Battery-less Micro-switch with Wireless Interface

Design and simulative optimization

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Abstract

The article presents a novel battery-less micro-switch. Based on an inductive energy harvester, the system transforms kinetic energy into the electrical domain. The energy of up to 0.9mWs is used to drive a micro-controller and a wireless communication interface that sends information of the switching status to a receiver unit. With a RF power of 10dBm a free space operating distance of 300m is feasible. Both, harvester and electronic circuits can be integrated in a housing with the dimensions 17x6x8mm^3. Within the article, a detailed description of the battery-less micro-switch is presented facing the electronic and magnetic circuitry as well as the packaging and integration technology. The functionality and the limits of the battery-less micro-switch are shown in combination with an automotive telemetry system.

Introduction

Recent trend analyzis show an increasing interest in battery-less systems. With growth rates of more than 10% an overall business volume of 527 Mio$ has been achieved in 2009 [1]. The success is mainly driven by the advances in research activities. Beside the overall miniaturization trend, three main research areas can be identified: low power electronic devices, energy managment, and an improved efficiency of the energy converter.

First investigations towards a reduction of the energy consumption of CMOS circuits have been done at the beginning of the 2nd millennium. At that time the activities have been driven by the growing market of mobile, battery-powered electronic applications [2]. Based on the results and the consecutive work, electronic circuits with smaller switching capacities and supply voltages as low as 1V have been realized, thus allowing the design of battery-less systems with sensor and data processing capabilities.

Further investigations focus the power management of battery-less systems. Due to a harmonized hardware and software design, the energy efficiency could be significantly increased. A common way is to use electronic devices with different sleep modes. It allows to partly disable the electronic circuitry, thus saving energy and extending the system operation time [4]. Similarly, the energy consumption of the radio interface can be reduced by balancing transmission rate and required input power. On the opposite system side, DC-DC converter and maximum power point tracker have been developed to get more energy from the harvester [5].

The system design is dominated by applicational concerns. In particular, this applies for the energy harvester, thus distinguishing three types with respect to their primary energy source: thermal, light and mechanical harvesters. The latter type comprises vibration and switch converters with piezoelectric and inductive conversion principles [6]. In industrial and building automation applications [7] inductive harvesters are preferred due to the improved cost-performance ratio and the higher reliability.

Regarding automotive technologies, only a few battery-less sensors, such as the tire pressure monitoring sensors can be found. This can be reasoned either by the lack of energy density or by the high costs compared with standard micro-switches.

The present article proposes a very small battery-less micro switch with a standardized housing size and actuation mimic. It has the potential to allow new functionalities and reduce the complexity of todays wiring harnesses.

Concept of the battery-less micro-switch

This section presents the design concept of the battery-less micro-switch. Figure 1 shows a block diagram with all function units. The energy harvester is implemented as an inductive generator, transforming energy from an external mechanical movement into the electrical domain. The output signal splits-up in the energy path and the signal path. In the energy path, a rectifier and an adjacent power adaptation circuit is used to maximize the available output power from the energy harvester. With the power-management that comprises an energy storage element such as a capacitor, the energy flux in the electronic circuit is controlled. In the signal path, the generator output voltage is used as a signal to detect the direction of the mechanical actuation. The signal is measured by the micro-controller unit. In addition, the micro-controller regulates the calculation and communication processes in order to reduce the overall energy consumption. The communication interface is a bidirectional RF circuit with an antenna adaptation circuit at its output. As carrier frequencies the ISM frequency band is used.

