IEEE-SEM, Volume 7, Issue 7, July-2019
ISSN 2320-9151

Piezoelectric Energy Harvesting: A New Approach

Anuj Kumar
Student, Electrical Engineering Department
National Institute of Technology, Patna, India
ranaak.162@gmail.com

Jayanti Choudhary
Assistant professor
Electrical Engineering Department
National Institute of Technology, Patna, India
jayantichoudhary@gmail.com

***Abstract*— Piezoelectric materials have a unique property of gaining a potential across its surface when subjected to some sort of distortion. This generated power can be used to provide some useful power. The energy extracted from the piezoelectric transducer is not constant and has a lot of fluctuations in it. We aim to reduce these fluctuations by using the external circuits with the piezoelectric transducer. The focus of this paper is to get an enhanced and constant power from the piezoelectric material. A new technique of electric energy generation is presented in this paper using mechanical excited piezoelectric material. This technique called "DOUBLE SYNCHRONIZED SWITCH HARVESTING TECHNIQUE" treats the output voltage of the piezoelectric material non-linearly. It consists of an intermediate stage, which boosts the harvested power irrespective of the load connected. This technique significantly increases the electromechanical conversion capability of the piezoelectric material. For wide range of connected loads, this technique gives a fixed harvested energy compared with the standard circuit; we are getting gain of about 250% in terms of maximum power using new technique. Mathematical model of the system is done. Simulations and calculations at 105.3 Hz frequency of the input current (piezoelectric micro generator), shows the validity of this method.**

Index Terms— **Piezoelectric materials, Standard Circuit and DSSH circuit**

I. INTRODUCTION

Jacques and pieri curie discovered a unique material in 1880. The material is known as Piezoelectric material, when subjected to some pressure would induced an electric charge on their edges and vice versa. These material are becoming more and more relevant with increase in demand of ultra-low power devices and autonomous devices.These days piezoelectric effect is one of the most investigated ways of electromechanical energy conversion.The equivalent circuit of piezoelectric material is Norton circuit in which source is AC current source and parallel impedance is capacitor. The frequency of AC current source depends on pressure vibration. At different pressure frequency is different. The output of piezoelectric materials is AC. AC can not be stored while DC can be stored. So for the purpose of energy storage AC to DC converter is necessary. This combined circuit is known as standard circuit. This circuit combines the advantages of extracted power optimization by nonlinear processing load independent energy scavenging. This technique consists of switching the piezoelement on an inductor synchronously with the available charges on a piezoelectric insert.Problem in the standard circuit is low Output. Power and long Dead Zone . By using DSSH technique, efficiency of standard circuit may be improved and Dead Zone may be reduced. It optimizes the electromechanical conversion and provides a load adaptation, allowing a constant harvested energy whatever is the load. In addition , this technique based on an intermediate energy storage using a capacitor offers a way of controlling the trade-off between energy harvesting and the intrinsic damping effect of the extraction process.DSSH circuit is combined circuit of standard circuit and buck-boost converter. Buck-boost converter can work in Buck mode or Boost mode depending upon duty cycle. If duty cycle is less than 0.5, then converter works in step-down mode. If the duty cycle is more than 0.5, then converter works in Step-Up mode. In DSSH circuit Converter work in Step-Down mode. In this paper operation of both circuit i.e. standard circuit and DSSH circuit is done at frequency 105.3 Hz. The maximum amplitude of piezoelectric equivalent AC current source is 1mA and the internal capacitance of piezoelectric material is taken 30nF. For both cases load is pure restive i.e. for comparison of both circuit in terms of Dead-Zone and efficiency, piezoelectric material and load is same .

II. STANDARD CIRCUIT [3]

It is the simplest circuit present in the market to extract energy from the piezoelectric element. It is designed for fixed load, as the load changes the circuit has to be modified according to the load.

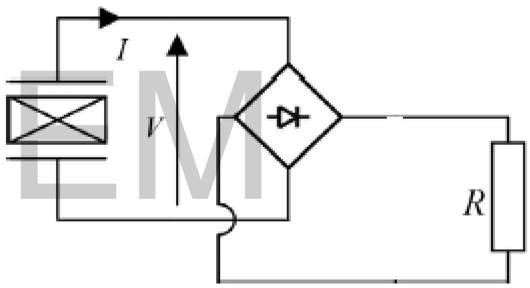

Fig.1. standard Circuit

There is no switching element in the standard circuit.

