Analysis of Pulsed vs. Continuous Power Delivery from an Electromagnetic Generator

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Abstract. The purpose of this work is to present alternative power conversion techniques for an energy harvester optimized to the power requirements of an activity monitoring device. Many energy harvesters designed to use human motion provide a pulsed type of output waveform, as the signal will be strongly related to the pattern of motion used for harvesting energy. Due to this type of discontinuous signal it is considered that wearable sources have the potential to provide higher energy values by pulses rather than continuous form. For this work an electromagnetic generator system was optimised to power a monitoring device located in the shoe. Rectification techniques as well as coil parameters design have been employed and powering conditions have been analysed. The generator system can provide pulses of power high enough to sustain a low power consumption device.

1. Introduction

The concept of energy harvesting has known an increase in popularity with the development of portable electronics. Although there are infinite sources of energy that have been considered for energy harvesting applications, in the context of portable electronics the human body represents the most obvious source. According to Starner [1] power can be obtained by unobtrusively converting the energy the human body consumes while performing every day activities. Based on literature [1] one of the most deliberate human actions that can offer a good potential for energy harvesting is walking. During walking power can be taken from rotation of joints, swinging motion of arms and legs or pressure applied at different points. It is calculated that by performing the swinging motion of the legs a human needs between 1.07 and 34.9 J/step. This is the equivalent of 2.1 to 69.8 W for each joint during a gait cycle [2]. In an investigation with accelerometers Romero et al. proved that the power values from walking at the ankle area are approximately 10 mW/cm², which is twice as much as for most of other body locations [3]. This work is centred on developing and optimizing an energy harvesting system that is capable of providing the highest amount of energy from walking and that is designed for integration in the shoes.

Energy can be harvested from human motion by using thermoelectric, piezoelectric, electromagnetic or electrostatic energy conversion [4], [5]. Previous work [6] has concluded that for an energy scavenger designed to convert the energy consumed during walking, an electromagnetic system is the most suitable. Although electromagnetic energy harvesting for walking is not new [7], the scope of this work is to demonstrate how a shoe-integrated electromagnetic generator system can be designed to provide useful levels of pulsed power for wearable sensing applications.

The industry of wearable sensors has known a rapid development over the past decade, with individual components decreasing in size and becoming more powerful. Nowadays, wearable technology has reached the point where some of these sensors can be employed in clinical
applications. Of particular interest in this work are activity monitoring devices which aim to provide both diagnostic and monitoring functions for recovering patients or elderly people who want to continue living independently [8], [9]. As monitoring devices need to be able to work for extended periods of time, the provision of a self-sustained system is desirable. Therefore, this work investigates the performance of a shoe-integrated electromagnetic generator in powering such a system. Due to the discontinuous nature of generated voltage pulses on one hand, and the intermittent power demand profiles of wearable sensors, it is proposed to deliver the generator power in large bursts (as it’s generated) rather than to filter the output to provide an averaged constant power. The remainder of the paper deals with optimizing the generator parameters and with analysing rectification techniques employed to obtain the maximum power under continuous and pulsed power conditions.

2. Power requirements of activity monitoring devices

Wearable activity sensors can have diverse functions, covering the care and monitoring of elderly people [10, 11], sports activities and performance monitoring [12-14], disease monitoring during daily activities [15], or gait analysis [16]. A typical wearable wireless sensor will contain a data control and processing block, a sensing block and a transmission unit. Although the power profile of recently developed microcontrollers and sensing modules are suggesting that energy harvesting solutions are applicable, the transmission modules are still representing a challenge in the development of self-sustained systems. Other research groups [17-19] have recently developed systems with particular consideration for the power consumption. Overall current consumption typically ranges between 3 mA for idle state and 20 mA for listening and data transmission modes. Similarly, transmission protocols specially adapted for wearable sensor nodes that minimize the power dissipation and compress data are emerging [20-21], [17].

In this context, the newest generation of microcontrollers require current values ranging from 0.19 mA for idle state to 6.5 mA for the active state [22]. An accelerometer needs 0.002 mA for stand by state and 0.2 mA for active mode [23]. Typical power consumption for transmission modules are 17mA for RF [24] or 14.6 for Bluetooth 4.0 [25]. However, the latter are peak values needed during listening and receiving the data and are usually needed for durations shorter than 1ms. A typical sensing cycle in the case of a wearable generator the MCU might be activated by the input voltage generated by the user walking. The movement would be recorded with the aid of an accelerometer, followed by data processing and transmission to indicate that the user has taken a step. The highest amount of power is required during transmission even if the active mode time interval is considerably smaller than those of the other components (1ms for active mode in the case of Bluetooth). Taking the supply voltage ranging between 1.8V and 3.6V the instantaneous power levels vary from 0.34mW for the microcontroller and sensing unit to a peak of 60mW for data transmission. Taking a typical wireless sensor power profile, with a microcontroller operating time of 100ms, sensor operation over 80ms and data transmission lasting for 10ms, the overall energy per sensing cycle is estimated as 1.04mJ.

