ADAPTIVE LOAD SYNTHESIS FOR AUTONOMOUS RESONANT FREQUENCY TUNING OF ELECTROMAGNETIC ENERGY HARVESTERS

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Abstract: This paper presents improvements to a previously reported resonant frequency tuning circuit that maximises the power output of an electromagnetic energy harvester when it is subjected to varying environmental excitations. This power electronic interface consists of four MOSFETs in an H-bridge topology to synthesise a generalised complex electrical load. In this paper, experimental results of an improved H-bridge switching scheme that increases the output power from the harvester and the total energy stored in a battery will be presented. In addition, a mechanical model of the energy harvester was used to calculate the coefficients of the optimal synthesised complex load as a function of the measured excitation frequency which allows the system to autonomously change its resonant frequency to match the excitation frequency.

Keywords: energy harvesting, resonant frequency tuning, maximum power transfer, H-bridge, adaptive load

INTRODUCTION

In practical applications of energy harvesting, the frequency and amplitude of the excitation source will vary over time. To achieve maximum power density, it is desirable to match the natural resonant frequency and electrical damping of the harvester to that of the source. Recent advances in tuneable energy harvesters include the application of discrete reactive loads on the transducer output [1] or alteration of the mechanical properties of the resonant system [2]. However, these approaches only offer discrete, non-adaptable changes to the transducer or feature additional mechanical actuators.

In two recent papers, we presented experimental results of a MOSFET H-bridge circuit used to synthesise a range of complex load impedances to continuously tune the resonant frequency and electrical damping of an electromagnetic transducer [3, 4]. This approach to resonant frequency tuning overcomes the limitations in [1, 2].

In this paper, we demonstrate an improved switching scheme for the H-bridge MOSFETs and an adaptive load synthesis, which autonomously tunes the electrical damping and resonant frequency of the generator to match the excitation frequency. The rest of this paper is organised as: electromechanical modelling of two wave energy harvesters, a review of the new switching scheme and controller operation to synthesise a generalised complex load, a discussion of the experimental results and finally, some conclusions are drawn from results obtained using the tuning method presented in this paper.

HARVESTER SYSTEM MODEL

Wave Energy Harvester Prototypes

The two wave energy harvesters described in this paper were designed to be deployed in an unmanned surface vehicle (USV) for water quality monitoring purposes. The pendulum harvester, shown in Fig. 1, uses the wave motion experienced by the USV to excite a pendulum, which drives the rotor of two electrically series-connected, brushed DC generators. Coupling of the pendulum's motion to the generators was achieved using a rack and pinion. An end-stop on either side of the pendulum forms the displacement limit of the harvester.

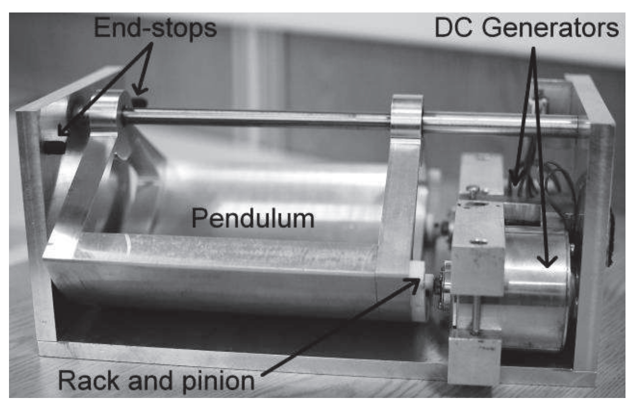

Fig. 1: Pendulum energy harvester.

The inertial cylinder energy harvester, shown in Fig. 2, is symmetrical around its rotational axis. A restoring force is created using a torsional spring that is fixed to the cylinder and the mechanical frame and thus the system has a mechanical resonance. The rotation of the USV about its bow-stern axis causes the cylinder to oscillate. Like the pendulum harvester, the rotation of the inertial cylinder drives the rotor of two brushed DC generators. However, the cylindrical energy harvester is not displacement limited, allowing potentially greater power output at larger displacements.

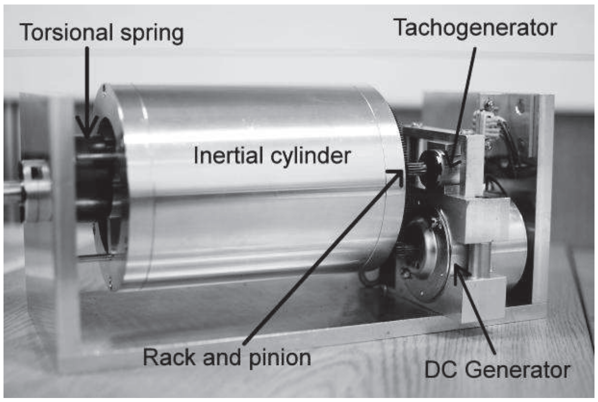

Fig. 2: Inertial cylinder energy harvester.

