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Photovoltaic single cell energy harvesting

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Anotace:
Jsou popsány možnosti využití fotovoltaických článků v uspořádání single-cell pro Energy Harvesting (EH) na velmi nízké energetické úrovni. Pokud není účinnost nejdůležitějším parametrem, může být single-cell uspořádání cenově výhodné v mnoha aplikacích. Srovnání vlastností příslušných technologií ukazuje, že pro zamýšlené použití jsou nejvhodnější tenkovrstvé anorganické fotovoltaické články. Je velmi důležité zvážit provozní podmínky, v nichž budou fotovoltaické články pracovat, a přizpůsobit tyto podmínky jejich výběru. Vzhledem k velmi malé ploše článku potřebné pro konvertory nízké energie není cena fotovoltaického článku významnou položkou v celkových nákladech na EH převodník. Pro toto použití byl navržen jednoduchý a spolehlivý převodník DC-DC s nízkou cenou.

Abstract:
The paper describes the possibilities of Energy Harvesting (EH) using photovoltaic single cell energy harvesting. When the efficiency is not the most important parameter single-cell can be cost-effective in many applications. Comparison of the properties of respective technologies shows that for intended application there are most advantageous inorganic thin film cells. It is very important to consider the operating conditions in which EH will work and adapt these conditions to the selection of the photovoltaic cell. Because of very small area of the cell needed for the low energy EH converters the price of the photovoltaic cell is not an important item in the total cost of an EH converter. Simple and reliable low price JFET driven DC to DC converter was designed for this application.

INTRODUCTION

For energy harvesting (EH) the photovoltaic cells are still the simplest and technologically most accessible energy converters. However, when using standard solar cells connected in serial configuration there are some drawbacks.

Cells must be sorted according the rated current to achieve maximum efficiency. With larger scattering of cell parameters at production, the cells must be selected and sorted from a large number of pieces.

When aging during normal operation, cell parameters may vary unevenly. Faster aging cells will then greatly reduce the overall efficiency of the assembly.

In non-uniform illumination, the achievable power is influenced by the least illuminated cell. In the event of a large difference in illumination, the least illuminated cells can even be polarized in the reverse direction. In order to ensure reliable operation of the whole assembly, there must be anti-parallel diodes connected to each cell. When the respective, less illuminated cell, comes to reverse polarization parallel diode will overtake the current generated by the rest of the assembly.

The structure of the single cell is simple and could be more reliable than the cells connected in serial configuration. Consequently, in some cases single-cells can be cost-effective, especially when efficiency is not the most important parameter.

However, Photovoltaic single cell (PSC) provide a low output voltage not sufficient for electronic devices. Therefore, there is a need to boost the voltage to a level sufficient for standard circuits. In silicon-cell technology there is also a possibility to integrate the boost-up converter directly into the structure of the cell [1].

PSC FOR ENERGY HARVESTING

The behavior of selected single cells under real operating conditions was tested for an EH converter operating at an energy level deep below 1 W. The low voltage at the cell output was boosted-up using the low voltage DC to DC converter described in [2].

Influence of the intensity and spectral distribution of the exciting radiation

When using photovoltaic converters for energy harvesting, it is necessary to consider a large range of light intensity.

Further, the wavelength from which a photovoltaic cell can absorb incident photons depends on the width of Band Gap of semiconductors in the structure of the respective photovoltaic cell. Spectral composition of the incident radiation is therefore very important. Spectral composition of the incident light may considerably change in different conditions. For example, in direct sunlight, great part of radiated energy is in red and infrared part of the spectra. Crystalline silicon cells, which have the maximum absorption just in infrared and red part, are best suited for this case. At cloudy sky diffused radiation prevails and the spectral distribution is shifted toward shorter wavelengths. Radiation in the field of visible part of spectra will also prevail in case of indoor applications. Here the semiconductors with wider Band Gap are preferred.

Photovoltaic cells in Low-light operation

The light dependence of generated voltage on the Si photovoltaic cell and its current and power is in Fig.1. It is evident that the current supplied by the cell is approximately linearly proportional to the illumination. The dependence of the voltage generated by the cell on the illumination is approximately logarithmic. Changing the intensity of light radiation will therefore primarily reflect the change in the current of the cell.

