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Evaluation of Power Consumption Minimization Approaches for Autonomous Electronic Equipment

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***Abstract* –The use of electronic data logging device is studied for energy minimization approaches. The energy harvesting elements are described and specific design of power supply unit is provided. The main focus is on the minimization of energy loses at conversion and storage stages, as well as software optimisation is discussed, allowing to prolong the autonomous operation of the electronic device. The example of optimized data logger design is presented.**

Keywords* – Energy harvesting, Energy management, Energy storage, *Embedded software.

I. Introduction

The topic of sensing systems is well studied from the point of view of different applications [2-4]. The wireless sensor networks also became of high popularity due to simplicity of network organization, mainly because of integrated protocols (like ZigBee), that help in data acquisition from various locations. The data package being sent from one node reaches the destination node because of existence of special node in the network called router, which holds in memory the table of neighbour list of each node, helping to choose the optimized route for data package.

The advanced sensor network should also realize additional properties like maintenance-free operation, self organisation and self healing, because of various applications that deal with long-term data acquisition and which may be located in hardly achievable or dangerous places, where human life is threatened.

As the primary task of long term maintenance-free data acquisition is development of energy harvesting system, which utilizes some local energy source to supply the load. Additionally an energy storage element can be used to provide continuous operation of electronic system even in periods, when primary energy source is unavailable for any reason. Autonomous operation of electronic device requires efficient utilization of each Joule of energy. This claim affects on each stage of development of electronic device, meaning to have efficient energy harvesting and conversion stages and minimized consumption of processing unit by means of optimized program code. Data sensing, which acquires physical values, should also be optimized from the point of view of energy consumption.

This research investigates the efficient energy harvesting, power losses occurring in power conversion stages and optimization of the data processing algorithm. As an example the data logger has been chosen to study the possible ways to minimize the energy consumption of electronic device.

II. Choice of Energy Source

The number of available micro generators for electronic device is big enough, that allows supplying the load by means of energy harvesting element utilizing available source of energy at certain place. Some of “free” energy sources are mentioned onwards – thermal generators, piezoelectric transducer, small wind turbine or Solar panel. The choice of energy source (that can be used to realize the power supply unit for autonomous data logger) depends on certain application and location, where the data acquisition is planned to be organized.

The thermal generator and piezoelectric transducer are not so popular, due to their high prices. Nevertheless they are available on the market, meeting needs for special applications. These generators provide micro volts at the output that is unusable for direct connection of most electronics.

However with innovative energy management integrated circuits (for example LTC3108, LTC3588) it is possible to boost it to desirable 3.3V level. During the period of system operation it may consume about 50 mA @ 3.3 V (165 mW), but assuming that duty cycle of the system is 1% (10 ms with 1 s period), average power is only 1.65 mW, which makes possible to use thermo electric and piezoelectric transducers available with different power in a range of 10 µW-10 mW. To make output voltage more or less constant output capacitor should have enough capacity to provide low voltage drop during the operation period of the electronic device [6].

Wind power also is a form of “free” energy that can be harvested in the open air or in tunnels, where the air flow is present. Inconvenience of this power generation is related to windmill rotor dimensions. The delivered energy from the wind generator is proportional to the rotor area and wind speed cubed. That is why even for small power generation the size of rotor will not be so small at low wind speeds.

Besides that, windmill is a complicated device that is costly in comparison with the small electronic device that is planned to build.

From this perspective solar panels are much more attractive, firstly because they are available in the market in a range of different size and power with average price of 1-2USD per 1W including housing. Moreover it is possible to buy separate parts and make custom design solar panel fitting certain conditions.

III. Development of power supply unit

As it was described before the voltage generated by one of the mentioned energy harvesting elements is not suitable for direct powering of electronic components, which are powered mainly by 3.3 or 5 V. That is why the converter must be used. Another problem related with all ‘free’ energy sources is its unpredictability and inconstancy that requires using of some energy storage element providing constant output voltage.

