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# SUPERCAPACITORS IN STAND-ALONE PV SYSTEMS WITH INSTANTANEOUS HIGH OUTPUT ENERGY PULSES*

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Supercapacitors (SCs) as the energy storing devices find their way into contemporary electrical power engineering. While exhibiting certain properties of the batteries, they are distinguished by the ability of rapid charging and discharging as well as by the much higher durability and maintenance-free operation. The possible application range includes automotive systems, self-contained and mains-free energy sources as well as pulsed operation. This work is especially focused on the stand-alone photovoltaic (PV) systems fitted with batteries, but designed to periodically supply instantaneous energy pulses, which cannot be provided by the battery itself owing to its high internal resistance. Another subject matter of this work are the PV systems fitted with the supercapacitors, only. The paper discusses special methods of assembling the series supercapacitor banks in order to obtain elevated voltages. These methods consist in using sophisticated circuits, whose role is to ensure proper charging and discharging processes. The role of stabilising DC/DC and DC/AC output voltage of inverters used under changing supercapacitor voltage conditions is explained. The results of investigations are presented for the single and 6 - unit 3000 F 2.7 V supercapacitors. Some results were obtained and verified by means of the MATHCAD software. Practical solutions of ancillary electronic circuits are demonstrated.

***Keywords:*** supercapacitor, PV system, high energy pulse, voltage equalisation

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## 1. INTRODUCTION

Supercapacitors as the components extensively used in contemporary power engineering begin to play more and more important role because of their certain parameters, which cannot be imitated by other known electric devices. The main properties of the supercapacitors are connected with their very low internal resistance as the energy source, which also enables fast charging processes when using very high instantaneous current values. In comparison with even the best battery types, the supercapacitors may withstand up to a million full charging/ discharging cycles, which is ten times more than in case of the popular lead acid batteries. The most significant feature of the supercapacitors is their extremely large electric capacity, exceeding several thousands of Farads per unit at rather very low working voltage of the order of 3 volts. As a rule, this voltage of little practical use can be increased by connecting in series several supercapacitors, possibly of the same capacitance, thus creating the series capacitor bank. The resulting value of capacity of the bank decreases $n$ times, while the working voltage increases $n$ times, where $n$ is the number of supercapacitor units. This common method appears not to be simple in practice owing to certain safety measures and devices necessary to realise such series connections. Like in case of the batteries, it is not advisable to connect the supercapacitors in parallel in order to increase the capacity and stored energy.

The properties of supercapacitors, resembling those of conventional batteries and often much better, make them suitable for energy storing in some PV systems, as battery replacement. The maintenance-free and durable supercapacitors, though still expensive as the novel market products, may appear irreplaceable in certain types of PV systems for special applications, where the battery weight and system size offering similar effects from an energy standpoint would be less efficient and much more expensive.

Another interesting option is the energy storing unit, made of a battery and a supercapacitor connected in parallel, offering more significant reduction in the battery size and weight.

Generally the most appropriate application for a charged supercapacitor is utilising its energy in form of periodical instantaneous high power pulses, sufficient for generating the necessary amount of energy. Here, the welding process carried out periodically can be given as an example of the most typical application. Such a process is typically characterized by the very high power pulses of short duration, while the average welding power consumption is several orders lower compared to that delivered by even a small PV system. Similar effects characterise the pulsed laser devices, radar equipment, blinking warning light sources, sea signalling buoys, temporary radio pulsing signals etc. At present, very many solutions, though not purely pulsed-type, are applied in automotive engineering.

It is necessary to especially emphasise that all these items have to do mainly with the circumstance, where there is neither any access to the utility electrical grid practically offering unlimited energy quanta nor large and expensive battery units fed by PV modules, withstanding instantaneous peak power levels.

## 2. PROPERTIES AND FEATURES OF SUPERCAPACITORS

The SCs are components based on the same principle as all other capacitor types i.e. consist of two conducting plates separated by a solid or liquid dielectric. Their capacity is directly proportional to the electrode surface and dielectric constant and inversely proportional to the distance between the plates. A continuous progress in the capacitor construction began in 18th century and have resulted in the invention of the supercapacitor owing to the high technology methods, greatly influencing the parameters of four main capacitor elements. The development of SCs in 1960 was preceded by similar electrolytic capacitors, still widely used. At present, the SCs withstand a -40°C to +65°C temperature range, are hermetically sealed, robust and durable. As the nature of the SC parameters does not differ from that of the parameters common to all capacitors (Fig. 1.), all well-known mathematical equations applicable to the precedent low and medium capacity ranges apply to the SCs.