A separate tachogenerator was mechanically coupled to the pendulum and inertial disk so that the generated emf can be independently. The generator current was measured using a Hall effect current sensor.

Harvester Electromechanical Modelling

Resonant energy harvesters such as the two prototypes in Fig. 1 and Fig. 2, can be linearised and modelled as 2nd-order mechanical systems, which can then be mapped into the electrical domain, as shown in Fig. 3 [1].

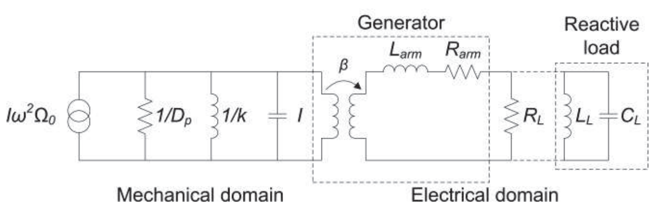

Fig. 3: Electromechanical model of an energy harvester with a generalised complex load.

The excitation is represented by an AC current source of magnitude $I\omega^2\Omega_0$, where ω and Ω_0 are the source excitation frequency and amplitude and I is the moment of inertia of the pendulum or inertial cylinder. The parasitic mechanical damping is represented by a resistance $1/D_p$, the spring constant by an inductance $1/k$ and the mass by a capacitance m.

The mechanical-to-electrical generator constant for the brushed DC generators is β, units of V·s, which is dependent on the gear ratio and motor constants of the tachogenerator and generators. The DC generator is modelled by a transformer with an armature resistance and inductance of R_{arm} and L_{arm} respectively. Several measured values of the system parameters for both energy harvesters are listed in Table 1.

Table 1: Measured mechanical parameters of both energy harvesters.

Parameter	Pendulum	Cylinder
I [kg·m^2]	23×10^{-3}	6.5×10^{-3}
D_p [Nm·s]	25.8×10^{-3}	7.6×10^{-3}
k [Nm/rad]	1.48	0.28

HARVESTER POWER ELECTRONICS

Synthesising a generalised load requires control of the amplitude and phase of the generator current with respect to the generator emf [3, 4]. In order to emulate both resistive and reactive loads, the H-bridge has to transfer energy from the generator into the battery and vice versa, for both polarities of generator emf. Fig. 4 shows the schematic of the H-bridge interface to the wave energy harvester.

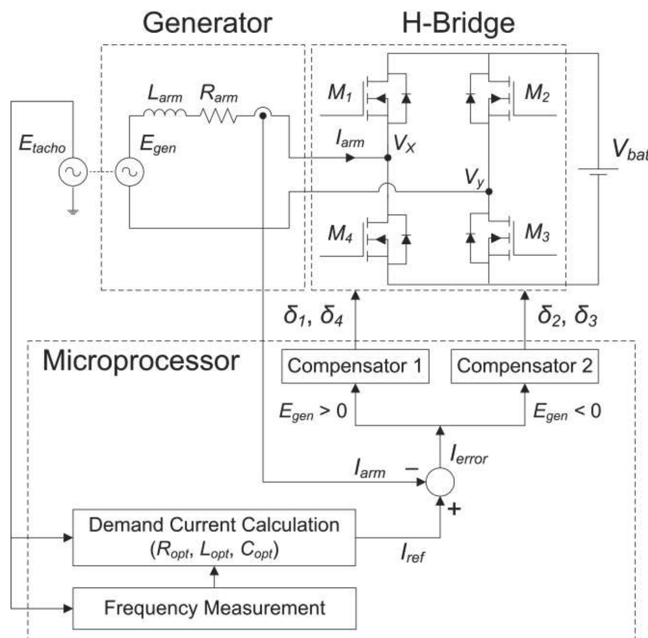

Fig. 4: Schematic of the harvester electronics.

Using the electromechanical model of the system, the optimal synthesised complex load is calculated as a function of source excitation frequency and the coefficients are stored in the microprocessor. During operation, the microprocessor uses these stored coefficients to synthesise a complex load based on the optimal load (R_{opt}, L_{opt}, C_{opt}) for the measured source excitation frequency, which is determined from the zero-crossings in the tachogenerator voltage. A PID compensator is used to match the armature current I_{arm}, to the reference current I_{ref}, by altering the duty cycles $\delta_1 - \delta_4$ of MOSFETs $M_1 - M_4$.

