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Simple and affordable circuit for energy harvesting applications

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Annotation:
The paper presents a circuit structure that can be used as an energy harvester. It is intended for photovoltaic panels (PV) or other sources of energy that can provide enough voltage level but that can source only low currents. The circuit is able to accumulate the energy until certain level and then to pass it to the load. The presented circuit exhibits similar functionality as a commercially available energy harvester EH300. The paper compares their technical properties, form factors and costs. The circuit was tested with IoT (Internet of Things) node that can periodically transmit measured data to the base station using just the powering from the PV panel. Worse electrical properties of the circuit are repaid by its low cost that allows mass applicability in the IoT.

Anotace:
Článek představuje obvodovou strukturu, která může být využita pro sběr energie z okolí (harvester). Je určena především pro spojení se solárními články nebo jinými zdroji energie, které poskytují dostatečně velké napětí, avšak mohou dodat pouze malý proud. Obvod je schopen akumulovat energii do kondenzátoru až do okamžiku, kdy je dosaženo příslušného napětí. Poté je kondenzátor připojen k zátěži. Obvod vykazuje podobnou funkčnost jako komerčně dostupný harvester EH300. Článek porovnává jejich elektrické vlastnosti, velikost a cenu. Obvod byl otestován s IoT (Internet of Things) uzlem, který periodicky odesílá změřená data do základnové stanice pouze s využitím napájení pomocí solárního článku. Horší elektrické vlastnosti navrženého obvodu jsou vyváženy jeho velmi nízkou cenou, která umožňuje nasazení tohoto obvodu v masovějším měřítku IoT sítí.

1. INTRODUCTION

Energy harvesting allows operate electronic devices without battery or support the battery to increase its lifetime. It is suitable mainly for places where the standard powering cannot be applied or where it is inconvenient to replace the battery. Typical application can be IoT nodes. Unfortunately the alternative energy sources are usually weak and cannot provide enough energy for direct powering of the device (e.g. small PVs [1]). The energy thus should be collected to the capacitor or battery first and afterwards it can be released to the load. These circuits are called energy harvesters. There exist commercially available circuits that can be used as the energy harvesters but their price is usually high and thus it cannot be used for high number of IoT nodes applications. This paper presents an alternative that can be a compact part of the IoT node powering electronic and its price allows mass applicability.

2. ENERGY HARVESTERS

Representative example of the commercially available module is the harvester EH300 [2] (Fig. 6 bottom). Its operational principle is following (see Fig. 1). The harvester EH300 stores the energy from e.g. PV cell to the capacitor 1 mF while the load is disconnected. When it is charged to 3.6 V (V_H), the capacitor is connected to the output port and the accumulated energy is provided to the load. The energy is available until the voltage on the capacitor drops down to 1.8 V (V_L) and it is disconnected. When the harvester's output is closed the energy from the energy source can be harvested again. For 1 mF capacitor the energy released in one charging cycle is 4.9 mJ. As the energy source can be used e.g. solar panel, piezoelectric converter or other sources that can provide voltage level above 3.6 V.

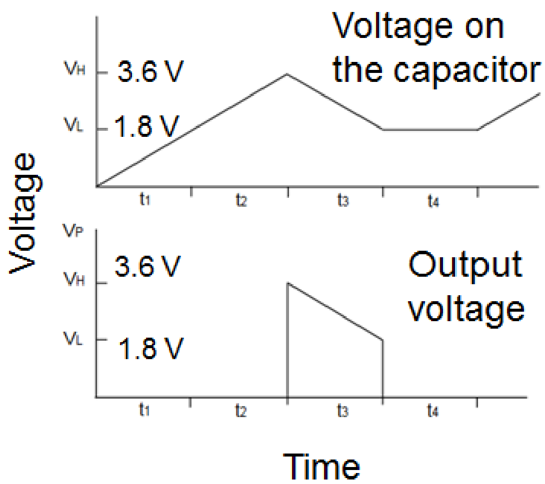

Fig. 1: Operating cycle of the harvester EH300 [2]