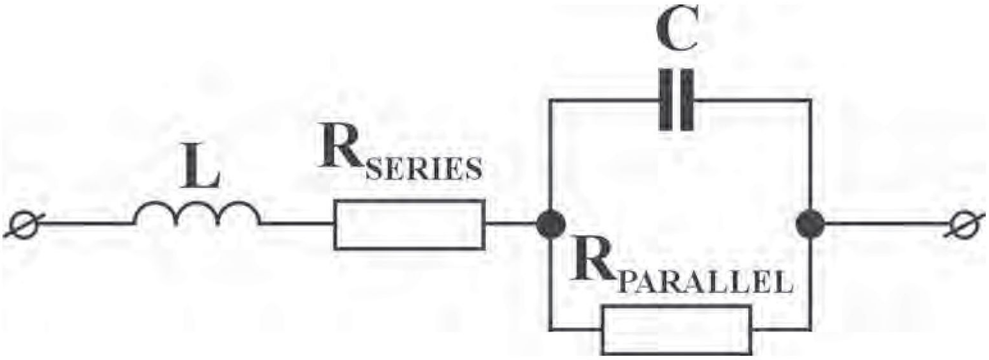


**Fig. 1.** Basic equivalent circuit of a capacitor.
**Rys. 1.** Podstawowy układ zastępczy kondensatora.

Especially important are the equations describing the capacitor discharge voltage-time characteristics:

$$U_C = U_O e^{-\frac{t}{RC}} \tag{1}$$

and capacitor charge voltage-time characteristics:

$$U_C = U_O\left(1 - e^{-\frac{t}{RC}}\right) \tag{2}$$

and charge stored in a capacitor:

$$Q = \frac{1}{2} C U_C^{2} \tag{3}$$

Owing to extremely high capacitance values of a SC of the order of many thousands of Farads, there exist in practice no capacitance meters. Thus, the capacitance is determined mainly by means of equation 1 while discharging an SC through a fixed resistor R of known resistance.

As there is no capacitance meter capable of measuring large capacitances, both mathematical and computer-aided calculation methods were tested during Authors' investigations carried out on a single SC as well as on the series supercapacitor banks. The effects and effort appeared to be similar, though each of the methods needed rather a large amount of time to be accomplished.

The value of capacitance can be determined manually by applying the voltage values measured at t=0 and after an exactly set period of time to the equation. This process can also be automated by using computer-aided methods, which not only enable one to draw and store the complete discharge characteristics but also to observe existing slight capacitance dependence on applied voltage (Fig. 2).

The problems already mentioned in the introduction concerning generally building the series SC banks have several technical aspects. The main of them is the equalisation of working voltages across each capacitor in the bank, as the excessive voltage even across one component threatens to destroy the entire bank. The dange-

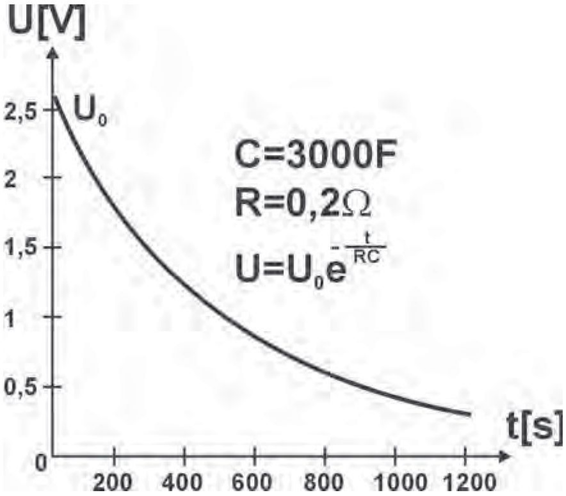


**Fig. 2.** Exemplary computer graph of a SC discharge U = f(t) curve, calculated and drawn with MATHCAD software.
**Rys.2**. Przykładowy wykres komputerowy funkcji rozładowania U = f(t) superkondensatora, sporządzony za pomocą programu MATHCAD.

rously excessive voltages across certain SC units constituting the series bank may occur not only while charging, but also during rapid discharging processes. The well-known passive method of connecting the capacitors in parallel with resistors, all of the same value, appears to be inadmissible, because of excessive power losses due to the extreme capacities and low time constants (Fig. 3).

