# HARVESTING ELECTRICAL ENERGY WITH ELECTROACTIVE POLYMERS --- PART II. MATERIALS, DEVICE, AND SYSTEM CONSIDERATIONS

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**Abstract:**

Recent advances in electroactive polymers with their electromechanical performance, including The low elastic modulus, large strain and elastic energy density (~ 1 J/cm$^3$), and relatively energy conversion efficiency, approaching those of natural muscles create new opportunities for many applications. Harvesting electric energy from mechanical sources such as a soldier during walking is one such example. This paper describes several electroactive polymers developed recently and presents analysis on the key steps in achieving energy harvesting effectively. It is also shown that one may make use of smart electronics to modify the electric boundary conditions in the electroactive polymers during the energy harvesting cycle to realize higher efficiency in the material systems compared with the efficiency of the material itself.

## I. Introduction

Several classes of electroactive polymers (EAPs), developed in recent years, have exhibited many features resembling those of natural muscles.[1-3] For example, illustrated in Table I is a summary of a few key parameters of EAPs and some of these parameters are approaching those of nature muscles such as the strain level and energy density.[1] The large strain and stress level achieved in the EAPs represents a significant advancement in these bio-inspired materials, opening up new opportunities for many DOD related applications. In this paper, we investigate one of these applications---energy harvesting making use of these newly developed EAPs.

Table I.

| Materials | Max. strain (%) | Blocking stress (MPa) | Modulus (MPa) | Elastic energy density (J/cm$^3$) |
|---|---|---|---|---|
| VBH4910<br>Acrylic[3] | 158 (area strain)<br>215 (linear strain) | 7.2<br>2.4 | | 3.4<br>1.36 |
| Irradiated PVDF coplymer | $S_3$ -5<br>$S_1$ 4.5 | 20<br>40 | 400<br>1000 | 0.5<br>1.0 |
| P(VDF-TrFE-CFE) Terpolymer | $S_3$ -7<br>$S_1$ 4 | | 300<br>300 | 0.73<br>0.24 |

*$S_3$ is the thickness strain and $S_1$ is the lateral strain (along the film surface)

The modern warfare is marked by sophisticated electronics used in almost all parts of the weaponry systems which enhance significantly the military capability and reduce the battlefield causality. One of the prices for this increased reliance on the electronics is the increased weight of the batteries. Carrying these batteries can increase the backpack weight to upwards of 80 lbs. Our goal in this study is to develop a device that "harvests" some of the mechanical energy during walking and converts it to electrical energy to charge the batteries to reduce the amount of batteries that must be carried. To achieve this goal, it is necessary to use an integrative approach. An engineering approach in the absence of physiological measurements will likely fail, because even if a device is developed which can convert some mechanical energy to electrical energy, it might not be in the optimal anatomical position for harvesting, it might cause stability, maneuverability or orthopaedic problems, or it may be very energetically costly to the soldiers, requiring a much higher metabolic rate. Thus we must combine physiological/biomechanical approaches with engineering approaches to identify the best positions for energy harvesting and to form a set of physiological/ergonomic criteria which must be met by the device.

From the engineering point of view, there are also many issues to be addressed in order to maximize the energy harvesting from the available mechanical powers at various parts of human body. It is noted that there have been several attempts earlier in harvesting electric energy from the mechanical power during walking in the footwear; however, the power level achieved in those early attempts was at about 10 mW, which is too low to be useful for this program.[4,5] To increase this power level to a few Watts which are required for soldiers in battlefields, as will be shown in this paper, one has to address the mechanical impedance match issue so that the mechanical power can be effectively transferred from the mechanical sources to the electroactive materials which perform the energy conversion. Furthermore, the electromechanical conversion efficiency is one of the key parameters to realize effective energy harvesting. In this paper, we will discuss how to make use of the electric boundary conditions applied to the electroactive materials to enhance this energy conversion efficiency to beyond the efficiency of the materials. In addition, special electronic circuits have to be developed to achieve high electric power extraction from the electroactive materials. In this paper, the backpack carried by a soldier will be used as an example to illustrate various parameters related to the energy harvesting process.

