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Maximization of the extracted power in resonant electromagnetic vibration harvesters applications employing bridge rectifiers

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ABSTRACT

The capability of a resonant electromagnetic vibration harvester to provide power to a load, in given vibration conditions, is usually quantified by considering the power P_{OPT} that can be transferred to the harvester optimal impedance. In this paper it is explained that, in presence of a bridge rectifier between the harvester and the DC load, it is instead necessary to consider the power P_{SUBOPT}, that is the power that can be transferred by the harvester to its optimal resistive load. $P_{SUBOPT} \leq P_{OPT}$ and represents a more accurate estimate of the upper bound of the average power P_{tot} that can be actually transferred to the load in case a bridge rectifier is placed between the harvester and the DC load. In particular, in this paper it is shown that a bridge rectifier is able to roughly emulate a resistance and hence $P_{tot} < P_{SUBOPT} \leq P_{OPT}$. By means of a suitable theoretical analysis, it is also demonstrated why and how the power that can be transferred to the load by the harvester strongly depends on the value of the DC voltage V_0 at the output of the bridge rectifier. Moreover, a closed form estimate of the optimal value V_0^* of V_0 is also provided. Experimental results are also reported and discussed in order to validate the theoretical findings. In particular, a resonant electromagnetic vibration harvester prototype has been used. The values of its main parameters are: resonance frequency 16.2 Hz, max output power 0.25 mW (at a vibration amplitude equal to 1 g), optimal DC voltage 1.2 V, coil resistance = 5720.4 Ω, coil inductance = 0.56 H.

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1. Introduction

The use of Vibration Energy Harvesters (VEHs) allows to limit or to avoid the drawbacks associated to the use of batteries (expensive maintenance/replacement, insufficient or unpredictable duration of operational life, not eco-friendly disposal due to the hazardous chemical content) in Wireless Sensor Nodes applications [1–7]. Most VEHs belong to one of the three main categories: piezoelectric [8–11], electrostatic [12–15], and electromagnetic [16–19]. This paper is focused on Resonant Electromagnetic Vibration Energy Harvesters (REVEHs) in which a seismic mass m (a permanent magnet) is linked to a spring with constant k_s and moves out of phase with respect to the generator housing, when such a generator vibrates [17]. A coil is fixed to the housing; therefore the relative displacement x(t) between magnet and coil leads to the conversion of mechanical energy into electric energy. In fact, the magnetic field of the permanent magnet induces an e.m.f. $\varepsilon(t) = \theta \cdot \dot{x}(t)$ in the coil (θ is the electromechanical coupling coefficient) and hence a current i(t) flows in the load [17]. The equivalent electric circuit of a REVEH is shown in Fig. 1 [20,21].

L_c is the coil inductance, R_c is the coil resistance, $\ddot{y}(t) = A_{MAX} \cdot \cos(\omega t)$ is the base acceleration with an angular frequency ω. Moreover, the values of the resistance R_m, of the inductance L_m and of the capacitance C_m depend on the electromechanical parameters of the harvester: $R_m = \theta^2/c$ (c is the viscous damping coefficient), $L_m = \theta^2/k_s$, $C_m = m/\theta^2$. Obviously, in REVEH applications, the maximization of the extracted power is mandatory. In order to maximize at each vibration frequency the power which is transferred from the vibration source to the load it is necessary to get, by means of a proper power electronic interface driven by a proper control technique, the optimal matching between the source device (the circuit at the left of the terminals A and B of Fig. 1) and the load device. Since the vibration frequency can vary, it is also necessary to carry out a sort of tracking process in order to allow such an optimal source-load matching in any possible operating condition just like in PhotoVoltaic (PV) applications it is necessary to get the optimal matching between PV source and load in any operating irradiance and temperature condition [22–24]. While in the PV case, the optimal matching is obtained by controlling the power electronic interface so that its input port is

