World Academy of Science, Engineering and Technology
International Journal of Energy and Environmental Engineering
Vol:18, No:11, 2024

Hybrid Energy Harvesting System with Energy Storage Management

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Abstract**—**In recent years, the utilization of supercapacitors for energy storage (ES) devices that are designed for energy harvesting (EH) applications has increased substantially. The use of supercapacitors as energy storage devices in hybrid energy harvesting systems allows the miniaturization of electronic structures for energy storage. This study is concerned with the concept of energy management capacitors – supercapacitors and the new electronic structures for energy storage used for energy harvesting devices. Supercapacitors are low-voltage devices, and electronic overvoltage protection is needed for powering the source. The power management device that uses these proposed new electronic structures for energy storage is better than conventional electronic structures used for this purpose, like rechargeable batteries, supercapacitors, and hybrid systems. A hybrid energy harvesting system with energy storage management is able to simultaneously use several energy sources with recovery from the environment. The power management device uses a summing electronic block to combine the electric power obtained from piezoelectric composite plates and from a photovoltaic conversion system. Also, an overvoltage protection circuit used as a voltage detector and an improved concept of charging supercapacitors is presented. The piezoelectric composite plates are realized only by pressing two printed circuit boards together without damaging or prestressing the piezoceramic elements. The photovoltaic conversion system has the advantage that the modules are covered with glass plates with nanostructured film of ZnO with the role of anti-reflective coating and to improve the overall efficiency of the solar panels.

Keywords**—**Supercapacitors, energy storage, electronic overvoltage protection, energy harvesting.

I. Introduction

THIS paper presents a concept of hybrid energy harvesting system as well as the energy storage management. The usually energy storage systems include rechargeable batteries [1], supercapacitors [2]-[4], and hybrid systems [5], [6]. The use of supercapacitors, which allows high energy storage, can be a solution for powering the Internet of Things (IoT) devices and also autonomous devices, e.g. wireless sensor arrays. Using the supercapacitors allow miniaturized constructions of the electronic structures for energy storage. In this paper, we will use the new electronic structures for energy storage by using the concept of energy management capacitor – supercapacitor type [7], [8] and with electronic module of overvoltage protection. The new energy harvesting systems based on new materials, which uses DC/DC converters, are presented in [9]. As a source of electrical energy, a photovoltaic conversion system and piezoelectric composite plates are used. But a photovoltaic conversion system, used as a source of electrical energy, can provide different voltage levels depending on the lighting levels [10], [11]. The electronic circuit for energy storage with supercapacitors can act as a buffer zone, so that it can power IoT devices and/or sensors with a wireless transmitter for all lighting levels of photovoltaic conversion system.

II. Energy Harvesting Sources

A. Energy Source with Piezoelectric Composite Plates

For the round piezoelectric materials (PZT) having 15 mm in diameter and fabricated on a 20 mm brass disk, a semi-flexible composite matrix structure was adopted. In Fig. 1 a general electrical scheme is presented, only 5 PZT elements are shown on a single row, for 9 elements connections are similar.

The long composite plate effectively uses both piezoelectric and pyroelectric effect, with the same material, because it is composed of piezoceramic elements (1) glued on brass discs (2) with the role of mechanical contact, see Figs. 2 and 3, vibration amplifiers and to achieve a temperature gradient. Two printed circuit boards (PCB), each with a thickness of 0.4 mm, are attached together by using small pop rivets and by using a plastic spacer having the same thickness as round piezoceramic elements, 0.6 mm. The plastic spacers with 21 mm and 16 mm round holes, where piezoceramic elements are inserted, have the same thickness (as piezoceramic elements) in order not to damage or prestress the piezoceramic elements. Each PCB board has a double layer, on the inner parts the round copper contact masks were printed on an Ultra Violet (UV) flatbed printer, and then the outer copper layer was corroded. The round copper contacts are directly attached to each piezoceramic element by pressing the two PCB plates together. The boards are at least five times longer than their width, on the bottom side having copper contacts for piezoelectric parts and electrical connections (6) with the outer side for modules (5) with two Schottky type SMD rectifier diodes, all rectifier bridges are connected in parallel, at connections (7), to increase the total rectified current. The plastic plate and PCB sheets are disposed with four holes (9) around the piezo disk for fixing the copper

