Piezoelectric polymer wind generators

by Hadi Darejeh

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Physics
Montana State University

Abstract:
Small wind generators based on the piezoelectric effect in poly(vinylidene fluoride), or PVF2 for short were designed, built and tested. The design was based on developing a voltage across a bimorph made of two PVF2 sheets glued back-to-back and coated with electrodes. Suitable means of setting these bimorphs into oscillation in the wind were developed. One of these designs (oscillating leaf) is based on forcing the blades into oscillation at 60 Hz and feeding the output directly into the ac line. The other two designs had the blades as parts of rotors which were forced to rotate by the wind. For these designs the power was brought out through the rotor bearings and could be fed into the line by means of a rectifier and synchronous inverter. The poled PVF2 is very expensive, but reducing the cost of the poling process could make PVF2 wind generators practical for commercial use.

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APPROVAL

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Hadi Darejeh

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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ABSTRACT

Small wind generators based on the piezoelectric effect in poly(vinylidene fluoride), or PVF_2 for short were designed, built and tested. The design was based on developing a voltage across a bimorph made of two PVF_2 sheets glued back-to-back and coated with electrodes. Suitable means of setting these bimorphs into oscillation in the wind were developed. One of these designs (oscillating leaf) is based on forcing the blades into oscillation at 60 Hz and feeding the output directly into the ac line. The other two designs had the blades as parts of rotors which were forced to rotate by the wind. For these designs the power was brought out through the rotor bearings and could be fed into the line by means of a rectifier and synchronous inverter. The poled PVF_2 is very expensive, but reducing the cost of the poling process could make PVF_2 wind generators practical for commercial use.

CHAPTER 1

INTRODUCTION

When Coulomb stated the well-known law of the force between two charges, it was thought that electricity could be produced by pressure. First Hauy and then A. C. Becquerel conducted experiments in which particular crystals showed electrical effects when pressure was applied.

Credit should also be given to the brothers Pierre and Jacques Curie for the discovery in 1880 that some crystals when compressed in particular directions produce positive and negative charges on certain portions of their surfaces, these charges being proportional to the pressure, and which then vanish when the pressure is removed.

This wasn't just a lucky discovery, because Pierre Curie's previous study of pyroelectric phenomena led both of them to look for electricity from pressure. They also looked for a particular direction of applying the force and studied which groups of crystals exhibit the effect. So the name piezoelectric, which means electricity by pressure, was given to this class of material.

One of these piezoelectric materials is a piezoelectric polymer, namely poly(vinylidene fluoride), abbreviated PVDF or PVF_2. The piezoelectric effect in PVF_2 was first discovered by Kawai, a Japanese scientist, in 1969. As the name implies, this phenomenon is an electric polarization of the polymer (solid) on which forces are acting. For reasonable forces the polarization is proportional to the applied force. If the external force is reversed in sign the polarization changes direction. An inverse effect is a dimensional change (a strain) caused by applying an electric field.

PVF_2 and some of its copolymers have been shown to be ferroelectric, while other piezoelectric polymers are less likely to be. PVF_2, whose molecular chain formula is $(CH_2-CF_2)_n$, appears to be the strongest of piezoelectric and pyroelectric polymers.

In order to make these polymers macroscopically polar, there has to be mechanical extension and electrical poling. Mechanical extension causes a reorientation of the original spherulitic structure into an array of crystallites which now has its molecules oriented in the direction of the force. Now the final step consists of evaporating electrodes on the sample and connecting them to a high voltage source, applying a field of 0.5 megavolt per centimeter. This step creates a permanent polar film.

Wind generator application of PVF_2, which is the main aspect of this project, is explored herein in great detail. Today wind power can be used to provide electricity by conventional windmills, but a piezoelectric wind generator is quite a different technique to produce this electricity.

If a piezoelectric polymer is set into oscillation by means of wind, the strain in the polymer creates a voltage and since the polymer is oscillating the voltage output will be alternating. Suitable means of setting these polymers into oscillation are developed through three different types of generators. They are named lateral leaf rotor, Savonius rotor, and oscillating leaf. Their engineering aspects are dealt with mainly in the Theory and Procedure sections.

The reason for the design of the lateral leaf rotor is to have as large a rotor as possible consistent with the requirement of 60 Hz blade oscillation frequency so that its 60 Hz power output can be fed into the utility line.

The Savonius (S-cross-section) vertical axis rotor has a low tip speed ratio, but its design shape is very suitable for oscillating blades. This has a flexible blade root made of PVF_2 attached to a central rod which holds the entire assembly together.

For both of these designs the output current from the rotor is taken out through the rotor bearings and fed into a resistor as a test load, with an oscilloscope measuring the voltage created due to the strain in the bimorph blade.