## II.Materials and device considerations

Figure 1 illustrates schematically the power flow for the energy harvesting from the body motion. Although the major component of the whole device is the electroactive materials, there are other key components which can also significantly influence the amount of electric power to be extracted. For example, assuming there are 20 Watts mechanical power generated in an 80 lb backpack from the soldier walking, to maximize the transfer of this power to the electroactive materials requires a careful design of a mechanical transformer (to achieve the mechanical impedance matching). To illustrate this point, we use the energy harvesting using a piezoelectric ceramic as an example. As the 80 lb backpack undergoes a 5 cm motion (assuming sinusoidal motion at 1.5 Hz), the peak force exerting on the piezoceramic is 160 N. Assuming this force is applied to a 1 $cm^2$ area of piezoceramic with an elastic modulus of 60 GPa, the strain generated in the ceramic is only 0.0027%, which translates to an elastic energy density of $2x10^{-5}$ $J/cm^3$. To capture all 20 watts power will require $6.7x10^5$ $cm^3$ piezoceramic which will be very heavy even though piezoceramics possess relatively high electromechanical conversion efficiency (the longitudinal mechanical coupling factor $k_{33}$ is 0.75, which is more than 50% energy conversion efficiency, which is proportional to $k^2$). On the other hand, if a mechanical transformer is used to strain the piezoceramic to 0.2%, which is the strain limit at which the ceramic can be safely operated, and the elastic energy density is increased to 0.12 $J/cm^3$, the piezoceramic required to capture the whole 20 watts input mechanical power is reduced to 110 $cm^3$, a significant reduction. Furthermore, if an electroactive polymer is used which can be strained to 4% with an elastic modulus of 0.3 GPa, the elastic energy density is increased to 0.25 $J/cm^3$. The total volume of the polymer required is only about 56 $cm^3$. If we also take into account the density difference (the density for the piezoceramics is 7.8 $g/cm^3$ while for polymers, it is 1.9 $g/cm^3$ or less), the total weight in the polymer based system is much lower.

This analysis points out several important features on the mechanical side of the energy harvesting system: (1) a mechanical transformer is preferred to maximize the mechanical energy transfer from the external environment to the electroactive material; (2) electroactive materials with high strain energy density are preferred to reduce the volume and weight of the electroactive materials needed; (3) since in most energy harvesting cases, the force or stress level is not very high, materials with a modulus much smaller than piezoceramics are preferred (that is, EAPs are preferred). An added advantage of using electroactive polymers is their low density which is more than 4 times less than that of the piezoceramics, which also significantly reduces the weight of an energy harvesting system.

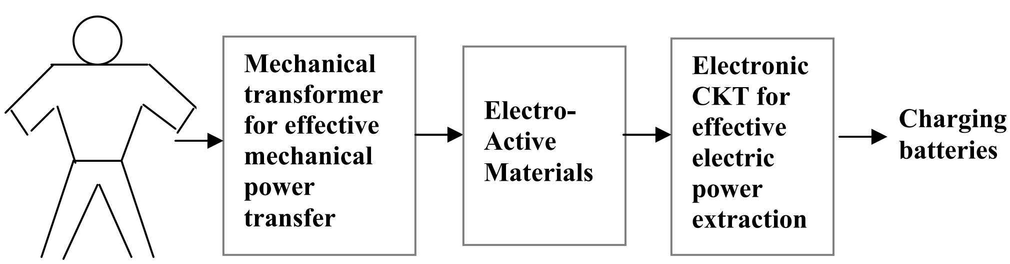



**Figure 1. Schematic of energy flow in an energy harvesting system**

**(2.1) Constitute relations for the electroactive polymers used for energy harvesting**

In the earlier investigations of energy harvesting, the piezoelectric ceramics were utilized. The piezoelectric effect is a linear electromechanical effect where the mechanical strain (*S*) and stress (*T*) are coupled to the electric field (*E*) and displacement (or charge density *D*) linearly, i.e.,

$$S = d\,E \qquad (1a)$$

$$D = d\,T \qquad (1b)$$

In the literature, the effect in Eq. (1a) is often known as the converse piezoelectric effect and in Eq. (1b) as the direct piezoelectric effect which is related to the generation of charge due to an applied stress and is the basis for the energy harvesting. Adding the linear elastic (Hook's law) and dielectric relations to Eq. (1) and writing it out in the full tensor form, we will have the piezoelectric constitutive equations:[6,7]