III. OPERATION OF STANDARD CIRCUIT

The operation of the standard circuit is simple. As the pressure is applied, AC current is generated. This generated electrical energy is converted in DC form through the AC to DC converter.

IV. DSSH CIRCUIT [4]

DSSH technique uses double switching. DSSH technique uses an intermediate capacitance C_{int} at the intermediate

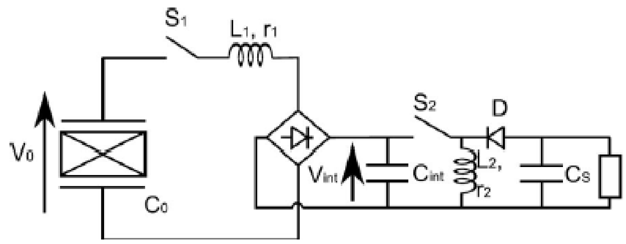

Fig.2. DSSH circuit

energy storage stage. In intermediate stage C_{int} stores some energy and passes the extra energy to the inductor L_2. Finally this energy is transferred to the load through the smoothing capacitor.

V. OPERATION OF DSSH CIRCUIT

The operation of DSSH technique is complex. In DSSH circuit switching S_1 take place when generated piezoelectric voltage across the internal capacitance of piezoelectric material is maximum. Switch S_1 is open when current through this switch is zero. Switch S_2 is closed when current through S_1 is zero and switch S_2 is open when current through S_2 is zero.

VI. MATHEMATICAL MODELLING AND CALCULATION DSSH CIRCUIT

This modelling consists of a spring mass damper (second order system) that is electromechanically coupled as shown as figure.3. This model has been presented in [4] and gives a simple but realistic modelling when the electro mechanical system is excited near one of its resonance frequencies. The constitutive equations of this model is given by

$$M\ddot{u} + C\dot{u} + K^{E}u = F - \alpha V \quad \text{.......................................(1)}$$

$$I = \alpha\dot{u} - Co\dot{V} \quad \text{...(2)}$$

Where u = Flexural displacement of structure
F= driving force ,
V=Piezoelectric element Voltage ,
I=Current flowing out of the piezoelectric element ,
M=Dynamic mass ,
C=Structural damping coefficient
=short circuit stiffness ,
α=force factor ,
Co=Blocking capacitance of the piezoelectric element

Although more detailed mechanical model and its equivalent electric circuit are shown below

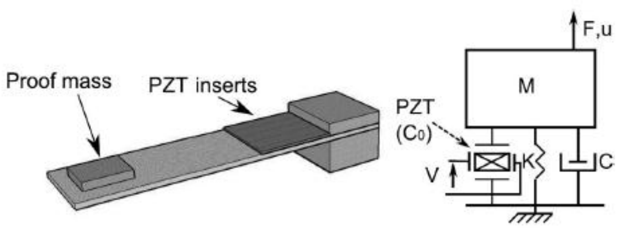

Fig.3 Micro generator structure and model [4]

Parameters of DSSH circuit

Element	Value	Element	Value
Piezoelement current	1 Ma	Piezoelement capacitance	30 Nf
Piezoelement voltage	50 V	Resonance frequency	105.3 Hz
Inductor L_1	1 H	Capacitance C_{int}	30 nF
Inductor L_2	2 H	Smoothing capacitance C_s	0.128 uF
Resistance r_1	50 ohm	Resistance r_2	10 ohm
Force Factor α	0.234 mNV^{-1}	constant Vibration magnitude µm	2 mm

WHEN SWITCH S_1 IS OPEN

The piezoelectric element is not connected to the resonant circuit. The circuit is given below-

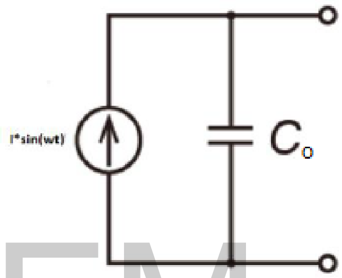

Fig.4. Piezoelectric equivalent circuit [2]

The current flowing through the closed loop is calculated by the following equation-

$$I(t) = Ip * \sin(\omega t) \quad \text{...(3)}$$

The voltage across the capacitor is given by the equation below-

$$V(t) = \frac{-Ip}{W * Co}\cos(\omega t) \quad \text{.......................................(4)}$$

The voltage will be maximum when:

$$\cos(\omega t) = -1$$

Or

$$t = \frac{\pi}{\omega}$$

At frequency f= 105.3 Hz

t= 4.7483 ms

IEEE-SEM, Volume 7, Issue 7, July-2019
ISSN 2320-9151

Hence switch S_1 is closed after 4.7483 ms with respect to applied pressure.

