Piezoelectric Energy Harvesting: A New Approach

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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 Pierre 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 piezo element 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 resistive 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

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energy storage stage. In intermediate stage \( C_{\text{int}} \) 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

\[
M\ddot{u} + C\dot{u} + K^T u = F - \alpha V
\]

\[
I = \alpha u - C_0 \dot{V}
\]

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
\( \alpha = \) force factor,
\( C_0 = \) Blocking capacitance of the piezoelectric element

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

Parameters of DSSH circuit

<table>
<thead>
<tr>
<th>Element</th>
<th>Value</th>
<th>Element</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Piezoelement current</td>
<td>1 Ma</td>
<td>Piezoelement capacitance</td>
<td>30 Nf</td>
</tr>
<tr>
<td>Piezoelement voltage</td>
<td>50 V</td>
<td>Resonance frequency</td>
<td>105.3 Hz</td>
</tr>
<tr>
<td>Inductor ( L_1 )</td>
<td>1 H</td>
<td>Capacitance ( C_{\text{int}} )</td>
<td>30 nF</td>
</tr>
<tr>
<td>Inductor ( L_2 )</td>
<td>2 H</td>
<td>Smoothing capacitance ( C_s )</td>
<td>0.128 uF</td>
</tr>
<tr>
<td>Resistance ( r_1 )</td>
<td>50 ohm</td>
<td>Resistance ( r_2 )</td>
<td>10 ohm</td>
</tr>
<tr>
<td>Force Factor ( \alpha )</td>
<td>0.234 mNV(^{-1})</td>
<td>constant Vibration magnitude ( \mu m )</td>
<td>2 mm</td>
</tr>
</tbody>
</table>

WHEN SWITCH \( S_1 \) IS OPEN

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

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

\[
I(t) = I_p * \sin(\omega t)
\]

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

\[
V(t) = \frac{-I_p}{W} * \cos(\omega t) \cdot C_0
\]

The voltage will be maximum when:

\[
\cos(\omega t) = -1
\]

Or

\[
t = \frac{\pi}{\omega}
\]

At frequency \( \omega = 105.3 \) Hz

\( t = 4.7483 \) ms
Hence switch $S_1$ is closed after 4.7483 ms with respect to applied pressure.

**WHEN SWITCH $S_2$ IS CLOSED AND $S_1$ 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-

$$ L_1q_p^2 + r_1q_p + \frac{V_p}{C_{equ}} = 0 \tag{5} $$

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-

$$ I_p = -C_{equ} \cdot V_p \cdot \frac{\omega_o}{\sqrt{1 - \delta_o^2}} \cdot e^{-\omega_o t} \cdot \sin(\omega_o \sqrt{1 - \delta_o^2})t \tag{6} $$

Where $\omega_o$ is the natural frequency

$$ \omega_o = \frac{1}{\sqrt{L_1 C_{equ}}} $$

And $\delta_o$ is the damping coefficient

$$ \delta_o = \frac{1}{2} \times r_1 \times \sqrt{\frac{C_{equ}}{L_1}} $$

**CALCULATION**

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

$$ I_p = 0 $$

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.

$$ \Delta q_o = \int_{0}^{t} \left( \frac{\omega_o}{\sqrt{1 - \delta_o^2}} \right) I_p \cdot dt \tag{7} $$

$$ \Delta q_o = \frac{-C_{int} \cdot C_0}{C_{int} + C_0} \left( 1 + \gamma_o \right) V_p \tag{8} $$

Where $\gamma_o = e^{-\omega_o \sqrt{1 - \delta_o^2}}$

For given data

$$ \delta_o=0.9904 $$

And $Y_o$ is known as inversion factor.

$$(V_{cco})_{end} = V_o + \frac{\Delta q_o}{C_0} \tag{9} $$

$$(V_{cint})_{end} = \frac{\Delta q_o}{C_{int}} \tag{10} $$

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

$$ E_{ext} = \frac{1}{2} \cdot \left[ \frac{C_o}{C_{int} + C_0} \right] \left( 1 + \gamma_o \right)^2 \tag{11} $$

At given parameter

$$ E_{ext} = 14.856 \text{ nj} $$

Output energy from DSSH technique=16.7*10^{-3}*0.3848*10^{-3} =6.426 \mu j 

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

$$ C_{int} = x \cdot C_0 $$

$$(C_{o})_{end} = \left[ 1 - \frac{x}{1+x} \left( 1 + \gamma_o \right) \right] V_p \tag{12} $$

$$(V_{cint})_{end} = \left[ \frac{C_o}{C_{int} + C_0} \left( 1 + \gamma_o \right) \right]^2 \tag{13} $$

**WHEN SWITCH $S_1$ 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-

$$ L_2q_{int} + r_2q_{int} + \frac{q_{int}}{C_{int}} = 0 \tag{14} $$

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-

$$ I_{int} = -C_{int} \cdot (V_{cco})_{end} + \frac{\omega_o}{\sqrt{1 - \delta_o^2}} \cdot e^{-\omega_o t} \cdot \sin(\omega_o \sqrt{1 - \delta_o^2})t \tag{15} $$

**CALCULATION**

Switch $S_2$ is open when current $I_{int}$ is nil

i.e. $I_{int}=0$

It is possible when transient time $t=0.3848$ 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]

$$ V_o = 2 \cdot \frac{\mu_m}{1 + \gamma_o} \cdot \frac{\Delta q_o}{C_0} \tag{16} $$
Where $\mu_m$ Constant vibration magnitude

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

At $\mu_m=2$ mm 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

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

STANDARD CIRCUIT [3]

CALCULATION

Output energy from Standard circuit $= 6.68 \times 10^{-3} \times 0.3848 \times 10^{-3}$

$=2.57 \mu J$

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.

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

Fig.(5-c). Output voltage (volts) 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 6.68 mW. 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.

\[
\text{% Gain in efficiency} = \frac{16.7}{6.68} \times 100 = 250\%
\]

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


5. Martin S. Rødgaard, Michael Weirich and Michael A. E. Andersen “Forward Conduction Mode Controlled Piezoelectric transformer-Based PFC LED Drive.” IEEE transactions on power electronics, vol-28, no-10