Some features of the power supply unit may affect the power (and size) of the chosen energy harvesting and energy storage elements. So far the design of power supply unit should meet the following claims:

1. efficient harvesting;
2. efficient conversion;
3. minimized leakage currents in standby mode or in off state;

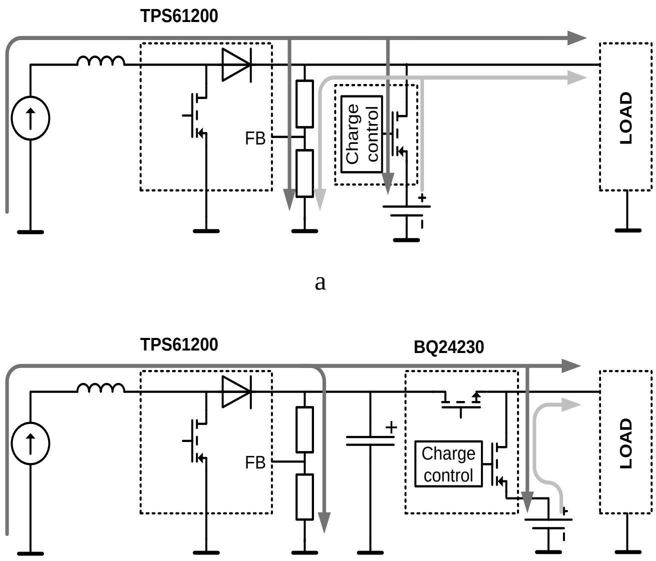
The first claim means the effective utilization of available energy from the source. As an example there are various Solar energy conversion integrated circuits (IC), but they operate at different input voltage range, meaning that some IC can harvest greater amount of energy from the same size of Solar panel, if the IC has lower start-up voltage. This feature of IC can affect the size of energy harvesting element.

Second claim has the same affect on the end device, because efficient conversion provides more energy for the load, thus it allows to choose smaller size of the energy harvesting element.

The last claim (about the leakage currents) is important for effective use of energy during the periods, when load is powered from the energy storage element. This feature affects the capacity of the storage element, because the leakage currents may discharge the storage element faster, that will cause decreased period of autonomous operation of the electronic device.

This forces to use special ICs, which suit the mentioned requirements. The first IC that should be used to adopt the voltage from Solar panel for load is Boost converter, which needs to have wide range of input voltage for operation and high impedance of feedback circuit, to prevent high leakage current. TPS61200 IC was used as Boost controller that is possible to harvest energy from solar panel starting from 0.3 V and boost it up to 5 V. The feedback input of the IC consumes about 0,01 uA, that requires about 1 uA flowing through voltage divider, to provide stable operation of the Boost controller.

Another key element of the power supply unit that has been used in the proposed power supply unit is named “System Power Path Management” – this IC (BQ24230) can provide power for the load and implement the battery charging. If the input voltage becomes lower than that of the battery, the “Power good” condition disappears and IC starts to supply the load from the battery, at the same time disconnecting the main input circuitry (see Fig.1). This IC implements Constant Current Constant Voltage (CCCV) charging algorithm. Main set points of this algorithm (charging current and termination current values) are programmed by two resistors connected to ILIM and ISET pins.



b

Fig. 1. The functional block diagram of power supply unit (dark grey – energy source current path; light grey – energy storage current paths): a – without Power path Management; b – with power path management

IV. Optimization of data logger algorithm

The main components of the electronic data logger are microcontroller unit (MCU) and flash card, which has to be chosen very carefully. The MSP430F2132 from Texas Instruments was chosen for this test, which is low-energy consumption MCU, it implements SPI interface for communication having Direct Memory Access (DMA) module and various stand-by modes with different power consumption rates.

The micro SD card has been connected to MCU as data storage element. It has relatively small consumption rates and allows to communicate over SI interface.

Many examples of microcontroller and SD card interface software source codes are available on the Internet. However the problem is that none of them considers the issue of energy consumption. As an example (taken from [5]), the byte sending procedure can be analyzed:

```
unsigned char spiSendByte(const unsigned char data)
{
  while ((IFG2&UTXIFG0) ==0); //wait while not ready
  U0TXBUF = data; // write
  while((IFG2&URXIFG0)==0);
//wait for RX buffer (full)
  return (U0RXBUF);
}
```