WHEN SWITCH S_1 IS CLOSED AND S_2 IS OPEN [4]

When S_1 is closed, piezoelectric element is connected to the resonant circuit. The current flowing through the closed loop circuit is calculated by KVL equation given below-

$$L1\ddot{qp} + r1\dot{qp} + \frac{qp}{Cequ} = 0 \quad \text{...(5)}$$

Where q_p is the charge on the piezoelectric element
L_1 is the series inductor connected to the series inductor
r_1 is the internal resistance of the inductor
C_{equ} is the equivalent capacitance of C_o and C_{int}
V_p is the voltage just before the switching.

The current flowing through the loop may be calculated by solving the equation 3 and as given below-

$$Ip = -Cequ * Vp * \frac{\omega o}{\sqrt{1-\delta o^2}} * e^{-\omega o \delta o t} * \sin\left(\omega o\sqrt{(1-\delta o^2)}\right)t \quad \text{.........(6)}$$

Where ω_o is the natural frequency

$$\omega o = \sqrt{\frac{1}{L1\ Cequ}}$$

And δ_o is the damping coefficient

$$\delta o = \frac{1}{2} * r1 * \sqrt{\frac{Cequ}{L1}}$$

CALCULATION

Switch S_1 is open when current through the loop is nil i.e.

$$Ip = 0$$

It is possible only when transient time t=0.3848 ms

Thus switch S1 is closed after the time (4.7483+0.3848) 5.1331 ms.

Thus first switching stops after 5.1331 ms. In this time period the amount of transferred charge.

$$\Delta qo = \int_0^{\frac{\pi}{(\omega o^2\sqrt{1-\delta o^2})}} Ip * dt \quad \text{.....................................(7)}$$

$$\Delta qo = \frac{-Cint * C0}{Cint + C0}(1+\gamma o)Vp \quad \text{.....................................(8)}$$

Where $\gamma o = e^{-\pi\delta o/\sqrt{1-\delta o^2}}$

For given data

δo=0.9904

And γo is known as inversion factor.

$$(Vco)end = vo + \frac{\Delta qo}{C0}$$

$$(Vco)end = [1 - \frac{Cint}{Cint + Co}(1+\gamma o)]vp \quad \text{........................(9)}$$

$$(Vcint)end = \frac{\Delta qo}{Cint}$$

$$(Vcint)end = \frac{Co}{Cint + Co}(1+\gamma o)Vp \quad \text{............................(10)}$$

Thus, the extracted energy for a single switching is given below

$$Eext = \frac{1}{2}Cint\left[\frac{Co}{Cint + Co}(1+\gamma o)\right]^2 \quad \text{...........................(11)}$$

At given parameter

Eext= 14.856 nj

Output energy from DSSH technique=$16.7*10^{-3}*0.3848*10^{-3}$
=6.426 µj

[4]When the structure has a constant vibration magnitude μ_m, like in the case of weakly coupled structure the intermediate capacitance and microgenerators internal capacitance are not eqaual but related as follows

C_{int} = xCo

$$(C_o)_{end} = \left[1 - \frac{x}{1+x}(1+\gamma o)\right]Vp \quad \text{..(12)}$$

$$(V_{Cint})_{end} = \frac{1}{1+x}(1+\gamma o)Vp \quad \text{..(13)}$$

WHEN SWITCH S_2 IS CLOSED [4]

At this time switch S_1 should be open. And intermediate capacitance is connected to the inductor L_2. The KVL equitation of the closed loop is given below-

$$L2\ddot{qint} + r2\dot{qint} + \frac{qint}{Cint} = 0 \quad \text{....................................(14)}$$

Where q_{int} is the charge on the intermediate capacitance
L_2 is the inductor connected between two capacitor and
r_2 is the internal resistance of inductor L_2
Solving equation 4 following equation is obtained-

$$Iint = -Cint * (Vp)end * \frac{\omega o}{\sqrt{1-\delta int^2}} * e^{-\omega int * \delta int * t} * \sin\left(\omega int\sqrt{(1-\delta int^2)}\right)t \quad \text{............(15)}$$

CALCULATION

Switch S2 is open when current I_{int} is nil

i.e. I_{int}=0
It is possible when transient time =0.3848 ms

Hence time for Switch S_2 is delayed by 0.3848 ms with respect to time of Switch S_1.
The expression for output voltage at constant vibration magnitude [4]

$$V_o = 2\frac{1+x}{2+x-x\gamma o} * \frac{\alpha}{co}\mu m \quad \text{..(16)}$$