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Funding: This research was funded by the Ministry of Research, Innovation and Digitization, Romania, the research and development grant PN23140102 "High efficiency and reliability equipment used for propulsion, power supply, storage and energy management in the field of electric mobility", the contract 42N/2023. The authors sincerely appreciate the financial support.

contacts and to stop it from moving between the contacts. The only disadvantage of the composite board is the rivets fastening system itself, because it brings extra rigidity to the board (see 5), but even so the electrical connector pad (6) between upper and lower layers cannot be eliminated in this configuration. The only solution to preserve the configuration is to use PCB boards as thin as 0.2 - 0.4 mm, rivets smaller than 2.4 mm in diameter and even longer PCB plates.

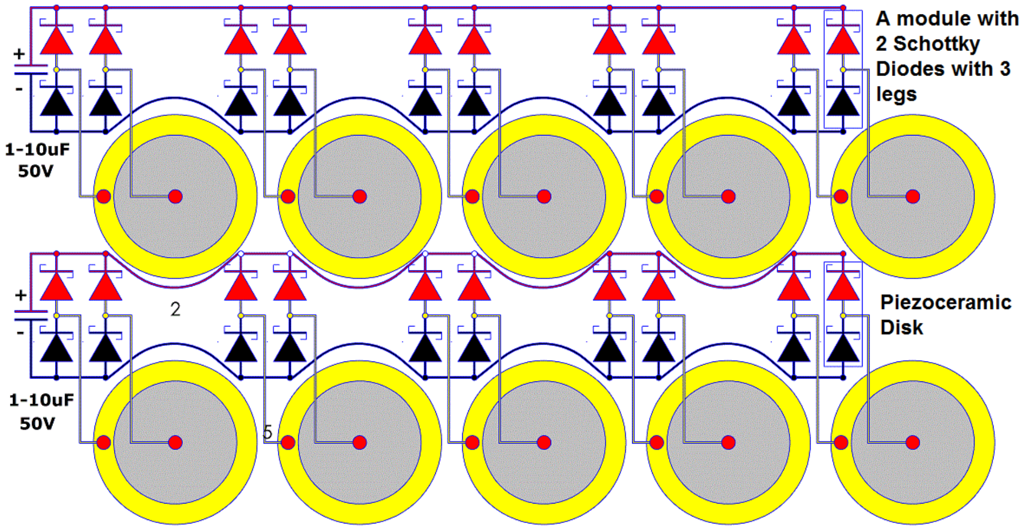

Fig. 1 Electrical scheme of 210 mm in length composite PZT plate

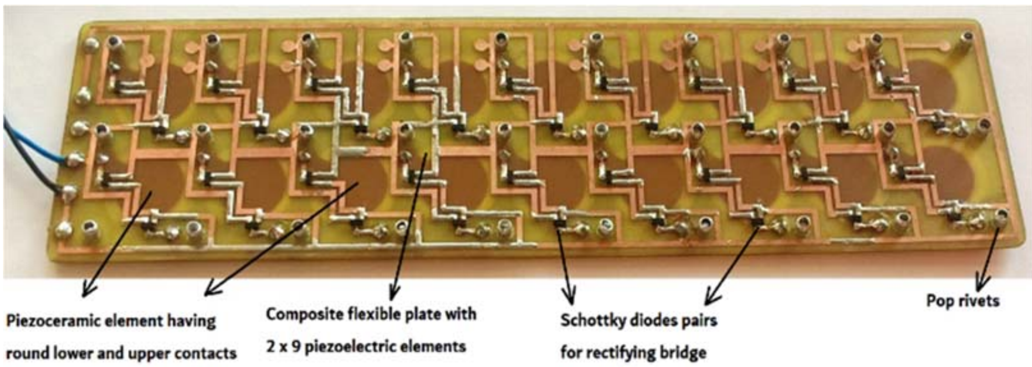

Fig. 2 Composite plate 210 mm in length encapsulating a matrix of 2 x 9 piezoceramic elements, each having 20mm in diameter

