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ПРИЛОЖЕНИЕ НА СУПЕРКОНДЕНЗАТОРИ В ХИБРИДНИ СИСТЕМИ

Владимир Лазаров, Брюно Франсоа, Християн Кънчев,
Захари Зарков, Людмил Стоянов

Резюме. *В доклада са описани приложенията на суперкондензатори в хибридни системи с възобновяеми източници на енергия, както и в други устройства за съхранение на енергия. Суперкондензаторите са подходящи за компенсиране колебанията в мощността на възобновяемите източници на енергия, дължащи се на непостоянния характер на първичния ресурс. Описаните приложения могат да бъдат използвани в много области, като електротранспорт, захранване на електронни устройства и за автономно захранване в отдалечени местности. Представени са също основните параметри на суперкондензаторите и техните еквивалентни схеми.*

APPLICATION OF SUPERCAPACITORS
IN HYBRID SYSTEMS

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Zahari Zarkov, Ludmil Stoyanov

Abstract. This paper presents the applications of supercapacitor energy storage in hybrid systems with renewable energy sources, as well as with other energy storage technologies. Supercapacitors are capable to compensate the power variations of renewable energy sources due to the stochastic nature of the primary resources. These applications can be used in numerous domains, such as electrical transport, power supply to electronic devices and in combination with renewable energy sources for autonomous power supply in remote areas. The supercapacitors main parameters and equivalent circuits are also presented.

1. Introduction

Electrochemical Double Layer Capacitors (EDLC), or Double Layer Capacitors (DLC) are called Supercapacitors. Their operation principles are similar to the well known electrostatic capacitors. The two electrodes are made from a porous substance and between them there is a solution of electrolyte and an ion-permeable membrane. If no voltage is applied between the electrodes, the ions in the solution are dispersed. When voltage is applied, the ions are collected on the electrodes. This process gives them the name "Electrochemical Double Layer Capacitors"[1]. The capacity of such capacitor can be as high as thousands of Farads [2], [3]. They have high power density and very low time of charge/discharge. Their long cycle life (~10^6) makes them very convenient for applications needing high power for short periods of time [4], [5] and [6]. The last years, supercapacitors are subject to numerous researches for their use in hybrid systems with Renewable Energy Sources (RES), as well as with other energy storage technologies. In the hybrid system with RES, supercapacitors can compensate the power fluctuations from RES, which are due to the fast changing stochastic character of the primary source (wind, sun) [7], [8]. Moreover, supercapacitors can be used to supply electricity for electro mobiles or tramways [9], [10], [11] and [12]. In this paper a review is made on the supercapacitors structure, parameters, equivalent circuits and applications.

2. Comparison of supercapacitors and other storage technologies

On fig. 1, 2 and table 1 a classification, based on specific power (W/kg) and specific energy (Wh/kg) of electrostatic capacitors, supercapacitors, batteries, fuel cells, flywheels and SMES (Superconducting Magnetic Energy Storage) is presented [13], [14], [15], [16] and [17]. It is visible, that based on specific power, the supercapacitors have better characteristics than batteries and based on specific energy, they are situated between batteries and conventional capacitors. The advantage of supercapacitors are that they have a high specific power, they can be charged and discharged with a greater current than batteries and their theoretical life is about 10^6 cycles of charge/discharge. Their capacity can be as high as 5000 F. When working in AC, their capacity drops and the equivalent series resistance increases. At frequencies higher than 1 kHz the drop in capacity is 10 times the nominal value [18]. On Table 2 are presented several supercapacitor technologies. With advanced carbon/metal oxide technology specific energies as high as 15 Wh/kg can be achieved, which is comparable with some of the lead-acid battery technologies. The nominal operational voltage of supercapacitors V_W is between 1.5 and 3,3 V per cell. Although specific power of all supercapacitor technologies is much higher than batteries.