3. Electromagnetic generator design

The generator prototype proposed in this work is based on the sliding magnet principle described in [26]. Based on the theory that as long as the mass of the magnet is considerably smaller than the mass of the foot, continuous movement of the magnet can be sustained by external forces due the movement of the foot with no additional or deliberate effort from the user. The prototype generator was assigned a volume of 50x15x15mm³ and 10mm diameter disk shaped NdFeB magnets were determined to be optimum for the generator’s cross sector. Applying optimization rules from [26], it was determined that the most suitable generator prototype consists of 1 magnet of length 15mm and one 17.3mm long coil, centred along the 50mm generator length. In this way, the magnet has sufficient scope to travel into and out of the coil at either end, while the coil is just long enough to capture the majority of magnetic flux gradient. Therefore, the generator is optimised to provide the maximum output voltage...
by power product. A 300 turn version of this generator shown in Figure 3(a) has been tested with the generator attached to the outer heel of a shoe for walking speeds ranging from 2 to 12 km/h [6].

It was observed previously that the maximum peak power was achieved at values approximately equal with half the value of the open circuit voltage. However, maximum loaded voltage pulses of 0.7 V peak are outside of the 1.8 V to 4.1 V operating voltage range required by most sensor system components. In order to counteract this issue the number of generator winding turns is increased by a factor of 5 in this work. However, with the space constraints remaining the same, the diameter of the wire needs to be reduced to 0.1 mm, resulting in a coil of 10 layers with 150 turns per layer and an estimated resistance of 160 \( \Omega \). Simulations have concluded that the new design will produce output voltage pulses of approximately 8 V peak under open circuit conditions; this corresponds to a maximum load power voltage of \(~4\) V as required for sensor operation. Predicted open circuit waveforms are included in the results of Figure 2 later. These are based on measurements for the 300 turn generator at a walking speed of 8 km/h.

4. Rectifier design for pulsed and continuous power delivery conditions

Most energy harvesting systems apply AC/DC conversion stages to provide a steady DC output voltage. However as described in Section 2 the power requirements of most wireless sensor loads are more pulsed in nature. Given that the generator is producing a pulsed output, the design of a simple half-wave rectifier is investigated with a view to matching the pulsed load demand every time a step is taken. The average power under pulsed and continuous conditions is compared in simulations in Figure 1(a), with corresponding peak voltage levels included in Figure 1(b). These were predicted for a range of constant RC values of a capacitive filter, where for operation under continuous conditions, the choice of RC is based on the repetition period of a walking step (1 step per second), while a lower RC constant is chosen in the case of pulsed power with the aim of eliminating ripple within an individual generator voltage pulse. Two values of the ripple are included for each case. It is clear that the maximum average power settles at around 1 mW for all values of RC. However this is achieved for R = 1925 \( \Omega \) and C = 0.65 mF (RC = 1.25) for the continuous case and for R = 769 \( \Omega \) and C = 65 \( \mu \)F (RC = 0.05) under pulsed conditions. The corresponding peak voltages for the maximum power points are 3.6 V for the pulsed case and 2.1 V for continuous conditions.

Figure 1: (a) Output average power for a half-wave rectifier under pulsed and continuous conditions (b) Output peak voltages for a half-wave rectifier under pulsed and continuous conditions

The high values of R and C needed to achieve the maximum average power point under continuous conditions combined with the lower values of output voltage are suggesting that the pulsed power delivery method is more practical. Simulated output voltages are compared for pulsed and continuous operation in Figure 2. The voltages produced under pulsed conditions provide instantaneous peak power levels of 17 mW with a corresponding current level of 3.3 mA compared to 8.9 mW and a current level of 1.1 mA for the continuous case. In terms of time, it is found that the pulsed power output lasts \(~150\) ms per walking step, giving an overall energy per step of approximately 0.7 mJ.
As discussed in Section 2, typical energy levels needed per wireless sensing & transmission operation are of the order of 1 mJ and therefore the application of the generator for supplying this energy is plausible. The predicted performance of the system is summarised in Figure 3(b) where available current and voltage levels for the generator are compared with those required by various sensing components. It is clear that the continuous case supports sleep mode operation while pulsed operation is more suited to active power consumption.

5. Measurements results

Measurements have been conducted with a prototype consisting of a 300 turn coil that occupies the pre-allocated volume of 50x15x15 mm$^3$. Results are presented in Figure 4 for a speed of 10 km/h with the RC product designed for maximum power under pulsed and continuous conditions. It is clear that the trends predicted by simulations are observed. The peak voltage under the pulsed conditions is of 0.5V and is higher than the 0.3V peak achieved for continuous conditions resulting in instantaneous peak power values of 5.5mW and 0.37mW respectively. The maximum average power also confirms the trends shown in simulations with similar values of ≈220µW for both cases. Lower power levels than predicted in Section 4 are explained by a higher percentage source voltage drop across the rectifier diodes.
6. Conclusions and future work

An electromagnetic generator system has been designed and optimised for a typical wearable sensor load. Alternative power delivery methods have been analysed and simulations show that using a rectifier designed to deliver pulses of power each time the generator is activated can satisfy typical power requirements of a wearable sensor.

Work is on-going to investigate full-wave rectifiers which are expected to provide a higher output power. Future work will also be focused on verifying the generator capabilities by measurements for a demonstrator wireless sensor.

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