

WIRELESS SENSOR NODE USING A ROTATIONAL ENERGY HARVESTER WITH ADAPTIVE POWER CONVERSION

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Abstract: In this paper, we present and demonstrate a rotational energy harvester with a component-optimised maximum power point tracking (MPPT) circuit for adaptive power conversion. An AM-transmitter and receiver was used to instrument the harvester during operation. Experimental results on the effects of current limiting the harvester and the end-to-end efficiency of the MPPT circuit are shown. Finally, preliminary work on the design of a self-powered wireless tachometer using accelerometers is described.

Keywords: energy harvesting, rotational generator, maximum power point tracking, self-powered tachometer

INTRODUCTION

Battery-less, wireless condition monitoring of rotating machinery can be achieved using vibration energy harvesting devices, such as those marketed by Perpetuum [1]. However, as practical online frequency tuneable devices are in their infancy, existing solutions are only really suitable for fixed speed rotating machines [2]. In addition, many machines will have low levels of vibration. A potential solution is to use a harvester powered directly from machine rotation, with a single point-of-attachment onto the rotation source [3].

We have previously reported work on energy harvesters powered from continuous rotation, along with a MPPT circuit which was validated using external power supplies [3]. In this paper, we present a rotational energy harvester interfaced to a self-starting MPPT circuit which transmits information about generated energy over a wireless link. The addition of accelerometers to the system would then allow the realisation of a self-powered wireless tachometer and shaft encoder.

OPERATION OF THE ROTATIONAL HARVESTER

The harvester is essentially a direct-current (DC) motor deployed as a generator, and in the present configuration the rotor is coupled to the rotation source and the offset mass attached to the stator, as shown in Fig. 1 [3]. In Fig. 1, the rotation source or host rotates at ω , causing the mass to deflect at an angle θ with respect to its initial position along the vertical axis.

As current is drawn from the rotational harvester, a torque causes the proof mass to rotate such that the counter-torque from gravity, $T_g = mgL \sin(\theta)$

counteracts the motor torque, $T_m = K_E I_A$, where, K_E is the motor constant and I_A is the armature current in the rotor. The transduction mechanism of this harvester relies on the relative speed between rotor and stator. In the event θ exceeds 90° , the stator will rotate synchronously with the rotor, causing a sharp decrease in output power from the harvester. Under matched load conditions (i.e. the output load, R_L , connected to the generator is matched to the armature resistance, R_A , of the generator), maximum load power can be transferred from the generator to the load. Therefore, the maximum electrical output power is given by:

$$P_{elec(max)} = \frac{(K_E \omega)^2}{4R_L} \quad (1)$$

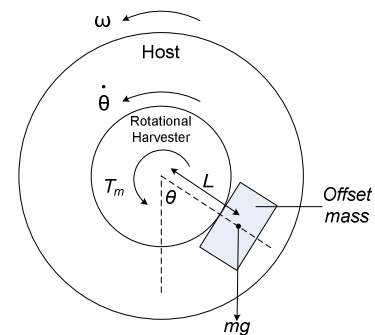


Fig. 1: Schematic of the rotational harvester.

POWER PROCESSING CIRCUITRY

A highly optimised boost converter of a previously developed MPPT circuit performs the impedance match to the generator's armature resistance, and pushes energy into a storage capacitor which feeds a wide-input output voltage regulator that supplies a regulated voltage of 3.3 V to the load [3]. The storage

capacitors function as an energy reservoir; storing energy when there is excess power available from the harvester and discharging when insufficient energy is harvested. The boost converter in Fig. 2 forms an integral part of the MPPT circuit because it has to extract power from the harvester and push the excess power into the storage capacitors. Furthermore, the inductor on the input side of the boost converter results in a smooth input current waveform in the converter which is required for an impedance match.

One notable change from the circuit in [3] was the use of a PIC18F1320 microcontroller from Microchip to run the impedance match control loop as well as to monitor and encode the storage capacitor's voltage for transmission using an AM-transmitter (AM-RT4-433 [4]). The transmitter sends the storage capacitor's voltage in the form of an 8-bit serial data stream every 6 ms at a Baud rate of 9600. This is picked up by an AM-Receiver (AM-HRR16-433s [4]), which then relays the 8-bit data stream to be decoded and displayed in LabVIEW.