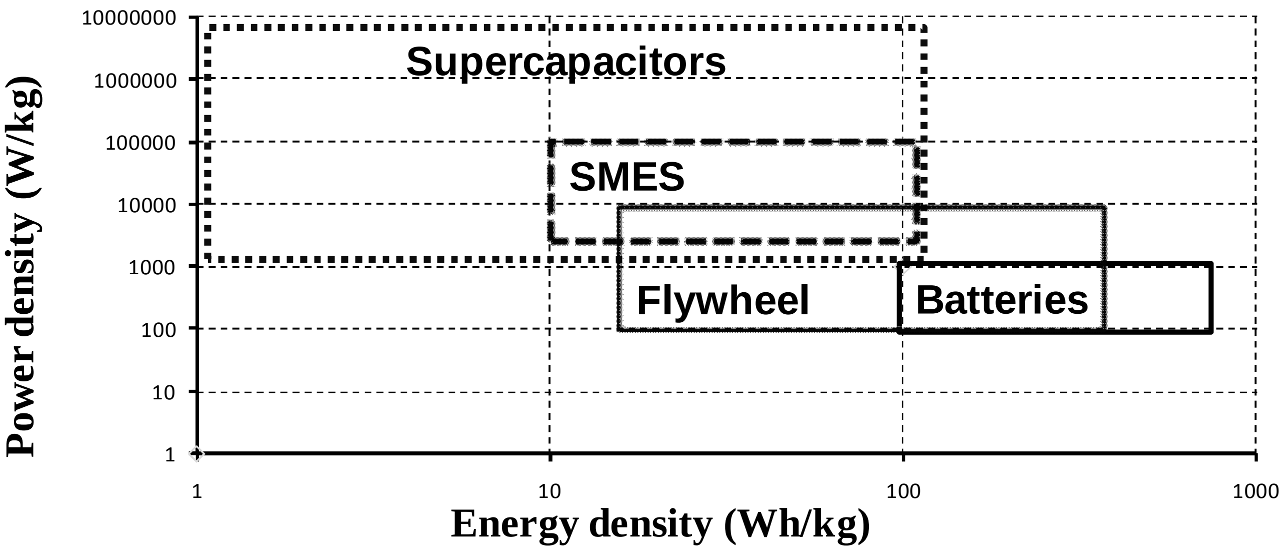

Fig. 1. Specific power and specific energy characterization of Supercapacitors, SMES, Flywheel and Batteries

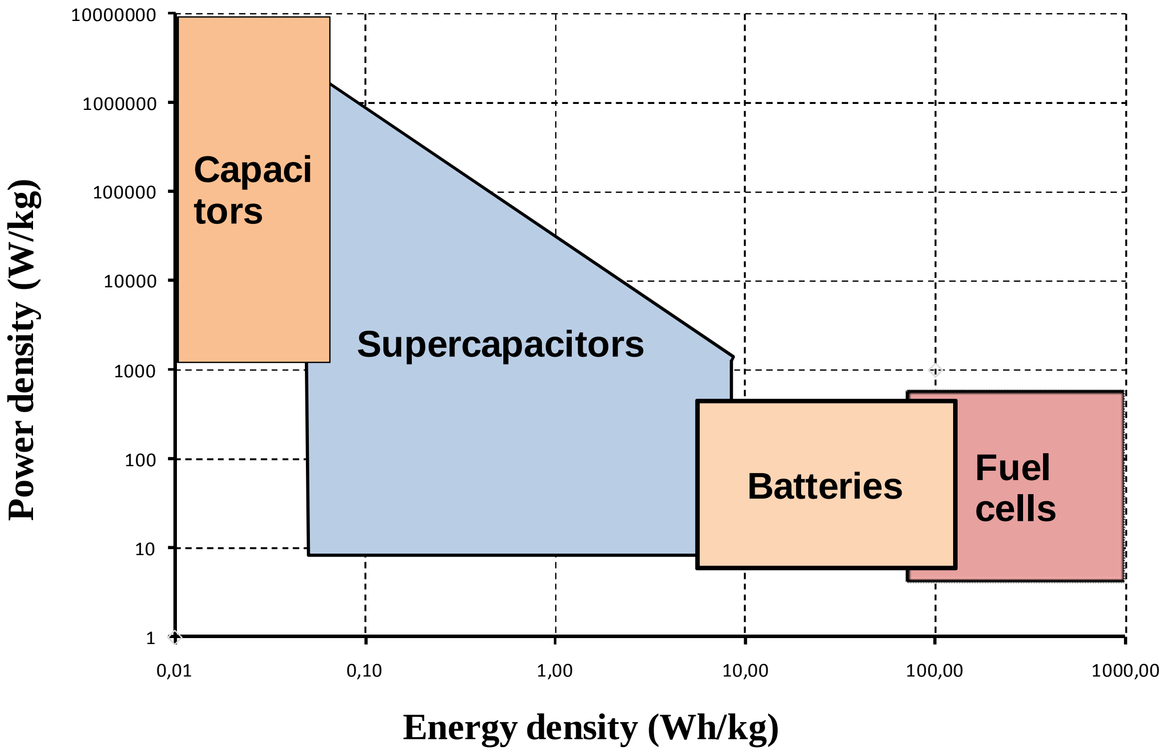

Fig. 2. Specific energy and specific power of conventional capacitors, supercapacitors, batteries and fuel cells

