Power Management with Dynamic Power Adaption for a Rotational Energy Harvester in a Maritime Gearbox

J Esch¹, D Schillinger², D Stojakov¹, D Hoffmann¹ and Y Manoli¹²

¹ Hahn-Schickard-Gesellschaft für angewandte Forschung e.V., 78052 Villingen-Schwenningen, Germany
² Fritz Huettinger Chair of Microelectronics, Department of Microsystems Engineering - IMTEK, University of Freiburg, Germany

Jonas.Esch@Hahn-Schickard.de

Abstract. Rotational Energy Harvesting becomes increasingly important for rotating sensor applications. Most of these applications rotate with changing revolution speed, which is a significant challenge for the energy harvesting system. This work presents an energy harvesting system for rotational motion with a new power management concept to generate energy for a wireless condition monitoring system. The challenge is to generate enough energy with a high efficiency factor at the minimum revolution speed but also to avoid problems with energy excess and high voltages at the maximum revolution speed. The power management includes solid state relays for coil switching to avoid the generation of excess energy that would lead to increased temperature. At 500 rpm the energy harvester generates 193 mW. With an efficiency of 54% the power management provides an output power of 106 mW.

1. Introduction

New sensor applications in wireless sensor networks require a sustainable power supply. Energy harvesting is a possible solution to supply such devices. A big industrial market is condition monitoring systems (CMS), which are used in machines like engines, pumps, gears or rollers. Many of those machines have rotating parts like drive shafts, gear wheels or clutches [1]. To generate energy on rotating parts with a rotational energy harvester, a power management is required, which can handle the voltages and currents over the whole revolution speed range. In this work a rotation energy harvester with power management is presented to supply a CMS inside a maritime gearbox. In a previous project a CMS was placed outside of a gearbox [2]. The required power for operation was delivered either by a thermoelectric system or by a vibration energy harvester.

2. Application and Concept

A maritime gearbox is placed between the engine and the drive shaft of the propeller. It transfers torque with a fixed ratio, whereas both directions of rotation are possible. Gearboxes have a recommended maintenance interval. In order to achieve an extension of the maintenance interval, it is very important to monitor the condition of the gearbox. The presented energy harvester is mounted at the clutch and generates energy when the clutch is rotating. The generated energy powers a sensor system with a wear sensor [3], a temperature sensor with contactless read out and a Bluetooth LE module for wireless data transmission. In the used gearbox the drive shaft rotates with revolution speeds of 500 to 2700 rpm. The system has to work continuously for the whole speed range in a
temperature range of 0 to 80° C. With such a condition monitoring system damage can be prevented, because information is received from the gearbox in real time and in critical situations the engine can be stopped or the clutch disengaged.

2.1. Energy Harvester

In the process of development many different concepts for rotational energy harvesting were considered. The main system requirements included a small assembly space with a maximum thickness of 18 mm, a wide revolution speed range and a power consumption of 100 mW at the lowest revolution speed. After many simulations of different concepts the concept shown in figure 1 was left. Two coils are mounted on the rotating clutch while three magnets are mounted at the gearbox wall. A voltage is induced in the coils due to the relative motion between coils and magnets.

In figure 2 the final device is shown with two coils in front of a back iron, which are placed in an oil proofed housing with a wired connection to the wear sensor. The power management board, the transmission board and the coil for the temperature sensor with wireless read out are inside the housing.

![Figure 1. Schematic of operation for the energy harvester placed at the clutch.](image1)

![Figure 2. Photograph of the energy harvesting system.](image2)

2.2. Power Management

As shown in figure 1, the permanent magnet induces a voltage in the moving coil. Hence the coil can be seen as a harvester with an open circuit voltage $V_{OC}$ and an impedance consisting of the coil’s winding resistance $R_{COIL}$ and the coil’s reactance $j\omega L$, where $\omega$ is the angular frequency and $L$ is the coil’s inductance. Due to the low frequencies, $j\omega L$ is much lower than $R_{COIL}$ and the harvester can be modelled as a voltage source $V_{OC}$ with a resistance $R_{COIL}$. The maximum energy can therefore be extracted if the load resistance $R_{LOAD}$ equals the harvester resistance $R_{COIL}$ as shown in figure 3 (a). Thus, the harvester output voltage is always half of the open circuit voltage as illustrated in figure 3 (b).

The optimal load resistance can be emulated by a switching converter [4] which results in a high harvesting efficiency ($P_{GEN}/P_{MAX}$) where $P_{GEN}$ is the power that is delivered from the harvester to the extraction circuit and $P_{MAX}$ is the power extracted from the harvester with the optimal load resistor. On the other hand, the regulation effort is high and therefore a lot of power is consumed by the regulation of the extraction circuit.

![Figure 3. (a) Harvester with optimal load, (b) corresponding waveform of (a), (c) harvester with rectifier and smoothing capacitor, (d) corresponding waveform of (c)](image3)
Another option is shown in figure 3 (c), (d) where the generator’s AC signal is smoothed by a capacitor, resulting in a constant maximum power point (MPP) voltage $V_{MPP}$ over the input waveform’s period [5,6]. The optimal voltage $V_{MPP}$ is 40% of the peak open circuit voltage for a sinusoidal input. Since the harvester waveform changes only 93% of $P_{MAX}$ can be extracted with a sinusoidal input [6] but the regulation effort is much lower, therefore the power consumed by the regulation is reduced significantly.

As shown in figure 4 the PCB space is critical in this application therefore the fixed $V_{MPP}$ version is chosen since the version with a DC-DC converter emulating the optimal resistance needs a lot of circuitry. This is due to the fact that no IC is available that fulfills this task, so the circuit has to be built with discrete components.