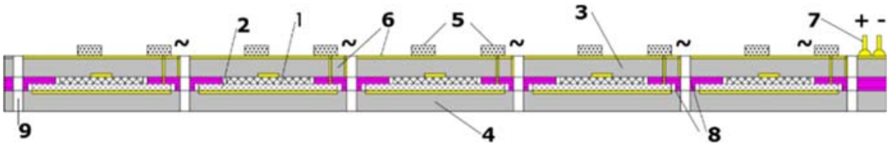

Fig. 3 Lateral view of the piezoelectric composite plate

TABLE I
COMPOSITE PZT PLATE CHARACTERISTICS

Composite Plate with 2 x 9 PZT elements	Applied Force Average (< 1N)	Applied Force Maximum (> 1N)
Measured Voltage [V]	17.2	23
Measured current [µA]	80	214
Generated Power [mW]	1.37	4.92
Total Capacitance [nF]	500	1140

From the plate with 18 PZT elements we can extract a maximum power of 5 mW, the construction is optimal when the length is maximum 250 mm for 9 piezoceramic elements, 20 mm in diameter each, placed in a single row. The maximum composite plate thickness is 1.4 mm, without considering the surface-mounted devices (SMD) diodes type. The maximum obtained voltage for an applied force greater than 1 N is 23 V_{DC} and a 220 µA rectified current, see Table I.

It is observed from experiments that a single 15 mm PZT with 20 mm brass disk placed in the center of the plate can generate a maximum current of 20 microamps and an average voltage of 7 V. Two piezoceramic disks connected in parallel at the center can generate approximately a double voltage 11-16 V and a current of 30-35 microamps.

B. Energy Source with Photovoltaic Conversion System

An electrical energy generation system through photovoltaic conversion, with anti-reflective coating with nanostructured film of zinc oxide (ZnO), is used for Energy Harvesting applications, respectively for the supply of electrical energy to consumers in isolated locations, [10].

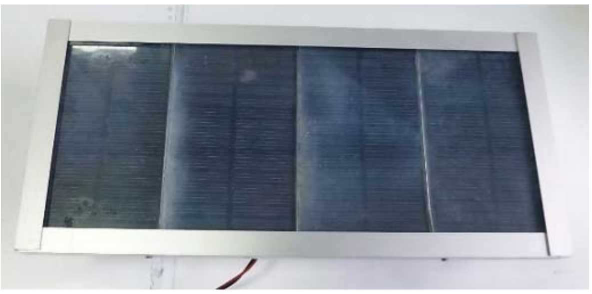

Fig. 4 Photovoltaic conversion system

Photovoltaic conversion system, Fig. 4, has the active part made up of 4 polycrystalline Si photovoltaic modules having 36 cells connected in series (the surface of one cell is 3.42 cm^2). The modules are covered with glass plates with nanostructured film of ZnO with the role of anti-reflective coating [10], [11]. For the photovoltaic conversion system, the following functional parameters were taken into account: the efficiency of converting solar energy into electricity and the power generated by the photovoltaic system for different values of solar radiation. The solar panel characterization was performed on SIM 3C HIGHLIGHT PASAN solar simulator and was determined the efficiency and output power for different irradiation namely for standard test conditions, 1000 W/m^2, as well as for lower solar radiation values, 700 W/m^2, 400 W/m^2, 200 W/m^2 and 100 W/m^2.

In this study, it was used a commercial polycrystalline silicone solar cell (*Conrad Electronic SE*) and covered with a glass with nanostructured ZnO obtained by chemical method for improving the efficiency and power. Technical data for polycrystalline solar panel (123 cm^2) are: output power 1.35 W, nominal voltage 9 V, open circuit voltage 10.5 V and short-circuit current 150 mA, Fig. 5.