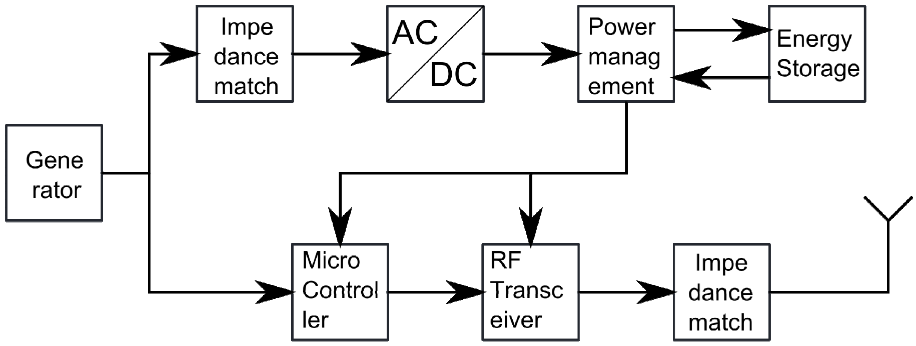

Figure 1: Block diagramm of the battery-less micro switch.

Figure 2 shows a cross-section of the battery-less switch that has an overall volume of 18 x 9 x 25mm^3. The switch is characterized by a waterproof housing (1) with sealing lip (2) and auxiliary actuator (3). Inside the package, the functional components such as the electronic circuitry (5) the inductive coils (6) and the magnet-block (7) with the spring assembly (9) can be seen. Finally, the radio antenna (4) of the wireless link is situated between the generator block and the sealing lip.

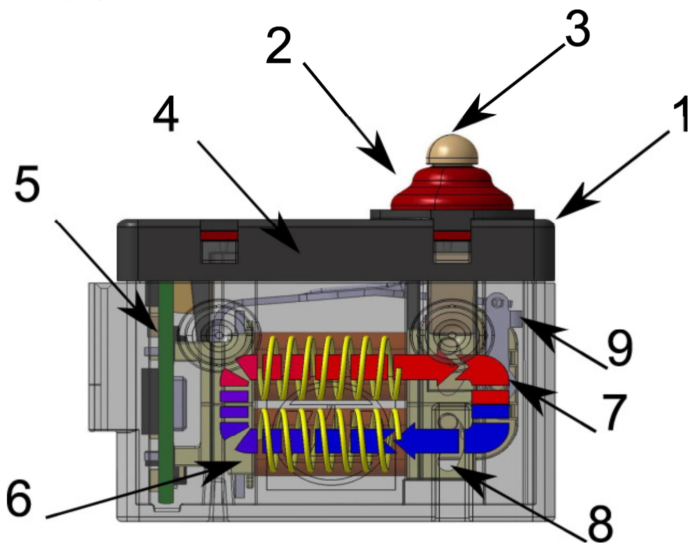

Figure 2: Cross-sectio of the battery-less micro switch.

According to the setup, the coil carrier as well as the electronic circuitry is fixed to the housing. In contrast the magnet-block and the spring assembly are flexibly connected to the coil carrier. By pressing onto the auxiliary actuator a vertical force moves the auxiliary actuator down and biases the mechanical spring assembly. In combination with the slide rail (8) of the magnet-block an upper and lower dead center is produced.

The energy conversion principle of the inductive generator responds to the law of induction and depends on the number of coil windings, the magnetic flux, and the time in which the flux changes. Since the electronic circuitry can be easily scaled down, the dimension of the battery-less switch is significantly influenced by balancing the energy consumption with the energy yield. The produced energy can be increased by a low response time, a high magnetic flux density, and a large number of coil windings. Comparing these parameters with the design concept, they have been considered by the dead center mechanism, the double coil arrangement, and the magnetic circuit.

In detail, the dead center mechanism allows to accumulate mechanical energy and release it instantaneously after a certain point has been overcome. Beside the increased switching speed the mechanism has the advantage to define a specific switching characteristic which is especially important in automotive applications.

The magnetic circuit consists of the magnetic south-pole shoe, the permanent magnet, the magnetic north-pole shoe, and the ferrite core of the inductive coils. In static state, the magnetic circuit is closed, thus producing a static magnetic flux. After the spring assembly has been biased to overcome the upper dead center, the magnet-block moves down from the upper to the lower position. Thereby, the direction of the magnetic flux in the magnetic core is inverted, thus producing a maximum flux $\Delta\Phi$ in the coils.

