Interface circuit using SMFE technique for an inductive kinetic generator operating as a frequency-up converter

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Abstract. This paper presents a novel interface circuit for an inductive kinetic energy harvester, which is designed based on the SMFE (Synchronized Magnetic Flux Extraction) technique. The generator is designed to fit into a shoe sole to power a telemetric device. It operates as a frequency-up converter and possesses a small output series resistance, allowing the SMFE scheme to be applied as an energy harvesting enhancement technique. A prototype has been implemented and simulated using discrete components in order to demonstrate the SMFE concept and compare it with typical standard interfaces used (Full Bridge and Voltage doubler rectifiers). Compared to the standard schemes, the SMFE method is able to extract a considerably higher amount of energy for a wide range of output voltages. Assuming one walking step per second, the complete system could provide 18.8 mW output power using the SMFE interface, compared to 8 mW with the full bridge and 12.3 mW using the voltage doubler.

1. Introduction
The increasing interest in recent years to develop wireless sensor networks capable to be autonomous in a reduced size, have turned the eyes to energy harvesting from ambient sources. Vibration energy harvesting is such a source and interesting new applications where miniaturization plays a key role have been widely proposed [1, 2]. Kinetic generators are mainly based on the piezoelectric, electrostatic and electromagnetic principles. The electromagnetic type has been documented to entail a high power density per cubic volume for devices in the centimeter size range [1].

Full bridge diode rectifiers and voltage doublers are considered as standard interfaces that rectify the AC output of an electromagnetic generator [3]. These schemes are efficient only at a specific output voltage at the buffer $V_{out}$ that depends on the open circuit voltage of the generator. Therefore their behavior strongly relies on a continuous excitation or additional circuitry to fix the output voltage. Maximum power point tracking (MPPT) is an enhancement technique to overcome this, setting the output voltage to its efficient value [4]. Nevertheless, this technique has only been studied for excitations that have a continuous behavior for at least a short period of time. For the case of frequency-up conversion in which the generator voltage magnitude varies depending on the mechanical and electrical damping, MPPT schemes presented until now are not able to operate efficiently.
The large coil series resistance \( R_g \) of many electromagnetic generators (> 500 \( \Omega \)) limits the harvesting capabilities of the different electric interfaces, with MPPT being the scheme that achieves most promising results. The generator used in this work possesses a small \( R_g \) (5 \( \Omega \)) which allows the SMFE scheme to be applied as an energy harvesting enhancement technique [5]. This paper presents the development of the SMFE interface for this specific generator, proposing a control circuit using discrete components, and analyzing the results obtained by comparing them with the standard interfaces. The generator is also modeled, and the special cases where the SMFE scheme is suitable are discussed.

2. Electromagnetic Generator

The generator used for this work is shown in figure 1a. It operates as a frequency-up converter which allows the extraction of energy from low mechanical frequencies by means of a conversion to a resonant higher frequency mode [6]. It is designed to fit into a shoe sole and power a telemetric device that wirelessly provides the location of the user to an external receiver. The generator is excited through a push button when the user takes a step. A beam with attached magnets then becomes deflected and is released to self-oscillate around a coil.

The kinetic generator is modeled using a low damped spring-mass-damper system [7]. Using the electrical analogy of the mechanical system [8], the generator can be modeled using electric components as shown in figure 1b. The values of the generator parameters are summarized in figure 2a. The open circuit voltage of the generator (a) and the energy extraction dependency on \( R_g \) (b).
Table 1. \( F_{\text{ext}} \) represents the external force that the driver exerts to the tip of the cantilever. The mechanical parameters are the spring stiffness \( k \), the mass \( m \), the mechanical damping \( d_m \), and the coupling coefficient \( c \). The inductance of the coil and its series resistance are represented by \( L_g \) and \( R_g \), respectively.

For continuous resonant systems the excitation is modeled by a sinusoidal current source with a magnitude \( F_{\text{ext}}/c \). However, in frequency-up conversion the system is excited by a pulse, and the force profile is similar to a saw-tooth signal with a relatively slow rise time, very fast fall time and with a peak magnitude \( F_{\text{ext}}/c \). Hence the system emulates the deflection and release of the beam, which can then self-oscillate until its energy is damped. The resultant waveform of the voltage across the generator terminals in open circuit condition \( V_{g,oc} \) can be observed in figure 2a.

As stated in the previous section, the series resistance of the generator limits the energy extraction capability. This behavior can be observed in figure 2b, where the energy harvesting capability of the two standard techniques and the one of the SMFE are presented with respect to a variation in the value of \( R_g \). It can be observed that for low values the SMFE scheme is better suited as an enhancement technique, whereas for large \( R_g \) the standard interfaces perform better. Since the proposed generator possesses a 5 \( \Omega \) series resistance, the SMFE interface is suitable as an efficient interface.