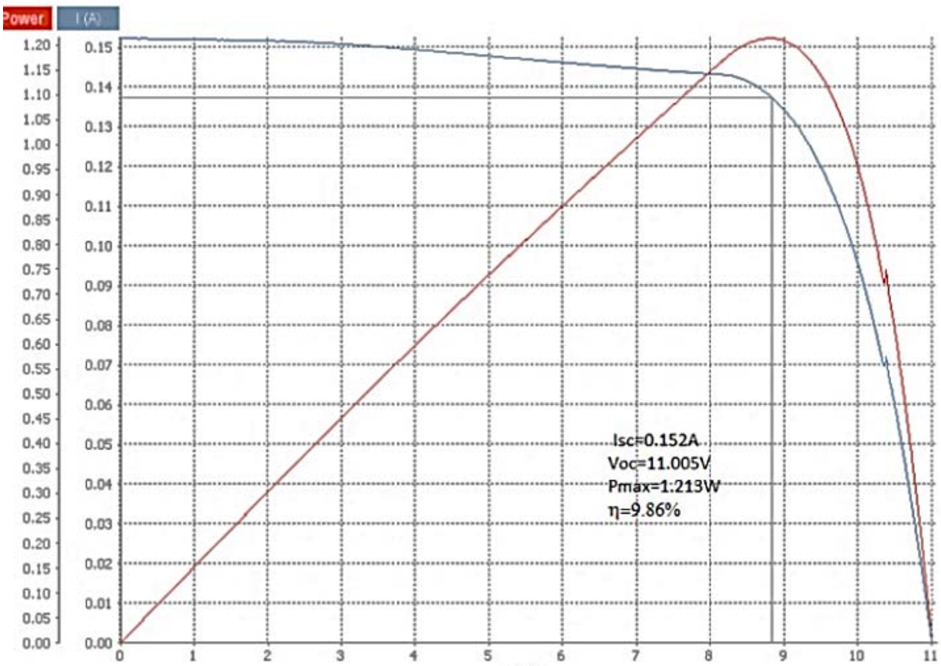

Fig. 5 Technical data for polycrystalline silicone solar cell (*Conrad Electronic SE*)

By using an anti-reflective coating in the form of a ZnO nanostructured film, the functional parameters of the photovoltaic generation system at reduced values of solar radiation were improved, [11], namely solar energy conversion efficiency:

(a) of 8.06% for solar radiation of 100 W/m^2 (0.27% improvement compared to the known simple glass covered system);
(b) of 8.44% for solar radiation of 200 W/m^2 (improvement by 1.08% compared to the known simple glass covered system);
(c) of 8.95% for solar radiation of 400 W/m^2 (improvement by 1.25% compared to the known simple glass covered system);
(d) of 9.2% for 700 W/m^2 (improvement by 1.67% compared to the known simple glass covered system);
(e) of 9.26% for solar radiation of 1000 W/m^2 (improvement of 0.04% compared to the known simple glass covered system).

The power generated by the photovoltaic system is:

(a) of 0.109 W for solar radiation of 100 W/m^2 (improvement of 0.0047 W compared to known simple glass covered system);

(b) of 0.208 W for 200 W/m^2 solar radiation (improvement of 0.27 W compared to the known simple glass covered system);

(c) of 0.451 W for solar radiation of 400 W/m^2 (improvement of 0.265 W compared to the known simple glass covered system);

(d) of 0.814 W for the solar radiation of 700 W/m^2 (improvement of 0.147 W compared to the known simple glass covered system);

(e) of 1.139 W for solar radiation of 1000 W/m^2 (improvement of 0.005 W compared to the known simple glass covered system).

C. The Summing Electronic Block

The electronic design of the summing electronic block, Fig. 6, is achieved by using analog integrated circuit AMP 03 type, instrumentation operational amplifier from Analog Devices, [7]. This operational amplifier is used in specific connection of summing.

At the exit V_{OUT}, Fig. 6, it obtains the sum of all two signals that are applied to the inputs, i.e. from piezoelectric composite plates and from photovoltaic conversion system. By introducing a summing electronic block, as part of hybrid energy harvesting system, can effectively take power from two sources of energy, simultaneously.

III. Concept of Energy Management Designed for Energy Harvesting Applications

Using only supercapacitors for energy storage can be a solution for power supply the regular consumers.