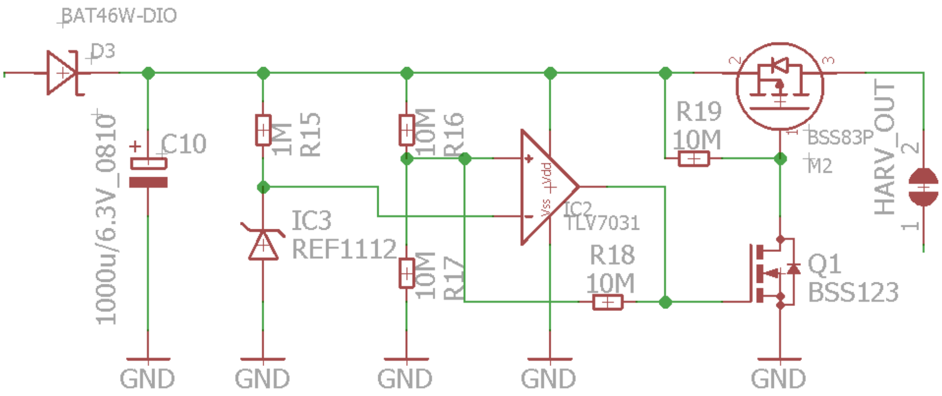

Fig. 2: Schematic of the harvester circuit

Developed circuit structure in Fig. 2 has the same functionality. Energy is charged to the capacitor C10. The voltage is compared with the voltage reference (R15, IC3) using the comparator IC2. The comparator has implemented a hysteresis using the resistors R16, R17, R18. The comparator directly drives the CMOS transistors Q1 and M2 that connect the capacitor C10 to the load.

The resistor values R16, R17, R18 and voltage reference V_{ref} (IC3, R15) can be set to different V_L and V_H to accommodate the operational voltage levels. Equations (1) and (2) define coefficients K1 and K2 that were calculated from the voltage divider R16, R17, R18 for switched and released comparator and for the reference voltage 1.25 V on its inverting input.

$$K_1 = \frac{V_{ref}}{V_L} = \frac{R_1R_2 + R_2R_3}{R_1R_3 + R_1R_2 + R_2R_3} \qquad (1)$$

$$K_2 = \frac{V_{ref}}{V_H} = \frac{R_2R_3}{R_1R_3 + R_1R_2 + R_2R_3} \qquad (2)$$

The resistors' values can be expresses from these equations for any voltage levels V_L, V_H and optional resistor R1 (3).

$$R_1 = R;\ R_2 = \frac{RK_2}{1-K_1};\ R_3 = \frac{RK_2}{K_1-K_2} \qquad (3)$$

In order to keep the self power consumption to be minimal the resistors should be as high as possible. For given values from the schematics in Fig. 2 the operational voltage levels are similar to the EH300 device (1.875 V and 3.75 V).

3. COMPARISON OF THE PROPERTIES

Presented circuit and the commercial harvester differ namely in their leakage currents. The leakage currents were measured and calculated indirectly from the voltage drop on the capacitor during the time (Fig. 3). The storage capacitors were charged to the voltage 3.5 V and then the self-discharging of the circuit was checked during the time. The leakage current was calculated from the voltage drop ΔV_C between two consecutive measurements with time difference ΔT using the eq. (4) - see Fig. 4.

$$I_{leakage} \sim \frac{\Delta V_C \cdot C}{\Delta T} \qquad (4)$$

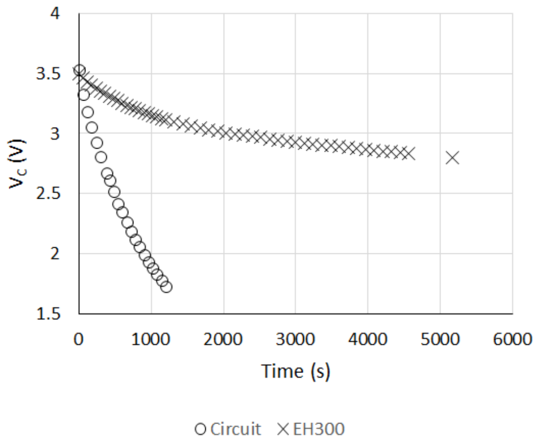

Fig. 3: Measurement of the voltage drop on the storage capacitor during the time caused by the leakage currents