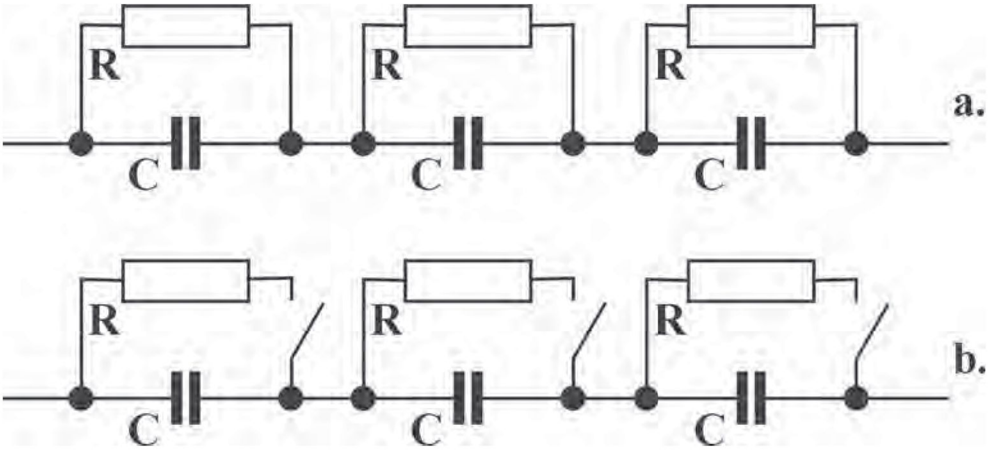


**Fig. 3.** Standard (a) and improved (b) methods of SC voltage equalisation [1].
**Rys. 3.** Metody konwencjonalna (a) i ulepszona (b) symetryzacji napięcia [1].

An improved method consisting in temporary use of switches also is not too attractive because of the necessity to control electrically the voltage across SCs and to switch appropriate contacts. Recently, purely active electronic systems are preferably used (Fig. 4) in the series SC banks. Examples are shown in Figs. 5 - 8.

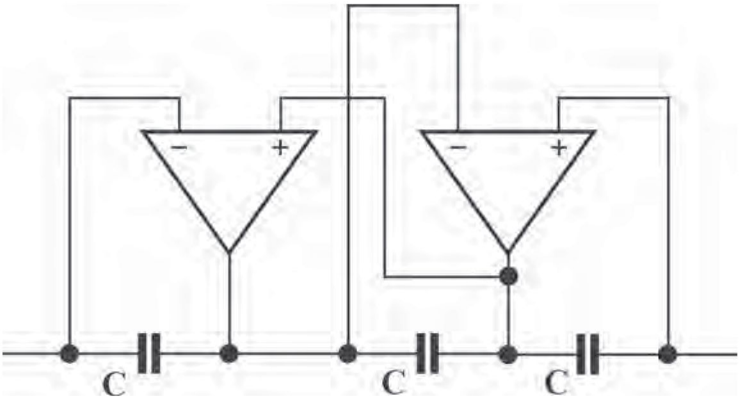


**Fig. 4.** Simplified active balancing method.
**Rys. 4.** Uproszczona aktywna metoda symetryzacji napięć.

During initial tests, the authors fitted the circuit in Fig. 4 with special operational amplifiers of their own design, furnished with high power output transistors. The results were satisfactory except for excessive power consumption of the Op-Amp supplementary components.

The circuit shown in Fig. 5 is mounted on the pair of electrodes of each SC in the bank and controls excessive voltage across it. In Fig. 6, a transformer system of a flyback converter with sectional secondary windings is shown. It privileges these SC units across which the lowest voltage appears.