A. The Electronic Circuit of Energy Storage with Supercapacitors

The electronic diagram circuit for storing energy with supercapacitors is shown in Fig. 7. Four supercapacitors arranged in parallel with the value 0.1 F are used, which are equivalent to a supercapacitor with the value of 0.4 F. They are arranged at the output of a regulator of type LM 1117T, of Texas Instruments production [12], which provides at the output a voltage of 3.3 V_{DC}. Diode D1, Fig. 7 has the role of directing the current from the output of the linear regulator only to the consumer.

Fig. 8 presents the practical implementation of the energy storage electronic circuit with supercapacitors.

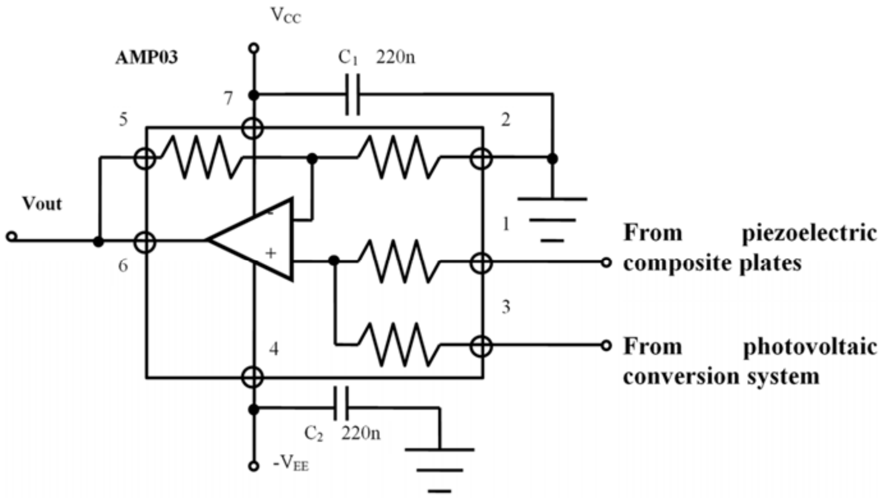

Fig. 6 The electronic design of the summing electronic block

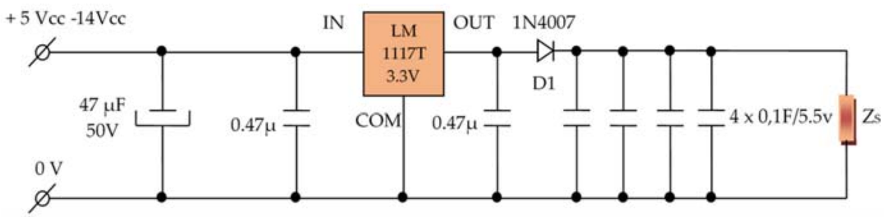

Fig. 7 Electronic diagram of the electronic circuit of energy storage with supercapacitors

The electronic circuit of energy storage with supercapacitors can power IoT devices and/or sensors with a wireless transmitter for lighting levels with a corresponding input voltage of over +5Vcc.

B. The Concept of Energy Management Type Capacitor – Supercapacitor

The electronic circuit of energy storage by using the concept of energy management capacitor – supercapacitor allow of powering IOT devices and/or sensors with a wireless transmitter for all lighting levels of photovoltaic conversion system. An energy storage device is required to capture the energy when available and power the application when needed. Most ambient energy harvesting systems also produce very low current and variable voltage, which energy storage devices can address by serving as an "energy buffer" to provide the voltage and current needed by the load. Because the state of charge of the storage capacitors will fluctuate between various partial levels of charge, is necessary an energy management system. The concept of the energy management capacitor – supercapacitor system is presented in Fig. 9. It contains two energy storage elements. Firstly, short-term energy storage buffer is realized by capacity C1, 0.47 mF, Figs. 9 and 10. This capacitor must have a low leakage current and a low resistance. A good solution is a solid tantalum capacitor. Secondly, long-term energy storage element is realized by capacity C2, 0.5 F, Figs. 9 and 10. This capacitor must have also a very low leakage current, high internal resistance and depending on technology, features low nominal voltage between 2.7 V and max 5.5 V, Table II. A good solution is a supercapacitor, C2 = 0.5 F and nominal voltage U = 2.7 V. A circuit to interface two energy harvesting sources, like photovoltaic conversion system and piezoelectric composite plates to a supercapacitor as seen in Fig. 9, should respect three conditions:

1) Maximum power tracking, maintaining the output voltage or current of the energy-harvesting source so it delivers the maximum possible power;
2) Overvoltage protection, to ensure the supercapacitor-rated voltage is not exceeded;
3) Active balancing to maintain the supercapacitor cells at the same voltage with a low-current circuit.