The oscillating leaf generator sets a PVF_2 bimorph blade into oscillating bending motion, thereby creating an ac voltage. A cantilever mounted thin spring steel bar has a PVF_2 blade mounted on the free end. That puts the entire system into oscillation if bar and blade have the same resonant frequency. The blade consists of two sheets of the piezoelectric polymer PVF_2 glued back-to-back onto an inert plastic central layer. The bending alternately causes one PVF_2 sheet to be in tension and the other one in compression, producing a net electric field in the same direction in both sheets for one half cycle, while both fields reverse in the next half cycle.

CHAPTER 2

THEORY

Piezoelectric crystals do not have a center of symmetry. If they have net dipole moments in their unit cells piezoelectrics are also pyroelectrics. However, not all piezoelectric unit cells have net dipoles and therefore not all piezoelectrics are pyroelectrics, Piezoelectricity is produced when a suitable crystal is subjected to mechanical stress. Conversely, if the surfaces of the crystal are electroded and an electric field is applied, deformation of the crystal will result. Some of the electromechanical coupling effects are shown in figure 1.

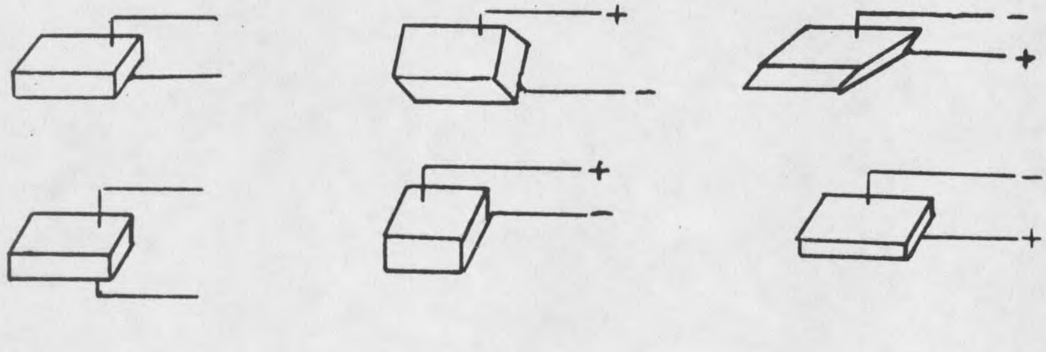

Figure 1. Electromechanical coupling in piezoelectrics.

As the name implies, this phenomenon is a polarization of a solid on which forces are acting (figure 2). For reasonable forces, the amount of polarization is proportional to the magnitude of the applied stress. If the external force is changed in direction, the polarization changes direction accordingly.

The relationship between P and F can be expressed (for a simple geometric figure) as P = constant * F.

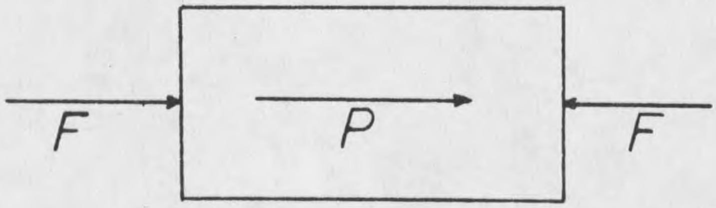

Figure 2. An applied force produces electric polarization in piezoelectric solids. This polarization is shown here collinear with F. In general, P can make any angle with F.

The inverse piezoelectric effect exists also. That is, a dimensional change (a strain) is produced in a crystal when it is placed in an electric field. The inverse piezoelectric effect however is a linear function of the first power of the applied field (for appreciable fields). Therefore the magnitude of the piezoelectric strain S_x in a specimen placed in an electric field E for a simple shape specimen is given by the relationship S_x = constant * E.

The geometry of the above relation is shown in figure 3. With initial length (no field present) represented by l and the length in the field by l+Δl, then the strain is $S_x = \Delta l / l$. The inverse effect is sensitive to the direction of the applied field. If the field is reversed, the strain is a contraction.

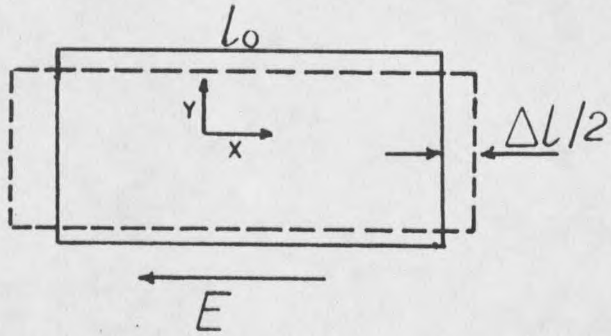

Figure 3. Dimensional changes of a piezoelectric solid in an external field.

A description of what truly happens in the case of applying a field to the polymer is shown in figure 4. This figure also shows the reason for generation of a sound wave.