Where μ_m Constant vibration magnitude

α is the force factor of piezoelectric element which is equal to 0.234 mNV^{-1}

At µm= 2mm and x=1

V_o=31.05 V

Output energy E= P*t... (17)

Where P is the power and t is the switching time

$$E=\frac{V^2}{R}*t=\frac{31.05^2}{10000}*0.3848*10^{-3}=0.0371\ \text{mj}$$

STANDARD CIRCUIT [3]

CALCULATION

Output energy from Standard circuit= 6.68* 10^{-3} *0.3848*10^{-3}
=2.57 µj

VII. SIMULATION

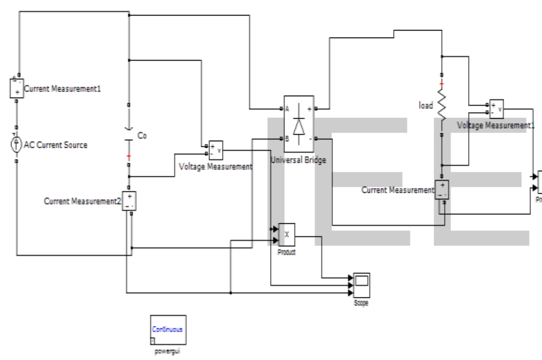

Fig.(5-a) Simulink diagram of standard circuit

The maximum output power of standard circuit is equal to 6.68 mW as shown in the figure.5

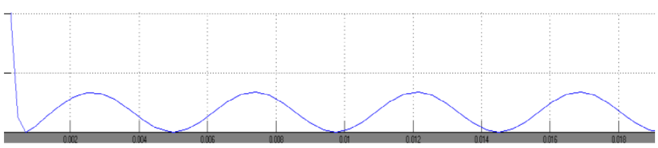

Fig.(5-b). Output power (mW) versus time (ms)

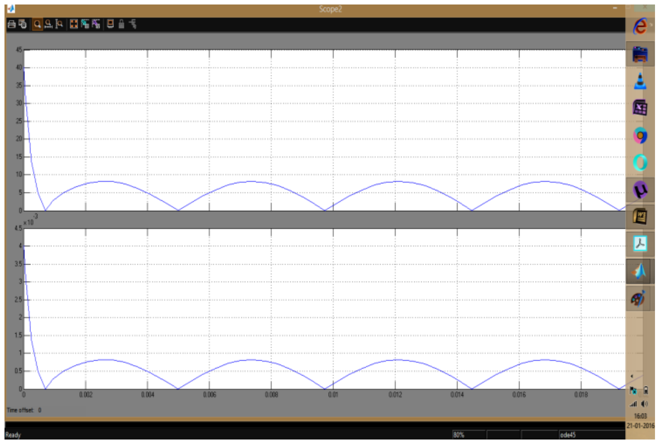

Fig.(5-c). Output voltage (volts) versus time (ms)
Output current (mA) versus time (ms)

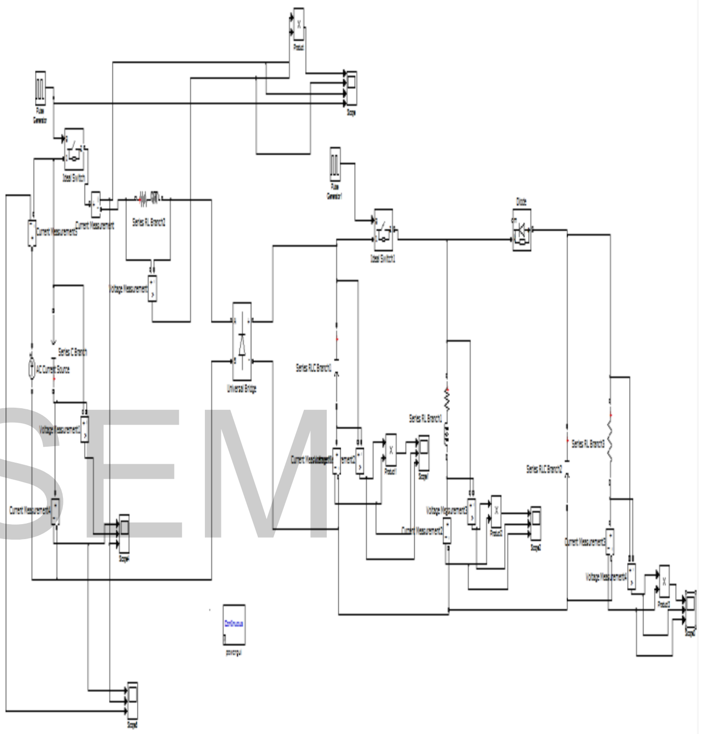

Fig.(6-a) Simulink diagram of DSSH circuit

The maximum output power of DSSH circuit is equal to 16.7 mW as shown in the figure