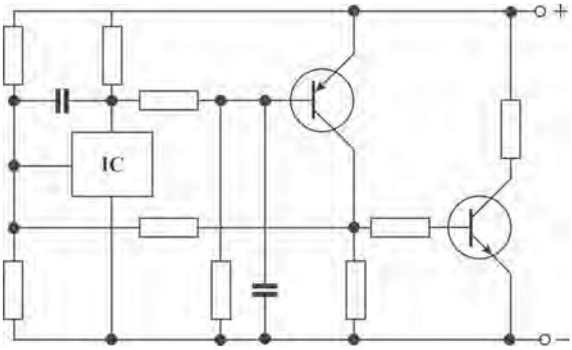
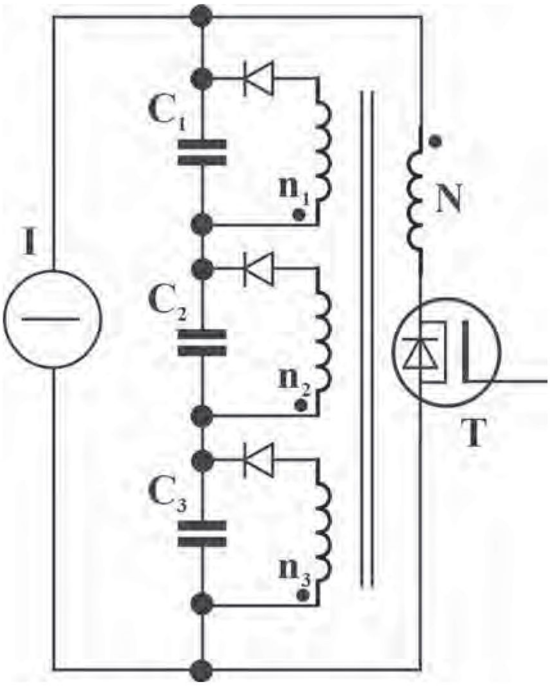


**Fig. 5.** Exemplary circuit for reduction of excessive SC voltage [1].
**Rys. 5.** Przykładowy układ elektroniczny do redukcji nadmiernego napięcia na superkondensatorze [1].

**Fig. 6.** Equalisation by means of a flyback converter with sectional secondary winding [3].
**Rys. 6.** Symetryzacja za pomocą przetwornicy transformatorowej o dzielonych uzwojeniach wtórnych [3].



The circuit presented in Fig.7 needs no transformer. It is designed for the voltage equalisation on two consecutive SCs by means of the current control.

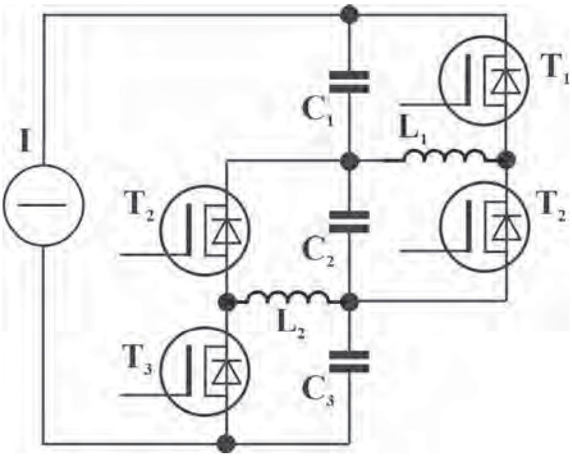


**Fig. 7.** Equalisation by means of buck-boost DC/DC converters [3].
**Rys. 7.** Symetryzacja napięć za pomocą przetwornic obniżająco-podnoszących [3].

Main advantages of the two previous versions are demonstrated in Fig. 8. Here, a power converter is connected to each supercapacitor. The energy stored by an SC with the highest voltage is transferred to the units with the lowest voltage. No energy is stored in the transformer as it is directly transferred.

In practice, the circuits similar to those in Figs. 2, 5, 7 and 8 were initially tested by the authors with satisfactory results. Finally, the idea of Fig. 8 offering the best result has been adopted. As no practical data except for general idea can be found in technical literature [3], all circuit details had to be designed, calculated and tested to fit in with each particular set of supplementary components of the 6 - unit 3000 F series SC bank with an overall voltage of 16.2 V. Except for the multi-winding transformer, the optimum MOSFETs as electronic keys had to be chosen. The SC bank made in this manner fulfilled all technical requirements in final tests.

