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## PVF<sub>2</sub> BIMORPHS AS ACTIVE ELEMENTS IN WIND GENERATORS

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**Abstract** The application to wind electric generation of bimorphs constructed of two sheets glued back-to-back of the piezoelectric polymer poly(vinylidene fluoride), or PVF<sub>2</sub>, is discussed. First, some fundamentals of piezoelectric behavior and of cantilever beam oscillations are reviewed. Then test results are presented for electrically driven PVF<sub>2</sub> bimorphs oscillating in air and in vacuum, from which damping factors are derived. Next, two particular vertical axis wind generator designs are described employing such oscillating cantilever bimorphs which are forced into oscillation by the alternating direction of the wind forces acting on them during each rotor revolution. Wind tunnel test results for both designs are presented. Finally, the effect of possible improved polymer properties on generator output and cost is discussed.

### INTRODUCTION

Piezoelectric polymers to date have been used primarily as electrical-to-mechanical energy converters, with the exception of transducers in which the electrical output provides information rather than power. In this paper we explore the use of PVF<sub>2</sub> bimorphs as converters of mechanical (wind) energy to electrical energy. We describe generators of two designs, and discuss how the properties of the polymer, in particular the electromechanical coupling coefficient, affect the design philosophy, efficiency, output power, and cost per kilowatt installed capacity.

## BIMORPH DESIGN AND CONSTRUCTION

The simplest form of bimorph consists of two sheets of PVF<sub>2</sub> glued together back-to-back. Then, to the extent determined by the  $d_{31}$  coefficient of the polymer, if the bimorph is mounted as a cantilever and bent, the outer sheet is in tension and the inner in compression, but the piezoelectrically induced electric field is in the same direction for both and a voltage is applied to the external circuit.

The induced field is proportional to the distance from the bimorph neutral axis, so portions of the sheets near this axis are ineffective in producing power. An inexpensive nonpiezoelectric polymer is sometimes introduced as a third, central layer. It is important to short around this central layer to reduce the capacitive impedance of the generator.

Several considerations govern the design of a bimorph as an electrical power generator. It is inherently an ac generator, because the bimorph must oscillate to produce power continuously. It is a relatively high-voltage and low-current generator. One must decide whether the system will be independent or connected to a power grid. If it is independent, rectifiers and batteries are required to provide power during periods of low wind, and inverters could provide ac power at fixed voltage and frequency if needed. If power is to be fed into the grid, the generator can be operated independently or synchronously. For independent operation, rectifiers and a synchronous inverter are needed. For synchronous operation, a synchronizing mechanism must be provided.

The practicality of a synchronizing mechanism depends strongly on the magnitude of the electromechanical coupling constant  $k_{31}$ , where  $k_{31}^2 = Y_{11}d_{31}^2/\epsilon_3$ . Values quoted<sup>1</sup> for PVF<sub>2</sub> are  $1.5 \times 10^9$  N/m<sup>2</sup> for Young's modulus  $Y_{11}$ , 24 pC/N for  $d_{31}$ , and  $12 \times 8.85 \times 10^{-12}$  f/m for the dielectric susceptibility  $\epsilon_3$ . For

these values,  $k_{31}^2 = 0.0081$ . This is the fraction of the energy expended in bending the bimorph in one quarter-cycle of operation which can be delivered as electrical energy. Thus, most of the force on the blade comes from air resistance and internal friction, as described in the following section, so the blade itself cannot provide the synchronizing mechanism. Provision for external synchronization appears too complex to be practical.

Polymers of improved properties could provide a sufficiently large coupling constant to allow the bimorph oscillations to be self-synchronized to line frequency. Then if the current fed into the line is kept in phase with the line voltage and the output power is maximized, the bimorph emf must lag the line voltage by 45 degrees and be  $2^{0.5}$  as great as that voltage, taking into account that the source impedance is  $-j/\omega C$ , where  $\omega$  is the line angular frequency and  $C$  is the bimorph capacitance. The average power into the line under these conditions is  $\omega CV^2$ , where  $V$  is the rms line voltage. A final consideration is whether the blade should operate at mechanical resonance. This is unimportant if the coupling coefficient is high so that mechanical power is converted almost completely to electrical power during each oscillation. But if the coupling constant is low, the electro-mechanical damping can be low also, as seen in the following Section, and it is desirable to operate the blade at resonance to get large deflection and correspondingly large electrical output. Our two models described in the fourth Section both use a resonant design.

