Wireless Autonomous Transducer Solutions for Hybrid Electrical Vehicle Applications

V. Pop, R.J.M. Vullers, D. Hohlfeld, T. Sterken, A. Schmitz, J. De Boeck
Holst Centre / IMEC-NL, High Tech Campus 48, 5656 AE Eindhoven, Valer.Pop@imec-nl.nl

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I. INTRODUCTION

Energy scavenging is the process of converting unused ambient energy into usable electrical power. Harvesting ambient energy, for example from mechanical vibrations or temperature gradients, is very attractive for autonomous sensor networks. Additionally, it is also very important to systems which do not allow battery replacement or wired power coupling, *e.g.* tire pressure sensors. As these energy harvesting devices shrink in dimension, while still providing sufficient energy, they will be key enablers for autonomous wireless transducer systems. For such purpose harvesting devices are being investigated which feature a footprint of 1 cm^2 and an average power harvesting level of 100 μW [1]. Two popular principles are mechanical energy scavenging based on electrostatic and piezo-electric principles as well as thermo-electric generation exploiting a temperature gradient [2].

This abstract deals with scavengers and energy storage devices as important building blocks for autonomous sensor networks with a focus on automotive applications, especially on Hybrid Electrical Vehicles (HEVs). The basic task of the scavenger is to convert ambient energy, *e.g.* HEV engine vibrations and/or centripetal tire acceleration into electrical energy. The power module will convert this highly irregular energy flow further into regulated energy suitable to charge the battery or to directly power the autonomous sensor network modules.

In such a module, the battery's basic task is to store energy obtained from the scavenger and to release it to the load when needed. In some cases it may be desirable to place a supercapacitor in parallel to the battery for providing a current boost on high load demands. Two or more supercapacitors (depending on the electrode material) can replace the battery altogether, when connected in series in order to obtain sufficient operating output voltage.

The battery's voltage, current and temperature may be monitored by the Analog-to-Digital Converter (ADC) in combination with a signal processor. The ADC information will be the input for a State-of-Charge (SoC) indication algorithm running in the processor. The result will be an indication of the battery's SoC and/or remaining time of use under the present functional conditions [3].

A general block diagram of an autonomous sensor network is given in Fig. 1. A complete wireless autonomous node has more functional blocks besides micropower module, the ADC and the processor. A sensor device will capture the required physical or chemical parameter. The ADC and signal processor will be used for transforming the measurements into useful (digital) information. A radio module will allow communication with external portable devices or with the HEV's board computer. Consequently, important information regarding the tire pressure or the engine state can be transmitted. The focus in this abstract will be on the micropower module, consisting of the scavenger and the energy storage functions. The basic principles of the energy scavenger are introduced in section II. The battery and supercapacitor technologies are presented in section III. Section IV focuses on preliminary experimental results. Finally, section V presents the concluding remarks and future work.

II. ENERGY SCAVENGING

The electrostatic scavenger consists of a seismic mass, suspended by springs, fabricated by bulk micromachining in silicon. Hereby a variable capacitor is fabricated. The device consists of three parts (see Fig 2): a fixed electrode, a seismic mass and an electret. The movement of the seismic mass, resulting from an external vibration, is translated into a change of the capacitance and thus changing the charge on the capacitor. This results in a current through the load circuit. Such a scavenger system has been modelled and the result is shown in Fig. 3. Clearly, the performance of the device is greatly influenced by the resonance frequency of the mass-spring system (typically ~1 kHz) and it has thus to be carefully matched with the frequency spectrum of the external vibration.

A *piezo-electrical scavenger* has also been developed. This device consists of a mass that is attached by a thin beam to the vibrating package. The piezoelectric generator is located on top of the beam and consists of a piezoelectric layer sandwiched between a bottom and top electrode (see Fig 4). The movement of the seismic mass results in a deformation of the piezo-electric layer, which will in turn generate power. A model for the piezoelectric devices is based on electromechanical differential equations. According to this model the predicted power output of the devices is in the range of 10-50 μW (see Fig. 5). Again the resonance frequency has to be matched carefully to the frequency of the external vibration.

Thermal energy scavengers are thermoelectric generators (TEGs) which exploit the Seebeck effect to transform the temperature difference into electrical energy. A TEG is made of thermopiles sandwiched between a hot and a cold plate. Thermopiles are in turn made of a large number of thermocouples connected thermally in parallel and electrically in series. The maximum electrical power is generated when the load is matched to the electrical resistance of the generator and when the thermal conductance of the thermocouples equals the one of the air between the plates. Depending on the application a specific design will be required in terms of thermal flow and package a.o..