On the occasion of the tests of Fig. 2, the effect of a small SC capacitance voltage dependence, not exceeding 2% per volt was investigated. It was considered, though unexpectedly, to have little practical influence. An important, but almost forgotten problem is the realisation of high current switches, especially threatened to be damaged during the discharging and charging processes in the SC circuits. Here, the MOS-FETs, as most convenient, though not fully satisfactory, were analysed and underwent testing, on a parallel with mechanical systems.

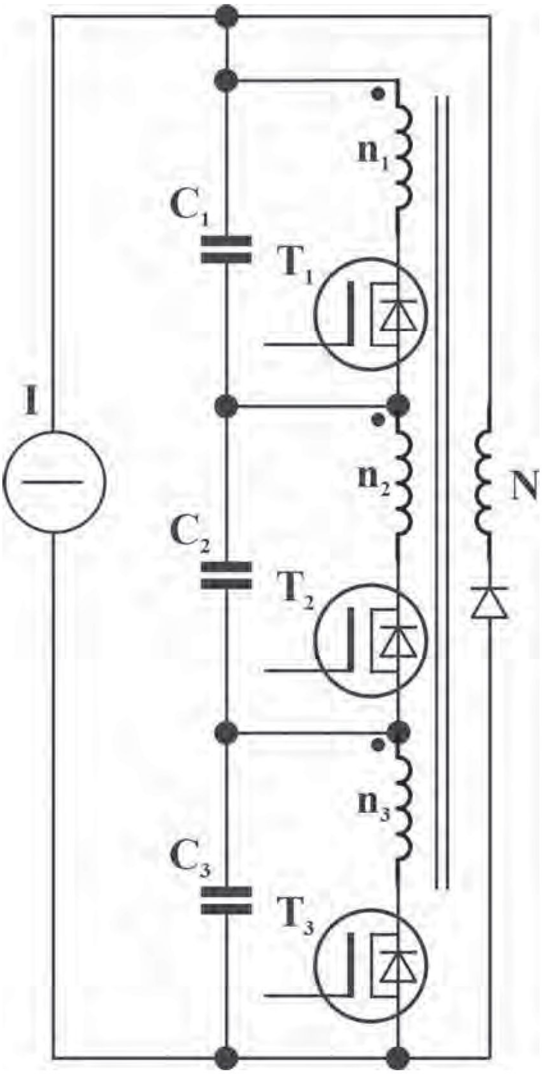


**Fig. 8.** Voltage equalisation by means of a forward DC/DC converter with sectional primary windings [3].
**Rys. 8.** Symetryzacja napięć za pomocą przetwornicy transformatorowej o dzielonych uzwojeniach pierwotnych [3].

An exemplary PV system using instantaneous high energy pulses was improvised by the authors under laboratory conditions. A 100 W PV module directly powered a DC power supply with variable stabilised output voltages from 0-16 V to perform a function of the voltage-controlled power source charging the described 500 F 16.2 V SC bank. The max 100 W electric power, originally produced by the PV system serving as the energy source of the SC bank, was used under repeatable welding conditions in an exemplary way, where instantaneous welding power could be in the order of 1 kW, as well as in intermittently emitted laser pulses of approximately same power (Fig. 9). In both cases, closing period of the switch *S*, whose function was performed by a set of MOSFETs, was electronically adjusted according to the switching time required, as well as the repetition rate.