Two loops are used during which the microcontroller checks the special register IFG2 content on presence of transmit complete (UTXIFG0) or receive complete (URXIFG0) event notification bits. During those loops the microcontroller operates in active mode with maximal energy consumption, which in that case will be (per sector write operation):

$$E_{AM} = N_{bytes} \cdot P_{MCU\_AM\,(@3V;8MHz)} \cdot \left(T_{byte@400kHz} + T_{code@8MHz}\right) = $$
$$= 512 \cdot 3 \cdot 320 \cdot 8 \cdot \left(8 \cdot \frac{1}{400 \cdot 10^{3}} + 17 \cdot \frac{1}{8 \cdot 10^{6}}\right) = 87\ \mu J \qquad (1)$$

The simplest way to minimize the power consumption is to write interrupt driven program. For example, byte transferring procedure (mentioned in the previous example) should be replaced with the following code:

```
unsigned char spiSendByte(const unsigned char data)
{
  U0IE |= UTXIE0;
  U0IE &= ~URXIE0;
  EINT();
  _set_SR_register(CPUOFF);
  DINT();
  U0TXBUF = data; // write
  U0IE &= ~UTXIE0;
  U0IE |= URXIE0;
  EINT();
  _set_SR_register(CPUOFF);
  DINT();
  return (U0RXBUF);
}
```

The CPU will remain in sleep mode till the "*receive complete"* interrupt will occur. In this case the power consumption will be as follows:

$$E_{IRQ} = N_{bytes} \cdot (P_{MCU\_LPM0(@3V;8MHz)} \cdot T_{byte@400kHz} + P_{MCU\_AM(@3V;8MHz)} \cdot$$
$$\cdot T_{IRQ\_ISR@8MHz}) = 512 \cdot \left(3 \cdot 70 \cdot 10^{-6} \cdot \frac{8}{400 \cdot 10^{3}} + 3 \cdot 340 \cdot 10^{-6} \cdot \frac{12}{8 \cdot 10^{6}}\right) = \qquad (2)$$
$$= 2.93\ \mu J$$

Another approach to minimize MCU's energy consumption is to use DMA module which is capable to transmit the data from one place in memory to another without using energy consuming CPU. This module is programmable for various event handling, particularly for the events generated by the USART module. For example, this module can be used to perform the captured data transfer from RAM to USART transmit buffer, while CPU remains in off state. If DMA is used when microcontroller is in LPM3 mode (only ACLK is working and MCLK is set to LFXT1CLK source) it needs only 5 MCLK cycles to transmit the byte.

This approach allows to send a block of captured data in LPM3 mode (when digitally controlled oscillator (DCO) generator is off, central processing unit (CPU) is off, SMCLK clock is off). The amount of energy consumed per sector write operation is:

$$E_{LPM3} = N_{bytes} \cdot P_{MCU\_LPM3(@3V;8MHz)} \cdot \left(T_{byte@400kHz} + T_{DMA@8MHz}\right) = $$
$$= 512 \cdot 3 \cdot 1 \cdot 10^{-6} \cdot 8 \cdot \left(8 \cdot \frac{1}{400 \cdot 10^{3}} + 5 \cdot \frac{1}{8 \cdot 10^{6}}\right) = 0.253\ \mu J \qquad (3)$$

The algorithm of "Sector write" procedure is illustrated on the block diagram below (see fig.2).

