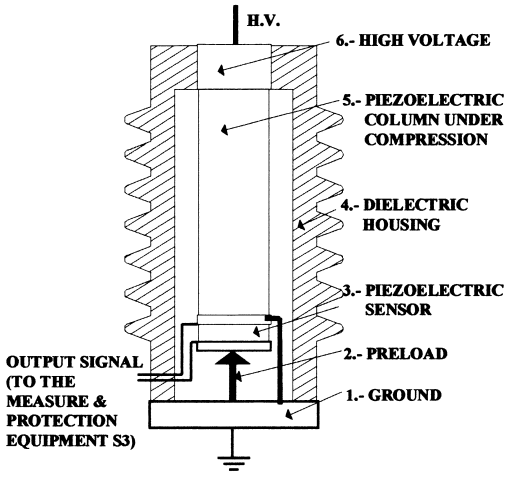

Fig. 2. Experimental prototype of the piezoelectric measure transformer of two columns.

3.2 Displacement of the actuator column

The displacement ΔL of the unloaded actuator piezoelectric column can be estimated by the eqn (1):

$$\Delta L = S \cdot l_0 \approx \pm E \cdot d_{ij} \cdot l_0 \qquad (1)$$

where S is the strain, L_o is the ceramic length, E the electric field strength and d_{ij} [m/V] the piezoelectric coefficient of the ceramic.

Particularly, d_{33} describes the strain parallel to the 3 axis.[3,4] For the material used to make the actuator, PZT-8, d_{33} is on the order of $225 \cdot 10^{-12} \mathrm{mV}^{-1}$. Nevertheless, these values are only guaranteed for new samples at room temperature and low driving signal.

3.3 Limitations due to the intense electric field

Two electrical specifications should be rigorously respected in the design:[5]

1. The electric strength ranges, usually from 2 to $3\,\mathrm{kVmm}^{-1}$, limit the allowable electric field in the poling direction. The maximum voltage depends on the ceramic properties and the insulating materials. Exceeding the maximum voltage may cause dielectric breakdown and irreversible damage of the PZT.
2. In this application, the piezoelectric actuator column is subjected to high alternating electric fields. To obtain a linear response in the material, its depoling and the hysteresis losses must be controlled. This is specially critical when we work with inverse field 4 (contraction). In this case, the limit is due to the change of sense in the polarization of the material. The standard ceramic materials are limited to aprox. $300\,\mathrm{Vmm}^{-1}$ in inverse sense (Fig. 3). Exceeding this value yields to an electric depoling of the material.

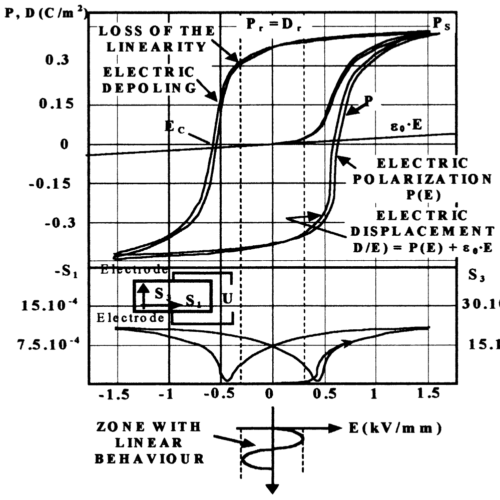

Fig. 3. Poling and displacement generate in a piezoelectric standard ceramic when an alternating electric field is applied.

The PZT-8 material belongs to the group of the so-called *hard ceramics*, as it can work with high signals levels. It can work with alternating fields up to $1{\cdot}5\,\mathrm{kVmm^{-1}}$, and about $1\,\mathrm{kVmm^{-1}}$ with very low hysteresis.

3.4 Dynamic forces generation

Every time the actuator column drives voltage changes, the piezoelectric ceramic changes its dimensions (if not blocked). Due to the inertia of the PZT mass (plus any additional mass), a rapid change will generate a force (pushing or pulling) acting on the ceramic.

Force generation is always coupled with a reduction in displacement. The maximum force (blocked force) available to accelerate the ceramic is equal to the blocked force shown in eqn (2) and depends on its stiffness k_T [N/m] and maximum displacement without external load ΔL_0 [m] as shown in the following:

$$F_{\max} \approx \pm k_T \cdot \Delta L_0 \tag{2}$$

This expression indicates the maximum force that can be generated in an infinitely rigid restraint (infinite spring constant). At maximum force generation, displacement is zero.