With a double-coil arrangement, the magnetic flux is transformed into the electrical domain. The arrangement allows to maximize the number of coil windings in the magnetic circuit and optimizes the efficiency of the energy conversion by using the magnetic field in an optimal way. To increase the energy output, the two coils are connected in series, thus increasing the inductance of the coil by a factor of four and doubling the energy output of the generator. Since no periodic events have to be recognized, disadvantages in the dynamic behavior can be neglected.

Beside these simple considerations, a deeper understanding of the interdependencies is necessary to get a magnetic circuit with a high efficiency. Unfortunately, in most cases the optimization of the magnetic flux directly interferes with the specification of low actuating forces. In the following section different approaches will be presented that allow to minimize this problem.

Simulation Model

The optimization process concentrates on the energy path of the battery-less system. In detail this includes the generator and the input of the electronic circuitry. To calculate the behavior of the energy path, the generator and the electronic circuitry have been implemented in a simulation model. The model is divided up into three parts: the mechanical, the magnetic, and the electric subsystem.

The mechanical subsystem is shown in figure 3. It describes the mechanical characteristics with two coupled springs k_g and k_k, a mechanical load m, and a damping element d. The values F_H and F_M describe the acting and counteracting forces, respectively.

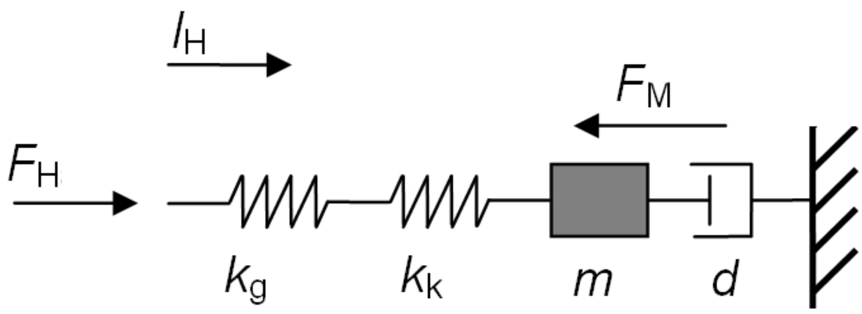

Figure 3: Spring assembly, describing the mechanical subsystem.

The counteracting force is considerably influenced by the mechanical constrains of the magnet block. To give a correct description of the kinematic behavior the guiding grooves of the magnet block are implemented in the differential equation.

The magnetic subsystem is derived from the magnetic circuit by transforming it in a magnetic reluctance model. The resistance network can be seen in figure 4. It comprises the resistances of the pole shoes, the ferrite core, and the permanent magnet.

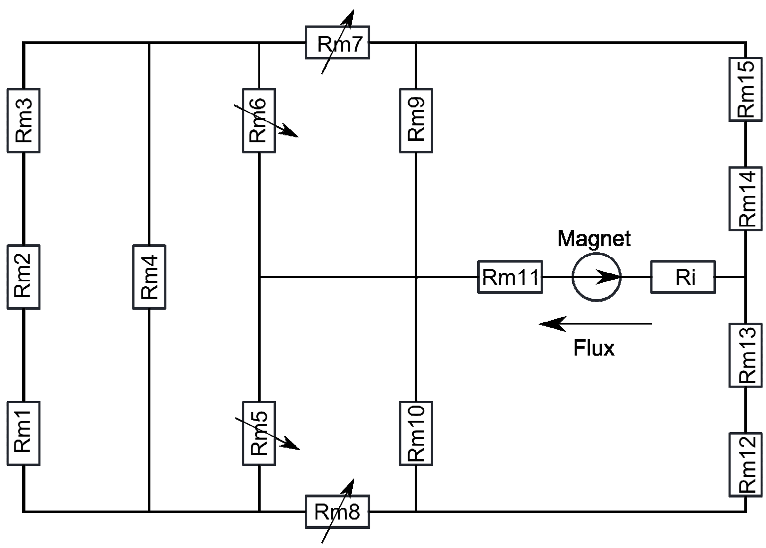

Figure 4: Magnetic reluctance model.

