TEM Journal. Volume 5, Issue 3, Pages 401-405, ISSN 2217-8309, DOI: 10.18421/TEM53-22, August 2016.

Model of Piezoelectric Polymer Energy Harvesting System

Orlin Stanchev [1], Angel Marinov [1], Emilian Bekov [1]

[1] *Technical University of Varna, Department of Electronic Engineering and Microelectronics, 1 Studentska Str., 9010 Varna, Bulgaria*

***Abstract* – This paperproposes a specialized model of an energy harvesting system powered by a piezoelectric polymer element. The model allows a complex system based evaluation and can be used as a general design tool. The model is implemented into a general purpose simulation environment. The simulation results are presented and analysed. The model is verified trough a dedicated experiment.**

***Keywords* –Energy Harvesting, Piezoelectric, PVDF, Simulation model, Wireless sensors.**

1. Introduction

Energy harvesting from piezoelectric elements can provide electrical energy for low power electronic devices like data loggers and wireless sensors [1][2]. However,the generated instantaneous powernormally is not enough even for such low power devices due to the relatively low efficiency of mechanical to electrical energy conversion when using piezoelectric elements (typically 1 ÷2 % for Polyvinylidene fluoride - PVDF) [3][4]. Therefore energy harvesting systems withthe capability of accumulating electrical energy and at some level providing stabilized voltage for a finite period of time have to be used. The behavior of such complex systems is hard to predict especially when the mechanical stress, applied on the piezoelectric element, has random nature. In such situations a complex model can be used to simulate the system's behavior and interaction with the load at different piezoelectric element mechanical excitation conditions. Piezoelectric elements are made of various materials like piezo ceramics (PZT) or piezo polymers (PVDF) [1][3]. PVDF is available in the form of flexible, lightweight and tough piezo film that has the following advantages, when considering energy harvesting [5]:

- high elastic compliance;
- high mechanical strength and impact resistance;
- high stability resisting moisture, most chemicals, ultraviolet radiation etc.;
- can generate up to 30 V/µm for given thickness;
- can be fabricated into unusual forms;
- can be glued with commercial adhesives to flat or rounded surfaces.

The piezo film has typical thickness of 9, 28, 52 or 110 µm and is commercially available in the form of elements with relatively small surface (5 cm^2) up to full size sheets (580 cm^2). They can operate at temperatures in the range – 40 ÷ 80 ºC, generatingenergy up to 20 µJ/cm^2 for one strain cycle. The piezo film is insensitive to pre-load or static strain however about 1 % strain is considered repeatable.

When calculating the generated voltage or charge, the mechanical stress is considered to be applied on one mechanical axis due to the film dimensions that can be length (direction "1"), width (direction "2") or thickness (direction "3"). The material characteristics and especially the piezoelectric coefficients differ slightly in length/width and thickness direction.

2. Model structure and requirements

The model, presented at Figure (1), includes all elements of an energy harvesting system so that it

DOI: 10.18421/TEM53-22
https://dx.doi.org/10.18421/TEM53-22

Corresponding author: Orlin Stanchev,
Technical University of Varna, Varna, Bulgaria
Email: or.stanchev@gmail.com

can simulate the full system functionality under different operation conditions and settings. It consists of the following blocks:

(1) Mechanical power source;
(2) Piezoelectric polymer element;
(3) Current rectifier and energy storing capacitor;
(4) Switching voltage regulator withfeedback controller and load.

The general functionality of the model can be described as follows:A stimulusgenerator produces a force with random amplitude in a specified rangeor with a fixed value depending on the specifics of the mechanical power source. This force is thentransformed into electricity by the piezoelectric element. One needs to provide enough energy for powering the load for a given period of time so that the energy is stored in a capacitor.When the initial voltage of the storage capacitor is zero the piezoelectricelement produces relatively small amount of charge [4]. In order to increase its efficiency the capacitor is kept at some initial positive voltage level. In this case the available energy U_e for powering the load is given byEquation (1).

