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Development of Hybrid Power Supply for Wireless Sensor Node Using Alternative Energy Sources

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Abstract: The study describes the main features of the development of a hybrid power supply for wireless sensor node using alternative energy sources. The concept of a hybrid power supply is based on the presence of energy in various forms like vibration, optical or radio frequency energy. The study discuses a block diagram of the hybrid power supply that includes a power control integrated circuit, a micro-energy cell, a piezoelectric vibrating energy harvester, a solar panel, a RF-DC energy harvester, a microcontroller. The study shows the characteristics and waveforms of the power supply that depend on the control signals from the microprocessor and on the charge cell micro-energy cell from the energy harvester. The study also describes the usage of micro-energy cells for harvested energy storage.

Key words: Hybrid power supply, RF harvester, micro-energy cell, piezoelectric vibration energy harvester, solar panel, microcontroller

INTRODUCTION

Nowadays wireless sensor network is an up-to-date technology in the field of self-organizing control and monitoring systems for different processes. The main application of autonomous sensor networks is the nonstop monitoring of a production process at manufacturing objects (Sukhanov *et al*., 2014). The problem that technicians face during monitoring sensor networks maintenance is to constantly replace the batteries of sensor nodes.

The development and production of a hybrid power supply for autonomous sensor node will improve the reliability and resiliency of the monitoring system. Intelligent power supplies are the next generation in electronics relevant to the systems where it is easy to replace the battery. In particularly these are the systems which require continuous operation of sensors and that are inaccessible for operators. The concept of the intelligent power supplies is based on the presence of energy in various forms like mechanical (vibration energy, acceleration and mechanical stress), heat (in the presence of a temperature gradient), optical, fluid and RF energy. Collecting the energy from the environment, storing and using it can power the wireless sensor nodes and other components without battery life limits and increase the available output. The hybrid power supply can be created using the alternative energy sources like solar cells, radio and piezo harvester (Tan and Panda, 2011; Rahman *et al*., 2012; Collado and Georgiadis, 2013). Thus, an autonomous sensor node with a hybrid energy supply will run without failure in the monitoring system for several years. The structure of a hybrid power supply includes three hardware units: the source of energy, energy transducer, power management unit (Fig. 1). Each hardware block is indispensable in such a power source.

The main features of the development of the hybrid energy supply with alternative energy sources for autonomous sensor node will be discussed below. The autonomous sensor node for which hybrid power supply has been developed consists of: microcontroller, digital or analog sensor, ZigBee transceiver with IEEE 802.15.4 standard, flash memory unit, debugging unit, power management controller with circuit for alternative energy sources charge.

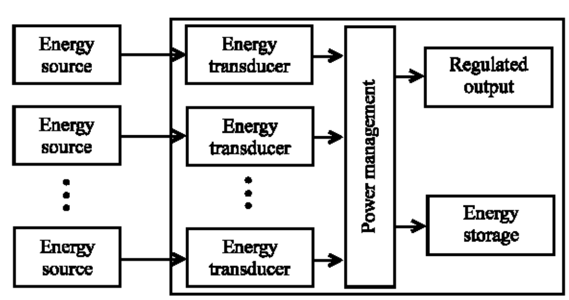

Fig. 1: The block diagram of hybrid power supply levels

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POWER MANAGEMENT

The hybrid power supply consists of power control integrated circuit, micro-energy cell, piezoelectric vibration energy harvester, solar panel, RF-DC energy harvester and microcontroller. The basis for building a hybrid power supply is a power supply integrated circuit which collects the energy from the low-power energy harvesters and stores it in the battery. The chip MAX17710 from the Maxim Integrated Products company is one of such commercially successful products of controllers for the batteries charge from the low-power energy sources. Maxim Integrated Products Company offers a complete solution for the management of the battery charge from low-power energy sources (solar, piezoelectric elements, RF radiation receivers) (Maxim Integrated, 2012).