#### TESTS OF ELECTRICALLY DRIVEN BIMORPHS

We constructed two bimorphs for tests in air and vacuum to determine their damping by air friction and internal friction. The bimorphs were mounted as cantilevers and excited at fixed

ac voltage over a frequency range near resonance. The amplitude was measured as a function of frequency, and the quality factor  $Q$  of the response was calculated to determine the damping. Test results are reported in more detail elsewhere.<sup>2</sup> A triangular blade had a  $Q$  of 20 in air, while a thinner rectangular blade had a  $Q$  of 7 in air and 30 in vacuum. These results show that both air resistance and internal friction are important in causing damping.

#### WIND GENERATOR CONSTRUCTION AND TESTING

We have constructed vertical-axis wind generators of two designs. The first is a Savonius-type rotor which has an S-shaped cross section when viewed axially. It consists of a vertical shaft bisected by a vertical PVF<sub>2</sub> bimorph which has a C-shaped aluminum cap glued in at each end to provide the overall S-shape needed to produce torque. The design considerations for this type of rotor and a sketch of its cross-section appear elsewhere.<sup>3</sup> The bimorph was made quite stiff, so that large deflections occurred only when the rotation rate coincided with the blade natural frequency. The best arrangement of this design achieved 144 volts peak-peak and 0.52 mW output power at 1120 rpm for a bimorph of two sheets each 1.6 x 5 cm x 28 microns.

Our other rotor design is related to vertical axis wind turbines which achieve variable pitch with hinged blades, but in our design the two bimorph blades are mounted as cantilevers. The blade roots extend tangentially, and the blade tips are tied together by a nylon line so that each blade is curved through a 90 degree arc on an imaginary cylindrical surface in the absence of wind forces, so that the blade has zero pitch angle. The wind bends the upwind blade toward the rotor axis and the downwind blade away from the axis, giving both blades a positive pitch angle. A drawing of this rotor and an electromechanical analysis of its design appear elsewhere.<sup>2</sup> It produced 5 volts peak-peak

at 1350 rpm in a 15.9 mph wind in wind tunnel tests.

## DISCUSSION

Polymers with improved piezoelectric coefficient  $d_{31}$  and consequently larger electromechanical coupling coefficient are needed to improve efficiency and to make possible synchronous generators to simplify the overall system and reduce cost. In the expression  $\omega CV^2$  for electrical power output,  $C = \epsilon_3 A/z$ , where  $A$  is the area and  $z$  the thickness of the bimorph, so one might think that  $\epsilon_3$  must be increased to obtain more power per unit volume of polymer. However, the maximum field in the polymer is not limited by the breakdown field, but rather by the yield stress  $X_y$  according to the formula  $d_{31}X_y + \epsilon_3 E_3 = 0$  (valid for open-circuit and isothermal conditions), so that the power per unit volume is given by  $\omega d_{31}^2 X_y^2 / 4 \epsilon_3$ . Here  $X_y$  is  $4.5 \times 10^7$  N/m<sup>2</sup>. This limitation on field is 15 times smaller than the breakdown field of  $1.5 \times 10^8$  V/m. Under adiabatic conditions as expected at 60 Hz, the pyroelectric response will cancel about 18% of the piezoelectric response.<sup>4</sup>

If  $d_{31}$  could be increased fivefold to 120 pC/N and  $\epsilon_3$  decreased threefold to  $4 \times 8.85 \times 10^{-12}$  f/m, then  $E_3$  would no longer be limited by the yield strength. Further, the electromechanical coupling constant  $k_{31}^2$  would rise to 0.60, which would allow a synchronous design. Finally, the volume of polymer per kilowatt output would drop to 40 cm<sup>3</sup>/kW (in this calculation the maximum field was held 3 times lower than the breakdown field as a safety factor). At the current price of 70 dollars per cm<sup>3</sup> of PVF<sub>2</sub>, the cost would be 2800 dollars per kilowatt just for the polymer, which is comparable to the cost for conventional plants per installed kilowatt. However, a hundredfold drop in price for poled PVF<sub>2</sub> can be expected if a large market develops.

## CONCLUSIONS

We have shown the technical feasibility of two types of  $PVF_2$  piezoelectric polymer bimorph wind generators. Eventually we hope to eliminate the rotors and employ fixed-mount blades, but as yet we have not developed such blades which will oscillate strongly and reliably over a wide range of wind speeds.

Wind generators based on piezoelectric polymers will become practical if moderate improvements in polymer properties are achieved and the cost of the poling process is reduced, provided that temperature extremes and fatigue under operating conditions do not limit lifetime too severely. The volume of poled piezoelectric polymer required for this application would be huge.

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