$$S_{ij} = d_{kij} E_k + s^E_{ijkl} T_{kl} \qquad (2a)$$

$$D_i = \varepsilon^T_{ik} E_k + d_{ikl} T_{kl} \qquad (2b)$$

where $s^E_{ijkl}$ is the elastic compliance, $\varepsilon^T_{ik}$ is the dielectric permittivity, $d_{ij}$ is the piezoelectric coefficient, and *i*, *j*, *k*, l = 1−3. In the equation, the convention in which repeated indices are summed is used. The superscripts *E* and *T* refer to the condition under which these quantities are measured. That is, compliance is measured under a constant electric field (short circuit condition) and dielectric constant under a constant stress. Due to the electromechanical coupling in a piezoelectric material, the elastic compliance under a constant electric field can be very different from that under constant charge.

It should be pointed out that because of the symmetry, the EAPs listed in Table I showing high elastic energy density are not piezoelectric. Rather, they are operated in the electrostriction mode and/or by Maxwell stress (electrostatic force) effect. The electrostrictive effect is a quadratic dependence of strain on the polarization P in the material under zero stress (or a constant stress),

$$S_{ij} = Q_{ijkl} P_k P_l , \qquad (3)$$

where $Q_{ijkl}$ is the charge related electrostrictive coefficient. For an isotropic polymer,

$$S_3 = Q_{33} P^2 \text{ and } S_1 = Q_{13} P^2, \quad (4)$$

where $S_3$ and $S_1$ are the strains along and perpendicular to the polarization direction, known as the longitudinal and transverse strains, respectively. In Eq. (4), the compressed matrix notation is used. For an isotropic polymer, experimental evidence and theoretical consideration indicate that $Q_{33} < 0$ and $Q_{13} > 0$.[8,9] For a linear dielectric polymer, the polarization is related to the dielectric permittivity as

$$P = (\varepsilon - \varepsilon_0)\,E , \qquad (5)$$

where $\varepsilon_0$ is the vacuum dielectric permittivity (= $8.85 \times 10^{-12}$ F/m). Hence, Eq. (4) can be converted into

$$S = Q\,(\varepsilon - \varepsilon_0)^2 E^2 = M\,E^2 , \qquad (6)$$

where *M* is known as the electric-field-related electrostriction coefficient. For an isotropic solid, the longitudinal strain is $S_3 = M_{33}E^2$ and the transverse strain $S_1 = M_{13}E^2$. Therefore, for an isotropic polymer, $M_{33} < 0$ and $M_{13} > 0$. That is, it will contract along the thickness direction and expand along the film direction when an electric field is applied across the thickness.

Analogous to the electrostriction where the strain is approximately proportional to the square of the applied field [Eq. (6)], there is another electromechanical actuation mechanism whose strain response is also approximately proportional to the square of the applied field. That is the electrostatic force (Maxwell stress)-induced strain, which can be quite significant in soft polymers.

The general expression for the Maxwell stress for a dielectric material has been derived as[10,11]

$$T_{ij}^{M} = -E_i D_j + \frac{1}{2}\delta_{ij} D_k E_k \ , \qquad (7)$$

where $\delta_{ij} = 1$ when $i = j$, and $\delta_{ij} = 0$ otherwise and the superscript M indicates the Maxwell stress. Using $D_i=\varepsilon_{ij}E_j$, Eq. (7) can be rewritten as

$$T_{ij}^{M} = -\varepsilon_{jm} E_i E_m + \frac{1}{2}\delta_{ij}\varepsilon_{kl}E_l E_k \ . \qquad (8)$$