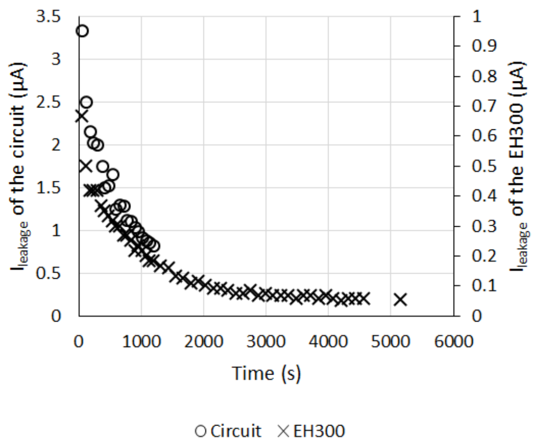

Fig. 4: Leakage currents of the devices calculated from the voltage drop

The leakage current can be also recalculated to the actual voltage on the capacitor V_C (Fig. 5).

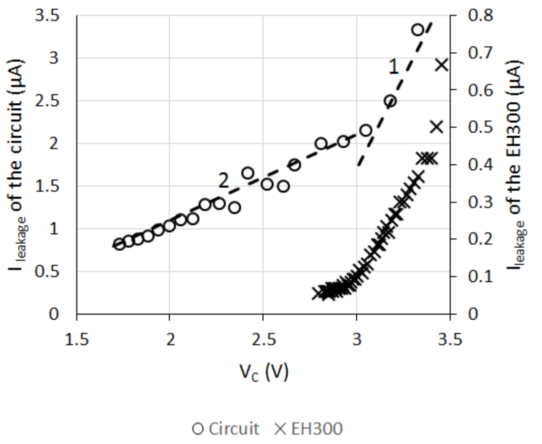

Fig. 5: Comparison of the presented circuit and harvester EH300 leakage currents versus the actual voltage on the capacitor

There are evident two regions of the characteristics - see dash lines in Fig. 5. When the capacitor is charged to the maximum, the leakage currents are high. It decreases quickly and then it steadies to the low linear dependent decrease.

The fast decrease at the beginning (dash line 1 in Fig. 5) is caused namely by the leakage current of the capacitor because the actual voltage is close to the capacitor's rated voltage [6]. When the capacitor's leakage is stabilized to its minimum the leakage of the circuit structure takes dominant role (dash line 2 in Fig. 5).

The steady leakage current of the circuit can be estimated from the schematic and considering the quiescent currents of the devices (5).

$$I_{leak} = \frac{(V_{C10} - 1.25)}{R15} + \frac{V_{C10}}{R16 + R17 \| R18} + I_{TLV7031} + I_{C10} \quad (5)$$

The quiescent current across the voltage reference is given by the resistor R15 and should be at least 550 nA [3] for the minimal voltage 1.8 V. This is why the resistor R15 is 1 MΩ. The voltage reference current is proportionally bigger for higher voltages on the capacitor. The voltage divider R16, R17, R18 loads the capacitor by a resistance of 15 MΩ and the quiescent current of the comparator is circa 300 nA [4]. Leakage current of the electrolytic capacitor C10 should be always lower than 3 µA [5] but it is sharply dependent on the voltage when it is close to its rated voltage [6]. The maximal leakage current of the capacitor in the circuit was measured to be 700 nA @ 3.5 V, 25 °C and rated voltage 6 V.

It is evident from the measurement that the leakage current of the presented circuit is circa 3.3 µA @ 3.5 V which is 5 times bigger than the leakage of the EH300. Interesting result of the measurement is also fact, that the real leakage of the EH300 if about 700 nA for 3.5 V which is 3.5 times more than it is declared in the datasheet. The leakage current of the harvester EH300 is declared to be 200 nA but it is higher probably due to the storage capacitor.

Worse leakage current of the circuit compared to the EH300 is repaid by 31 times lower price of the components (2.2 € vs. 70 € @ mouser.com). It allows mass applicability of the circuit in the IoT where the harvested energy is able to cover the leakage and provide also the useful energy to the system. Table 1 presents comparison of the key properties.

