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Characteristics of Piezoelectric Energy Harvesters in Autonomous Systems

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Abstract:

A basic autonomous system powered by a piezoelectric harvester contains three components apart from the harvester: a full-wave rectifier, a reservoir capacitor and an electronic device performing the primary task of the system. In this contribution, a model describing the operation of such a system is derived. It is found that in steady-state operation, the piezoelectric harvester experiences two alternating load conditions due to the rectification process. These alternating load conditions can have a significant effect on the operation of the harvester and must be considered in the design of autonomous systems. The results also show that such an autonomous system works efficiently if it is connected to a high impedance load and excited by a frequency matching the anti-resonance frequency of the piezoelectric harvester.

Key words: Energy harvesting, harvester modeling, load dependence, generated voltage

Introduction

Energy harvesting or scavenging are commonly used terms describing the process of converting energy available in the environment into electrical energy. For about a decade, engineers have been challenged to design autonomous systems which fulfill their task and power themselves from available ambient energy. Such systems are known as autonomous or stand-alone systems.

The basic configuration of an autonomous system powered by a piezoelectric harvester typically contains three elements apart from the harvester: a full-wave rectifier, a reservoir capacitor and an electronic device performing the primary task of the system. Such a system is called "basic autonomous system" (BAS) in the following. The BAS can be split into two main parts as shown in Fig. 1: the electromechanical part, i. e. the piezoelectric harvester, and the electrical part.

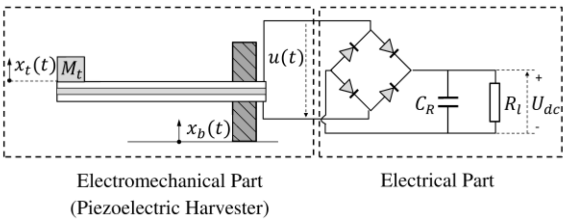

Fig. 1: Schematic of a basic autonomous system (BAS)

In many publications, for example [1] to [5], the output DC voltage of a BAS is modeled. All these models assume that the AC voltage generated by the piezoelectric harvester is sinusoidal and uninfluenced by the electrical part of the autonomous system. In reality, especially for low impedance loads, shape and amplitude of this voltage can be influenced significantly by the electrical part, in which case the above-mentioned models are inaccurate.

In this contribution, a BAS is modeled, taking into account the effect of the rectification process on the performance of the piezoelectric harvester. The electrical part of the BAS is analyzed first in order to determine its effect on the loading conditions of the piezoelectric harvester. The piezoelectric harvester is then modeled based on these conditions.

Electrical Part – Theoretical Investigation

Figure 2 shows an electrical representation of a BAS in which the piezoelectric harvester is modeled as a voltage source. The rectifier circuit consists of four diodes D_1, D_2, D_3 and D_4. These diodes are connected in the standard arrangement to convert the AC voltage $u(t)$ generated by the harvester into a DC voltage U_{dc} in order to power the load R_l. The capacitor C_R is used to smooth the DC voltage. It can also serve as an energy storage for times without sufficient AC voltage.

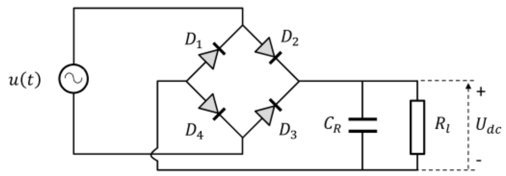

Fig. 2: Electrical representation of a BAS

In the following first step, the AC voltage is assumed to be sinusoidal, i. e. $u(t) = \hat{u} \sin \omega t$. Figure 3(a) shows this voltage for two periods of operation, where t_p is the period. The corresponding DC voltage is shown in Fig. 3(b), assuming the capacitor C_R is properly chosen and discharged at the beginning. In this case, the first period of operation includes four intervals: The dead zone interval t_0, the transient conduction interval t_{tr}, the open circuit interval t_{op} and the steady-state conduction interval t_{ss}. The lengths of these intervals depend on the properties of the system components.

During the dead zone interval t_0, AC voltage is applied but there is no corresponding DC output voltage because the magnitude of the input voltage $|u(t)|$ is less than the barrier voltage $2U_d$ of two diodes. The dead zone interval exists only in the first quarter of the first period of operation (between 0 and t_0) as shown in Fig. 3(b).