Therefore, the strain due to the Maxwell stress in a dielectric material is

$$S_{ij} = -(s_{ijkm}\varepsilon_{ml} - \frac{1}{2}\delta_{ij}s_{ijmn}\varepsilon_{kl})E_k E_l \ , \qquad (9)$$

which has the same form as the electrostriction [Eq. (6)]. For an isotropic material without mechanical constraints, the longitudinal strain induced by the Maxwell stress is

$$S_3 = S_{33} = -\ \frac{1}{2}\varepsilon(s_{11} - 2s_{12})E_3^{\,2} \ , \qquad (10)$$

and the transverse strain is

$$S_1 = S_{11} = \frac{1}{2}\varepsilon s_{11}E_3^{\,2} \ . \qquad (11)$$

Equations (6), (10), and (11) relate the strain in the material to the applied field. Now the question is what is the corresponding equations (or relations) for the electric signal generated due to the applied stress or strain (similar to the direct piezoelectric effect). Assuming an isotropic electroactive material forming a parallel plate capacitor with area A and thickness t, the total change Q in the capacitor under a DC voltage $V_D$ is

$$Q = \frac{\varepsilon A}{t}V_D \qquad (12)$$

If a tensile stress $T_i$ is applied to this parallel plate capacitor, Q will be changed, corresponding to the energy harvesting process, and ΔQ is,

$$\Delta Q = (\frac{A}{t}V_D \, \partial\varepsilon/\partial T_i + V_D\varepsilon \frac{\partial}{\partial T_i}(A/t)\ )\ \Delta T_i \ (13)$$

where the first term is due to the electrostriction, 2 $M_{i3}$= $\partial\varepsilon/\partial T_i$ ,[12] and the second term is from the Maxwell stress effect. Making use of the elastic relations, equation (13) can be simplified to ($D_3$=ΔQ/A and $E_D$=$V_D$/t)

$$D_3 = (2M_{i3}E_D - \varepsilon(s_{3i} - s_{1i} - s_{2i})E_D)\Delta T_i \quad (14)$$

Equation (14) shows that in order to performing energy harvesting from either the electrostrictive or Maxwell stress based effect, a DC bias field is required to induce a non-inversion symmetry in the material. If the stress is applied along the same direction as the DC bias field direction, equation (14) becomes

$$D_3 = (2\,M_{33} - \varepsilon(s_{11} - 2\,s_{12}))E_D\,T_3 \qquad (15)$$

where we have made use of the relation $s_{33}$=$s_{11}$ for an isotropic material and replaced $\Delta T_3$ with $T_3$. Combining the electrostrictive effect and Maxwell stress effect and assuming the applied field $E$=$E_D$+$E_{ac}$ with $E_D$>>$E_{ac}$, the ac strain $S_3$ under the field of $E_{ac}$ is

$$\Delta S_3 = (2M_{33} - \varepsilon(s_{11} - 2\,s_{12}))E_D\,E_{ac} \qquad (16)$$

which is shown in the figure 2. Therefore, under a DC bias field, both the electrostrictive and Maxwell stress effect yields effective piezoelectric coefficients which are the same for the direct and converse "piezoelectric" effects and here the effective $d_{33}$ = ($2M_{33}$-- $\varepsilon(s_{11} - 2\,s_{12})$)$E_D$. Similar equation can also be derived for a tensile stress $T_1$ applied in perpendicular to the applied DC field,

$D_3 = (2M_{13}+\varepsilon s_{11})E_D T_1$ (17)

These results indicate that under a DC bias field, the electroactive polymers possessing the electrostrictive and/or Maxwell stress effects can be treated as a poezielectric material with an effective piezoelectric coefficient $d_{33}=(2M_{33}-\varepsilon(s_{11}-2s_{12}))E_D$ and $d_{31}=(2M_{13}+\varepsilon s_{11})E_D$. Hence, in the following, we can discuss the energy harvesting from the materials with piezoelectric effect. Similar treatment can be extended to include the non-linear effects, for example, when $E_{ac}$ is on the same order of magnitude as $E_D$.

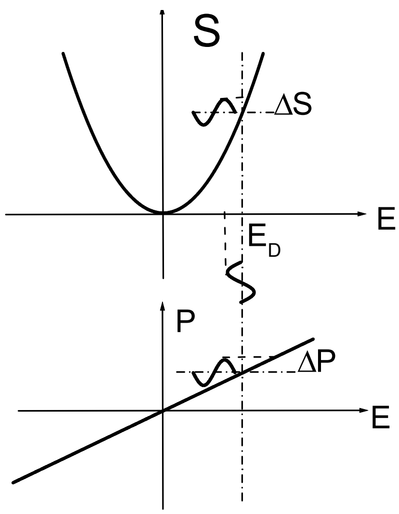



**Figure 2 A schematic view of an electroctrictive polymer with a small ac electric field superimposed on a dc bias field**