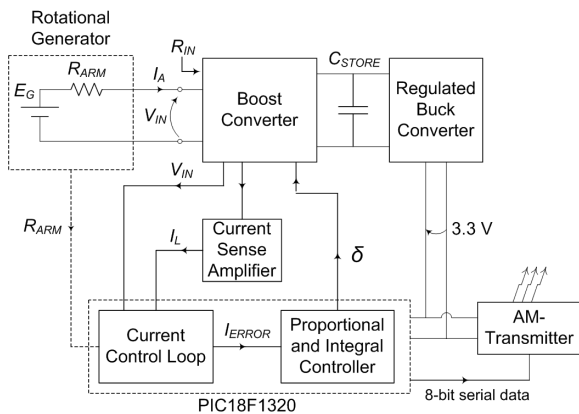


Fig. 2: Schematic of the energy harvester node.

In accordance with the rotational nature of this harvester, a circular printed circuit board (PCB) was manufactured to accommodate the MPPT circuit, microcontroller, storage capacitors, output voltage regulator and the AM-transmitter (Fig. 3).

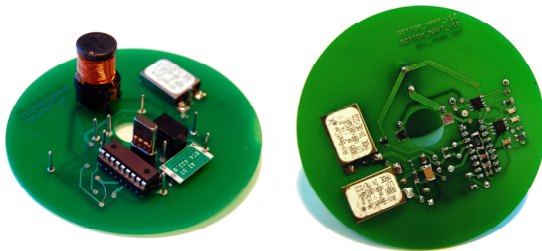


Fig. 3: Top (left) and bottom (right) sides of the MPPT circuit.

The free-end of the generator's stator was fitted through the middle of the PCB while the mass was

attached to the stator, and the rotors of the harvester and host rotation source were coupled together as shown in Fig. 4.

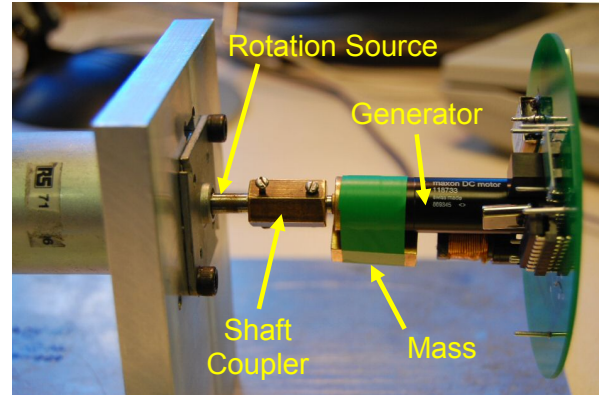


Fig. 4: Experimental setup of the rotational harvester.

BOOST CONVERTER LOSS MINIMISATION

An essential constraint on the impedance matching circuit is for it to be self-sufficient and only dependent on the power generated by the harvester whilst still leaving power available to power a useful load such as a sensor. In the design of a power conditioning circuit where the control overhead is a small fraction of the processed power, additional components such as gate drivers and active-filters are deployed to eliminate the effects of the Miller capacitance at the gate of the transistor and high frequency switching noise respectively. However, for a circuit that is powered by harvested energy, these components can consume a significant fraction of the harvested energy and so their loss must be kept to a minimum.

In order to perform the optimisation of the power converter losses in the converter must be minimised. Equations expressing the power losses for each component were developed using parameters which are available through the manufacturer's datasheet and operating conditions of the converter. Examples of the parameters for the switching transistor and diode are the rated operating current and total gate charge.

Once the expressions for power losses of each component have been obtained as a function of these parameters, they are then subjected to a stringent minimisation routine in Matlab (`fmincon`). This routine computes the minimum value of a constrained non-linear multivariable function, in this case, the total power loss of the converter. `fmincon` would try every possible combination of parameters (within a constraint) that would result in the least amount of power loss in the converter and finds a value for each parameter. The values in Table 1 were obtained with the following constants: the harvester has a K_E of 589 RPM/V, an armature resistance of 11 Ω and was

coupled to a host rotation source of 500 RPM.

Table 1: Results from the optimisation process.

