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Electrical Optimization of Piezoelectric Energy Harvesting System in Vehicles

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Abstract

Most of the work on the piezoelectric energy harvester are limited to the minimum performance of such systems when applied to automobiles. However in piezoelectric energy harvesting systems, non-linear techniques are known to amplify the output voltage and the maximum recovered energy. One of the difficulties in this technique lies in the design of the amplifier circuit. This paper proposes to quantify the improvement of the performance of piezoelectric micro-generators applied to automobiles when Synchronized Switch Harvesting on Inductor (SSHI) technique is used. From the spectral properties of the available vibration inside the moving automobile, an electric model of piezoelectric composite QP20W of Midé Technology, is proposed. From this model, the contribution of the technique SSHI is then quantified. The circuit used is based on the switching characteristics of BTS132 NMOS transistors of Infineon. Simulation results show an amplification of the open circuit voltage of the generator of 2.2 times that obtained with the standard circuit. The recovered energy is also improved by 135 % compared to the standard circuit.

Keywords: Energy Harvesting; Piezoelectric transducer; Energy modelling; WSN; SSHI technique.

1. Introduction

To meet the needs of its customers, the automotive industry has reliability and security requirements increasingly important. Thus, more and more vehicles are equipped with many sensors to both monitor the status of the vehicle and support the driver. More specifically, the sensors in vehicles, measure temperatures, control engine speeds and regulate angles and positions etc. Usually, these sensors are powered by wired connection with the vehicle's battery. Since the introduction of these many sensors in vehicles, the function of batteries is not just starting because it became much more important to feed many embedded sensors. However, due to the fact that the number of sensors is increasingly growing, wired connections turn to be troublesome for the vehicle. Furthermore, some sensors cannot be powered by wire connection, such as tire pressure monitoring sensors [1].

The lifetime of a sensor node being linked to that of the battery, it is important that it is equipped with a power supply having the longest life possible to limit maintenance operations. This issue of energy autonomy has been accompanied in recent years by the emergence of a new field of activity namely the recovery of the ambient energy in the immediate environment of the system to be powered. Some ambient energy sources well known as the sun or wind can generate significant energy that can be returned on a national electrical network. For applications such as automobile, these sources cannot be considered. Therefore, as well as small-scale energy recovery systems are experiencing a great boom in recent years [2]. These systems can capture energy from environmental sources such as heat, interior light, radio waves and vibrations [2].

In this paper, an electrical optimization of the recovery via piezoelectric transducers of the energy contained in the available vibration inside a moving automobile is proposed. For this, we will recall in section 2 previous work and describe the optimization principle. The analysis of the results obtained will be then made in section 3. This work ends in its section 4 to a conclusion in which we recall the main results and future work.

2. Problem identification and basic principle

2.1. Previous work

The possibility to empower embedded WSN in vehicles by means of vibration energy has been studied recently [1, 3]. The authors in [1] have measured the vibrations that spread in the trunk of a car. They assessed the potential of their operations by developing a piezoelectric recovery based on QP21B composite of Midé Technology. They observed depending on the road conditions that the peak-to-peak open circuit transducer varied between $2\,V$ and $10\,V$. The average power to a load resistance of $91\,k\Omega$ was between $1.1\,\mu W$ and $13.3\,\mu W$. Authors in [3] for their side, have characterized vibrations present in the co-pilot's seat inside the vehicle. The vibration spectrum obtained showed a maximum power density of $-16.9\,dB/Hz$ around $15\,Hz$. By combining a cantilever beam with a natural frequency of $15\,Hz$, the composite QP20 W of Míde technology, a maximum power of $3\,\mu W$ has been reached for an $73.13\,k\Omega$ optimum load resistance. The output open circuit voltage showed an amplitude of $1.56\,V$.