## (2.2) Materials considerations for energy harvesting

In an energy harvesting experiment, an important question is what the electric energy harvested after one complete mechanical cycle. Figure 4(a) illustrates a typical mechanical cycle for a piezoelectric material which has been discussed in many publications.[7] In this cycle, as the stress is increased from 0 to $T_0$, the external environment inputs mechanical energy to the piezoelectric material and the this energy density is

$$U_1 = ½ s^E T_0^2$$

where $s^E$ is the compliance under constant electric field (short circuit condition). When the stress is reduced from $T_0$ to 0, the piezoelectric material is doing work to the external medium. Now if the material is under the open circuit condition, this returned mechanical energy $U_2$ is

$$U_2 = 1/2\, s^D T_0^2$$

is less than the input one since the elastic compliance under the open circuit condition $s^D$ is smaller than $s^E$. If the dielectric loss and elastic loss are very small, from the energy conservation consideration, the difference between $U_1$ and $U_2$ is the electric energy harvested by the piezoelectric material. The ratio between the electric energy harvested and the total initial input mechanical energy is the material efficiency in the energy harvesting. For the case that the external stress $T_3$ is applied along the direction of polar axis, this efficiency is equal to the square of the longitudinal electromechanical coupling factor $k_{33}$,

$$\frac{U_1 - U_2}{U_1} = \frac{d_{33}^2}{s_{33}^E \varepsilon^T} = k_{33}^2 \qquad (18)$$

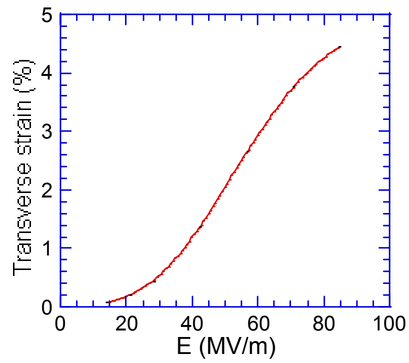
Similarly if the stress is applied in perpendicular to the piezomaterial polar direction, this equation becomes

$$\frac{U_1 - U_2}{U_1} = \frac{d_{31}^2}{s_{11}^E \varepsilon^T} = k_{31}^2 \qquad (19)$$

Therefore, in order to achieve a high electric power output from the energy harvesting, a material with a high coupling factor is highly desirable. Furthermore, even for the same material, its coupling factor will depend on the direction of the input mechanical stress and strain with respect to the piezomaterial poling direction. For example, for the PZT ceramic which is the material used in several previous energy harvesting investigations, the coupling factor $k_{33}$ is 0.75 while $k_{31}$ is below 0.39.[13] The ratio of $k_{33}^2/k_{31}^2$ is near 4. Unfortunately, it is the smaller $k_{31}$ effect that was utilized in the earlier energy harvesting investigations.[4,5]

Several EAPs developed recently also exhibit relatively high electromechanical coupling factor. For example, should in figure 3 is the transverse strain response for an high energy electron irradiated P(VDF-TrFE) copolymer and the electromechanical coupling factor deduced from the strain, polarization, and elastic modulus data.[14]
Apparently, the irradiated copolymer can exhibit a relatively high $k_{31}$, which can reach 0.65 under an external DC bias field of 80 MV/m. Because for electroactive polymers, the processing conditions can have significant effect on the electromechanical responses, it is interesting to investigate how the electromechanical conversion efficiency can be improved in these materials.

The electroactive polymers listed in Table I are insulators and if ignoring the dielectric loss, any input electric energy can be recovered near 100% (which will also depend on the external electronics and recently, Campolo et al. reported that a theoretical 100% recovery efficiency for a carefully designed electronic circuit).[15] Therefore, one may make use of the electric boundary conditions to modify the mechanical cycle shown in figure 4(a) to achieve a higher system efficiency and furthermore to even increase $U_1$, the initial input mechanical energy under a given $T_0$.