Parameter	Value
Transistor rated current	4.52 A
Diode rated current	0.56 A
Switching frequency	36.2 kHz
Inductance	0.68 mH

To validate the results from Table 1, each parameter was subjected to a sweep of its values around the optimal points. The graphs in Fig. 5 confirm that the minimisation process was accurate and as a result, the boost converter was built using components rated as close as possible to the values shown in Table 1. Also, the predicted maximum obtainable net power from the harvester is 400 mW – an encouraging amount of power partly due to the high efficiency of the converter.

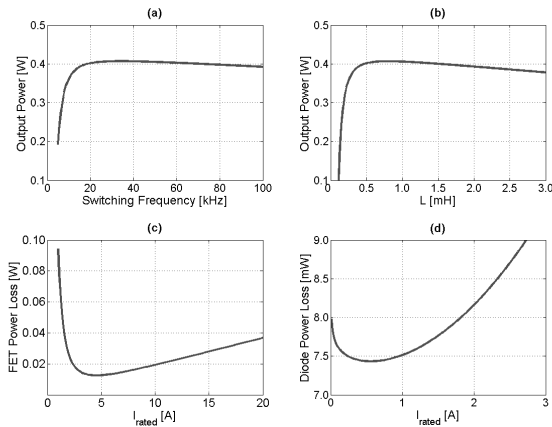


Fig. 5: Validation of the results from the optimisation in Matlab.

Performance of the Boost Converter

Choosing the components based on the results from the optimisation function, the efficiency of the stand-alone boost converter was found to have a peak value of approximately 96% for duty cycle values of less than 0.8, as shown in Fig. 6. The PWM signal was provided by an external signal generator and was set up such that the PWM frequency and peak-to-peak values (3.3 V) were the same as what the PIC18F1320 would provide. In addition to that, a 500 Ω load resistor was connected to the output. This choice of load resistor results in approximately 20 mW of dissipated power when the voltage across it is 3.3 V, which should be sufficient for many wireless sensor node applications. It should be noted that at higher

duty cycle values, the efficiency of the converter decreases due to higher I^2R -losses and poor on-state conduction of the switching transistor due to its finite switching speed.

The boost converter's voltage transfer characteristics (Fig. 7) were investigated by applying various input voltages (0.2 V, 0.5 V, 1.0 V and 2.0 V) with a 500 Ω load resistor at the output. A maximum voltage gain of 11.1 was achieved at a duty cycle of 0.95 for an input voltage of 0.5 V. There was no apparent roll-off point on the voltage gain except when the input voltage was 0.2 V, indicating a satisfactory monotonic response between voltage gain and duty cycles up to 0.95. In general, the experimental results closely matched the ideal voltage gains very closely.

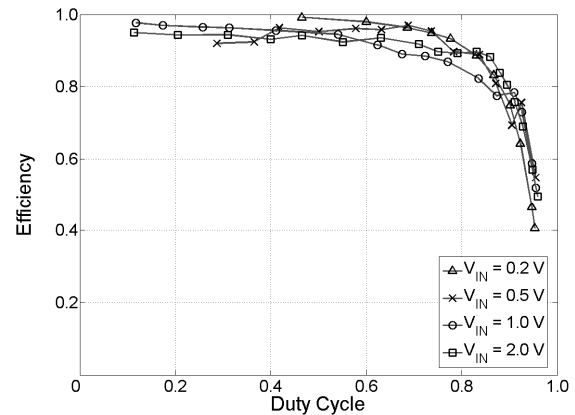


Fig. 6: Efficiency of the stand-alone boost converter at different duty cycles and input voltages.

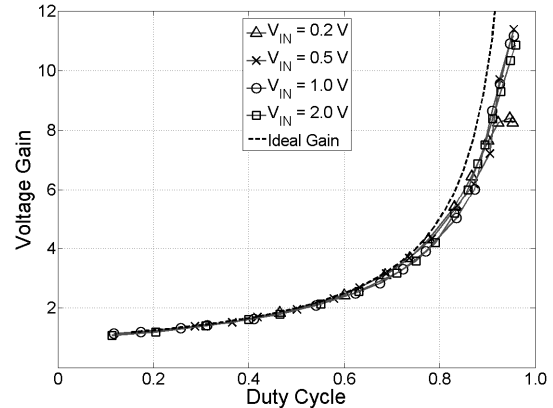


Fig. 7: Voltage gain characteristics of the boost converter at different input voltages.