Power management chip MAX17710 can work with unstable sources having an output range from 1-100 mW. The device has a built-in boost converter to charge the battery from sources with a typical output voltage value of 0.75 V. It also has a built-in regulator to protect the batteries from overcharging. The output voltage passes to the consumer through a highly configurable LDO-regulator and the voltage value can be selected from 3.3, 2.3 or 1.8 V. The output controller is configured to operate at either a high or low power mode, minimizing the leakage current of the battery. Distinguishing feature of the controller is its power consumption of 1 nA in sleep mode and 625 nA in charge mode. Figure 2 shows a Simplified diagram of the usage of the battery charge controller for low-power energy sources.

The microcontroller of the sensor node directly controls the output voltage of the power supply as well as analyzes the energy stored in the micro-energy cell. In this case, the intelligent power supply can be developed using the microcontroller to manage the output voltage of the energy harvester. The usage of microcontroller control signals makes it possible to change the phase of the sensor node energy cycle, for example to switch to the "sleep mode" or to the active receive-transmit mode.

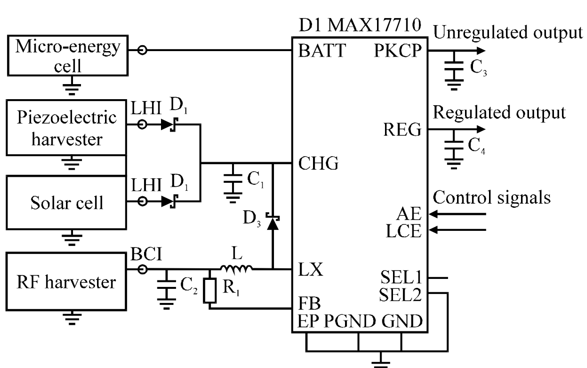

Fig. 2: Simplified diagram of the usage of the battery charge controller for low-power energy sources

Three or more unstable energy sources can be connected to the chip. To do this several energy harvesters should be connected via diodes to pin CHG of MAX17710. To achieve the highest possible efficiency, charging energy is transferred directly from the CHG pin to the micro-energy cell, whenever the voltage at the CHG pin exceeds the cell voltage. In addition, the voltage at the CHG pin is also limited by an internal shunt protection (IEEE Xplore, 2015). Diodes D1 and D2 block reverse currents between the two high voltage sources. If a solar module is connected to a high voltage input, the series diodes also prevent the solar cell from draining the micro-energy cell in the absence of light. A Schottky diode with a very low leakage current was chosen to minimize the voltage drop and the leakage current from one source to the other. Charging the micro-energy cell from a low-voltage DC source is implemented by means of a boost regulator controller which is only enabled when the source, connected to the BCI, provides more power than the boost converter consumes for operation.

Figure 3 presents the operation modes of the power management chip MAX177710. Figure 3 shows the time diagram of the battery voltage supply and regulated/unregulated outputs voltage that depends on the microcontroller control signals and on the harvesters input currents.

Battery charge management controller works with micro-energy cells. Designed to outperform Lithium coin cells, printed batteries and other thin-film batteries, the Thinergy micro-energy cell family includes four models of varying size and capacity. Each micro-energy cell is a thin, flexible unit that can be easily incorporated into compact hardware designs. Multiple micro-energy cells can be stacked to increase capacity and output without increasing the unit's footprint. The Thinergy micro-energy cells are even thin enough to be embedded and laminated into printed circuit boards or other materials.

The Thinergy micro-energy cells are made from sold-state chemistry with no liquid or organic polymer electrolytes used. This construction allows the micro-energy cell to support more recharge cycles than other rechargeable batteries and to hold their charge longer with less loss. A fully-charged micro-energy cell will lose <1% of its charge over a year.