In particular, in sinusoidal operation with frequency f and the amplitude $\Delta L/2$, peak dynamic forces can be expressed as:

$$F_{\mathrm{dyn}} = \pm 4\pi^2 \cdot m_{\mathrm{eff}} \cdot \frac{\Delta L}{2} \cdot f^2 \tag{3}$$

where m_{eff} is the effective mass.

In actual application the load spring constant, k_s [N/m], can be larger or smaller than the ceramic spring constant, k_T [N/m]. In this case, the force $F_{\max}$ eff generated by the PZT is indicated at (4):

$$F_{\mathrm{maxeff}} \approx k_T \cdot \Delta L_0 \cdot \left(1 - \frac{k_T}{k_T + k_S}\right) \tag{4}$$

3.5 Limits in the dynamic forces

Compressive and tensile strength of the ceramic must be carefully respected in the actuator design:

1. The PZT ceramic material can withstand pressures up to 250 MPa before it breaks mechanically (for the PZT-8 this value is higher up to 500 MPa). For practical applications, this value must not be approached because mechanical depolarization of the material occurs at pressures in the order of 20–30% of the mechanical limit (about 80 MPa for the PZT-8). In practice, the recommended values for the mechanical load are quite conservative, which allow longer life of the material.
2. Tensile loads of non preloaded PZT ceramics are limited to 5–10% of the compressive load limit (34 MPa for the PZT-8 in dynamic work and 75 MPa in static conditions). Moreover the fatigue tensile limit is lower and very critic. This is because in practice is recommended not to allow tensile forces. Tensile forces can be compensated by mechanical preload of value around 20% of the maximum compressive stress.

3.6 Actuator displacement with external preloads

As we have commented before, the actuators are prestressed. Like any other actuator, a piezoelectric actuator is compressed when an external force is applied. Two cases must be considered:

(a) If the preload is applied with a constant force (Fig. 4), keeping within the mechanic limits, the new zero point will be offset by an amount:

$$\Delta L_N \approx \frac{F}{k_T} \qquad \text{(see Fig.4)} \tag{5}$$

This case corresponds to install a mass over the PZT ceramic, which creates a force $F = M \cdot g$ (M: mass, g: acceleration due to gravity).

In spite of the offset, full displacement can be obtained at full operating voltage.

(b) If the preload is done with a non-constant force (Fig. 5), for instance a spring, the maximum displacement will reduce, but the zero point is not modified. Part of the displacement generated by the piezoelectric ceramic is lost due to its elasticity. The total available displacement can be related to the spring stiffness by the following equations:

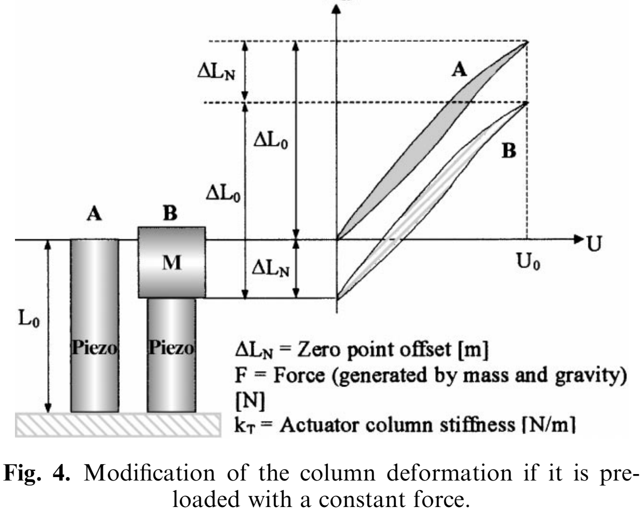

Fig. 4. Modification of the column deformation if it is preloaded with a constant force.

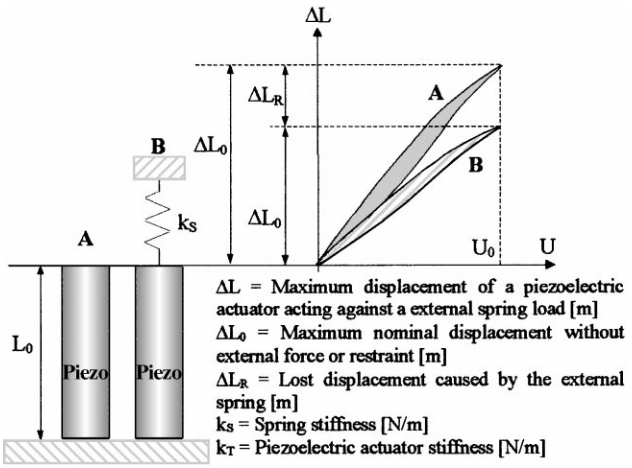

Fig. 5. Modification of the column deformation if it is preloaded with a non-constant force (spring).