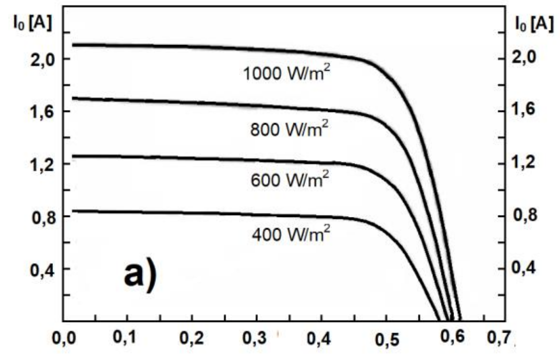

Fig. 1: A-V characteristics of the silicon photovoltaic cell

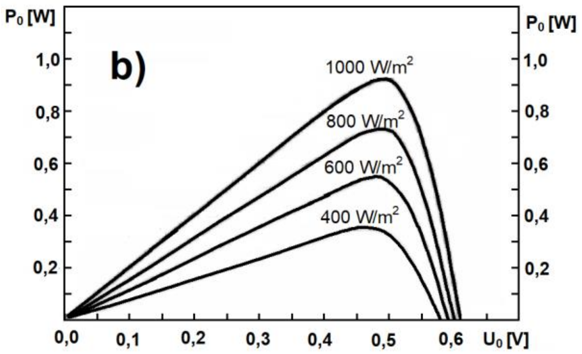

Fig. 2: The power extracted from the cell

From Fig. 2. it is obvious that there is an optimal voltage and current value for the maximum output of the cell. The voltage at which maximum power is reached decreases with light intensity very slowly. This means that even at an extremely low intensity of incident radiation the voltage on the cell will still be a few tenths of a Volt. Thus, the inverter operation will be possible, although the power output will be very low.

PHOTOVOLTAIC CELLS FOR EH TRANSDUCERS

Crystalline or polycrystalline silicon photovoltaic cells are still standard cells with the price level at approximately 2 USD per Watt, depending on the size and technology. However, a comparison of the properties of respective technologies shows that for the intended application inorganic thin film cells are most advantageous, especially the cells based on amorphous and multicrystalline silicon, cadmium telluride (CdTe) and copper indium gallium selenide (CIGS or CIS). Thin film manufacturing technology also makes it easier to adapt to special requirements. Approximately 1% of material is required to produce thin-film structures compared to crystalline cells. Compared to crystalline cells there are about of a 30% less technological steps and the entire production process consumes about 50% of the energy [3].

Comparison of the cells with different technologies

Amorphous silicon photovoltaic cells have the efficiency of energy conversion near 10 % but it rapidly drops in operation because of the light degradation process (Staebler–Wronski effect) to about 7 %. Nevertheless, amorphous silicon cells operate very well in low light conditions where the amount of produced energy could be comparable to crystalline silicon cells. Using non toxic silicon it represents one of the most environmentally friendly photovoltaic technologies.

Tab. 1: Most important parameters of examined photovoltaic cells with different technology:
E_G [eV] is Band Gap , λ_0 [nm] is Threshold Wavelength to the respective Band Gap, [V_{OC}] is Open Circuit Voltage

TYPE	E_G [eV]	λ_0 [nm]	V_{OC} [V]
C - .Si	1,12	1107	≈ 0,65
Micro - Si	1,4	885	≈ 0,6
Perovskite	1,2 - 2,3	1033 - 539	≈ 0,6 - 1,5
Amorph. Si	1,7	729	≈ 0,8
Am.+ Micro (Si-tandem)	1,7 / 1,4	729 / 885	≈ 1,3
CdTe	1,5	826	≈ 1,0
CGCIS	1,7 - 1,0	729 - 1240	≈ 0,8 - 0,5

Silicon thin film cells are often prepared as a tandem of amorphous and microcrystalline cells with a different Band Gap. The overall efficiency is then higher - reaching the level about 13%.
The lab cell efficiency for CdTe and CIGS cells is beyond 21 % which is comparable to crystalline silicon cells. Cadmium teluride (CdTe) is very cost-effective but uses toxic cadmium. The usage of rare materials may also become a limiting factor to the

large scale production. The Band Gap of CIGS cells varies continuously depending of content of indium and gallium from about 1.0 eV (CuInSe) to approximately 1.7 eV (CuGaSe).

