Laqua, Daniel; Husar, Peter:

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Intelligent Power Management enables Autonomous Power Supply of Sensor Systems for Modern Prostheses

D. Laqua[1] and P. Husar[1]

[1] Department of Biosignal Processing, Ilmenau University of Technology, Ilmenau, Germany, daniel.laqua@tu-ilmenau.de

Abstract— **Modern intelligent prosthesis or robotic extremities use a combination of mechanically, hydraulically and electronically controlled components and joints for motion. For precise controlling, stepping motors are used. Here, passive movement of the extremity, like the lowering of the arm caused by the gravity, produces unexploited energy. Utilization of this normally lost energy expands the lifetime of non-rechargeable batteries or the time for recharging the accumulators. Main component of the energy harvesting system is a double-layer capacitor (ultracap) for storing the electrical energy. This energy buffer is necessary, because a switching converter needs a startup time to work properly. A MOSFET switch is used to avoid a backflow into the motor or the motor driving unit. Charging up a RC-element indicates the stored energy and represents the load of the ultracap. It activates a high efficient DC/DC buck boost converter for stabilizing the voltage and driving a microcontroller or another sensor circuit. The rotation of the rotor through the limb produces a sinusoidal output voltage. The input energy is irregular and aperiodic. Its amplitudes are in the range of $2\ V$ to $4\ V$ with current pulses about $30\ \mu A$ depending on the type of the used stepping motor and the rotation speed of the rotor. The built energy harvesting system enables recovering of unused energy for driving a sensor circuit. Furthermore, it supports the power supplies by improving the efficiency. The advantages are that this system will be activated when enough energy is gathered and that there is no running out of power in comparison to a battery powered system.**

Keywords— **energy harvesting, intelligent implants**

I. INTRODUCTION

Over the last years a lot of research and investigation were done for building better and intelligent prosthesis or robotic extremities. These are using combinations of mechanically, hydraulically and electronically controlled components and joints for active motion. This work focuses on using unexploited energy from stepper motors to utilize this normally lost and unused energy and expand the lifetime of non-rechargeable batteries or the time for recharging the accumulators. Energy harvesting with a non periodical source which is only producing energy peaks requires a special energy harvesting circuit. After the transducer, which converts mechanical to electrical energy, a switching regulator or charge pump handles the supply for the load. This was already investigated in other work [1] [2]. Switching regulators need some time for stabilizing the output voltage and so they are appropriate for sources with a continuous output. For discontinuous energy supplies other concepts must be developed. This work describes a new concept where the pre-caching and measuring of energy is in focus and new fields of research and investigation will open to use intelligent energy harvesting.

II. MATERIAL AND METHODS

A. Capacitors

The Capacitor is the main energy storing unit. For a spontaneous and non-periodical energy injection, special requirements to the type of the capacitor have to be fulfilled. One example is a very small leakage current, otherwise you will lose a lot of energy in the resting period. If a capacitance loaded with the voltage U_0 will discharge over time. The reason for this is the finite isolation resistance R_{isol} of the dielectric material.

$$u(t) = U_0 \cdot e^{-\frac{t}{\tau_s}} \tag{1}$$

with

$$\tau_s = R_{isol} \cdot C \tag{2}$$

Appropriate capacitors are class 1 MLCC (Multi-Layer Ceramic Capacitor) with a isolation resistance of over $10\ G\Omega$. For example the used capacitor Vitramon from Vishay with a capacitance of $100\ nF$ and a isolation resistance of $100\ G\Omega$ [3] has a self-discharge constant of $10,000\ s$ or $2\ h$ $46\ min$. After this time you only have 37 % of the charged voltage U_0.

B. MOSFET switch

The capacitor stores the electrical energy from the transducer and represents the energy reservoir for the switching regulator with the voltage booster. Avoiding a backflow of energy into to transducer in the pause where no mechanical work at the transducer is done, a MOSFET transistor is used.

Input is the source and its also connected to the gate. The drain output current loads the storage capacitor directly. In the parallel and separated path a second MOSFET and a RC element measures the energy amount. A third MOSFET is the threshold switch and enables the switching regulator to run with the energy from the storage capacitor.

C. RC element

The central element of this concept is the RC element. The time constant is calculated thoughtful corresponding to the amount of energy which is needed for the task of the load. Charging the RC element up to the threshold voltage of the third MOSFET switch indicates the point, when enough energy is stored to supply the regulator. Hence, it is not important if the energy is provided continuously or discontinuously, it is detached from time. The amount of collected energy is crucial for the power management system to activate the rest of the circuit.