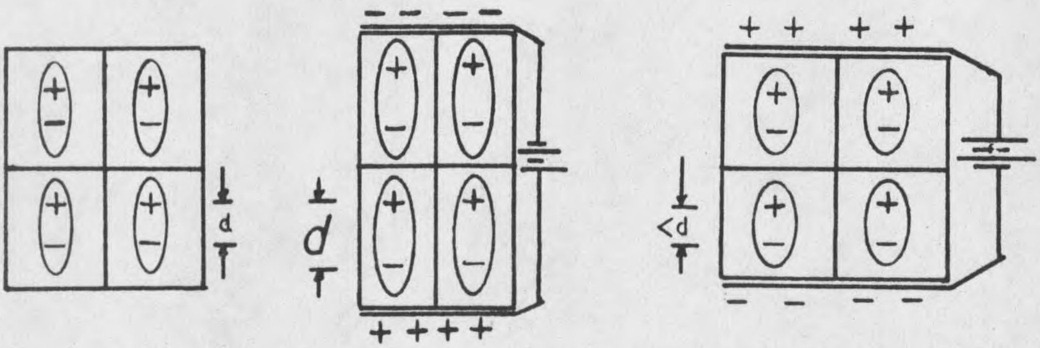

Figure 4. (a) Piezoelectric material. (b) An electric field induces dimensional expansion. (c) Reverse polarity produces a contraction.

The figure of merit for piezoelectrics K is called the coefficient of electromechanical coupling, or

$$K^2 = \frac{\text{Electrical Energy out}}{\text{Mechanical Energy in}} = \frac{\text{Mechanical Energy out}}{\text{Elect Energy in}}$$

K is also related to the dielectric constant ε in the following manner.

$$\varepsilon_{free}(1-K^2) = \varepsilon_{clamped}$$

where ε_{free} is dielectric constant at low frequency and the clamped dielectric constant is measured at high frequency where the device is effectively clamped by its own inertia. From the mechanical point of view K is also related to Young's Modulus Y, such that:

$$Y_{open\ ckt}(1-K^2) = Y_{closed\ ckt}$$

The value of Y is measured with closed circuit and with electroded surfaces connected to each other. When shorted the value of Y is less than that for an open circuit.

Let's consider that there is a single crystal with the dipoles of the unit cells aligned as shown in figure 4. In applying an electric field as exhibited, the crystal lengthens because the ions are attracted to the pole plates. If an AC voltage is applied, the crystal expands and contracts in oscillation, sending out a wave into the surrounding medium, whether air or water. If we apply a mechanical force, the charges shown above build up on the surface, creating a voltage which dies off exponentially when the force is removed. One of the most responsive piezoelectric polymers is poly(vinylidene fluoride), PVF_2, with the chemical formula $(CH_2-CF_2)_n$.

A few words on the chemical composition of PVF_2 would probably be useful in understanding the piezoelectricity of this material. Macromolecular chains have many elementary repeating unit cells, called monomers, that are linked chemically during polymerization. These monomers have polar chemical groups. To obtain good piezoelectric polymers, their constituents should not be so big that they prevent crystallization of the macromolecules or make them have helical shapes which produce internal gathering of polarization. These macromolecules should also be chemically stable and not cross-linked into infusible and insoluble solids. Because of the above considerations, fluorocarbons are the best monomers to yield piezoelectric polymer crystals. A schematic representation of the two most common crystalline chains is shown in figure 5.

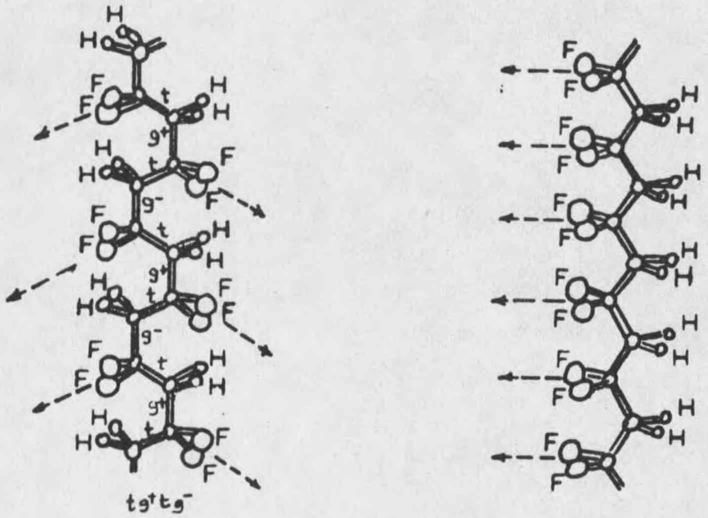

Figure 5. (a) tg+ tg- (b) (all trans). The arrows indicate projections of the -cF2 dipole directions on planes defined by the carbon backbone.

The tg+tg- configuration has its dipole moments both parallel and perpendicular to the chain axis, while the other one has its dipole moments perpendicular to the molecular axis.

The process by which piezoelectric films are obtained, mentioned on page 2, is shown schematically in figure 6.