2.2. Problematic

Most piezoelectric micro-generators proposed in previous work have focused their work on the resonant frequency of the system because this helps to maximize the recovered energy [4]. However, for wide bands vibration, it has been shown that non-linear techniques can increase the electromechanical coupling and therefore at the same time the recovered energy [5]. Furthermore as shown in previous results, the voltage levels provided by the transducers are low and cannot supply real sensor nodes, which in most cases has a microprocessor, which requires a minimum voltage of $5\,V$. To amplify the output voltage of piezoelectric generator micro, Synchronized Switch Harvesting on Inductor (SSHI) technique has been proven to be an effective method for improving the recovery system. However, sizing SSHI circuit requires an electrical modeling of micro piezoelectric generator. This work then provides an electrical modeling of the transducer to the appropriate recovery of the vibratory energy in the particular case of automobile. The proposed models will then be used to quantify the contribution of SSHI technique on such micro-generators.

2.3. SSHI technique principle

The recovered energy by the piezoelectric transducers in most designs is usually very low. The standard electrical model of a piezoelectric transducer is shown on the first part in Fig. 1 [6]. The piezoelectric element is modeled by a sinusoidal current source $i_P(t)$ in parallel with its internal capacitance C_P. The amplitude and frequency of the polling current depends on the spectral properties of vibration [7]. The model is completed by a resistance R_P, which symbolizes the losses in the piezoelectric material. This loss resistance is linked to the internal capacity as Eq (1).

$$R_P = \frac{1}{2\pi f_R C_P \tan\delta} \tag{1}$$

$\tan\delta$ is the coefficient of dissipation of the piezoelectric material. It is 1.5% for composites recently used [7]. f_R is the principal frequency of the detected vibrations.

SSHI technique that is known to amplify the recovered energy is based on the switching of an inductor in parallel with the piezoelectric micro-generator like shown on the second part in Fig 1. This technique involves the addition of a switching device in parallel with the piezoelectric element. Switching is done at the time for which the displacement of the vibrating structure is maximum, at these times the voltage of the piezoelectric generator is also at its peak. Once the switch is closed, the system consisting of the capacitor, the inductor and the resistive load forms a pseudo periodic oscillating system. The period T_{os} is defined as in Eq (2).

$$T_{os} = 2\pi\sqrt{LC_P} \tag{2}$$

The duration of introduction of the inductor T_{on} is equal to half the oscillation period.

$$T_{on} = \frac{T_{os}}{2} = \pi\sqrt{LC_P} \tag{3}$$

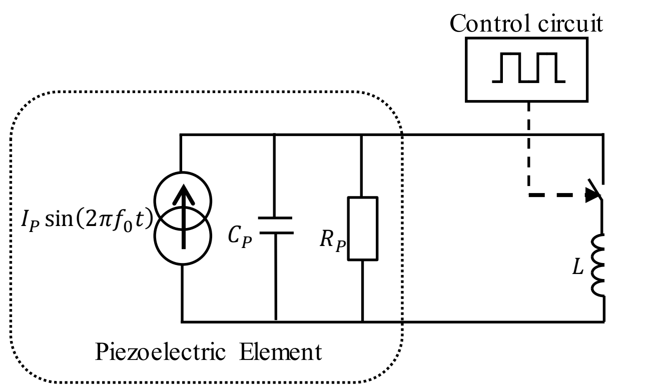

Fig. 1 Piezoelectric transducer with SSHI technique

The circuit show in Fig. 1 has two operating phases, which are highlighted in Fig. 2 [8].