D. DC/DC regulator

The stepping motor in a prosthesis or robotic extremity produces inconsistent voltage pulses, when its moved passively. An electronic circuit needs a continuous and constant power supply to work properly. For voltage regulation a DC/DC switching regulator is used. Considering the input voltage range between 2 V and 4 V with maximum peaks of 6 V a buck boost converter is used and fits best for this task. The load circuit should be powered with 3.0 V, but it is possible that the capacitor is loaded with less voltage, e. g. 2 V. In this case the voltage has to be boosted. To work properly, the device needs time to stabilize the regulation process.

E. Harvester circuit

The two MOSFET transistors in figure 1 T_1 and T_3 are avoiding a backflow of the energy into the stepper motor M. The threshold switch T_2 activates the DC/DC voltage converter U_1. This buck boost converter is especially for energy harvesting and stabilizes the output voltage for the implemented ultra low power microcontroller MSP430. This work uses instead of a sensor circuit a LED as load for demonstrating its functionality.

At the end the micro controller resets the complete storing and measuring system with the help of the bipolar transistor T_4. Now the system waits for the new energy pulses and starts charging again.

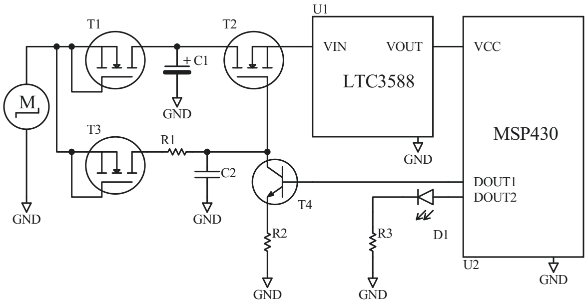

Figure 1: Simplified schematic of the energy harvesting circuit. Components: M - stepper motor, C_1 - storing capacitor, R_1 & C_2 - energy measuring RC element, T_1 & T_3 - MOSFETs avoiding backflow, T_2 threshold switch, U_1 LTC3588 DC/DC voltage converter, U_2 - MSP430 microcontroller, D_1 - LED and example for a load, T_4 - Resetting transistor

III. RESULTS

A. Output of the stepping motor

The stepping motor produces a sinusoidal output voltage. The rotation speed influences the frequency and amplitude, e.g. higher rotation speed results a higher signal frequency. Figure 2 shows the output amplitude over time with a maximum voltage of about 6 V. The enertia of the rotor causes a raising and falling of the amplitude during passiv motion.

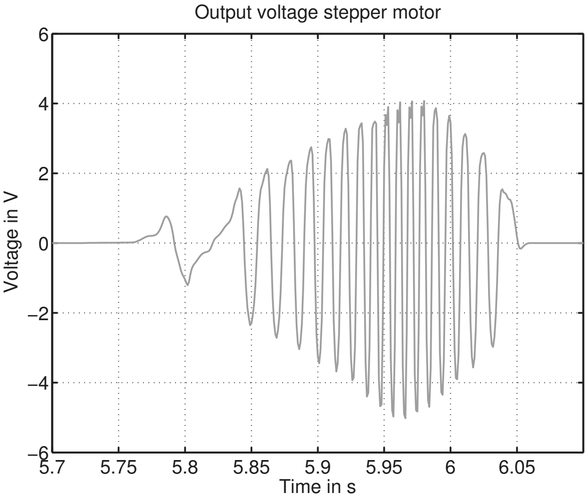

Figure 2: The output signal of the stepping motor has a rising an falling amplitude up to 8 V peak peak. The frequency raises depending on the rotation speed of the stepper motor up to 100 Hz

B. Charging of the capacitors

Storing and measuring the energy are the main tasks of the two capacitors. Figure 3 illustrates the charging process. In spite of a lower capacitance of the measuring capacitor, it is charging slower. Steps during charging are indicators for a non constant energy input and typical for its later application. In this example the LTC3588 starts to work and supplying the micro controller after 32 seconds .

