Energy Harvesting for Home Automation Applications

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Abstract— **In this paper a batteryless Home Automation application powered by Energy Harvesting technology is presented. The implemented case concerns a wireless thermostat. A ZigBee network, in combination with an ultra low-power RF-network, is used to transmit the data from the thermostat to the heating unit. A stepper motor and a solar panel are used to obtain the required energy. Two efficient energy level duty-cycling circuits are presented, each meeting the requirements of the energy harvesting system for which they are used.**

Index Terms— **Energy Harvesting, Home Automation applications, Wireless systems, ZigBee**

I. INTRODUCTION

Wireless systems are becoming more and more ubiquitous and their use offers several advantages over wired devices, for example more flexibility, easy implementation and the ability to place sensors in previously inaccessible locations. One of the major limitations is the restricted lifetime of such wireless systems, due to the limited capacity of finite power sources like batteries, which must be manually replaced when they are depleted. Much research has been done to extend the lifetime of these devices by minimizing energy usage [2]. Based on the IEEE 802.15.4 WPAN standard, the ZigBee standard has been proposed to interconnect simple, low-rate, and battery powered wireless devices [4]. The ZigBee standard is able to extend the lifetime of battery powered wireless systems to several months or even years depending on the requirements of the application. The ultimate goal however is to completely avoid battery replacement.

The solution is the introduction of energy harvesting technologies into wireless networks, which eliminates the need for batteries. Several technologies exist to extract energy from the environment such as solar, thermal and kinetic energy [8]. A device must use its harvesting abilities intelligently to increase its task performance and lifetime. Two design considerations should be taken into account. The device must operate in such a way that the energy used is always less than the energy harvested and the device must achieve the maximum performance level that can be supported in a given harvesting environment [9].

The harvested energy varies with time, depending on environmental conditions, which are, to a certain level, unpredictable. For instance the energy harvested from sunlight or wind is highly dependent on weather conditions. To achieve maximum performance, the wireless system needs an adaptive duty-cycle. In [10] an adaptive duty-cycling algorithm is described which uses the current energy level of the wireless system to make duty-cycling decisions.

In this paper a practical energy harvesting wireless home automation application is discussed: a wireless thermostat that controls the temperature of a room and communicates wirelessly with a heating unit. Two basic functions have been implemented in the thermostat: regular measurements of the room temperature and the possibility for the user to adjust of the target value of the room temperature. A solar panel is used to scavenge energy from the environmental light; this solar energy is used to measure the room temperature and communicate temperature changes to the heating unit.. A user can change the target room temperature by turning a rotary knob, which is connected to a stepper motor. This stepper motor then supplies energy, which is used to drive an LCD display showing the current room temperature and the target value and to send those two values to the heating unit. A schematic overview of this is given in Fig. 1. An adaptive duty-cycle circuit is provided to match the number of measurements to the available energy. The previously mentioned ZigBee standard is used to transmit the data (measured temperature and adjusted target value) from the thermostat to the heating unit.

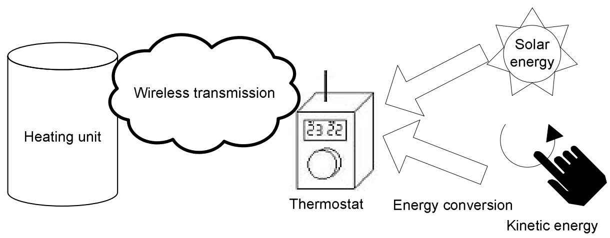

Fig. 1 Schematic presentation of the wireless thermostat

The specifications of this network will be explained in the following chapter. The third chapter is dedicated the needs of the home automation application. The forth and fifth chapter respectively describes how the energy is harvested using a stepper motor and a solar panel. The last chapter focuses on the possible improvements of the circuit.