III. BATTERIES AND SUPERCAPACITORS

In its simplest definition, a battery is a device capable of converting chemical energy into electrical energy and *vice versa*. The chemical energy is stored in the electroactive species of the two electrodes inside the battery. The conversions occur through electrochemical reduction-oxidation (redox) or charge-transfer reactions. These reactions involve the exchange of electrons between electroactive species in the two electrodes through an electrical circuit external to the battery. The reactions take place at the electrode/electrolyte interfaces. When current flows through the battery, an oxidation reaction will take place at the anode and a reduction reaction at the cathode. The oxidation reaction yields electrons to the external circuit, while a reduction reaction takes up these electrons from the external circuit. The electrolyte serves as an intermediate between the electrodes. It offers a medium for the transfer of ions. Hence, current flow is supported by electrons inside the electrodes and by ions inside the electrolyte [4] - [6]. Several types of rechargeable battery systems exist on the market [4]. The most important of them are discussed below and their suitability for autonomous transducer systems will be indicated..

A *Li-ion battery* consists of five regions: the negative electrode current collector made of copper, the porous composite negative insertion electrode, the porous separator, the porous composite positive insertion electrode and the positive electrode current collector made of aluminium [4]. At the beginning of discharge, the negative electrode is fully lithiated, while the positive electrode is ready to accept lithium ions. During discharge, the lithium ions deintercalate from the negative electrode particles and enter the solution phase, while in the positive electrode region lithium ions in the solution phase intercalate into the positive electrode particles. This results in a concentration gradient, which drives lithium ions from the negative electrode to the positive electrode. The cell voltage decreases during discharge, as the equilibrium potentials and overpotentials of the two electrodes are strong functions of the concentrations of lithium on the surface of the electrode particles [4].

Since the normal Li-ion battery exist of liquid electrolyte they cannot be applied everywhere. Therefore a Li-ion battery in solid state is developed which resulted in 1997 in the first *Li-ion-polymer battery* [5]. The use of a polymer electrolyte offers the possibility of fast production of the cells and the fabrication of thin cells [4].

Thin film and microelectronics integration technology was utilized to fabricate a *thin film battery* with high quality smooth interfaces and an ultra-thin electrolyte. Unlike conventional batteries, thin film batteries can be integrated directly in Integrated Circuit (IC) packages in any shape or size, and when fabricated on thin plastics, the batteries are quite flexible. Both the Li-ion-polymer and the thin film batteries can be candidates for integration in autonomous sensor nodes.

"Supercapacitor" is an energy storage component having low internal effective series resistance and high capacitance. Unlike batteries that store electrical energy in chemical bonds, supercapacitors store energy electrostatically between a solid electrode and oppositely charged electrolyte ions that migrate towards the electrode when a potential is applied. The supercapacitor technology is especially suited for applications where a large amount of power is needed for fractions of a second to several minutes. As mentioned before they could be applied in combination with a battery.

The main characteristics of the battery types and supercapacitors discussed in this section are illustrated in Table 1 [6].

IV. EXPERIMENTAL RESULTS

The most relevant test for a battery or supercapacitor (combination) in a micropower module for wireless transducers consists of pulse discharge steps. A first set of experiments has been carried out in order to check the battery behaviour under the autonomous sensor network (dis)charge C-rate currents condition. Fresh and fully activated Li batteries from two different battery manufacturers are used further for each condition to be investigated. Since the employed commercial batteries have a specified SoC upon delivery, the activation procedure performed at 25^{o}C started with Constant-Current (CC) discharging at a 0.5 C-rate followed by a one hour resting period [6]. Subsequently, the batteries were subjected to three standard Constant-Current Constant-Voltage (CCCV) and subsequent 0.5 C-rate discharge cycles, after which constant (dis)charge behaviour was attained. Standard charging was carried out with a constant maximum current at a 0.5 C-rate in the CC-mode until the maximum charge voltage of 4.2 V was attained in the subsequent CV-mode [6]. Evidently, the charging currents dropped in the CV-mode and charging was terminated at a predefined minimum current of a 0.05 C-rate, after which the battery has been considered fully charged, *i.e.* SoC = 100%. After a resting period of one hour, the batteries were discharged at a 0.5 C-rate. The same C-rate for the experiments has been chosen in order to study the behaviour of the batteries under the same relative conditions. Discharging was terminated when the cut-off cell voltage of 3.0 V was reached. A single activation cycle was completed by four hours resting period. The long rest step has been chosen in order to start a new cycle always from the equilibrium state [6].

The battery has been further charged by applying the above CCCV charging method. Subsequently, a pulse discharge step has been applied until the battery voltage reached the 3 V level. The discharging has been considered at a 0.25 C-rate for 0.55 ms and 0.25 10^{-3} C-rate for 4.05 ms. In this case, the pulse characteristics correspond with a possible autonomous sensor network load. Fig. 6 shows the battery voltages during the pulse discharge, where the upper and lower voltage values correspond with the 0.25 10^{-3} and 0.25 C-rate current, respectively.

It follows from Fig. 6 that the batteries show a different behaviour under the same discharging conditions. This can be explained by a different battery impedance and/or build-up of the overpotential [6]. In this case the Li_1 battery (○ in Fig. 6) shows higher discharge efficiency under the same pulse discharging conditions [6]. As a result, this battery will perform better in an autonomous sensor network.