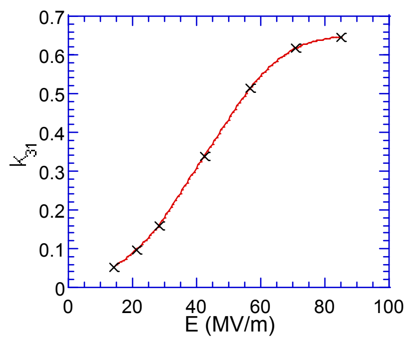




**Figure 3. The transverse strain for an irradiated copolymer along the film stretching direction and the corresponding coupling factor $k_{31}$ as a function of the applied electric field at room temperature.**

For example, in the part of the mechanical cycle in figure 4 in which the stress is reduced from $T_0$ to 0, if an external electric field is simultaneously applied to the electroactive polymer to maintain the strain level unchanged, then $U_2$ will become zero, which leads to a material system with an effective energy conversion efficiency much larger than that allowed by the material conversion efficiency ($k^2$). Such a mechanical cycle is schematically illustrated in figure 4(b), which indicates that by properly

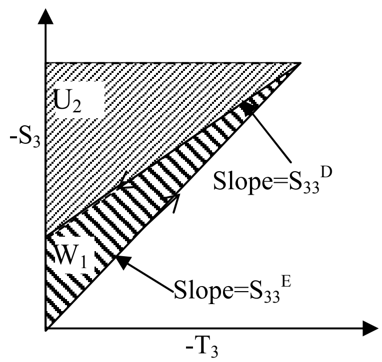



Figure 4 (a)

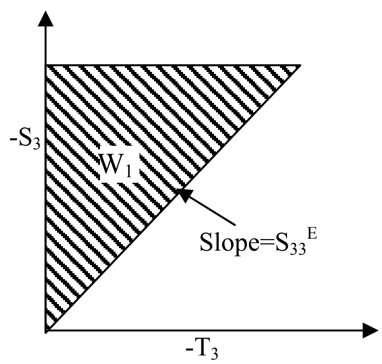



Figure 4 (b)

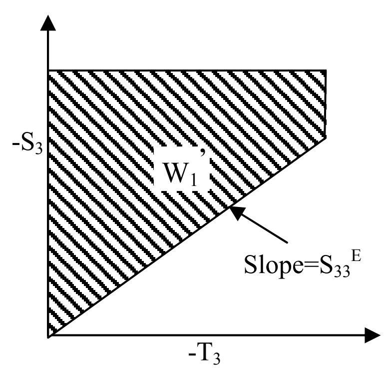



Figure 4 (c)

**Figure 4 The mechanical cycles for several energy harvesting systems ($W_1=U_1-U_2$, (See equations (18) and (19)).In (b) and (c),$U_2=0$)**

designing the electric boundary conditions, the energy conversion efficiency of a material system can exceed that of the material.

In an energy harvesting experiment, the electric energy density harvested by an EAP is $k^2$ $U_1$. Therefore, in order to achieve a high electric power output, besides optimizing the effective coupling factor k of the material system, how to maximize $U_1$ is another key issue which should be considered. For an energy harvesting system with a given $T_0$ (in most energy harvesting systems, there is a limit on $T_0$), an electroactive material with a higher elastic compliance is preferred. This is understandable since a material with a large compliance will produce large strain and consequently a higher $U_1$. On the other hand, one may further increase the input mechanical energy $U_1$ by following a mechanical cycle as shown in figure 4(c). In this experimental cycle, the electroactive material is strained as the stress is raised from 0 to $T_0$. After that, by applying an electric field E to the material under the constant stress $T_0$, there is an additional mechanical energy input from the external environment and the total input mechanical energy density is $\frac{1}{2} s^E T_0^2 + d E T_0$, where d is the corresponding piezoelectric coefficient and E is the applied electric field. The level of increase in the input mechanical energy density will depend on the ratio of d E versus $s_E T_0$. Furthermore, for a mechanical cycle as shown in figure 4(c), the effective electromechanical conversion efficiency is also increased to above the conversion efficiency of the material.

It should be emphasized that the discussions presented in the proceeding paragraphs regarding using the electric boundary conditions to raise the effective energy conversion efficiency and input mechanical energy density are based on the premises (1) the EAPs in the discussion are insulators and have low dielectric loss and mechanical loss and (2) the input electric energy used to modify the electric boundary conditions can be fully recovered. Therefore, in addition to the materials selections, the power electronics used in the energy harvesting must also be designed carefully. As will be shown in the following, the power electronics circuit will have a significant effect on the electric energy extraction from the electroactive materials. Most importantly, for the energy harvesting from a soldier in a battlefield, what are the physiology effects on the soldier is the most important concern and by a proper design of the mechanical cycle in the energy harvesting process, one may also achieve a positive physiology effect to the soldier.