The micro-energy cells have no "memory" effect like other battery technologies, so they retain their full capacity throughout their life. Each cell requires only 4.1 V for charging and can accept a charge with as little as

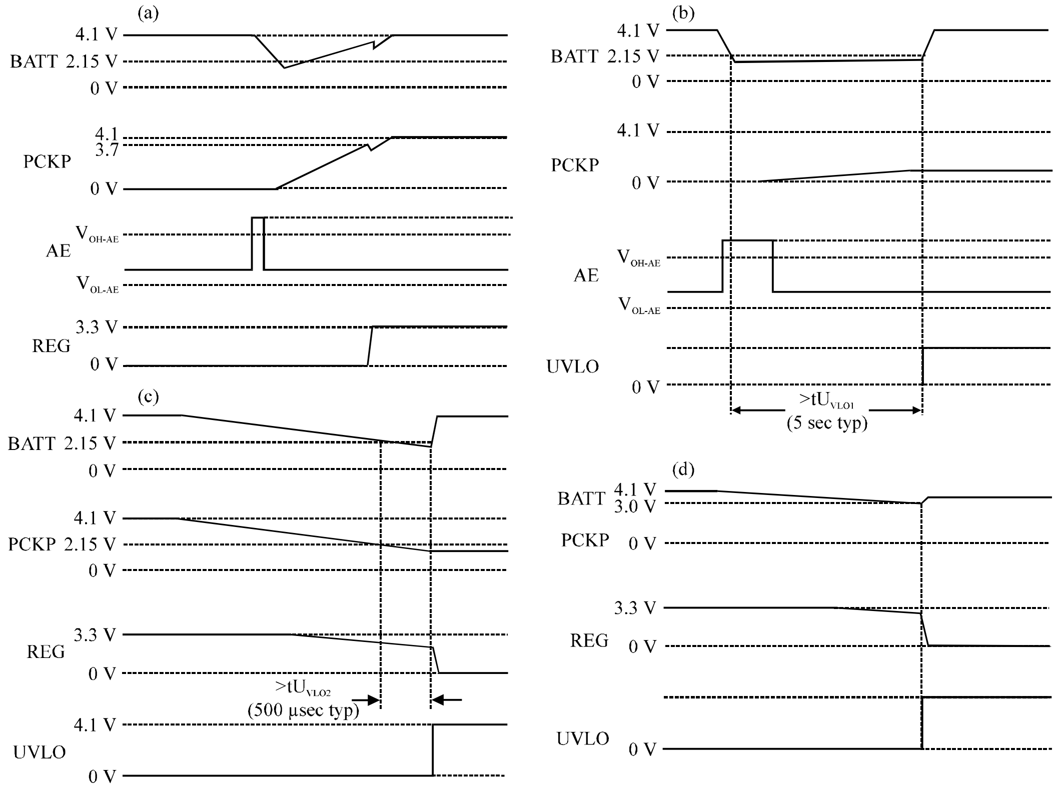

Fig. 3: Operation modes of power management chip MAX17710: a) normal regulator output enable sequence; b) regulator output enable fail due to UVLO timeout; c) high-current mode regulator output disabled due to UVLO timeout and d) low-current mode regulator output disabled due to UVLO detection

a few hundred nAmps of current. Depending on the charging current, a MEC can recharge in as little as a few seconds or as long as 10 min.

The active materials in the device include a Lithium Cobalt Oxide (LiCoO2) cathode and a Li-metal anode (Infinite Power Solutions, 2014). A solid-state electrolyte called LiPON (Lithium Phosphorus Oxynitride) with its high Li-ionconductivity is used to provide superior power performance. The extremely low electron conductivity within LiPON results in ultra-low self discharge, making this technology ideal for applications where energy must be reliably stored for many years without the ability to recharge or for low-power ambient energy harvesting charging solutions. In addition, this eco-friendly technology contains no toxic chemicals or heavy metals, providing industry-leading safety with absolutely no possibility for chemical leakage, thermal runaway or fire as experienced with other Li-ion batteries using liquid or gel electrolytes. A proprietary flex-circuit encapsulation methodology is used to achieve the ultra-thin and flexible form factor and to ensure reliability and performance under harsh environmental conditions, far exceeding other micro-energy storage technologies.