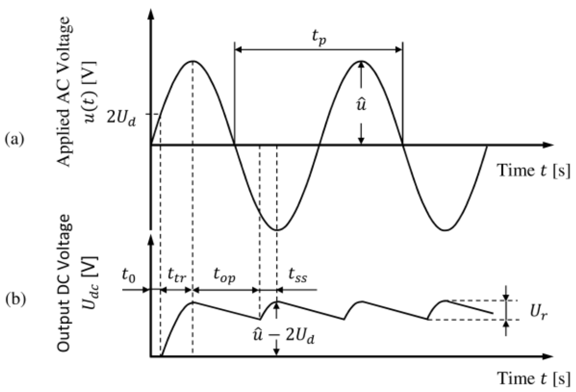

Fig. 3: (a) Applied AC voltage $u(t)$ and (b) output DC voltage U_{dc} across the connected load

When the magnitude of the AC voltage $|u(t)|$ rises above $2U_d$, the dead zone interval t_0 ends and the transient conduction interval t_{tr} begins. In this interval, one pair of diodes (D_2 and D_4 or D_1 and D_3) is conducting; current flows from the harvester into the parallel loads C_R and R_l. The size of the reservoir capacitor C_R should be calculated carefully so that it will be fully charged at the end of this interval; otherwise transient conduction intervals appear also in the next periods until the capacitor is fully charged and has a voltage of $\hat{u} - 2U_d$.

When $|u(t)|$ becomes less than the capacitor voltage, the diodes block any reverse current flow from the capacitor into the harvester. The latter is now disconnected from the load side, i. e. it is in open-circuit condition. This interval is thus called the open circuit interval t_{op}. In this interval, the load R_l is powered by the energy stored in the capacitor only.

When the capacitor voltage again becomes smaller than $|u(t)|$, the diodes become conductive and the steady-state conduction interval t_{ss} starts. During this interval, the load R_l is powered and the capacitor is recharged, both by the rectified AC voltage.

If the capacitor is chosen appropriately, the system is now in its steady state and all following periods consist only of the open circuit interval t_{op} and the steady-state conduction interval t_{ss} as shown in Fig. 3(b).

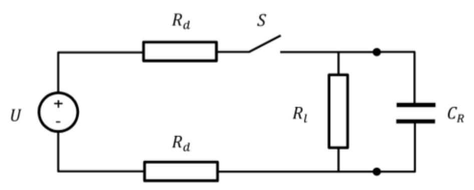

Fig. 4: Simplified electrical representation of a BAS

For analyzing the impedance of the autonomous system, its electrical representation shown in Fig. 2 can be simplified to the circuit shown in Fig. 4, where the resistance R_d is the bulk resistance of one diode, S is an electrical switch and U is a voltage source representing the rectified AC voltage. The state of the electrical switch (open or closed) describes the state of the diodes (conductive or blocking) and thus the operation interval of the harvester.

The time constant for charging the reservoir capacitor is

$$t_{ch} = 2R_d C_R \tag{1}$$

and the time constant for discharging is

$$t_{dis} = R_l C_R. \tag{2}$$

At typically 1 to 2 Ω, the diode bulk resistance R_d is much smaller than the load R_l. Therefore, the charging time t_{ch} of the reservoir capacitor is much smaller than its discharging time t_{dis}. This means that it is almost full during steady-state operation – the harvester mainly powers the connected load, only little current flows into the capacitor. The piezoelectric harvester thus experiences two alternating load conditions due to the rectification process: open circuit condition and resistive load condition.

Piezoelectric Harvester – Theoretical Investigation

The piezoelectric harvester has both mechanical and electrical characteristics which are closely related. The two boundary conditions which are relevant for its operation in an autonomous system – open circuit and resistive load – are shown in Fig. 5.

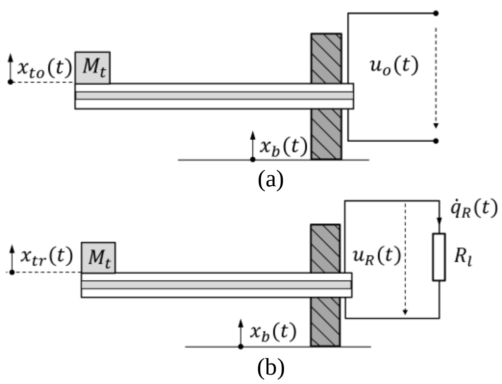

Fig. 5: Piezoelectric harvester with boundary conditions (a) open circuit, (b) resistive load

The amplitude of the generated voltage in open circuit condition can be calculated as

$$\hat{u}_o = \frac{(\alpha/MC_p)\hat{a}_b}{\sqrt{(\omega_a^2-\omega^2)^2+(2\zeta\omega_r\omega)^2}}, \tag{3}$$

and the amplitude of the generated voltage under resistive load condition can be calculated as

$$\hat{u}_r = \frac{\alpha R_l \omega\, \hat{a}_b}{\sqrt{\left[\omega_r^2-(1+2\zeta\omega_r R_l C_p)\omega^2\right]^2+\omega^2\left[2\zeta\omega_r+R_l C_p(\omega_a^2-\omega^2)\right]^2}}. \tag{4}$$

In these expressions, α, M, C_p and ζ are parameters describing the piezoelectric harvester: the coupling factor α between the electrical and the mechanical domains, the equivalent mass M, the capacitance C_p, and the system damping ratio at short circuit condition ζ. ω_a and ω_r are resonance and anti-resonance frequency of the harvester. ω is the excitation frequency and $\hat{a}_b$ is the amplitude of the exciting acceleration.