Tab. 2: Most important parameters of examined photovoltaic cells with different technology:
I_{SCA} [mA/cm^2] is Short Circuit Current per area of 1 cm^2, η [%] is Efficiency of Energy Conversion, t_{EL} [years] is Expected Lifetime

TYPE	I_{SCA} [mA/cm^2]	η [%]	t_{EL} [years]
C - Si	≥ 30	≈ 20	≈ 20
Micro - Si	≤ 15	≈ 8-15	≈ 10-15
Perovskite	≈ 20	≈ 15	≈ ??
Amorph. Si	≤ 12	≈ 7-12	≈ 10-15
Am.+ Micro (Si-tandem)	≤ 15	≈ 10-13	≈ 10-15
CdTe	≈ 30	≤ 20	≈ 10-15
CGCIS	≈ 30	≤ 20	≈ 10-15

Perovskite solar cells [4] have an ability to absorb light across almost all visible wavelengths and production technology is simple. They have exceptional power conversion efficiencies which are after only a few years of investigation comparable to crystalline silicone cells, Despite that there are many challenges, the probability that the perovskite solar cells will be commercialized in near future is high. Organic photovoltaic cells, unfortunately, still remain only a promising technology. Although there are currently many convenient materials for organic cells, the degradation processes still pose a difficult problem [5].

ADDITIONAL COMPONENTS

For optimal use of low energy low voltage EH converter there is necessary to use a voltage converter with extremely low power supply voltage. Low voltage EH transducers therefore implement boost converter that requires only microwatts of power to begin the operation. As stated above, the cost of photovoltaic cells usually does not exceed 2 USD per Watt of maximum power depending on type of the cell, the currently used technology and volume of production.

By full light an area of approximately 10cm x 10cm is required for 1 W of output power. However, for many applications (such as wireless sensors), the total daily power consumption of the device may be in order of several tens of milli-watt-hours. Then, even with very low light, we need much smaller cell area. The price of the respective photovoltaic cell can be therefore well below 1 USD and will not significantly affect the cost of the whole device.

The price of the necessary DC/DC converter should not be much higher than the price of EH transducer alone. The unit price of low voltage integrated circuits for EH applications is around 2 USD and the price of other components included small SMT PCB could be also estimated at around 2 USD. Simple and reliable JFET driven converter suggested here has material and production costs significantly lower.

Single J-FET DC to DC converter

To achieve higher efficiency the single JFET circuit shown in Figure 2 utilizes the energy stored in the transformer during the switch-on state.

1) As soon as the transistor turns on the secondary winding generates a voltage pulse. Capacitor C_1 is being charged by means of this pulse. Once the transformer core becomes saturated the voltage on the secondary winding starts to drop. Due to the positive feedback given with actual polarity of primary and secondary windings the transistor closes. With a negative voltage on the capacitor C_1, JFET is maintained in a closed state until the next part of the cycle where it passes into the on-state and consequently the whole process is repeated. The voltage on the capacitor C_1 is at the same time output voltage of the converter as a whole.

2) As soon as the switch-off starts a voltage pulse appears on the primary winding, which charges the capacitor C_2. This is due to the drop of magnetizing current and subsequent collapse of the magnetic field in the transformer core.