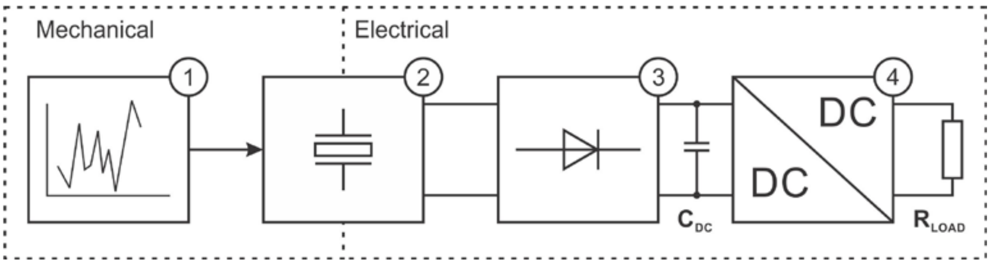

Figure 1. Model of piezoelectric polymer energy harvesting system

$$U_e = \frac{C_s \cdot \left({V_{on}}^2 - {V_{off}}^2\right)}{2} \qquad (1)$$

whereC_s is the storage capacitance, V_{on} and V_{off} are the switching voltage regulator turn on and turn off voltages.

The turn on and off hysteresis is provided by the feedback controller that generates the PWM control signal for the switching voltage regulator which has the topology of a buck converter. The system load is represented by a simple resistor.However, it can be replaced by a controlled current source thatmodels current consumption,which is variable in time.

Because of the complexity of the model the basic elements are divided into subsystems.

3. Modelling the piezoelectric polymer element

When the piezoelectric polymer elements are used as transducers forconversion of mechanical to electrical energy they can be considered as charge or voltage generators - depending on the connected interface electronics. In this paper they are considered as voltage generators as their equivalent circuit consists of a voltage source and a capacitor connected in series. The capacitor represents the capacitance of the piezofilm. The voltage source is dependent on the applied stress in the relevant direction. The original equations that describe the connection between stress and voltage [4] are transformed to Equation (2), when the force is applied on length or width direction and Equation (3), when the force is applied on thickness direction:

$$V_{31} = g_{31} \cdot \frac{F_{31}}{a} \qquad (2)$$

$$V_{33} = -g_{33} \cdot F_{33} \cdot \frac{t_{pvdf}}{A_{33}} \qquad (3)$$

where $V_{31}$and $V_{33}$are the output voltages, g_{31} and g_{33} are the proper piezo stress constants, a is the film width, t_{pvdf} is the film thickness, A_{33} is the film surface and F_{31} and F_{33} are the forces applied in the relevant direction.

The structure of the subsystem that models the piezo element is given in Figure (2). It operates in length or width direction. The input force F_{31} generated by a separate stimulus sourceis applied to ‘Divide’ and ‘Product’ blocks that perform the operations in Equation (2). The blocks ‘a’ and ‘g31’ are used to set the piezo stress constant and the width of the piezo film. The result from the equation is applied to a controlled voltage source ‘Vpiezo’ which is connected in series with capacitor ‘Cpiezo’ representing the piezo film capacitance. So at an open circuit the output voltage of the model is equal to the one of the voltage generator - the result from Equation (2) at the given force. However, when a load is present, this voltage is divided between the capacitor impedance and the load due to the frequency.

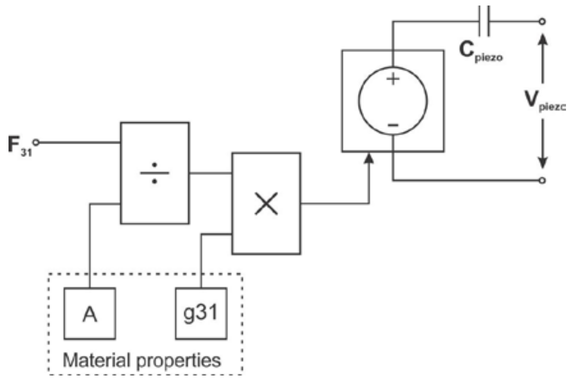

Figure 2. Piezoelectric polymer element 'l' direction

When the piezoelectric element operates in thickness direction the subsystem structure is modified so that it fulfills Equation (3). The new structure is given in Figure (3).

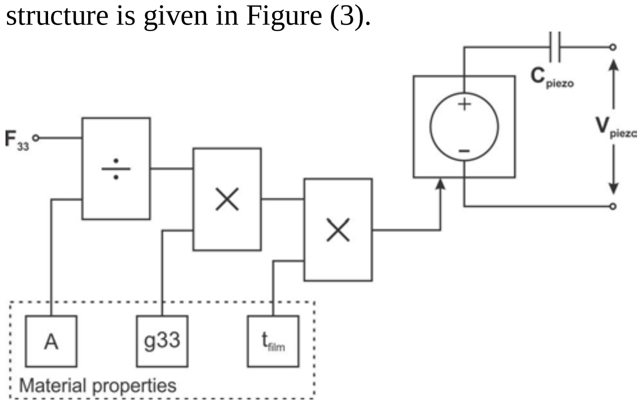

Figure 3. Piezoelectric polymer element 't' direction

4. Rectifier bridge

The generated voltage by the piezoelectric element is applied to a subsystem that models a bridge rectifierwhich is given in Figure (4). It consists of four rectifier diodes which are modelled with blocks 'D1', 'D2', 'D3' and 'D4'. Theyhave the characteristics of low forward voltage drop Schottky diodes so that the piezoelectric element should generate enough voltage to overcome the diodes and charge the storage capacitor. This dependence is expressed with the following equation:

$$V_{pvdf} > V_{Cs} + 2 \cdot V_F \quad (4)$$

whereV_{pvdf} is piezo element voltage, V_{Cs} is the storage capacitor voltage and $V_F$is theforward voltage drop.

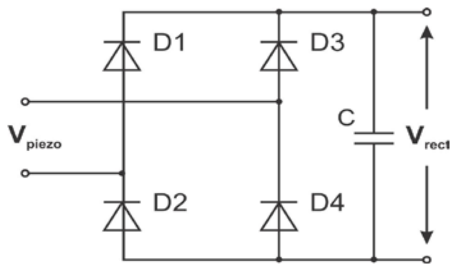

Figure 4. Rectifierbridge

5. Buck Converter

The storage capacitor is connected to the input of switching voltage regulator. It should have high efficiency and low losses therefore a synchronous buck converter topology is used [6]. It is modeled in a subsystem that is given in Figure (5). It consists of two N-channel power MOSFETs ('Q1' and 'Q2'), gate current limiting resistors('Rg1' and 'Rg2'), buck inductor ('L')and an outputcapacitor('Cout'). The power converter operates at high switching frequencies in the range of 100 ÷ 250 kHz in order to minimize the size of filtering elements. However switching losses are limited by using models of low power and voltage transistors with relatively small input and output capacitances.

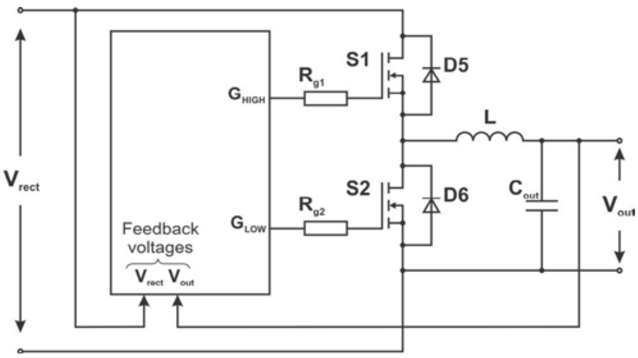

Figure 5. Buck converter

6. Feedback controller

The feedback controller monitors the storage capacitor voltage needed to enable the voltage regulator at a given voltage level and generates a PWM voltage with proper duty ratio to drive the MOSFETs and maintain constant output voltage. It is modeled in a subsystem which structure is given in Figure (6).

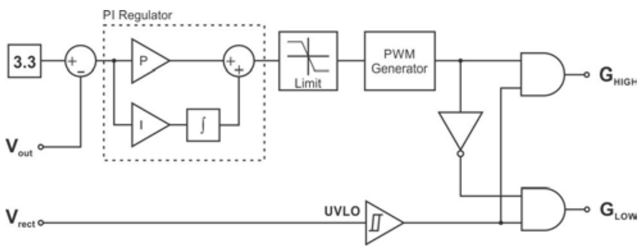

Figure 6. Feedback controller

The converter's output voltage is applied to a summing block that subtracts it from the reference value '3.3 V'. The result is deviation (error) from the desired output voltage, which isapplied to a PI regulatorprovidingsystem stability and sensitivity to the output voltage fluctuations. The result is limited by a saturation block that limits duty ratio in the range 5 ÷ 95 %. The result is applied to a block 'PWM generator' that generates modulated voltage with given frequency and amplitude.

The power transistors of the synchronous buck converter have to be driven with opposite signals but when the converter is disabled both MOSFETs have to be turned off, in order to avoid output capacitor discharge trough 'Q2'. These actions are performed by two AND and one NOT logic gates. The two gate drive voltages are then applied to the transistors.

The buck converter's input voltage is applied to a Schmitt trigger represented by block 'UVLO'(set to 3.6 V and 5 V) that performs hysteresis and enables or disables power transistors using the logic gates.