II. THE WIRELESS NETWORK

To create an energy harvesting application based on ZigBee, the code that runs on the ZigBee module has to be kept to a minimum to reduce the power consumption of the module. In an energy harvesting application the wireless module must be kept in a low-power sleep-mode as much as possible and it should only wake-up when relevant actions take place. The ZigBee standard however has significant overhead when a module starts up (discovery of neighbours, re-association in the network, ect.), which is a huge burden for the power consumption. A solution is modifying the ZigBee standard to skip the start-up procedures and directly transmit the data to a known module. This means the device will not fully comply to the official ZigBee standard. Another solution is to use a small low-power RF-network to transmit the data from the thermostat to a nearby ZigBee module, which forwards the data to the heating unit. This second solution has been implemented.

Due to the nature of the implemented wireless system, we don't need to meet very high reliability and security levels, which allows us to reduce the overhead of the RF-network. Since only information from the thermostat (adjusted and measured temperature) needs to be sent to the heating unit, a simplex network will satisfy our transmission requirements. Data is only sent when either the desired temperature is modified or the room temperature has changed.

In the thermostat we use an AM-RT4-433 transmitter from RF-Solutions, which is controlled by a PIC18F2550 microcontroller from Microchip. The receiver uses the same microcontroller and an AM-HRR3-433 receiver from RF-Solutions. Only the transmission side of the network needs to be low-power, which means the receiver can be permanently supplied. These conclusions help to simplify the wireless system. The thermostat just transmits a data packet whenever there is data to be sent and assumes the receiver will take care of it. A data packet consists of 4 address bits and 8 data bits. The total amount of energy needed to transmit one data packet is 28 µJ.

III. THE HOME AUTOMATION APPLICATION

As mentioned before, the implemented thermostat provides two basic functions: temperature measurement and temperature adjustment. The temperature can be adjusted by a rotary knob, which is connected to the stepper motor. In order to give the user feedback on the adjustment, a display is provided. The core of the thermostat is the same microcontroller used to control the transmitter. The microcontroller can run two procedures: the temperature adjustment procedure and the temperature measurement procedure.

In the adjustment-mode, energy is supplied to the thermostat by the stepper motor and the adjusted temperature is shown on the display, together with the previously measured temperature, which is stored in the memory of the microcontroller. The adjusted temperature is sent towards the heating unit. In the measurement-mode the thermostat is powered by the solar panel, and the room temperature is measured, and transmitted if the temperature has changed since the last measurement.

The display used, is an LCD (5026PHR from Clover Display). Its control signals are provided by an LCD-driver (ICM7211A from Maxim). This LCD-driver consumes only 11 µA at 3 V supply voltage. The temperature sensor used, is the TMP125 digital temperature sensor from Texas Instruments. This sensor consumes approximately 36 µA at 3 V supply voltage and has an analogue shut-down, in which it consumes less then 1 µA.

The overall consumption of the thermostat depends on which mode is running. In adjustment-mode, the thermostat uses all the available energy to send the data to the heating unit and then to keep the data as long as possible on the display. The minimum required energy for this mode (the energy used by the microcontroller and energy to feed the display for at least 3 seconds) is 243 µJ. In measurement-mode, the thermostat only consumes the energy required to execute a measurement, store it in memory and to transmit it to the heating unit if the room temperature has changed. The maximum energy required for this mode is 140,4 µJ.

IV. ENERGY HARVESTING WITH THE STEPPER MOTOR

The use of stepper motors as a source for energy harvesting applications has been the subject of research in [11]. The results of [11] indicate that a hybrid stepper motor is the best candidate for energy harvesting applications. The optimum number of effective poles was established between 50 and 100. The stepper motor used in this application is the Teco 4H5618. This hybrid stepper motor has 50 effective poles, which makes it a good candidate for energy harvesting purposes.