Four-Mode (4M) Operation

Instead of continuously switching both sides of the bridge with PWM signals, as was done in [3], the operation of the MOSFETs was divided into four modes. In each mode, one side of the H-bridge remains in a fixed switching state whilst the other side continues to switch with variable duty cycle PWM. By only switching half the H-bridge at a time, the MOSFET losses are halved as the conduction losses are found to be negligible. The desired operating mode is dependent on the polarity of the generator emf and demand current I_{ref} as listed in Table 2 which also shows the control signals for $M_1 - M_4$. Each side of the H-bridge is controlled by a separate PID compensator, as indicated in Fig. 4. In this new switching scheme, the H-bridge circuit effectively simplifies to boost modes (1 and 3) or buck modes (2 and 4) converter.

Table 2: Modes of operation for the H-bridge. "Comp" indicates a complementary switching state for the MOSFETs on the same side of the H-bridge.

Mode	E_{gen}	I_{arm}	M_1	M_2	M_3	M_4
1	> 0	> 0	Off	Comp	Comp	On
2	> 0	< 0	Comp	On	Off	Comp
3	< 0	< 0	Comp	Off	On	Comp
4	< 0	> 0	On	Comp	Comp	Off

Frequency Adaptive Load Synthesis

The aim of this H-bridge interface is to synthesise a generalised electrical load that will maximise the power output for a given source excitation frequency and to interface to a battery. The synthesised loads, R_{syn} and C_{syn} were determined by analysing the system model shown in Fig. 3 [1]. In this case, only one reactive load is required because the synthesised load is not a physical quantity and hence when a negative capacitance is synthesised by the H-bridge, it is representative of an inductor and vice versa. In a practical implementation, with two DC generators electrically connected in series, the synthesised load resistance and capacitance that will dissipate the maximum power in a load for a given source excitation frequency is given by (1) and (2).

$$R_{syn} = R_s + \frac{X_s^2}{R_s} \tag{1}$$

$$C_{syn} = \frac{1}{\omega}\left(X_s + \frac{R_s^2}{X_s}\right)^{-1} \tag{2}$$

where

$$R_s = 2R_{arm} + \frac{\omega^2 D_p \beta^2}{\left(I\omega^2 - k\right)^2 + \left(\omega D_p\right)^2}$$

$$X_s = \frac{\omega^2 \beta^2 \left(I\omega^2 - k\right)}{\left(I\omega^2 - k\right)^2 + \left(\omega D_p\right)^2}$$

Evaluation of equations (1) and (2) requires measurements of the source excitation frequency and this was determined using a microprocessor that detects the number of zero-crossings in the tachogenerator voltage.

EXPERIMENTAL RESULTS

Fixed Synthesised Load

In order to assess the improvements in output power provided by the pendulum harvester using the new switching scheme, the H-bridge was programmed to synthesise a fixed load of 250 Ω followed by a subsequent addition of 500 μF and -350 μF. For all three combinations, the energy harvester was subjected to varying source excitation frequencies on a laboratory rocking table whilst the flow of power into a battery was measured.

Fig. 5 presents the results for the pendulum harvester. For the resistive load case, the new switching scheme resulted in an increase in output power by 38% at the natural resonant frequency of 1.27 Hz. The addition of synthesised capacitances of 500 μF and -350 μF resulted in a frequency shift of the maximum power point of the harvester by +1% and -5% respectively.

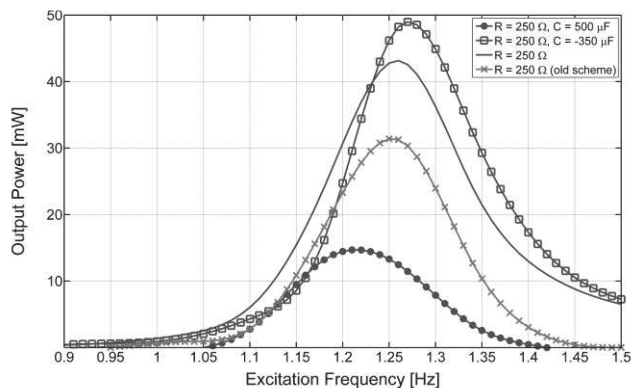

Fig. 5: Measured output power from the pendulum harvester with different synthesised loads.

Fig. 6 shows the measured output power of the inertial cylinder harvester with various synthesised complex loads, normalised to ω^2 to remove the frequency dependency of the output power. This emphasises the effects of the synthesised reactances on the maximum power point of the harvester. Although the peaks in output power are not as prominent compared to the pendulum harvester, the cylindrical harvester has a broader tuning range of up to 20% of the natural resonant frequency, 1.1 Hz. In the case of a purely resistive load, the peak power output increased by at least 25%.