It stores harvested energy in an external storage capacitor. Thus, it can be used as a supercapacitor. The supercapacitor's high energy storage and high-power delivery make it a good choice to buffer a high-power load from a low-power, energy-harvesting source.

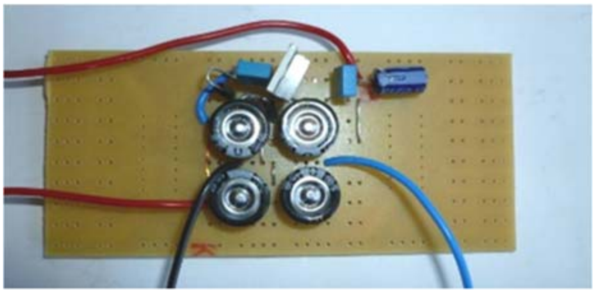

Fig. 8 The electronic circuit of energy storage with supercapacitors, practical implementation

TABLE II
CHARACTERISTICS OF SUPERCAPACITORS

Capacitor type	Manufacturer	Capacitance [F]	Leakage after first 100 hours charge [nA]	Voltage max [V]	Max.charge/discharge current [mA]
DBS-3R6D334T	ELNA Dynacap	0.33	200	3.6	72
DXS-R6V/H334U	ELNA Dynacap	0.33	200	3.6	72
DBS-3R6D224T	ELNA Dynacap	0.22	180	3.6	66
DXS-R6V/H224U	ELNA Dynacap	0.22	180	3.6	66
FCOV224ZFTBR24	NEC Tokin Supercap	0.22	500	3.5	0.2

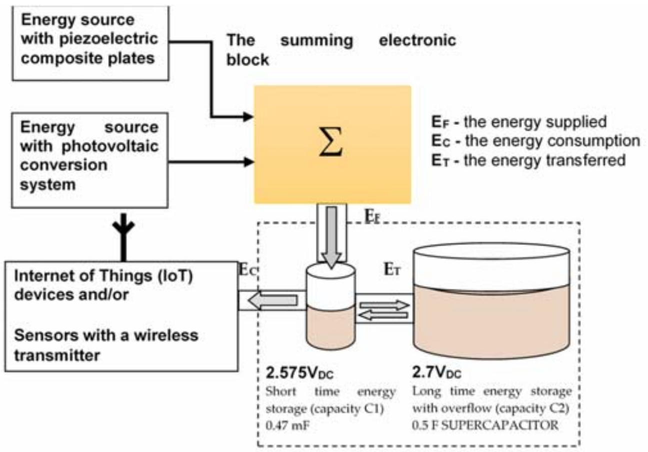

Fig. 9 The concept of energy management system, capacitor – supercapacitor type [7], [8]

The energy storage devices C1 and C2 provide "instant-on" capability, rather than waiting to harvest sufficient energy before the system can operate, which can take seconds or up to several minutes when charging a supercapacitor. In Fig. 10 is presented the electronic design for the charging C1 and C2 capacitors. Charge switcher is the PMOS transistor Q1, Fig. 10.

The block ∑ from Figs. 9 and 10 is the summing electronic block presented in Section II *C*. This block can have more than two inputs, but in our case only two inputs were shown, one to gather the signal from the piezoelectric composite plates and one to gather the signal from the photovoltaic conversion system.

The charge switcher connects both short-term storage and long-term storage parallel to the energy source. Supposing V_{DD} then falls below Von = 2.7 V, Fig. 10, the energy source will be switched back to short-term storage alone, for faster recharging. As long as the voltage on long-term storage remains below Von, the charge switcher will continuously switch the energy source between short-term and long-term storage, trying to ensure continuous device operation. That is because of the higher resistance and capacitance of long-term storage, which would lead too much too long charging. In addition, short-term storage cannot be charged over this threshold until the voltage on long-term storage exceeds Von = 2.7 V.