The signals that leave the stepper motor are sinusoidal (the rotor speed assumed constant). The signals are rectified by using two Graetz bridges, which charge a capacitor up to a voltage V_{High}. When the capacitor is discharging through the load, the voltage over the capacitor will fall bellow the threshold voltage V_{Low}. V_{Low} represents the lowest voltage usable to feed the electronic circuit. This means not all the energy stored on the capacitor can be used. The useful energy stored on the capacitor E_{Useful} is given by formula (1). The voltage over the capacitor is an indicator for the available energy.

$$E_{Useful} = \frac{C\left(V_{High}^2 - V_{Low}^2\right)}{2} \qquad (1)$$

When $E_{Useful} > E_{Adjustment}$ the thermostat can be activated to execute the adjustment procedure (hereby $E_{Adjustment}$ is the required energy for the thermostat to follow the adjustment procedure augmented by the voltage conversion losses). In Fig. 2 a suitable energy level duty-cycling circuit is presented.

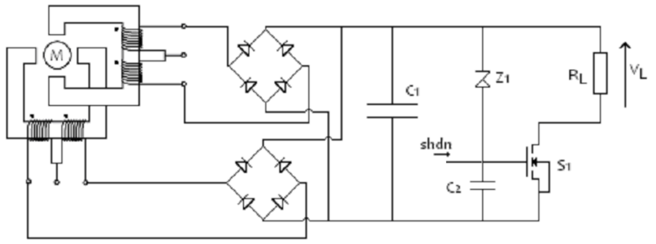

Fig. 2 The rectifier and energy level duty-cycle circuit of the stepper motor

When the voltage on capacitor C_1 is lower than the V_Z of zener diode Z_1, capacitor C_2 will not be charged and V_{GS} of the N-mosfet S_1 will be below V_T, providing no current can flow through the load. While C_1 is charging, no losses occur. When the voltage over C_1 increases above V_Z, capacitor C_2 will be charged and when V_{GS} rises above V_T, S_1 is switched on, providing a closed circuit for the load. S_1 is switched off by discharging C_2, the energy stored on this capacitor is lost (and kept to a minimum by choosing $C_2 << C_1$). By choosing S_1 with a very low $R_{DS,on}$, losses during discharging C_1 (through the load) will be negligible. A small loss occurs in S_1 when switching from cut-off to saturation. This loss is restricted to a minimum when the voltage over C_1 rises fast. The stepper motor generates its energy in a very short period, resulting in a fast rising voltage over C_1, making the presented circuit an excellent candidate for the duty-cycling needs of the stepper motor.

The thermostat requires (in adjustment-mode) two stable voltages: 2 V (for the microcontroller and the transmitter) and 3 V (for the display). The voltage delivered by the duty-cycling circuit is the voltage level over C_1. A low-power DC-DC converter is used to obtain the required voltages. In this application two MAX666 linear voltage regulators from Maxim are used. These voltage regulators include a low-battery detection function, which makes an open drain pin go low. We can use this function to discharge C_2 in the duty-cycling circuit when the input voltage drops below V_{Low}.

A shut-down circuit is provided for the MAX666, which powers the microcontroller. After the microcontroller has run through the adjustment procedure, it can shut down to reduce energy consumption. The display however is active until the energy runs out. The shut-down circuit cuts the microcontroller's power source off while the display is still active.

To ensure a correct adjustment, a rotation detection system for the stepper motor must be provided. The different phase signals generated by the stepper motor allow us to detect the rotation direction of the stepper. The phase shift between signals V_1 and V_3 is 90º when the motor is rotating clockwise and is -90º when rotating counterclockwise. By using two mosfet-inverters, these phase signals can be converted to square waves which can be forwarded to the microcontroller. This ensures no immediate losses by the rotation detection. The current sourced by the microcontroller input pins is very low (< 3 µA/pin), making this rotation detection circuit very low-power.

V. ENERGY HARVESTING WITH THE SOLAR PANEL

The solar panel used has an ideal V_{Load} = 3,3 V. Indoor, the scavenged power is up to a thousand times less than the ideal values. Therefore the output voltage will be low and insufficient to charge a storage capacitor. A NCP1400A boost converter is used to convert the voltage provided by the solar panel up to 5,4 V. The boost converter charges the storage capacitor (C_1 in Fig. 3). When enough energy is collected in C_1, the thermostat can be powered to execute the measurement mode. For this purpose, the energy level duty-cycling shown in Fig. 3 is used.