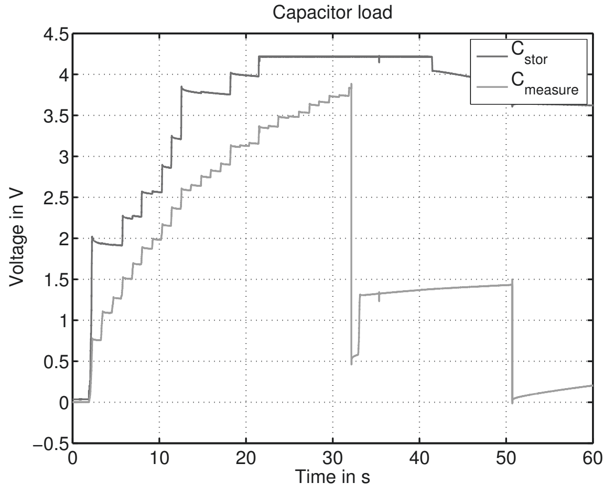

Figure 3: Direct comparison between charging the storage and the measuring capacitor. As intended the energy measuring capacitor charges slower. This is a result of the higher time constant.

C. Energy Harvesting

This section presents the hole harvesting process, which could be divided into two different parts. First is the collecting, storing and measuring part. In Figure 4 the hole working Process is plotted. The rotation was applied manually by a subject with arbitrary intensity and frequency.

When enough energy is collected the converting process (part 2) starts. Simultaneously the voltage of the measuring capacitor breaks down. The ripple voltage on the output voltage of the DC/DC converter its quiet dominant. The output voltage is stabilized for nearly 18 seconds before the micro-controller resets the circuit after finishing its program.

IV. DISCUSSION

Dielectric absorption is an effect, which occurs when a capacitor was charged for a long time. This influences the energy measurement in the circuit. Using class 1 ceramic capacitors NP0 consider this effect. Those parts have less then 1 % electrical lost and that is the reason why they are a good choice for this application.

The process of aging of the capacitor decreases the capacitance, because of the degradation of the dielectric in ceramic capacitors. High temperatures fasten aging, but should not appear in this scenario. Dependence of capacitance is expressed in parts per million (ppm) per $^\circ C$. The used VJ C0G (NP0) from Vishay is an ultra stable dielectric offering a temperature coefficient of capacitance (TCC) of $0 \pm 30\ ppm/^\circ C$ [3].

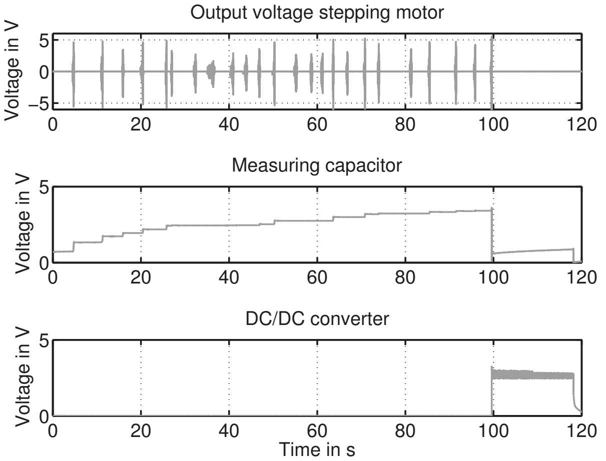

Figure 4: In the first subfigure the output of the stepping motor is presented. The rotation was done manually and with different intensities. The subfigure in the middle shows the charging of the energy measuring RC element. After approximately 100 seconds the threshold voltage is exceeded and the conversion process starts. In the lower subfigure the output voltage of the DC/DC converter is plotted.

After charging the capacitors, a 18 seconds lasting working period starts. This quite long time can be used for different applications, like powering a medical sensor. Of course, this time has to be adapted to the power consumption of the connected load circuit.

The output voltage of the DC/DC regulator carries a big ripple voltage with an amplitude of approximately $0.5\ V$ peak peak. This could be a problem for sensors, which need a stable supply and constant reference voltage. It is possible to filter this ripple or to reduce it by using a voltage regulator. Latter raises susceptibly the energy consumption of the whole circuit.

However, the combination of stepping motor and this intelligent power management have to be calculated and optimized for each case. There is no universal solution existing, because the output voltage of the stepping motor differ between model, size and mechanical implementation.

V. CONCLUSION AND FUTURE WORK

This work offers a new concept for intelligent energy harvesting. The main advantage is, that discontinuous energy sources can be used to drive sensor circuits for a defined pe-

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riod.

Combining the developed harvester with a sensor system enables new applications and possibilities on prosthesis or robotic extremities. Modern ultra low power microcontroller and wireless telemetry units are suited to work with this new harvesting concept.

Optimizing the threshold switch and the implementation of a power switch for low and high power input will be the next steps.

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