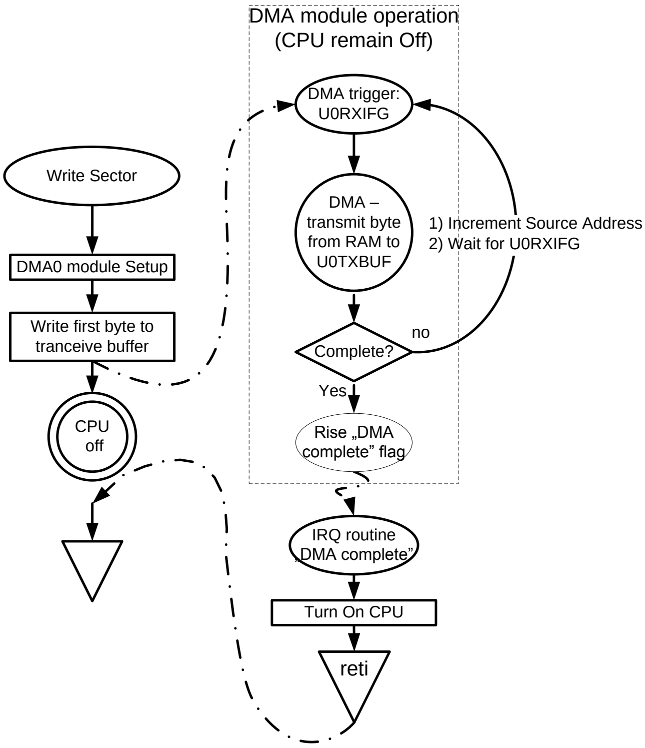


Fig. 2. Block diagram of Sector Write procedure using DMA (dashed lines are imaginary program jumps)

V. Evaluation of Software Code Optimisation

As the proposed system is a low power device, it was hard to measure precisely the amount of energy consumed during one period. For this reason a super capacitor (Maxwell PC10, 10F, 2.5V) was attached to the boost converter and tested at various operating modes, measuring capacitor's voltage (see fig. 3).

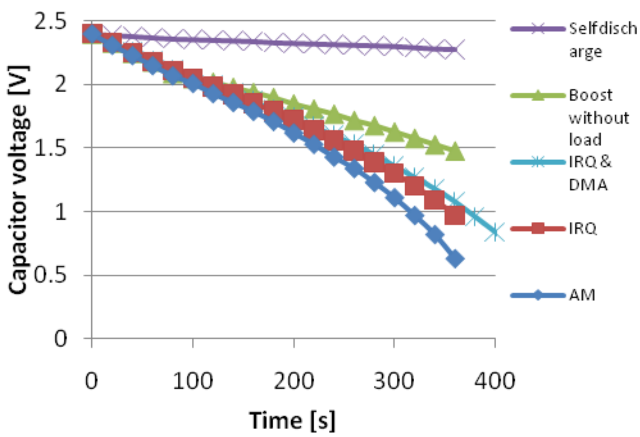


Fig. 3. Monitored capacitor voltage, which was attached to boost converter and tested at different operating modes (AM – active mode; IRQ – interrupt driven program, IRQ&DMA – the DMA module is used)

Another test, which was implemented in this research, was realized without boost circuitry, to eliminate energy conversion looses. In this experiment two serially connected super capacitors (Maxwell PC10, 10F, 2.5V) were used, initially charged till 3.3 V (see fig.4).

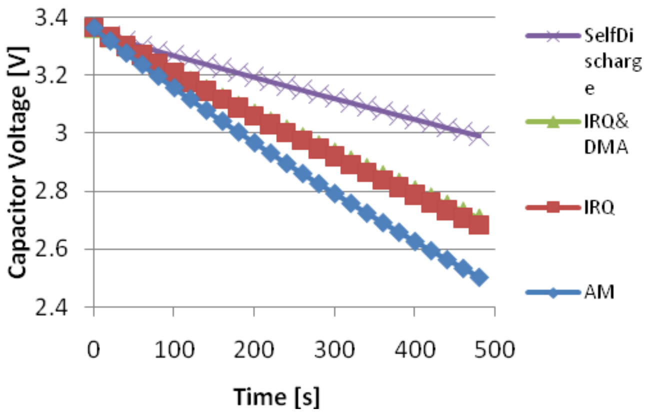


Fig. 4. Monitored capacitor array voltage, which was attached directly to the MCU and tested at different operating modes (AM – active mode; IRQ – interrupt driven program, IRQ&DMA – the DMA module is used)

The conducted demonstrated, that in practice the results are not so good comparable with theoretical calculations, mostly because of idle currents that were not taken into account that in period of operation can consume a significant part of energy consumed over the period, that is why two operation modes (IRQ and IRQ&DMA) in figure 4 are almost equal. For minimization of energy consumption in idle mode by SD card, it can be powered off, but as it was described in [1] the initialization could take as much energy as write operation of 2000 bytes.

VI. Conclusions

The proposed solution of autonomous data logger design describes several steps of system development. Firstly, solar energy harvesting system is proposed as the most suitable solution. Specific ICs are used to implement an uninterruptable power supply which uses also Li-ion battery. Several features of program code design which uses microcontroller's internal peripheral modules and significantly affecting energy consumption are described.

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