In addition, the most important air gap resistances were implemented, thus allowing a rough calculation of the magnetic leakage flux. A nonlinear model was used to describe the relative permittivities in the magnetic circuit. Therefore, an iterative optimization process was used to calculate the dynamic behavior of the magnetic resistances. As could be shown, the calculations of the material parameters of the magnetic core and the pole shoes as well as the behavior of the permanent magnet are the key challenges within the simulation process. Moreover, to get an exact model it is important to know the mechanical and chemical effects on the magnetic behavior of the materials.

Within the simulation, a magnetic resistance matrix $\underline{R_m}$ has been calculated from the magnetic reluctance model by solving the mash equations. With this matrix and the coercive field strength Θ of the permanent magnet the magnetic flux density Φ can be calculated:

$$\phi = \underline{R_m}^{-1}\theta \,. \tag{1}$$

In accordance to equation (2), the magnetic force F_M between the magnet-block and the ferrite core is proportional to the square of the magnetic flux Φ [8]:

$$F_M = \frac{\phi^2}{2A_{eff}\mu_0}, \tag{2}$$

with A_{eff} as the effective cross section and μ_0 as the permittivity.

The last part of the model describes the electronic input circuitry. It includes the differential description of the inductive coils, the buffer-capacity, and a variable load that simulates the power consumption of the micro-controller. The influence of the rectifier circuit in front of the buffer-capacity can be recognized by a simple resistance network.

Optimization concepts and results

In this section, two different ways to increase the generator efficiency will be presented based on simulation results. In a first instance, the simulation model was adapted on measurement data. Therefore, the output voltage of an existing inductive generator has been evaluated as a function of time. Figure 5 shows these data and the corresponding simulation results. Comparing both curvatures, a standard deviation of 6% and an energy deviation of 1% could be realized.

With a total amount of 0.8mJ, the energy is high enough to drive most transmitter circuits. However, the magnetic force of 13N is too high to allow a robust spring design. Therefore, the battery-less switch is optimized with respect to the overall efficiency by a mechanical and an electrical approach. Since the magnetic force between the magnet-block and the ferrite core directly depends on the flux density in the contact cross-section (cp. equation (2)), the mechanical approaches concentrate on the reduction of the magnetic flux in this area.

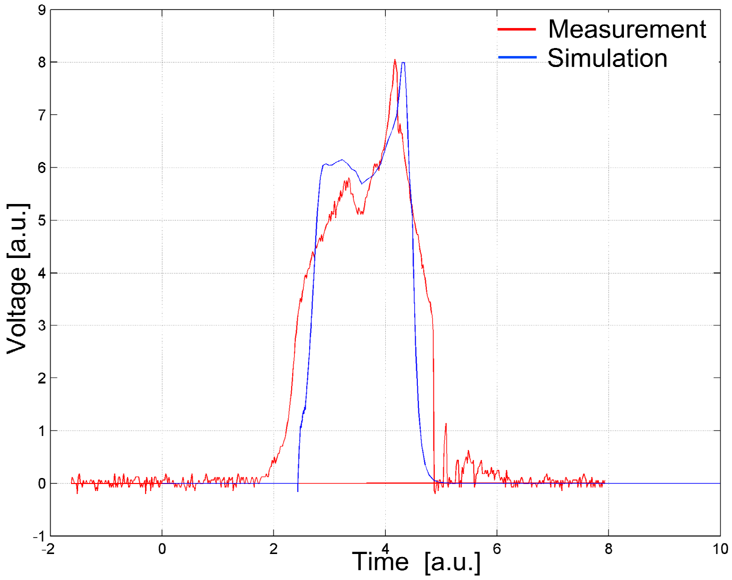

Figure 5: Comparison of simulation and measurement data.