C. Overvoltage Protection as Voltage Detector

Supercapacitors are low-voltage devices, so most of the time several devices must be connected in series to achieve a working voltage needed for an application. Overvoltage protection as voltage detector, Fig. 11, is implemented by the rail–to–rail input and output bipolar low voltage operational amplifier, dual AD 8527 from Analog Devices [13].

The first operational amplifier U1A realizes a comparator with hysteresis [13], electronic circuit and second U1B, a unity gain buffer, Fig. 11. In case of exceeding the voltage limit of 2.7 V, Fig. 12, it is possible to damage the supercapacitor, having as the consequence that as long-term energy storage to no longer be functional. As soon as the voltage on D2 anode or the voltage detector input exceeds the selected threshold, the voltage detector delivers a high level on its output connected to the Q2 emitter through D1, Fig. 10. The Q2 base is consequently lower polarized than its emitter and the transistor is turned off. That means Q1 is turned off to the energy source is switched off and long-term storage is protected, Fig. 10.

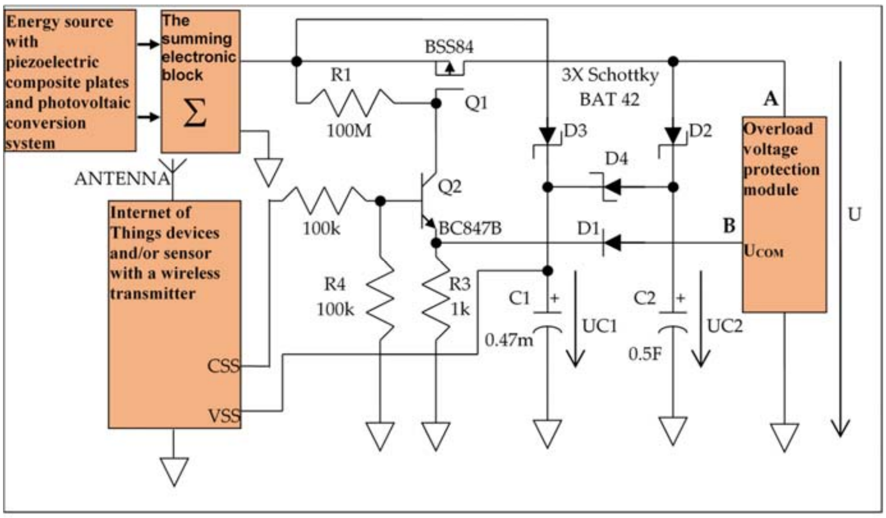

Fig. 10 The electronic design for the charging C1 and C2 capacitors [8]