EXPERIMENTAL RESULTS

Current Limit Effects

To prevent the mass from flipping over and rotating continuously with the rotor, the current through the

generator's armature was limited to a maximum value of $\frac{mgL}{K_E}$. As the generated voltage increases, the boost converter's duty cycle will decrease to reduce the amount of current drawn from the generator. This causes an increase of the converter's input impedance as shown in Fig. 8. During this current limit, the armature resistance is no longer matched to the converter's input impedance; this is a necessary trade-off so that power can still be extracted from the generator.

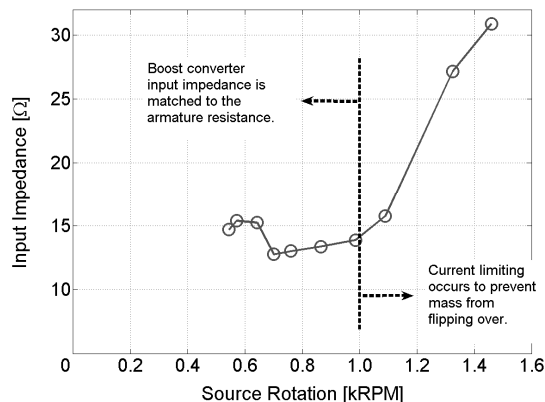


Fig. 8: Measured input impedance as seen by the generator. The armature resistance was 11Ω .

Overall Circuit Efficiency

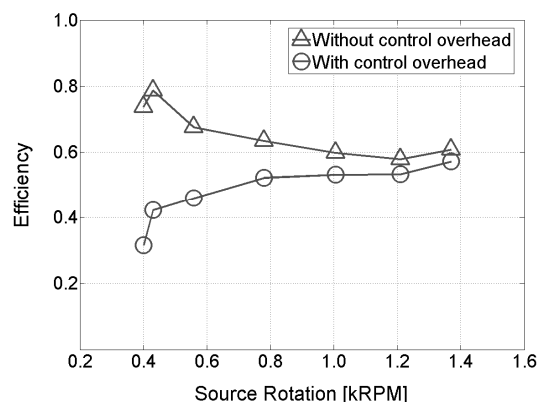


Fig. 9: Experimental results of efficiency with and without the control overhead at different source rotation speeds.

The experimental end-to-end efficiency of the MPPT circuit, storage capacitors and the output voltage regulator is plotted against the source rotation in Fig. 9, where the power consumption of the microcontroller and the transmitter constitute the control overhead of overall system. Here, the efficiency is defined as the ratio of output power dissipated on the load resistor (V^2/R) to the input power from the harvester under matched load

conditions (Eq. 1). With the control overhead taken into account, the achievable net efficiency is approximately 60 % at a source rotation of 1400 RPM. The net power at this speed is 1.45 W.

FUTURE WORK

The work reported in this paper will progress towards realising a self-powered wireless tachometer and shaft encoder from accelerometers powered by the rotational harvester. Preliminary tests were conducted using two Analog Devices ADXL320 analogue output accelerometers and the aforementioned microcontroller-transmitter-receiver-LabVIEW interface, independent of the generator.

Total power consumption of the accelerometers is rated at 1.6 mW, which includes two low-power operational amplifiers required for interfacing the accelerometers to the microcontroller. Fig. 10 shows the calculated rotation speed from the accelerometer against the measured rotation speed from an optical tachometer. On inspection, the gradient in Fig. 10 highlights an almost linear relationship between the measured and calculated rotation speeds – highlighting the feasibility of this approach.

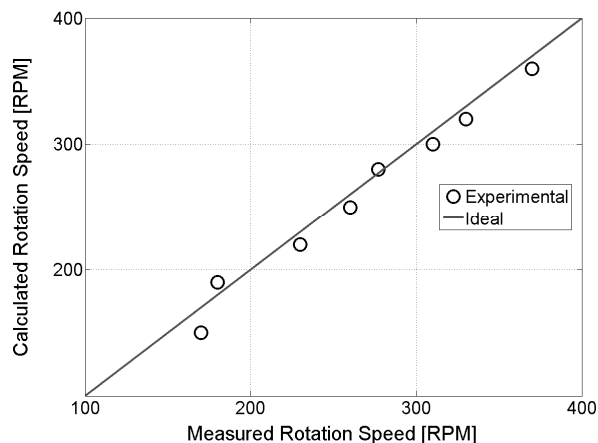


Fig. 10: Comparisons of the measured and calculated rotation speeds.

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