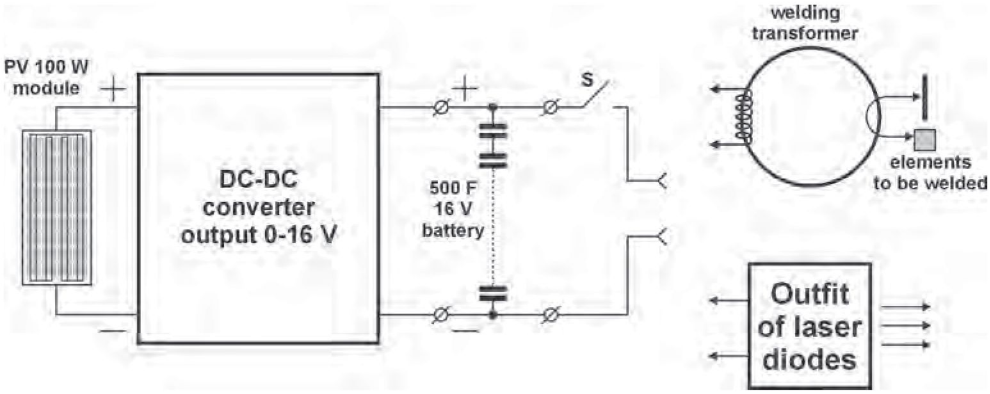


**Fig. 9.** Exemplary PV system utilizing instantaneous high energy pulses from an SC battery for welding and laser purposes (for the sake of simplicity, no components of the capacitor bank equaliser are shown).

**Rys. 9.** Przykład instalacji PV oferującej chwilowe impulsy o wysokiej energii z baterii superkondensatorów, przeznaczonej do zgrzewania lub emisji lasera (dla prostoty nie uwidoczniono elementów symetryzacji baterii).

As the natural run of voltage across a single SC or a SC banks as a function of load and time looks like in Fig. 2, often indispensable are electronic inverter solutions operating as voltage stabilisers of the SC banks. Such approach changes an SC into the constant voltage battery-like device but with the features different from the pulse delivery conditions. This is why this matter has not been discussed here.

## 3. CONCLUSIONS

The ever-growing role of SCs in power engineering compels us to disseminate and practice the SC-related technical knowledge, which has not been advanced very much thus far, while the world energy shortages urge the development of PV sources and advantages offered by them, strongly dependent on the progress in the use of SCs.

## 4. ACKNOWLEDGMENTS

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## 5. REFERENCES

[1] Halper M.S., Ellenbogen J.C.: Supercapacitors: a brief overview, MITRE Nanosystems Group, (2006)

[2] Barrade P.: Series connection of supercapacitors: comparative study of solutions for the active equalization of the voltages, *Electrimacs,* 2002, 18-21 August, Montréal, Canada

[3] Jung, Do Yang: Shield ultracapacitor strings from overvoltage yet maintain efficiency, *Electronic Design*, May 27, (2002)

## SUPERKONDENSATORY W INDYWIDUALNYCH INSTALACJACH PV O DUŻYCH CHWILOWYCH IMPULSACH ENERGII

Superkondensatory (SC) jako akumulatory energii są aktualnie wprowadzane do współczesnej elektroenergetyki. Wykazując pewne cechy konwencjonalnych akumulatorów wyróżniają się one możliwościami szybkiego ładowania i rozładowania, jak i znacznie wyższą trwałością i bezobsługową eksploatacją. Zakres ich zastosowań wiąże się głównie z motoryzacją, ze źródłami autonomicznymi odseparowanymi od sieci, a także z eksploatacją impulsową. Niniejsza praca poświęcona jest szczególnie autonomicznym instalacjom fotowoltaicznym (PV) wyposażonym w akumulatory, lecz przeznaczonym do okresowego, chwilowego dostarczania impulsów energii, niemożliwych do uzyskania z samych akumulatorów z powodu ich za dużej rezystancji wewnętrznej. Obiektem zainteresowań pracy są także instalacje PV wyposażone wyłącznie w superkondensatory. Praca omawia specjalne metody, niezbędne przy formowaniu szeregowych baterii superkondensatorów celem pozyskiwania wyższych napięć. Metody te bazują na specjalizowanych układach, nadzorujących symetryzację napięć w warunkach ładowania i rozładowania. Wyjaśniono rolę stabilizujących napięcie wyjściowe przetwornic DC/DC i DC/AC, stosowanych w warunkach zmienności napięcia superkondensatorów. Przedstawiono rezultaty badań pojedynczego oraz sześciu szeregowych superkondensatorów 3000 F 2,7 V. Niektóre wyniki pozyskano i zweryfikowano za pomocą komputerowego programu MATHCAD. Pokazano praktyczne układy elektroniki, towarzyszącej bateriom superkondensatorów.

***Słowa kluczowe:*** superkondensator, instalacja PV, impuls wysokiej energii, symetryzacja. napięcia