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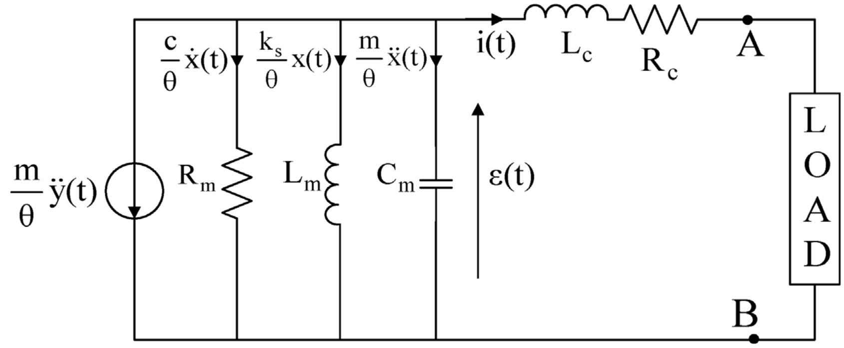

Fig. 1. Equivalent electric circuit of a REVEH feeding a load.

able to emulate an optimal load resistance, in the case of REVEHs the optimal matching can be obtained by controlling the power electronic interface so that its input port is able to emulate an optimal load impedance. In Section II a brief summary of the main concepts and theoretical findings concerning the optimal load impedance and the optimal resistive load in REVEH applications is reported. In Section III instead, it will be demonstrated, by means of a suitable theoretical analysis, why the most widely used power electronics interface for REVEHs, the full bridge rectifier, is not suitable to carry out the emulation of the optimal load impedance. It is worth noting that, even if such an aspect has been already more or less explicitly pointed out in various papers and also with reference to piezoelectric harvesters [25–27], to the best of the authors' knowledge, what is lacking in the literature is its closed-form theoretical explanation. The theoretical analysis that is discussed in Section III fills the gap left by such previous experimental and/or numerical research activities. More importantly, in Section III, the closed form expression of the power that can be transferred to the load by the REVEH as a function of the value of the DC voltage V_0 at the output of the bridge rectifier is also provided. In addition, a closed form estimate of the optimal value $V_0^*(A_{MAX},\omega)$ of V_0 is also provided. In Sections IV and V, numerical and experimental results that confirm the validity of the theoretical analysis are presented and discussed.

2. Optimal load impedance

The expression of the average power P which, under a sinusoidal acceleration $\ddot{y}(t) = A_{MAX}\cdot\cos(\omega t)$, is provided to a linear load $R_L + j\,X_L$ is given by [28]:

$$P\left(A_{MAX}, R_L, X_L, \omega\right) = \tag{1}$$
$$= \frac{0.5 \cdot A_{MAX}^2\theta^2 m^2\omega^2 R_L}{\left[R_{tot}\left(k_s\text{-}m\omega^2\right)\text{-}cX_{tot}\omega\right]^2 + \left[X_{tot}\left(k_s\text{-}m\omega^2\right) + \left(cR_{tot}+\theta^2\right)\omega\right]^2}$$

where $R_{tot} = R_c + R_L$, $X_{tot} = X_c + X_L$ and $X_c = \omega L_c$. For a given angular frequency ω, there is an optimal linear load $\dot{z}(\omega)$ which is able to maximize the value of P [29]:

$$\dot{z}(\omega) = R_{OPT}(\omega) + j\cdot X_{OPT}(\omega) =$$
$$= R_c + \frac{\theta^2\cdot c\cdot\omega^2}{\left(k_s\text{-}m\cdot\omega^2\right)^2+\left(c\cdot\omega\right)^2} + j\cdot\left[\frac{\theta^2\left(m\cdot\omega^2\text{-}k_s\right)\omega}{\left(k_s\text{-}m\cdot\omega^2\right)^2+\left(c\omega\right)^2} - \omega L_c\right] \tag{2}$$