The charging characteristics of these micro-energy cells make them ideal for applications involving energy harvesting from sources such as solar, RF (converting radio frequency into current), kinetic or thermoelectric. In addition, they can be charged using more conventional methods such as direct wire connection and inductive charging (using a magnetic field to induce current).

When using micro-energy cell the following thing should be taken onto account that the minimum threshold discharge voltage is 2, 1 V for currents >1 mA and 3 V for currents <1 mA. Discharging micro-energy cell below this voltage level will lead to its failure.

Figure 4 shows the charging curves for the advanced and standard model of micro-energy cell. The graph shows the recharge current and the level of the charge in percent. Charging up to 90% is carried out for 14-18 min. Figure 5 shows the discharge curves of micro-energy cell for various current consumptions. The voltage drop of cell is a function of current consumption.

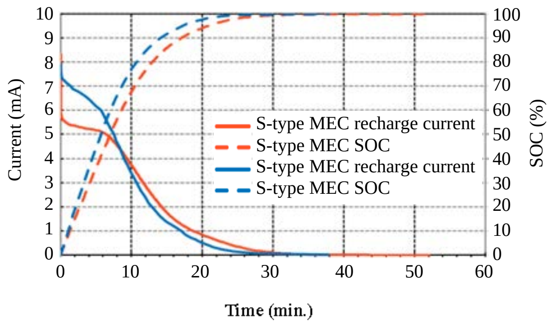

Fig. 4: The charge of micro-energy cell

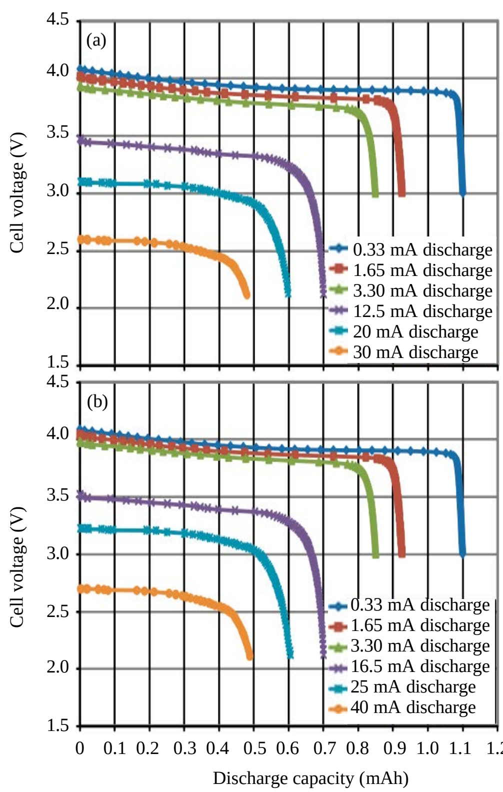

Fig. 5: The discharge of micro-energy cell for advanced and standard model: a) standard grade and b) performance grade

THE USE OF PIEZOELECTRIC VIBRATION ENERGY HARVESTER

The piezoelectric vibrating energy harvester can be used as an unstable power source (Minami and Nakamachi, 2012). Vibro-generators of volture company were selected for designing the test hybrid power supply of wireless sensor nodes. Currently, there is a solution for the collection of vibration energy which uses the technology of Ruggedized Laminated Piezoelectric (RLP). The piezoelectric transducer is the generator that converts the mechanical energy of vibration into electrical energy. The mechanical energy is collected by piezoelectric RLP-beams attached to the mechanical vibration structure. The basis of piezoelectric effect is a property of certain crystals to produce an electrical charge when compressed (direct piezoelectric effect). Also it is a property of crystals to change the shape (compress/expand, twist, bend) under applied voltage (inverse piezoelectric effect). The generator is mounted so that one of its ends is placed on a vibrating base while the other end remains free. The efficiency of this system depends on the resonant frequency of the resulting pendulum.