Figure 6 shows the amplitude of the generated voltage for different resistive loads, calculated for a cantilevered bimorph (Piezo Bending Actuator 427.0085.11Z from Johnson Matthey) using equation (4), with the parameters

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calculated as described in [6]. This diagram shows that for high voltage generation, operation at anti-resonance is recommendable and that the required voltage amplitude can be hard to reach if the electrical load R_l is small.

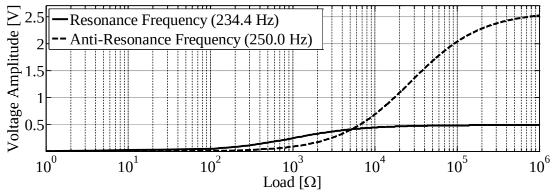

Fig. 6: Amplitude of the generated voltage in resonance and anti-resonance operation for different resistive loads

It can be concluded from Fig. 6 that an autonomous system with a low impedance load does not behave as described above in steady-state operation: Within the conduction interval, current flows from the harvester into both the resistive load and the partly charged capacitor. When the capacitor voltage reaches a level close to the harvester voltage, the diodes block the current flow. The harvester is now in open-circuit condition. But in this condition, the harvester voltage amplitude is much higher than the capacitor voltage, causing the diodes to conduct again. This again changes the loading condition of the harvester and current flows into load and capacitor. This switching between conducting and non-conducting diode states continues until the voltage generated by the harvester in open-circuit condition becomes less than the capacitor voltage.

Characteristics of the Generated Voltage – Experimental Validation

Figure 7 shows the voltage generated by a cantilevered piezoelectric bimorph of the same type as described above, operated under different resistive load conditions. The voltage was measured using an oscilloscope (Yokogawa DL1640) with an input impedance of 1 MΩ. The harvester is excited at its anti-resonance frequency of 238.1 Hz by a base acceleration with an amplitude of 5.5 m/s².

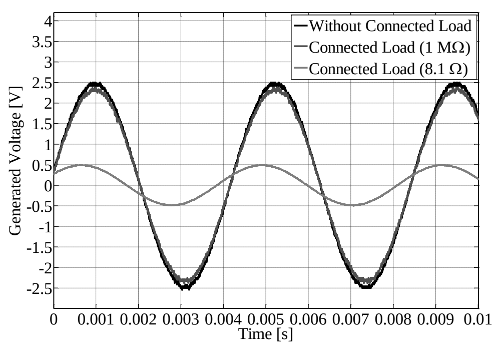

Fig. 7: Voltage generated by a piezoelectric harvester at different resistive load conditions (without rectifier and reservoir capacitor)

Figure 8 shows the measured voltage generated by the same piezoelectric harvester under different loading conditions, but this time connected to a full wave rectifier and proper capacitors for each load, i. e. as part of a BAS. The figure shows that the generated voltage is close to a perfect sine wave for high loads, but becomes more and more distorted with decreasing load.

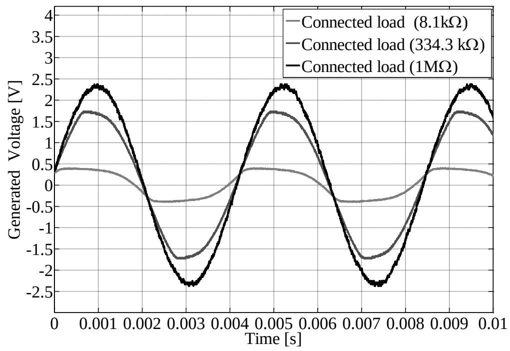

Fig. 8: Voltage generated by a piezoelectric harvester inside a BAS with different resistive loads

Conclusion

It has been shown that a piezoelectric harvester for autonomous system applications operates efficiently if it is excited at its anti-resonance frequency and connected to a high impedance load.

In an autonomous system in steady-state operation, the piezoelectric harvester experiences two alternating load conditions due to the rectification process. For low impedance loads, this can have a significant effect on the generated voltage which may impair the function of the autonomous system. Piezoelectric harvesters for use in autonomous systems should therefore always be designed with consideration of the electrical part of the system. In this way, the designer can ensure that negative effects on the voltage generated by the harvester are either negligibly small or countered by appropriate dimensioning of the piezoelectric energy harvester.

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