The drawback of the fixed $V_{MPP}$ version is that due to the non-sinusoidal waveform of the harvester less energy can be extracted since the capacitor voltage $V_{MPP}$ cannot be set to 40% of every input wave peak (figure 5). Therefore only 82% of $P_{MAX}$ can be extracted. This number changes with the shape of the waveform and can be determined numerically.

**Figure 4.** Photograph of both sides of the power management board. The free area can be used for an additional transmission board.

**Figure 5.** Simulated voltage signal of one coil with load resistance at a revolution speed of 500 rpm.

The complete power management circuit is shown in figure 6. Each harvesting coil is connected to a rectifier. Both rectifiers are connected to a common input capacitor $C_{IN}$. The voltage of the input capacitor is kept at the maximum power point by a hysteresis comparator and a current source. The maximum power point voltage $V_{MPP}$ is given as reference voltage to the comparator input, which compares the input voltage $V_{IN}$ with $V_{MPP}$. If $V_{IN}$ is larger than $V_{MPP}$ the current source is enabled discharging $C_{IN}$ until $V_{IN}$ drops under $V_{MPP}$, then the current source is disabled again. The current source transfers the energy to a bigger storage capacitor $C_{BUFF}$. The two DC-DC converters, which generate the supply voltage for the different load elements (sensors, microcontroller and wireless module) use $C_{BUFF}$ as their input capacitor. For the current source a LED driver IC is used which is a DC-DC converter with current output.

The circuit is required to start working at the lowest revolution speed of 500 rpm. Therefore, the reference voltage $V_{MPP}$ is chosen according to this value. For higher rotations the harvester delivers more energy than the load elements need and it is not necessary to operate in the maximum power point. If the harvester delivers more energy than required the first harvester coil is disconnected via a solid state relay. If the energy is still too high the second harvester coil is also decoupled in phases to limit the energy. This is done by the control unit. Whenever $V_{BUFF}$ exceeds an upper limit the window comparator gives a signal to the control unit, which then starts to disconnect both harvester coils. On the other hand, if $V_{BUFF}$ drops below a lower limit the control unit disables the DC-DC converters so that the control itself has enough power to work.

The harvester coils could either be decoupled before the rectifier with a solid state relay or behind the rectifier with a mosfet. When decoupled behind the rectifier, the rectifier sees high voltages due to the high open circuit voltage at high rotations. Thus, diodes with high voltage ratings would be
necessary, which have a higher forward voltage drop. This is not suitable for the use at 500 rpm which is the most critical scenario due to the low power available. When decoupled before the rectifier, an alternating current has to switch. For this case a normally on solid state relay is needed. When the harvester is disconnected the system has anyway too much energy so that this doesn’t matter. So diodes with smaller voltage ratings can be used which is beneficial for the critical 500 rpm case.

![Solid State Relays](image)

**Figure 6.** Schematic overview of the power management system.

3. Experimental Data
The energy harvesting system was verified on a rotational measuring station. In figure 7 the simulation is compared with some measurements for a revolution speed range from 0 to 700 rpm. The variation between the simulation and the experimental results are explained by some simplifications in the simulation model. The model is based on a linear movement between the coils and the magnets with a constant air gap. In fact, the coils move on a circular path so that the air gap is not constant. Also, for the magnetic field only a static simulation was realized, which does not include any eddy current losses.

![Figure 7. Comparison of power outputs: simulated at load resistance $R_{LOAD}$, experimental at load resistance and experiment with power management.](image)

![Figure 8. Voltage signals at different measurement points showing the functional operation of the power management: first MPP-capacitor (yellow), second system buffer (cyan) and third coil switch (magenta).](image)

The voltage signal over a load resistance connected to one coil, as shown in Figure 5, is characterized by a group of four peaks. The power management circuit can only handle a part of the peaks which is reflected by a MPP efficiency of 81%. Combined with a circuit efficiency of 67% there is a variation of 55% between the power through a load resistance and the output power of the power
management circuit at the 3.3 V output (figure 7). When changing the revolution speed, the efficiency decreases because the MPP is adjusted for 500 rpm. However, at higher revolution speeds there is an excess of energy and therefore a high efficiency is not needed.

For the measurement of the efficiencies a shunt with 0.12 Ω was used between the generator and the power management. This measurement method is not very precise because the shunt has an accuracy of 10%, it was only a two point measurement and the output power is affected by the shunt.

Figure 8 shows a measurement, which demonstrates the working principle of the power management. During start up the input capacitor gets charged (yellow). Once $V_{MPP}$ is reached the comparator ensures that the input voltage ripples around $V_{MPP}$. Due to this, $C_{BUFF}$ (cyan) gets charged. When $C_{BUFF}$ reaches its maximum voltage limit, which happens either for higher revolution speeds or for reduced power consumption, the coils will be disconnected by the SSR (magenta) in phases to limit $V_{BUFF}$. This avoids the generation of excess energy that would lead to increased temperature.

4. Conclusion

In this work we demonstrated an energy harvesting system for a CMS in a maritime gearbox including a power management with coil switch functionality. It is a robust and oil proofed system which is easy to install at a clutch. At the lowest revolution speed of 500 rpm an output power of 106 mW is provided at the 3.3 V output.

The system was tested with both sensors and the transmission board. There is enough power to measure and send the temperature signal every second and the data from the wear sensor every two seconds continuously at the lowest revolution speed of 500 rpm. This is a higher measurement interval then needed. For easier mounting the space between the magnets and coils can be increased to the adequate clearance to power the sensors and wireless data transmission. For this operating point and resulting coil signal an adjustment of the MPP is needed.

In further experiments the system will be implemented in a real gear box with the remaining parts of the CMS including wireless sensors for the measurement of revolution speed, revolution direction and torque and a central receiver unit, all powered by additional energy harvesting systems.

References

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