Some energy harvesters based on vibration piezo-element are composed of a piezoelectric biomorphic cantilever beam. Fixed end of the beam is connected to the structure vibration node and the free end of the beam has a small weight attached to increase the output power and to provide the adjustment of the resonance frequency. The beam is connected to the energy harvester circuit which has an electrical resistance which determines the amount of collected energy. From a physical point of view, it is assumed that an energy harvester circuit is purely resistive and can be simplified to the Thevenin equivalent circuit. Also, the method of Euler-Bernoulli Beam (EBB) modeling was used to determine the operation and efficiency of piezo-harvester. Considering the circuit model of energy harvester it is clear that the load current can be obtained by Ohm's law:

$$I_L = \frac{V_{TH}}{Z_{TH} + R_L}$$

Where:

V_{TH} = The load voltage
Z_{TH} = The internal resistance of the harvester
R_L = The load resistance

Then, the total power of the load is calculated by equation:

$$P_{L,rms} = \frac{1}{2}|I_L|^2 R_L$$

where, I_L is the current in the load resistor. The consumed power of energy harvester device is P_{in} $1/2|F||U|$ with the efficiency of energy transfer of $P_{L,rms}/P_{in} = |I_L|^2 R_L/|F\|U|$. When measuring the power of energy harvester it is assumed that the entire system is under the acceleration of the base excitation and the equivalent force is determined by equation:

$$F = M_m \alpha_o + M_{mg}$$

Where:

M_m = The mass of the beam
α_o = A bending stiffness of the different parts of the beam
g = The gravitational constant

THE USE OF RF ENERGY HARVESTER

The use of the ambient radio emission energy is one of the most promising technologies. Compact, weather and external conditions independent RF harvesters convert the energy of radio waves into DC voltage supply. The RF energy harvester can be used as an unstable energy source for the intelligent hybrid power supply. The main feature of the RF energy harvester is its efficiency which depends on the availability of appropriate infrastructure. The radio emission (energy density) is much weaker in rural or remote area than in the cities. However, the coverage of cellular networks and digital television is constantly growing and now the energy density has an appropriate level. According to studies (Pinuela *et al*., 2013), the most promising frequency ranges for energy collection systems are cellular ranges of 880-960 MHz (GSM900) and 1710-1880 MHz (GSM1800). This frequency band GSM900 will be considered for the wireless energy in the first place.

The optimized modules P1110 and P2110 from Powercast were used while designing the test hybrid power supply for wireless sensor node. The maximum efficiency (Wireless Power Solutions, 2015) of the Powercast modules is at 915 MHz frequency and exceeds the 60-70% for the P1110 and P2110. The maximum output current of the RF harvesters is 50 mA. Figure 6 shows the internal structure of Powercast P1110 and P2110 receivers. Figure 7 presents the efficiency of energy conversion of the receivers. The internal structure of P1110 differs from that of the receiver P2110 by absence of a voltage controller.

Powecast P2110 module requires an external storage capacitor and its capacity determines the amount of stored energy. Additionally the fact should be considered that the high value capacitor may have too high leakage currents. It is recommended to choose the capacitor with leakage current <1 uA at 1.2 V with series active resistance of less than 200 mOm. The capacitance value determines the switching on/off time of energy harvester. The energy harvester output voltage is formed by the storage capacitor voltage by means of boost converter. Powercast recommends to use the elements with leakage current level of not >1% per month, otherwise,