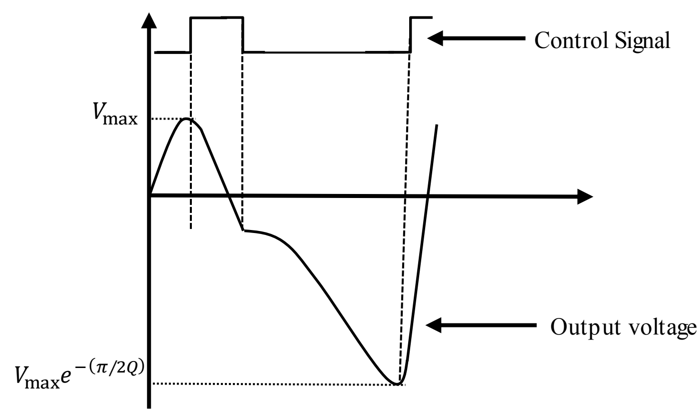

Fig. 2 SSHI waveforms

Before switching on, the capacitor is charged up to the maximum voltage V_{max}. The parallel connection of the inductance at the switching time causes complete discharge of the capacitance and increases the current in the inductor to a maximum value. At this moment the energy is stored in the capacitor in potential form. This energy is transformed in kinetic form in the inductance. Subsequently the current in the inductance decreases as the capacitor charge to a reverse voltage of the maximum voltage V_{max}. However, this reversal is not perfect because of the internal losses resistance R_P. It is then characterized by a damping coefficient γ which is related to the mechanical quality factor Q as Eq (4) like shown in Fig. 2[8].

$$\gamma = e^{-(\pi/2Q)} \quad (4)$$

3. Results and discussions

The approach adopted in this work is the same as that used in the work [3]. Measurements of vibrations in a moving car will be considered for electric modelling of piezoelectric transducer.

3.1. Detected vibrations in test vehicles

Fig. 3 shows the spectrum of vibrations taken on the engine of a kia spectra brand car when the engine is running at 2000 tr/min. Data are collected with a triaxial accelerometer associated with an oscilloscope for recording. These data are then processed in the Matlab workspace. The measurements show a maximum amplitude of 0.04 reached for a frequency around 40 Hz.

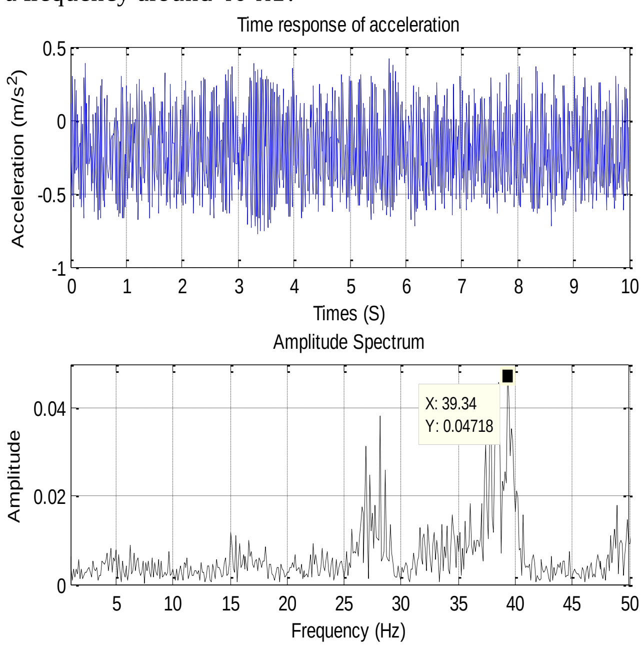

Fig. 3. Detected vibration at 2000 tr/min engine

3.2 Open Circuit Test

Composite QP20W of Míde Technology with dimensions $46 \times 33 \times 0.25\, mm^3$ is the piezoelectric transducer used in ours tests. The experimental device used is shown in Fig. 4. It includes a vibration generator U8556001 marketed by 3B Scientific. This generator can generate vibration frequencies between 0 and 20 kHz. The vibration generator is supplied by a function generator FG100 always marketed by 3B Scientific. The sampled signals are recorded with a Hantek Electronik oscilloscope.

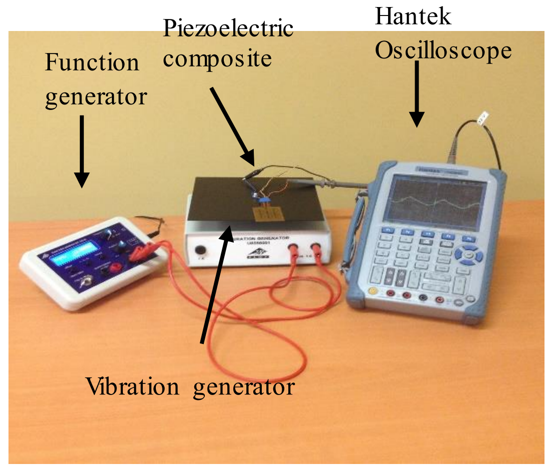

Fig. 4 Experimental setup

For a sinusoidal input vibration of 10 V amplitude at 40 Hz, the open circuit voltage provided by the composite is shown in Fig 5. The waveform shows an alternating voltage of amplitude 1.7 V which is quite close to the value of 1.8 V obtained in [3]. The values for the electrical model are carried out in Fig. 6. These values are obtained by using the same experimental procedure developed in [6]. A direct measurement of the capacitance at 40 Hz is made and the result gives 171.1 nF. The loss resistance is then determined from Eq. (1).