Tab. 1: Comparison of the key properties

Parameter	*EH300*	*Circuit*
Input current polarity	Bipolar	Unipolar
Leakage current	<700 nA	<3.6 µA
Footprint	48 × 14 mm^2	6 × 10 mm^2
Price	~ 70 €	~ 2.2 €

4. HARVESTER APPLICATION

Figure 6 presents a developed IoT node that is able to wirelessly transmit measured data (e.g. temperature and humidity) to the receiver. It can use only the harvested energy or it can be also supported by the battery (e.g. for biasing the sensor). The presented harvesting circuit is a compact part of the electronic and it occupies just 6 × 10 mm^2 (compare it with dimensions of the EH300).

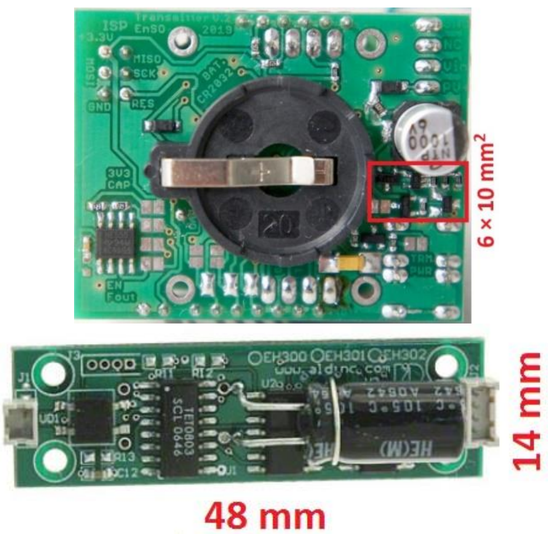

Fig. 6: Comparison of the harvesting circuit footprint (top) with the harvester EH300 (bottom)

The module uses a narrow band radio transceiver at ISM frequency 433 MHz. It can transfer measured data to the base station with the data rate up to 10 kbps and to the distance up to 1 km [8] (fruitfully tested for 2.5 kbps and distance bigger than 250 m within urban area). When the device is powered only from the amorphous solar cell SOLEMS [9] of the dimensions 2.5 × 2.5 cm^2, the data transmission rate is every 30 seconds for high intensities (8000 lx) and decreases down to 3 hours for very dark hall (15 lx).

5. CONCLUSIONS

The paper has presented a circuit structure that can be used as the energy harvester. Its functionality is similar to the commercially available harvester EH300. Electrical parameters are worse namely for the leakage current of the circuit that should be covered by the harvested energy source. The worse parameters are repaid by its very low price and compact footprint that allows mass applicability in IoT networks.

Functionality of the presented solution was proved on IoT node, which is transmitting measured data to the base station only using the powering from the PV cell. The device can operate even at very dark environment with illumination just 15 lx.

The maximal leakage current of the circuit is 3.6 μA and it can be decreased by changing the operation voltage levels. If the voltage V_L is increased to 2.5 V, then the resistor R15 can be increased to 2.27 MΩ. The maximal leakage current will decrease to 2.3 μA but also the energy released by one charging cycle will be just 3.3 mJ.

Presented solution was developed with special attention to minimizing the total price of the components while keeping the basic functionality. If the price is not the critical parameter of the design, it can be also improved the functionality in following aspects.

1. Leakage current of the structure can be decreased by substituting the resistor R15 by the constant current source LM334 and set it to the minimal value of 1 μA. The voltage V_L must be increased to 2.05 V (due to minimal voltage for the LM334) but also the voltage V_H can be increased to maintain the energy of the charging cycle. Total leakage current will be lower than 2 μA while the price will be increased of 0.3 EUR.
2. The output MOSFET transistors can be replaced by ultra-low leakage and quiescent current load switch with reverse blocking SiP32431. This device can provide bigger current to the load and it has lower power dissipation when voltage is close to V_L. The price of the components will increase of 0.3 EUR.
3. Input part of the circuit can be equipped by the rectifier to harvest also bipolar energy sources such as piezoelectric transducers. The rectifier can consist of Schottky diodes or the CMOS rectifier can be implemented [7].

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