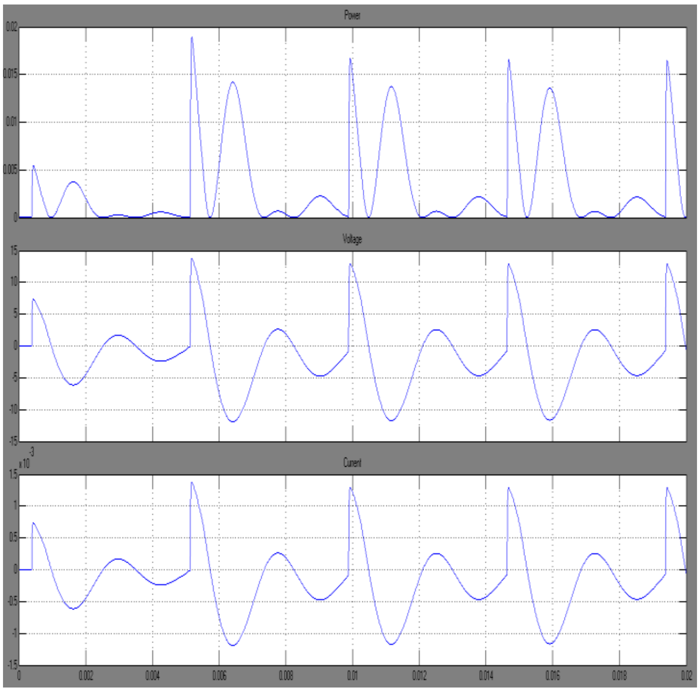

Fig.(6-b) Output power(mW) versus time(ms), Voltage versus time(ms) and current versus time(ms)of DSSH circuit

VIII. CALCULATION OF GAIN IN EFFICIENCY

From fig.6(b) maximum power of DSSH circuit is 16.7 mW. From fig.5(b) maximum power of Standard circuit is 6.68mW. Since the input parameters are same in both cases, so ratio of efficiencies for the two circuits will also be the ratio of maximum power.

$$\%\ Gain\ in\ efficiency\ = \frac{16.7}{6.68} * 100 = 250\%$$

IX. CONCLUSION

After mathematical modelling and calculation and simulation we find that the DSSH circuit with suitable switching has following advantages:

- Extracted energy in a single cycle is 6.426 µj for variable flexural displacement while 0.0371 mj for constant vibration magnitude. Both values are much larger than that in case of standard circuit (2.57 µj)
- Efficiency is 250% of that of the standard circuit
- There is no dead zone.
- Output Voltage is much smoother than standard circuit.

X. REFERENCE

1. C.N.Xu, M Akiyama, K. Nonaka and T Watanabe, "Electric power generation characteristics of PZT piezoelectric ceramics." IEEE transaction ultrasonic, ferroelectric frequency control,vol-45, no-04, pp-1065-1070,1998
2. Geffrey K. Ottman, Heath F. Hofmann, Archin C. Batt and GeorgeA. Lesieutre, "Adaptive piezoelectric energy harvesting circuit for wireless remote power supply" IEEE transaction on power electronics, vol-17, no-05,sep2002
3. Dainel Guyomar, Adrien Badel, Elie Lefeuvre and claude Richar, " Towards energy harvesting using Active material and conversion improvement by non linear processing." IEEE transaction on ultrasonic, ferroelectric and frequency control, vol-52, no-04,april-2005
4. Mickael Lallart, Lauric. Garbuio, Lionel Petit, Claude Richard, and Daniel Guyomar "Double Synchronized Switch Harvesting (DSSH): A New Energy Harvesting Scheme for Efficient Energy Extraction" IEEE Transactions on ultrasonic, ferroelectrics, and frequency control, vol.55, no. 10, oct 2008
5. Martin S. Rødgaard, Michael Weirich and Michael A. E. Anderse "Forward Conduction Mode Controlled Piezoelectric transformer-Based PFC LED Drive." IEEE transactions on power electronics, vol-28,no-10