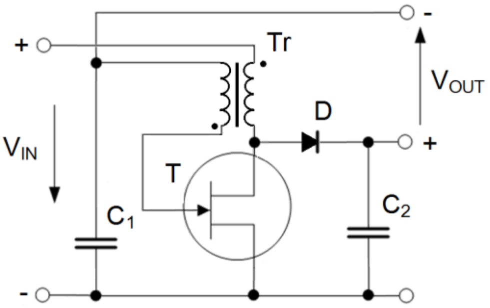

Fig. 3: Single J-FET DC to DC converter with increased output voltage

With optimal settings of the circuit the positive voltage on capacitor C_2 has approximately the same size as negative voltage on capacitor C_1. The output voltage can therefore be approximately twice as large. At the same time, there will be a slight increase in efficiency. At high current consumption, however, the output voltage decreases rapidly.

It was verified that the circuit can operate in a large range of frequencies. The working frequency of the circuit is determined by the transformer. To ensure high efficiency, it is necessary that the transformer should minimize leakage inductance.

At low frequencies, the switching losses are small but the transformer is bulky and it is a problem to achieve a small leakage inductance.

Using a toroidal transformer with a diameter of 8 mm the operating frequency of the circuit was 700 kHz. In this case, the efficiency has been limited by dynamic losses on the switch (JFET) and on the diode D.
To ensure high efficiency the transformer must have minimal leakage inductance. To limit the impact of dynamic losses the operating frequency of 100 kHz should not be exceeded. Here it is necessary to find a compromise between the size of the inverter and its effectiveness. Start-up voltage could be much lower by higher transformer ratio and/or when using the transistor with lower threshold voltage. In both cases however the energetic efficiency of the circuit drops.

Low current performance

After interruption of the oscillation, the inverter is temporarily blocked by a negative voltage on the capacitor C_1. Then the voltage on the capacitor gradually decreases, thus enabling the inverter to start again. However, if the voltage at the collection capacitor (V_{IN}) does not rise above the start voltage, the drive current taken in the quiescent state may prevent further voltage increase on the collector capacitor and the inverter will not start.
This situation can be avoided by modifying the described inverter according to Figure 4.
Here, the supercapacitor or the battery is used instead of the collector capacitor C_1, so its voltage does not change after the oscillations end. The inverter is therefore permanently in a locked state. The starting impulse with a repeating interval adjustable within a few seconds is used to start the converter.
The energy to generate start-pulses is taken from an auxiliary source using the diode and the capacitor C_2 that is powered by the energy stored in the transformer core when the transistor T_1 switches off. The starting impulse is produced by charging the capacitor C_3 when the transistor T_2 is switched on.

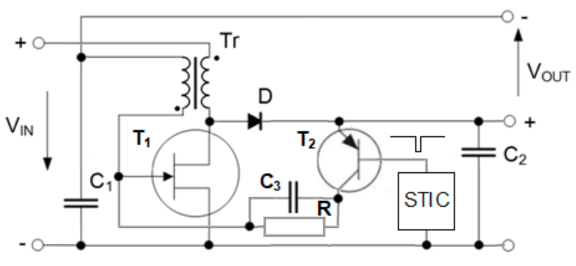

Fig. 4: Low voltage converter with improved low-current performance

The control pulses for this transistor are derived from the start-timing-circuit STIC. Resistor R connected in parallel with C_3 ensures that the "starting capacitor" C_3 is before each starting cycle discharged to zero voltage. The charge transmitted in each trigger pulse is therefore determined by the value of the capacitance of the "starting capacitor" C_3 and the voltage difference between capacitors C_1 and C_2.

CONCLUSIONS

When the efficiency is not the most important parameter single-cells can be cost-effective in many applications. Comparison of the properties of photovoltaic cells made by different technologies shows that for the intended application there are most advantageous inorganic thin film cells. It is very important to consider the operating conditions in which EH will work and adapt these conditions to the selection of the photovoltaic cell. Because of very small area of the cell needed for the low energy EH converters the price of the photovoltaic cell is not an important item in the total cost of an EH converter.
DC to DC converter able to operate from the voltage of few tenths of Volt was designed for this purpose. The output voltage could be in the level of several Volts and achieved efficiency of the apparatus is approximately 50%, but it could be possible to increase it in further optimization, particularly in the design of the transformer. Using the start-timing-circuit helps to extract the power from the photovoltaic cell even in the case of very low illumination.

ACKNOWLEDGMENTS

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