7. Simulation results

The proposed model can be implemented using various analytical software such as ORCAD PSPICE, PSIM, PLEXSIM, MATLAB, etc. For the purposes of the paper the model was realized and simulated in the MATLAB/Simulink environment [7].The mechanical force is applied on 'l'direction so that the structure from Figure (2) is used for modelling the piezoelectric polymer element - 171 mm long and 44 mm wide sheet made of PVDF material with 28 µm thickness. The maximum elastic deformation is calculated to be ε = 0.5 % which is equal to a maximum applied force ofF_{max} = 49.28 N. The more significant model elements' parameters are given in Table 1.

Table 1.Model elements' parameters

Variable	Value	Unit
a	38	mm
g31	$216 \cdot 10^{-3}$	V·m/N
Cpiezo	22	nF
Cs	1200	µF
L	15	µH
Cout	22	µF
Rload	330	Ω
Vref	3.3	V
Von	3.67	V
Voff	5.05	V
Kp	0.9	-
Ki	250	-

Due to hysteresis (on/off) values and Equation (1), total electrical energy, stored in the capacitor C, is about 15.3mJwhileonly7.22mJ are available to be transferred to the system output. The load is designed to consume 10 mA current for a given period of time, which is enough for low power radio transmitter that is controlled by a microcontroller to transmit data [8][9].

The simulation is accomplished for a period of 51 s using variable time step and trapezoidal numerical method to solve differential equations [10]. The solver is optimized in order to reducetotal simulation time which can be substantial for relatively long periods of time when simulating energy harvesting.

Generated force from the mechanical generator is given in Figure (6). It has a triangular shape due to linear change of applied force with maximum value of 49.8 N and period 0.033 ms.The graphic includes less than 1 % of the period in order to provide better resolution of the signal shape and tendency of variation.Voltage variation in time of the storage capacitor and the output voltage are given in Figure (7).At the current mechanical stress the system needs less than 50 s to accumulate enough energy in the storage capacitor from startup and enable the output switching voltage regulator.About14 s are needed to enable the output again.

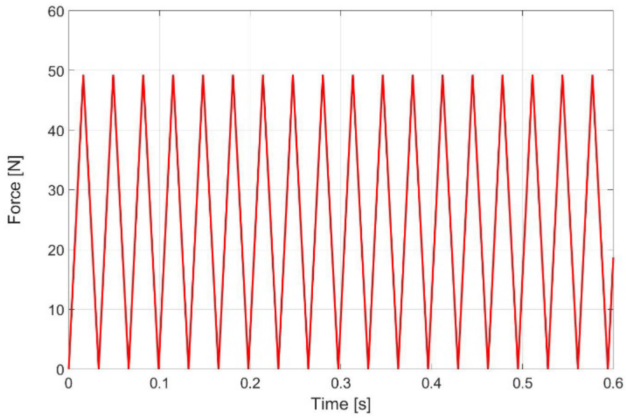

Figure 6. Generated force

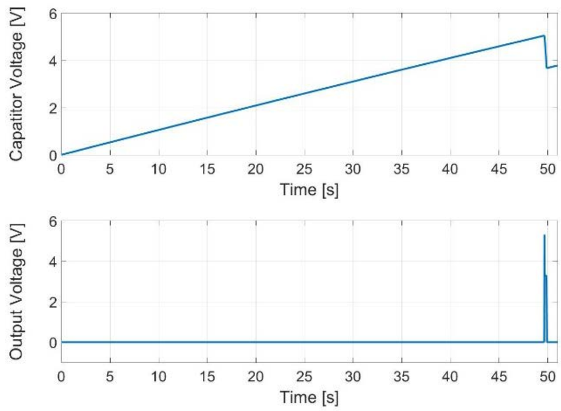

Figure 7. Capacitor and output voltage

Time interval, when the output is enabled, is given in Figure (8). The output voltage remains stable for the whole interval of about 220ms.