In a first approximation, magnetic circuits can be seen similar to electrical circuits. Therefore, the integration of a resistance in the magnetic circuitry should reduce the magnetic flux in the bulk material. Mechanically, the magnetic resistance was realized by a contraction in the ferrite core.

The contraction was recognized in the reluctance model by an additional resistance in the branch of the magnetic north-pole shoe. The effect of this change has been evaluated by calculating the magnetic force between the magnet-block and the ferrite core for different residual bulk width.

The simulation results are shown in figure 6. On the abscissa, the residual ferrite core width at the contraction and on the ordinate the relative change of the magnetic force and the energy output are plotted, respectively. In contrast to first expectations, the energy output is reduced disproportionately high compared to the magnetic forces. To get a deeper understanding of the effects, a static magnetic FEM simulation has been performed with *Maxwell*. Within this investigation, it could be shown that the flux density at the magnetic south-pole shoe is considerably higher than the flux density at the north-pole shoe. The contraction in turn could only affect the flux density of the magnetic north-pole shoe. Since the flux density takes a quadratic influence on the magnetic force, the contraction influences only the smaller summand of the total magnetic forces. The high energy losses as well as the difficult production process cast this solution into doubt.

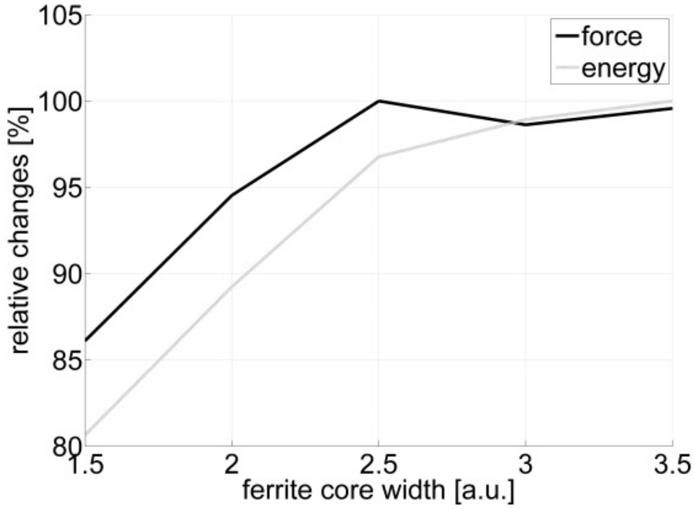

Figure 6: Simulation data of the ferrite core contraction.

Beside this mechanical approache, the output energy can be increased by an optimization of the impedance match between the generator and the electronic circuitry. As mentioned above, the calculation model is based on the differential description of the passive electronic input circuitry and the inductive coils of the energy harvester. Subjected to a constant number of coil windings, a variation of the wire cross-section and of the input capacity has been performed.

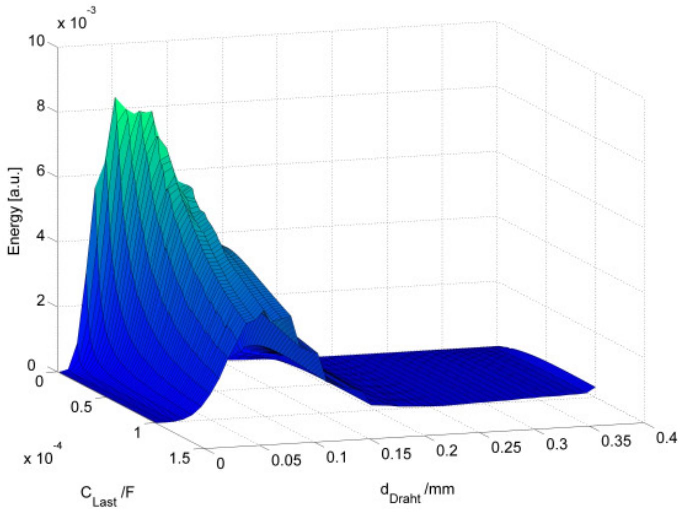

Figure 7: Energy yield as a function of the impedance match.