$$\Delta L \approx \Delta L_0 \cdot \left(\frac{k_T}{k_T + k_S} \right) (\text{see Fig. 5}) \tag{6}$$

A particular situation of this case is when the spring stiffness k_S is ∞ (infinitely rigid stiffness) the piezoelectric column only acts as a force generator. This occurs when the piezoelectric column is limited by load with a higher stiffness than the ceramic.

4 The Sensor and the Output Interface

The selection of the material used as a sensor is not as critical. It is possible to use ceramic, polymeric or another type of piezoelectric materials. The selection and dimensions of the sensor determinate the transformation rate. The range of the output voltage is in the range of 0–5 V, which allows a direct connection with electronic protection and measuring system.

There are two modes of operation for the sensor: operating as an acceleration sensor, or working as force sensor. Acceleration sensor imply to convert the force generated at the actuator column to acceleration by using a seismic mass, while the force sensor imply the direct detection of the actuator forces.

The most critical part of the sensor design is the output interface, because of the high impedance of this type of transducers. The interface basically must be a good amplifier that matches the impedance of the ceramic to the impedance of the protection and control system.

To do this, it is possible to use a charge amplifier, that measure the charge generated by the sensor and integrate to an output voltage, or voltage amplifier that measure the voltage generated at the ceramic under a very high external impedance.

5 Features of the System and Operation Range

The frequency linear measuring range of these transformers is estimated around 15 kHz (resonance frequency). The accuracy is in the range of 5%.

The phase response of the system can be approximated by a second order system and is described by:

$$\varphi \approx 2 \cdot g \left(\frac{f}{f_0} \right) [\text{deg}] \tag{7}$$

The phase precision is reduced near the resonance frequency.

Temporal drift due to the ageing are problematic in sensors and charge generation application (direct piezoelectric effect), but can be reduced using an auxiliary piezoelectric temperature compensator in the output electronics. In the actuator column the effect is not important, because continuous repoling occur every time that the high electric field is applied in the poling direction.

The operating range of the transformer is limited by the temperature. Above a temperature of about 300°C (hard ceramics) and 150°C (soft ceramics) the polarization of the ceramic disappears, thus reducing the expansion-compression capability. Actually, depolarisation is already evident at 150°C in hard ceramics and 80°C in soft ceramics, so the operating temperature should be less.

6 Conclusions

An analysis of the factors that determine the design of the piezoelectric instrument transformer to measure high voltages has been done.

The practical introduction of the transformer requires the output signal processing by using electronics to the control the time and thermal drifts. The reduction of the hysteresis implies an appropriate selection of the actuator material. Hard ceramics, like the PZT-8, allow an appreciate reduction of the hysteresis and of the mecanical and electrical depoling problems that can appear when strong alternating electric field are applied.

The measurement range of these devices is limited from the dielectric and depoling characteristics of the materials. Working with strong electric fields the height can be quite large to can be built. The frequency response in the tested prototypes is estimated higher than 15 kHz, although static measures are not possible.

The installation of the transducer to guarantee its insensibility to external mechanical vibrations or acoustic noise is the subject of futures research lines. The possibility to use piezoelectric technology to current transformer is being considered.

References

1. Korponay, N. and Minkner, R., Analysis of the new IEC drafts for 185 (44-1) and 186 (44-2) instrument transformers in relation to the requirements of modern protection systems. *Revue Generale d'Electricity*, 1990, 4.
2. Bosch Tous, R., Vázquez Carazo, A. and Alvarez Florez, J., El transformador piezoelectrico. Un transductor viable para medida de altas tensiones. Edicions CPDA, UPC, Barcelona, España, 1997.
3. *IEEE Standard on Piezoelectricity*, Institute of Electrical and Electronics, Inc, 1987.
4. *IRE Standards on Piezoelectric Crystals*: Measurements of Piezoelectric Ceramics, 1961, Proc, IRE, 1961, **49**, 1161.
5. Mason, W. P., *Piezoelectric Crystals and their Applications to Ultrasonics*. Van Nostrand, New York, 1965.