### 3. Electronic Interface

The SMFE scheme (figure 3a) consists of adding a switch \( S \) at the output terminals of the generator and before the rectification stage. After an excitation, \( S \) is closed, thus shorting the

| Table 1: Generator parameters and discrete components used. |
|-----------------------------------------------------------|
| **Electromagnetic generator** | **Discrete components used** |
| \( F_{\text{ext}} = 25 \text{ N} \) | \( c = 2.7 \text{ Vs/m} \) | Schottky diodes | BAT54 |
| \( m = 46 \text{ g} \) | \( L_g = 97.54 \text{ nH} \) | Comparators \( U_1, U_2, U_3 \) | LPC662A |
| \( k = 5000 \text{ kg/s}^2 \) | \( R_g = 5 \Omega \) | n-MOS Transistor | BS170 |
| \( d_m = 0.25 \text{ Ns/m} \) | \( f = 52.4 \text{ Hz} \) | p-MOS Transistor | BS250 |
| width = 30 mm & height = 26 mm | length = 80 mm | \( R_d, R_t = 100 \text{ M\Omega} \) | \( 1 \text{ pF} \leq C_t \leq 20 \text{ pF} \) |
| \( L_{\text{cmp}} = 61 \text{ mH} \) | | | |

Figure 3: Schematic of the SMFE interface (a) and its control circuit (b).
generator outputs and storing energy in $L_g$. When the generator current $I_g$ peaks (See figure 4), $S$ is opened and the energy stored in $L_g$ is transferred to the buffer capacitor $C_{buf}$. A compensation inductor $L_{cmp}$ is added in series to match its reactance with the impedance of the generator when $S$ is closed, thus achieving an efficient energy transfer.

The energy harvested every half wave cycle can be calculated using equation (1), where $X_{L_g}$ and $X_{L_{cmp}}$ are the reactances of $L_g$ and $L_{cmp}$ respectively. The oscillation frequency is represented by $f$, and $V_d$ represents the diode forward voltage.

$$E_{hrv} = \frac{1}{2} (L_g + L_{cmp}) \left( \frac{V_{g,oc}}{X_{L_g} + X_{L_{cmp}} + R_g} \right)^2 - \frac{I_{out} V_d - I_{out}^2 R_g}{2 f}$$

### 4. Implementation

The proposed scheme was implemented using discrete components. The switch $S$ is implemented by means of two n-MOS transistors, with their sources connected together to cancel the effect of the bulk diodes (figure 3a). The schematic of the proposed control circuit is presented in figure 3b. It consists of a current peak detector and a precision timer. If short circuited, $I_g$ peaks when $V_g$ crosses zero. The current peak detector monitors $V_g$ with comparator $U_1$, while $U_2$ detects any crossing of the ground level. $U_2$ is configured as a hysteresis comparator in order to avoid instability problems. $R_t$, $C_t$ and $U_3$ are used as an externally adjusted timer to turn off $S$ after the energy has been transferred.

The rectification stage is implemented using a full bridge diode rectifier with schottky diodes. The comparators are powered with external power supplies of 10V and −10V. The XOR gate is implemented using n-MOS and p-MOS transistors and is powered with an external 10V source.

### 5. Results

The proposed circuit was simulated in PSpice to demonstrate the SMFE concept and compare it with the standard interfaces. The waveforms of the generated current $I_g$, the current flowing to the output storage $I_{out}$, $V_g$ and $V_{sw}$ (switch control signal) are presented in figure 4.

The energy extraction profile after a single excitation is presented in figure 5a, whereas the standard interfaces and the SMFE have been configured to optimum conditions (Optimal $V_{out}$). The SMFE curve is well above the other two, harvesting around 135% and 53% more energy than the full bridge and voltage doubler rectifiers respectively after a single excitation.

The energy harvested by the different schemes at different output voltage levels is presented in figure 5b. It can be observed that for low output voltages both standard techniques harvest a considerably higher amount of energy. However, as the output voltage is increased the SMFE
scheme is able to outperform the standard schemes. This technique is also able to harvest a high amount of energy for a wide range of output voltages.

Assuming one walking step per second and using $P_{\text{avg}} = \frac{\Delta E_{\text{hrv}}}{\Delta \text{time}}$, the system could provide 18.8 mW output power using the SMFE technique in optimum conditions ($V_{\text{out}} = 10$ V). The full bridge and the voltage doubler rectifiers are able to provide roughly 8 mW and 12.3 mW respectively. The power consumption of the control circuit including the external power supplies is around 2 mW.

6. Conclusion

A novel interface circuit for kinetic electromagnetic generators with a low series resistance is proposed. The generator has been modeled using a mass-spring-damper system, providing special emphasis on the modeling of the input force for frequency up conversion.

The electronic interface for the SMFE has been implemented together with its control circuit using discrete components. The simulation results show a significant advantage when using the SMFE technique compared to standard schemes. It also harvests a large amount of energy with low sensitivity to changes in the output voltage.

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