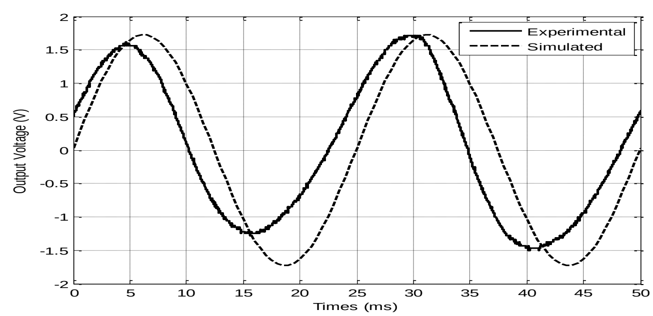

Fig. 5 Times response of output voltage

3.3 SSHI Improvement

The resulting electric model and the inductor switching circuit are shown in Fig 6. For the simulations, the Simscape of Matlab/Simulink software is used. The proposed circuit is based on the switching characteristics of the transistors NMOS BTS132 from Infineon. An inductance of 44 mH in series with a 53 Ω loss resistor as shown in Fig. 6, is used to evaluate the contribution of SSHI technique.

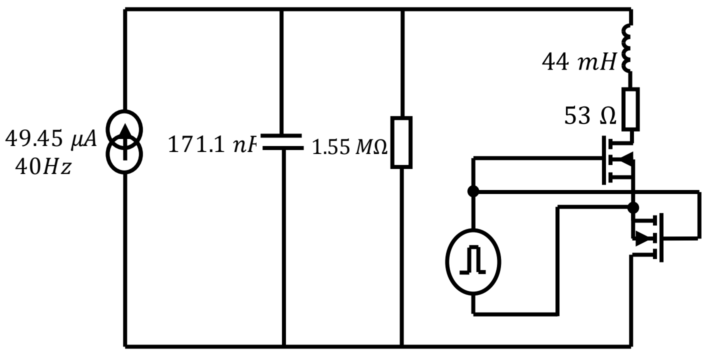

Fig. 6 Transducer model and SSHI stage

The simulation results compared to the experimental wave form of the open circuit voltage and the recovered power are respectively shown in Fig. 7 and Fig. 8.