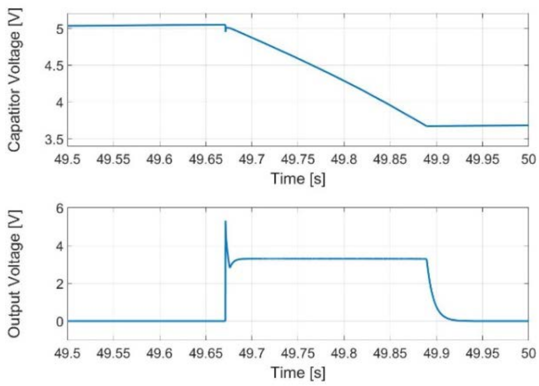

Figure 8. Capacitor and output voltage when output is active

8. Verification

The simulation model is verified with a laboratory experiment. Two DT04-028 [11] piezo film elementsare used and their electrodes are connected in parallel so that they are equivalent to the model parameters. The piezo elements are precisely stretched to 1 % length using a CNC machine. The mechanical stress frequency is 10 times lower than the frequency of the force generator in the model due to hardware limitations. Furthermore, the active surface of the piezoelectric elements is reduced by 18 % due to the attachment pads which reduce generated charge.The energy harvester consists of specialized integrated circuit LTC3588-1 [12] and an external high quality electrolytic energy storing capacitor. The system elements' parameters are corresponding to the values, given in Table (1). The results are given in Figure (9). The piezo element voltage, storage capacitor voltage and output voltage are denoted with yellow, blue and green. The voltages are measured using a digital scope Tektronix TPS2014, having four galvanic isolated analog input channels [13].

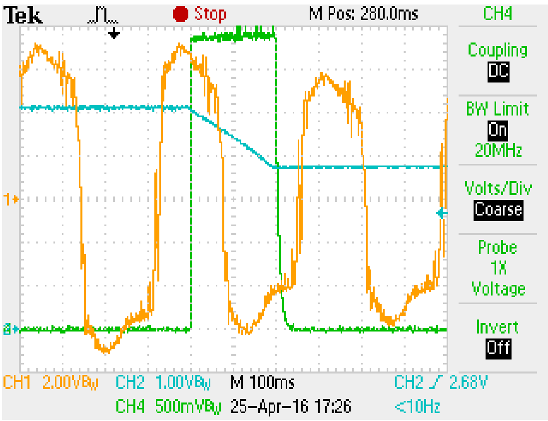

Figure 9.Piezo element, capacitor and output voltage when output is active

The storage capacitor is charged from 0 V to 5.05 V for 500 s at 3 Hz frequency. The secondary recharge from 3.67 V to 5.05 V takes about 150 s. The 330 Ω load resistor draws 10 mA current which is provided for 200 ms at each discharge cycle. The measured time periods are 10 times longer due to the 10 times lower frequencyof the generator. However about 1 % deviation occurs between the simulation model and the laboratory experiment which is negligible.

9. Conclusion

The proposed model of piezoelectric polymer energy harvesting system is a powerful tool for simulation, design, analysis and tuning of energy harvesting systems with different (in size and form and stress direction) piezoelectric polymer elements.

Verification of the model shows that it is operational within a certain degree of accuracy.

Further studies will be implemented to determine and describe model accuracy and integrate theautomated design procedures, where additional development may include integration of the model into a dedicated software tool that can operate on its own.

References

[1]. Tan, Y. K. (2013). Energy harvesting autonomous sensors systems, CRC Press

[2]. Drew, J. (2010). Energy Harvester Produces Power from Local Environment, Eliminating Batteries in Wireless Sensors. *Electronic Design*, *58*(14).

[3]. Schwartz, M. (2002).Encyclopedia of Smart Materials, New York: John Wiley & Sons. Inc.

[4]. Brown, R. (2013). Piezo Film for Energy Harvesting," Measurement Specialties Inc., www.meas-spec.com

[5]. Measurement Specialties Inc. (2008).Piezo Film Sensors Technical Manual, http://www.meas-spec.com

[6]. Linear Technology Corp. (2010). LTC3588-1 Piezoelectric Energy Harvesting Power Supply – datasheet, www.linear.com

[7]. Mathworks (2016). Matlab& Simulink - Simscape User's Guide, www.mathworks.com

[8]. Wenshing Electronics Co. LTD. (2010). Wireless Hi Power Transmitter Module datasheet, www.wenshing.com.tw

[9]. Nordic Semiconductor (2012). nRF24L01 Single Chip 2.4 GHz Transceiver Product Specification, www.nordicsemi.com

[10]. Iserles, A. (2009). *A first course in the numerical analysis of differential equations* (No. 44). Cambridge university press.

[11]. Measurement Specialties Inc. (2008). DT Series elements with Lead Attachment, http://www.meas-spec.com

[12]. Linear Technology Corp. (2010), LTC3588-1 Piezoelectric Energy Harvesting Power Supply, www.linear.com

[13]. Tectronix Inc. (2015). Digital Storage Oscilloscopes TPS2012, TPS2014, TPS2024, www.tek.com