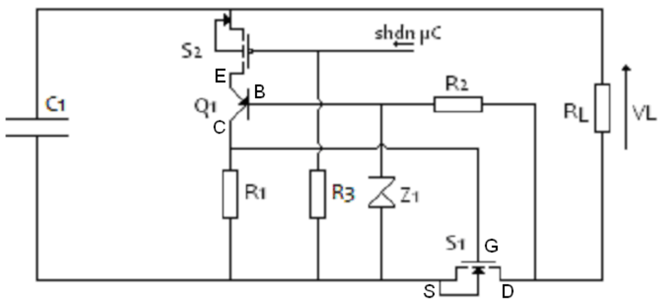

Fig. 3 The energy level duty-cycling of the solar circuit

When the voltage over C_1 is below V_Z of the zener diode Z_1, no current can flow through the collector of PNP-transistor Q_1, ensuring V_{GS} of N-mosfet S_1 is 0 V. No losses occur when C_1 is charging. When the voltage over C_1 reaches V_Z + 0,6 V, a positive voltage will occur over V_{EB} of Q_1, inducing a current through the collector. The current induces a voltage over R_1, thus making V_{GS} high. S_1 goes slightly out of cut-off thus reducing V_{DS}, making the voltage over the base of Q_1 drop, which brings the transistor in saturation, inducing a collector current high enough to create a voltage over R_1, which brings S_1 in saturation. The switching occurs very fast, even when the voltage over C_1 rises slowly. During the discharging of C_1 (through the load) a small current will flow through R_1 introducing a small loss. This loss can be restricted by choosing a high value for R_1. By making the gate of P-mosfet S_2 high, the duty-cycling circuit is powered down. This circuit has a little more losses than the duty-cycling circuit used in the stepper motor circuit, but has the advantage that the switching occurs instantly.

To supply the thermostat two voltages are required: 2 V for the microcontroller and transmitter and 3 V for the temperature sensor. We can use the same voltage regulating circuit as the stepper circuit uses, except that we don't need to consider any shut-down arrangements, since the duty-cycling circuit takes care of this.

VI. FURTHER RESEARCH

The efficiency of the energy harvesting with the solar panel can be increased by ensuring that the solar panel works on its maximum power point (MPP). This can be done by using a maximum power point tracker (MPPT) [14]. In [12], a simplified MPPT is proposed, which uses the open circuit voltage V_{OC} to determine the MPP with the following formula:

$$V_{MPP} = K_{FOC} V_{OC} \tag{3}$$

Hereby K_{FOC} is a constant between 0,71 and 0,78. Indoor V_{OC} will be approximately constant, which allows us to further simplify the MPPT: a hysteresis circuit with small hysteresis centered around the fixed MPP would probably satisfy.

The efficiency of the energy harvesting with the stepper motor can be increased by matching the load to the optimum load of the stepper motor. In [15] a circuit is presented to optimize the efficiency of an AC-voltage source with rectifier with a boost-buck converter, which input impedance is matched to the optimum load of the stepper motor.

An other factor that has an impact on the power consumption of the thermostat, is the encoding of the data, which is send over the wireless network. There needs to be made a adequate trade-off between the encoding algorithm, the frequency used to encode the data, the minimal number of packages which need to be send, and the of the reliability transmission.

VII. CONCLUSION

A successful implementation of different Energy Harvesting systems for home automation applications has been presented. In order to achieve this result, the energy consumption of the application has been reduced to a minimum. A small low-power RF-network reduces the required energy to transmit data to 28 µJ. By using low-power hardware and efficient software, the energy required for the thermostat is restricted to 243 µJ in adjustment-mode and 140,4 µJ in measurement-mode. Two efficient energy level duty-cycling circuits are presented, each meeting the requirements of the energy harvesting system for which they are used. These duty-cycling circuits have the advantage no energy is lost during the charging of the storage capacitor.

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