The power P_{OPT} provided to the optimal load is [28,29]:

$$P_{OPT}(A_{MAX}, \omega) = P\left(R_{OPT}(\omega), X_{OPT}(\omega), \omega\right) =$$
$$= \frac{1}{8}\frac{A_{MAX}^2\theta^2 m^2\omega^2}{R_c\left(\left(k_s\text{-}m\omega^2\right)^2+\left(c\omega\right)^2\right)+c\left(\omega\theta\right)^2} \tag{3}$$

The frequency f_{OPT} where P_{OPT} assumes its maximum value P_{MAX} is the resonance frequency of the harvester:

$$f_{OPT} = \frac{\omega_{OPT}}{2\cdot\pi} = \frac{1}{2\cdot\pi}\sqrt{\frac{k_s}{m}} \tag{4}$$

$$P_{MAX} = P_{OPT}(A_{MAX}, \omega_{OPT}) = \frac{1}{8}\frac{A_{MAX}^2\theta^2 m^2}{R_c c^2 + c\theta^2} \tag{5}$$

It is worth noting that the optimal linear load $\dot{z}(\omega)$ depends on the frequency of vibrations. Therefore, if such a frequency changes during the harvester operation, then also $\dot{z}(\omega)$ changes as well. Therefore a proper power electronic interface must be controlled in order to be able to emulate $\dot{z}(\omega)$ and to track it if the vibration frequency changes. Single stage or double-stage active topologies have been proposed in the scientific literature [25–27] in order to carry out the emulation of the optimal impedance of the REVEH. But they are characterized by the increase of the complexity and of the power loss (due to both the power stage and the control circuitry) and therefore they are not suitable for most low-power practical REVEH applications. The particular case of a purely ohmic load ($X_L = 0$) is of great interest in view of the discussion which is contained in Section III. In case the REVEH linear load is purely ohmic, there is an optimal resistive load $R_{subopt}(\omega)$ which is able to maximize the value of the average power $P(A_{MAX}, R_L, 0, \omega)$ for a given angular frequency ω:

$$R_{SUBOPT}(\omega) =$$
$$= \sqrt{R_c^2 + X_c^2 + \frac{2\omega\theta^2\left[X_c\left(k_s - m\omega^2\right) + R_c\cdot c\cdot\omega\right] + \omega^2\theta^4}{\left[\left(k_s - m\omega^2\right)^2 + \left(\omega\cdot c\right)^2\right]}} \tag{6}$$

The corresponding expression of the average power P_{SUBOPT} is:

$$P_{SUBOPT}\left(A_{MAX}, \omega\right) = P\left(A_{MAX}, R_{SUBOPT}, 0, \omega\right) =$$
$$= \frac{0.5\cdot A_{MAX}^2\theta^2 m^2\omega^2 R_{SUBOPT}(\omega)}{\left[\left(R_c+R_{SUBOPT}(\omega)\right)\left(k_s\text{-}m\omega^2\right)\text{-}c\left(X_c\right)\omega\right]^2 + \left[X_c\left(k_s\text{-}m\omega^2\right)+\left(c\left(R_c+R_{SUBOPT}(\omega)\right)+\theta^2\right)\omega\right]^2} \tag{7}$$

Of course, for any value of ω, it is:

$$P_{SUBOPT}\left(A_{MAX}, \omega\right) \le P_{OPT}\left(A_{MAX}, \omega\right) \tag{8}$$

The above inequality can be justified by considering that, while $P_{OPT}(A_{MAX},\omega)$ represents the max value of $P(A_{MAX},R_L,X_L,\omega)$ for any possible value of the impedance $R_L + j\cdot X_L$, instead $P_{SUBOPT}(A_{MAX},\omega)$ represents the max value of $P(A_{MAX},R_L,0,\omega)$ (which is of course only a particular instance of $P(A_{MAX},R_L,X_L,\omega)$) for any possible value of R_L (which is of course only a particular instance of $R_L + j\cdot X_L$). Therefore $P_{OPT}(A_{MAX},\omega)$ must represent an upper bound for $P_{SUBOPT}(A_{MAX},\omega)$. As an example, in Fig. 2, the behaviors of P_{OPT} (continuous line) and of P_{SUBOPT} (dashed line) as

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