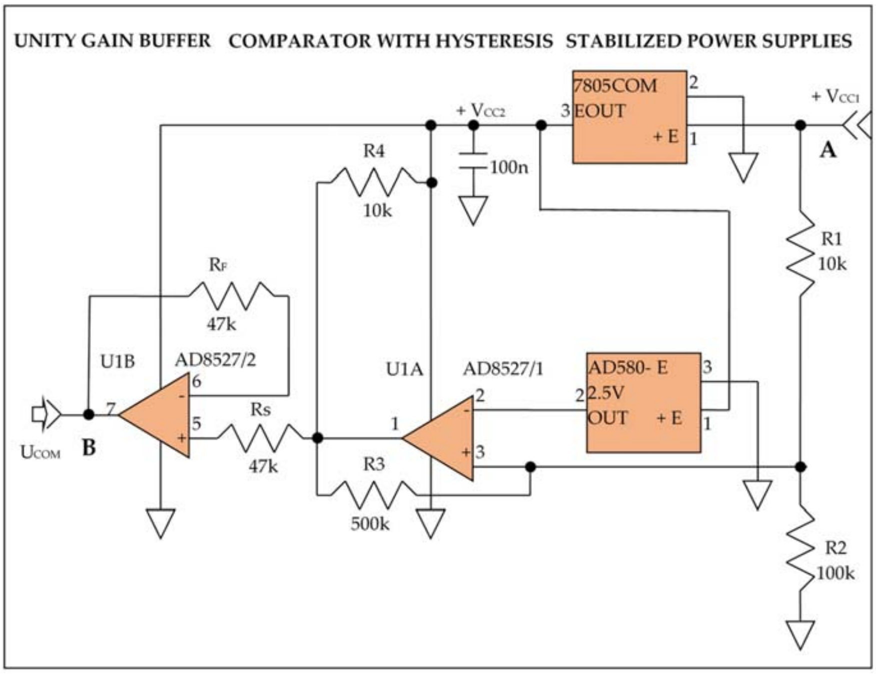

Fig. 11 The overvoltage protection, electronic module design

The selected voltage detector must have a very low quiescent current in the operating range, and an appropriate threshold voltage, corresponding to the selected long-term energy storage voltage. We have, Fig. 11:

$$V_H = 2.5V\left(1+\frac{R_1}{R_2}+\frac{R_1}{R_3}\right)=2.7V \quad (1)$$

$$V_L = 2.5V\left(1+\frac{R_1}{R_2}-\frac{R_1(5V-1.3V)}{2.5V(R_3+R_4)}\right)=2.575V \quad (2)$$

The +2.5VDC is realized by AD 580 Analog Devices high precision voltage reference, [14], which provides a fixed 2.5 V output for inputs between 4.5 V and 30 V, Fig. 11.

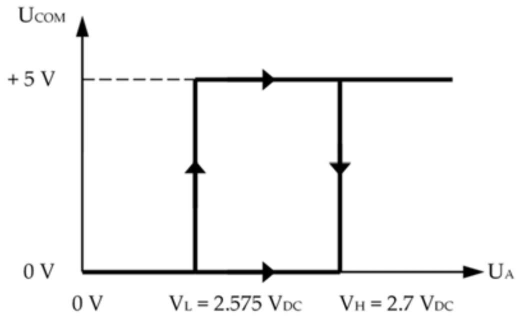

Fig. 12 Voltage command, U_{COM}, at the fail comparator with hysteresis, depending on the voltage U_A

IV. Conclusions

This paper presents a concept of energy management designed for energy harvesting applications that use the supercapacitors for energy storage. Because the energy source is represented by a photovoltaic system, the voltage is set by the lighting level. But, the powering of the consumers like IoT devices and also autonomous devices, e.g. wireless sensor arrays, requires a constant voltage, regardless of the energy required for data transmission. One solution may be to use supercapacitors in tandem with a stabilized linear low drop voltage source. This solution is only valid for the case when the photovoltaic system is irradiated with a higher degree of illumination than the one corresponding to the minimum supply voltage of the stabilized linear voltage source. In the case when the piezoelectric composite plates are bended by applying a force over 0.5 N the resulted voltage will be higher enough, over 5 V, to supply the linear voltage source.

In the case when two or more 2.7 V rated supercapacitors are connected in series the LM1117T linear voltage source can be replaced by MAX666 voltage regulator. The long composite piezoelectric plates will keep the elasticity and the degree of freedom for each piezoelectric disk, because neither of upper or lower contacts are glued to them and the electrical and mechanical contact is realized just by pressing these two PCB plates together, with the help of the small pop rivets. The plastic foils used as spacers with 21 mm and 16 mm round holes, where piezoceramic elements are inserted, have nearly the same thickness (as piezoceramic elements) in order not to damage or prestress the piezoceramic elements.

A summing electronic block is used to combine the electric power obtained from piezoelectric composite plates and from a photovoltaic conversion system. Over a commercial polycrystalline silicone solar cell (Conrad Electronic SE) is superimposed a glass covered with nanostructured ZnO obtained by a chemical method, with the role of anti-reflective coating, for improving the efficiency and power.

The concept of energy management capacitor – supercapacitor is using a short-term energy storage and also long-term energy storage. By using this concept electronic devices can be created to power consumers regardless of the lighting level of the photovoltaic system. The use of supercapacitors most often involves the use of an electronic circuit overvoltage protection as voltage detector type.

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