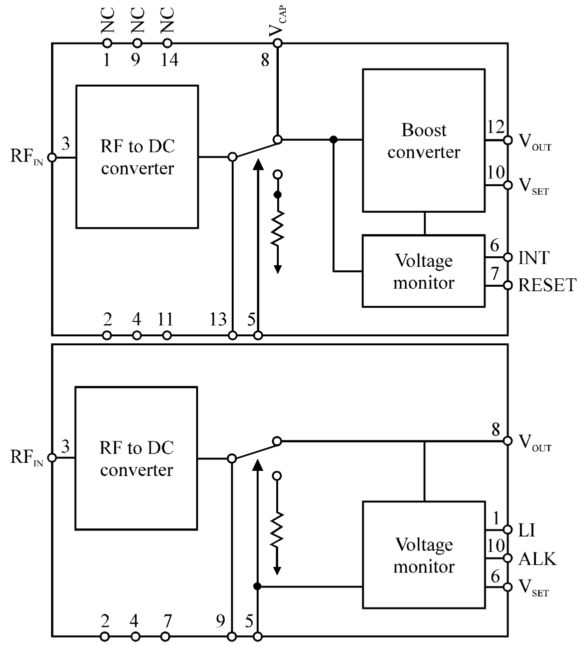

Fig. 6: The internal structure of receivers Powercast P2110 and P2110

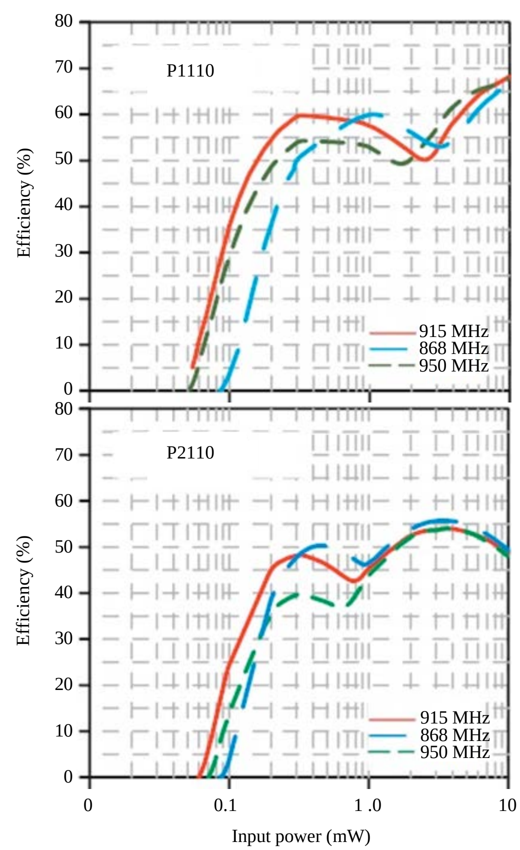

Fig. 7: The efficiency of energy conversion of the receivers Powercast P1110 and P2110

the most part of the collected power will be wasted. The RF harvester requires standard antenna with 50 Ω impedance for its operation.

Friis Transmission Formula is sorely used to study RF communication links. The formula can be used in situations where the distance between two antennas is known and a suitable antenna need to be found. Using Friis transmission equation, one can solve for the antenna gains needed at either the transmitter or receiver in order to meet certain design specifications:

$$P_r = P_t G_t G_r \left(\frac{\lambda}{4\pi R} \right)^2$$

Where:

$G = 10\times^{G_{dB}/10}$ and $\lambda = c/f$, c	=	The speed of light in meters per second
f	=	The frequency in Hz
P_r	=	The received power in Watts
P_t	=	The transmitted power
G_t	=	The transmitting antenna's gain
G_r	=	The receiving antenna's gain
λ	=	The wavelength of the transmitted and received signal in meters
R	=	The distance between the antennas in meters

The gain of the antennas, usually measured in decibels can be converted to power ratio using. A simplified version of the Friis equation is provided by the Powercast company for quick and easiest calculation on a spread sheet (Wireless Power Calculator, 2010) where a reasonable estimate of the amount of power generated, received and available for use are calculated.

CONCLUSION

The main advantage of the hybrid power supply is the possibility to collect the energy from the very scarce natural resources for powering sensor devices. And it allows placing them without connection to external power sources. Each of the existing alternative energy sources has its advantages and application features. The usage of background RF radiation for powering small electronic devices weakly.

Depends on weather conditions and thus, it is ideal for building passive and active sensors networks. The designed miniature power supplies are the solution for rapidly developing wireless sensor networks. Theirs unique features allow the effective usage of low-power energy sources for powering the autonomous devices which greatly simplify the process of deploying wirelesssensor networks and permanently solve the problem of remote networks elements power. Collecting the energy from the environment, storing and using it can power the wireless sensor nodes and other components without battery life limits and increase the available output.

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