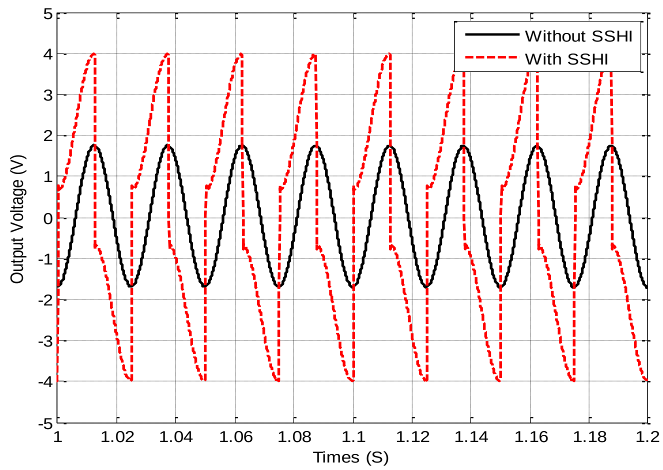

Fig. 7 Open circuit voltage of transducer

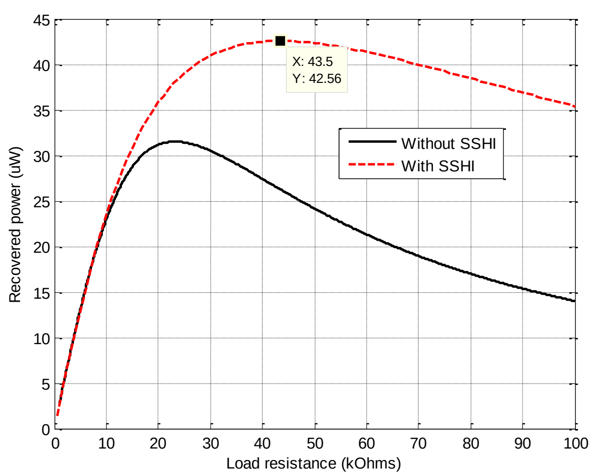

Fig. 8 Variation of power as a function of load

Fig. 7 shows an increase of 2.2 times the initial tension. The recovered power via SSHI technique is approximately 42.5 μW on an optimal load resistance of 43 Ω while in the standard circuit, we have a maximum power of 31.5 μW at maximum load resistance of 23 Ω.

4. Conclusions

This work was aimed to quantify the contribution of SSHI technique on the vibrational energy harvesting in an automobile. For this purpose, the experimental measurements of the vibration spectrum at the engine level car are considered. Open circuit test of the composite QP20W of Míde technology helped to establish the equivalent electric circuit of the transducer. From this circuit, the simulations results showed an amplification of 2.2 times the initial voltage when the SSHI technique is applied and an increase of 135% of the recovered power. Although the reached power level is sufficient to empower the commonly used sensors nodes, it would be important from the perspective of validating the work to carry out an experimental verification of the results.

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Focussing on Multidisciplinary Research, Promoting Future Low Carbon Innovations, Transferring Knowledge and Stimulating Networking among Stakeholders to Ensure the UK Achieves World Leading Status in Energy and Sustainable Development. https://www.weentech.co.uk/cesd-net/

The 1st International Conference on Energy, Environment and Economics (ICEEE 2016) was held at Heriot-Watt University, Edinburgh, EH14 4AS, UK, 16-18 August 2016. ICEEE2016 focused on energy, environment and economics of energy systems and their applications. More than fifty eight delegates from 31 countries with diverse expertise ranging from energy economics, solar thermal, water engineering, automotive, energy, economics and policy, sustainable development, bio fuels, Nano technologies, climate change, life cycle analysis etc. made conference true to its name and completely international. During conference total 51 oral presentations and six posters were shared between delegates. The presentations showed the depth and breadth of research across different research areas ranging from diverse background. ICEEE2016 aimed:

- To identify and share experiences, challenges and technical expertise on how to tackle growing energy use and greenhouse gas emissions and how to promote sustainability and economical, cost effective energy efficiency measures.

In total 11 technical sessions and two invited talks both from academia and industry provided insight into the recent development on the proposed theme of the conference. Preparation, organisation and delivery of the conference started from July 2015 and further co-ordinated by vibrant team of Conference Centre, Heriot Watt University. Conference organisers would like to acknowledge support from the sponsors particularly World Scientific Publication ltd and its team members for the delivery of the conference. Organisers are also thankful to all reviewers who contributed during peer review process and their contributions are well appreciated. At the end and during vote of thanks following awards have been announced and we would like to congratulate all well deserving delegates.

- Best Paper –Academia: Amela Ajanovic, EEG, TU Vienna, Austria
- Best Paper – Student : Christian Jenne,University of Duisburg-Essen, Germany
- Best Poster – Student: Yoann Guinard, University of New South Wales, Sydney, Australia
- Best Poster – Academia: E. Salleh, Universiti Kebangsaan Malaysia, Malaysia
- Active Participation Award - Yoann Guinard, University of New South Wales, Sydney, Australia

At the end we would like to extend our gratitude to all of you for your participation and hopefully welcome you again during ICEEE2017.

Editors:
Dr. Singh is Senior Scientist at Indian Agricultural Research Institute, New Delhi, India. Her area of expertise are bio energy and bio fuels, environmental engineering, carbon accounting and renewable energy integration for rural development.
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