### (2.3) Power electronics for energy harvesting

An important aspect of energy harvesting is the power electronic circuitry. An optimized power electronic circuit will impose the appropriate electrical boundary conditions on the piezoelectric or electrostrictive material and convert the electrical energy harvested to a useable form. These boundary conditions are chosen to serve the dual purpose of maximizing energy harvested while at the same time satisfying physiological concerns for the soldier. Care must also be taken not to exceed the limitations of the device.

There are two types of electrical boundary conditions that can be imposed on the device: charge $q$, which in turn imposes an electrical flux density $D$ of the device, and voltage $V$, that controls the electric field $E$ in the device. Using the constitutive relationships presented in Section 2.1, electrical boundary conditions can be determined for a given mechanical cycle that achieves the desired objectives, and the appropriate power electronic circuitry can then be designed. It is possible for certain power electronic circuit designs to be capable of either voltage or charge regulation or both, through the use of appropriate algorithms that control the switching of transistors in the circuit. The transistors in efficient power electronic circuits are typically operated in "switch" mode (i.e., either "on" or "off") due to the lower power dissipation of the transistor under these conditions.

The design of appropriate power electronic circuitry for energy harvesting will depend upon the type of device used. One of the main differences in the design of circuits for piezoelectric or electrostrictive devices is the ability to apply bi-directional fields and flux densities to the piezoelectric device. Due to the linear nature of the piezoelectric device's constitutive relationships, energy harvesting can be effectively doubled with this bi-directional capability when considering device limitations. Because of the dependence of electrically-induced strain on the square of the electric field in electrostrictive devices, bi-directional field capabilities do not offer any increase in energy harvesting, and therefore a simpler circuit can be used.

The application of electrical boundary conditions to the device to maximize energy harvesting will possibly require that the power electronic circuitry be capable of bi-directional power flow, or the ability of power to flow from the device to the electrochemical battery and vice-versa. However, approaches which require significant power to flow back and forth from the battery to the device during a cycle to accomplish a significantly smaller net power flow from the device to the battery may not be practical because of the losses incurred during the power swings. Hence energy harvesting approaches which seem desirable from a device standpoint may not be as desirable when considering the power electronic circuitry.

In general, the efficiency of the power electronic circuitry must be taken into account, and so the investigation of techniques to maximize energy harvesting cannot focus solely on the device properties. Circuit implementations that require several transistors switching at high frequency may be undesirable, as the losses incurred in the switching process may be a significant fraction of the total power. Transistor properties must be carefully chosen so that the total switching and conduction losses in the transistor are minimized. Finally, the power consumed by the circuitry that implements the control algorithm may also be a significant fraction of the energy harvested from the device[16].

**III Conclusions**

This paper analyzed energy harvesting using electroactive polymers from a soldier with a backpack during walking. In order to effectively harvesting energy from the mechanical source, one has to ensure an effective mechanical energy transfer between the source and the electroactive material (to realize mechanical impedance match). The high strain level and large elastic energy density of the electroactive polymers make it possible to capture the available mechanical energy with a much reduced device volume in comparison with the devices investigated earlier. The relatively high electromechanical conversion efficiency of these newly developed electroactive polymers is another key parameter to achieve higher electric energy harvested from the available mechanical source. Furthermore, by making use of smart power electronics to properly modify the electric boundary conditions of the electroactive polymers, one can realize a material system with the energy conversion efficiency exceeding that of the material itself. A smart power electronic circuit is also required to maximize the electric energy transfer from the electroactive polymers to the electric load, for example, to charge a battery. Finally and most importantly, the engineering design and development of the energy harvesting system should be integrated with the physiological/biomechanical approaches so that, in addition to reduce the weight of the batteries, the energy harvesting system will also have positive impact on the soldier's capability in the battlefield. That part of the work is carried out in collaboration with Professor L. Rome of University of Pennsylvania who has been supported by a parallel program from ONR.

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