The results can be seen in figure 7. On the first and second abscissa, the wire cross section and the load capacity are plotted, respectively. On the ordinate, the total output energy can be seen. There is an optimal energy yield for the parameter set $C_{load} = 25\mu F$ and $d_{wire} = 0.2mm$.

Basically, the shape of the simulation results can easily be explained by the interaction of the coil and the storage capacitor in the input circuit. Increasing the wire cross section decreases the internal resistance of the coils, thus reducing the output voltage U_{out}. Similarly, the stored energy in the capacitor is reduced by increasing the load capacity C_{load}, because the simultaneously reduced output voltage U_{out} overweights the capacitor due to the quadratic relation. However, this is quantitatively correct only if the inductance of the generator is constant. In the case of the battery-less micro switch, the variation of the inductance has to be recognized for a correct adaptation of the electronic circuitry, thus reasoning the simulative calculation.

Application

Battery-less systems are mainly motivated by the reduction of wiring harnesses, the gain in flexibility, and the realization of new functionalities. Regarding for example the automotive telemetry system in figure 8 vehicle date are typically served by a wired interface from the CAN-bus. New functionalities in coaches such as an automated confirmation system of routine checks, similar to the preflight check of airplanes, require data that is not directly available on any data bus.

However, the integration of a number of additional switches in the vehicles periphery results in complex wiring harnesses, thus not being accepted by many manufacturers due to the high application costs. In addition, wireless components with batteries are avoided from an ecological point of view and due to their high service costs.

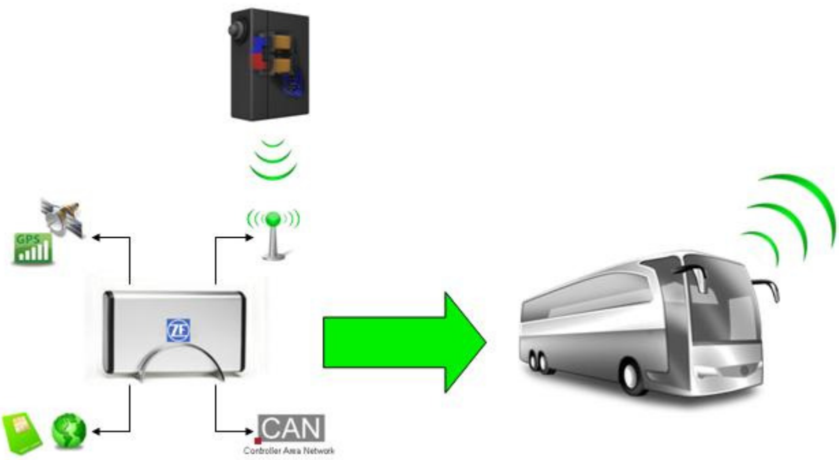

Figure 8: Telemetry system with a battery-less sensor device.

The presented battery-less switch brings up an alternative way. With the wireless interface the switch can be flexibly placed in the vehicles periphery while the receiver unit is installed in the driver's cabin for example in the existing telemetry box. In contrast to wired connections where each component is directly assigned to a specific functionality, the switches have first to be mapped on their special application within a teaching process. In a quite simple way, the teaching process can be built by a memory function in the receiver unit that joins the ID of each switch to the corresponding function or location. Beside the switch ID additional information such as the temperature can be transmitted. To ensure the correct transmission a bidirectional communication can be implemented. By integrating the battery-less switch for example in the cap of a cooling water tank, the cooling water level check can be automatically documented, thus allowing the date to be used within an upper level quality processes.

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