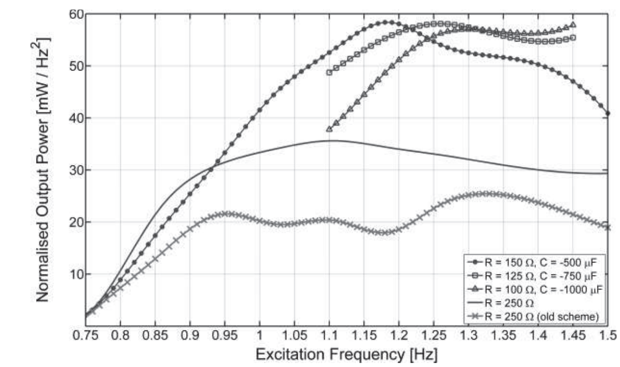

Fig. 6: Measured output power from the inertial cylinder harvester with different synthesised loads.

Adaptively Synthesised Load

Fig. 7 and Fig. 8 shows the energy accumulated in a 6 V, 1.2 Ah lead-acid battery, which was initially discharged to approximately 5.6 V, when either harvester was subjected to varying excitation frequencies for 20 minutes to simulate deployment conditions.

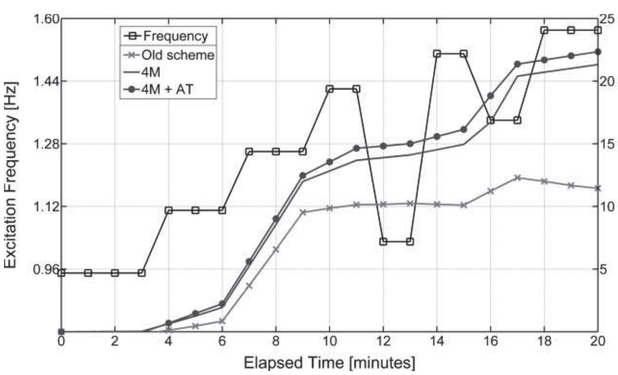

Fig. 7: Energy accumulated in the battery when the pendulum harvester was subjected to various excitation frequencies during a 20 minute cycle.

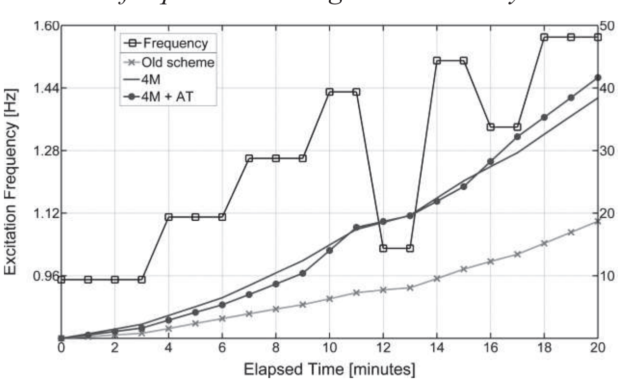

Fig. 8: Energy accumulated in the battery when the inertial cylinder harvester was subjected to various excitation frequencies during a 20 minute cycle.

In both figures, the old switching scheme from [3] is represented by the line with crosses. The lines labelled "4M" represent the new switching scheme which consists of the four-mode operation of the H-bridge as detailed in Table 2. The results from using the combination of adaptive frequency tuning and four-mode operation is represented by the line with filled circles and is labelled "4M + AT".

As a comparison between the old and new switching schemes and taking into consideration the additional feature of adaptive frequency tuning, the accumulated energy increased from 11 J to 22 J in the pendulum harvester and from 19 J to 42 J in the cylinder harvester. This represents an improvement of about 50% and 120% for the pendulum and cylinder harvesters respectively. The adaptive frequency tuning feature results in a steeper gradient of the energy curve for both harvesters compared to the case where only the four-mode operation is implemented.

CONCLUSION

Increasing the operational bandwidth of inertial energy harvesters is crucial when the device is subjected to varying source excitation characteristics. This paper presents a new switching scheme for an H-bridge interface that is capable of adaptively tuning the resonant frequency and electrical damping of an inertial energy harvester.

The choice of synthesised loads, R_{syn} and C_{syn}, to optimise the energy transferred to the battery is dependent on the source excitation frequency. The tuning range of any interface utilising switching devices is limited by the losses in the power electronics. The new switching scheme implemented here has successfully reduced the losses incurred in the circuit by half.

A tuning range of 6% and 20% was achieved in the pendulum and cylinder harvester respectively. When the harvesters were subjected to a 20 minute cycle of varying source excitation frequencies, the pendulum harvester managed to store 22 J of energy into a battery whereas the cylinder harvester accumulated 42 J over the same frequency variation. For the pendulum and cylinder harvesters, the increase in energy stored in a battery using the new switching scheme is 50% and 120% respectively.

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