V. CONCLUSIONS AND FUTURE WORK

Energy scavenger and battery technologies for HEV applications have been presented. In the near future, tests are planned under real life conditions with the scavenger module. Also, more battery tests at different conditions, *e.g.* different temperatures, C-rate currents and aged batteries will be reported, as well as results from tests with other battery chemistry types and with supercapacitors. The obtained information will be essential for designing the optimum micropower module for autonomous sensor network required for HEV.

VI. REFERENCES

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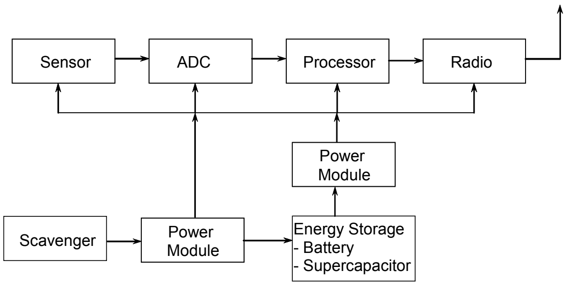

Fig. 1. Example of an autonomous sensor network node for automotive applications.

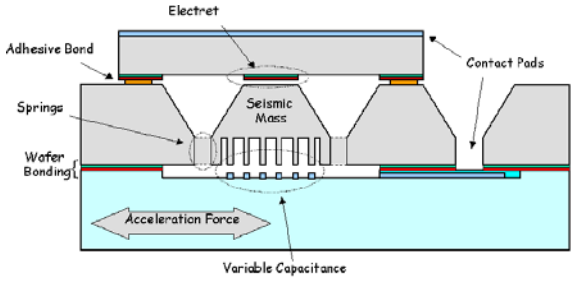

Fig. 2. Design of an electrostatic scavenger consisting of a lower fixed electrode, a suspended seismic mass and an electret on top.

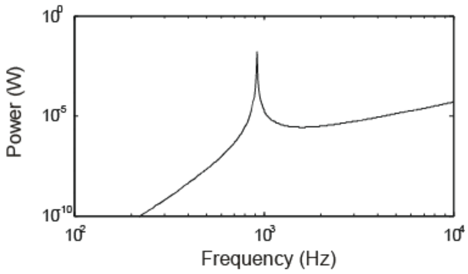

Fig. 3. Output power of electrostatic scavenger. Significant power generation occurs at the mechanical resonance frequency.

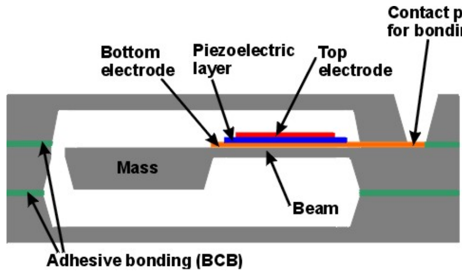

Fig. 4. Design of a piezo-electric scavenger. The system uses a cantilever with an attached mass. The piezoelectric material is placed on the beam.

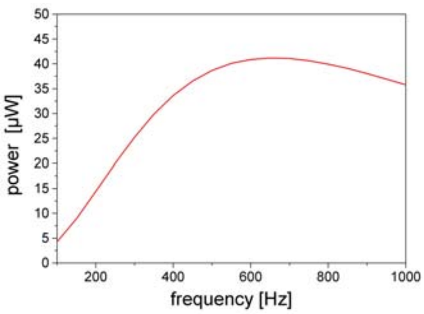

Fig. 5. Modelling results for the generated power from a piezo-electric device.

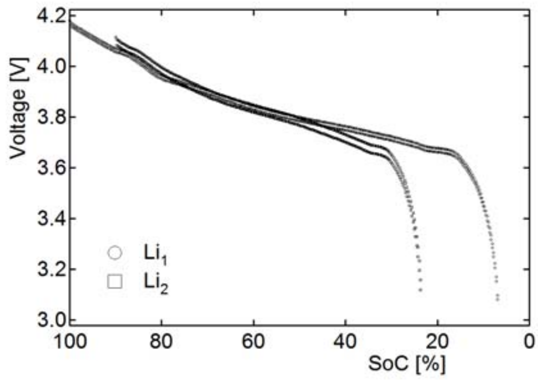

Fig. 6. Discharge voltage curves measured under pulse discharging conditions for different battery chemistries as function of SoC [%] normalized to the maximum capacity.

Table 1. Overview of the main characteristics of rechargeable battery and supercapacitor systems.

	Battery system			Supercapacitor
	Li-ion	Li-ion-polymer	Thin film	
Average operating voltage (V)	3.60	3.60	3.60	1.25
Energy density (Wh/l)	200 - 280	200 - 250	< 900	-
Specific energy (Wh/Kg)	90 - 115	100 - 110	< 300	< 10
Self-discharge rate (%/month) at 20°C	0.1 – 1.0	1.0	0.1	1.0 - 10
Cycle life	1000 - 2000	200 - 1000	> 1000	> 10000
Temperature range (°C)	-20 - 50	-20 - 50	-20 - 140	-40 – 65