Table 1. Characteristics comparison of several energy storage technologies

Technology	Discharge time	Specific Power(W/kg)	Specific Energy(Wh/kg)	Expected cycle-life	Charge/ discharge efficiency (%)
Lead-acid battery	> 0,3 h	10÷1000	10÷100	<500	0,7÷0,85
Li-Ion and Li-polymer battery	>1h	600÷1800	60÷180	1000÷2500	85÷90
Supercapacitors	1÷30 s	$10 \div 10^6$	1÷10	$\sim 10^6$	0,8÷0,98
Capacitors	$10^{-3} \div 10^{-6}$ s	$10^4 \div 10^7$	<0,1	$\sim 10^6$	0,9÷0,98

3. Supercapacitor equivalent circuits

On figure 3 is presented the simplified equivalent circuit of a supercapacitor. In this circuit to the capacity C are connected an Equivalent Series Resistance (ESR) and Equivalent Parallel Resistance (EPR) [19], [20]. ESR represents the operational losses inside the capacitor and EPR represents the self-discharge (leakage). When these parameters are determined, an approximation of real supercapacitor operation is achieved for short-term applications (<10s). However, for long-term application a more precise model with three branches is created [21], [22]. The three-branch supercapacitor equivalent circuit is presented on Figure 4. In this circuit each branch has a different time constant.

Table 2: Characteristics of different Supercapacitor technologies

Technology type	Electrode materials	Energy storage mechanisms	Cell voltage (V)	Specific energy (Wh/kg)	Specific power (W/kg)
Electric double-layer	Activated carbon	Charge separation	2,5÷3	5÷7	1000÷3000
Advanced carbon	Graphite carbon	Charge transfer or intercalation	3÷3,5	8÷12	1000÷2000
Advanced carbon	Nanotube forest	Charge separation	2,5÷3	Not known	Not known
Pseudo-capacitive	Metal oxides	Redox charge transfer	2÷3,5	10÷15	1000÷2000
Hybrid	Carbon/metal oxide	Double-layer/charge transfer	2÷3,3	10÷15	1000÷2000
Hybrid	Carbon/lead oxide	Double-layer/faradaic	1,5÷2,2	10÷12	1000÷2000

The first branch, containing R_i (immediate) characterizes the supercapacitor behavior for short term applications (from a few milliseconds to a few seconds). The second one represents supercapacitor behavior in the time domain form a few seconds to a few minutes and the third one is for long-term (more than a few minutes). As on the simplified equivalent circuit, the equivalent parallel resistance R_{lea} represents the leakage.

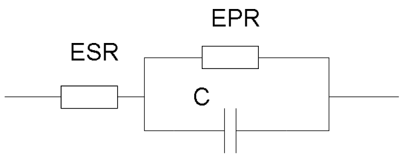

Fig. 3. Simplified equivalent circuit of supercapacitor

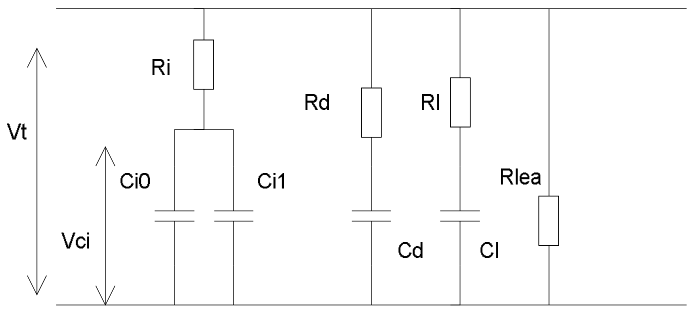

Fig. 4. Three-branch equivalent circuit of supercapacitor

4. Supercapacitor applications

4.1. Supercapacitor and wind turbine

Due to the non-constant nature of the prime mover, the wind turbine energy yield can vary quickly. In the frame of seconds these variations might have high values. In order to compensate this, batteries are associated to wind turbines. Due to the high power and the fluctuations double nature (positive and negative), a supercapacitor can be added to the system in order to serve as a "power buffer". The sueprcapacitor "shaves" peak power and delivers short term power for balancing the system [23], [24]. In this case, battery is used only in long term. On Figure 5 is presented the system's bloc scheme. The battery used in this system is a VRB (Vanadium-Redox Battery). The wind turbine is coupled to an AC/DC converter and on the DC circuit are coupled the supercapacitor and the battery via DC/DC converters. The battery and the supercapacitor are controlled by a management system that monitors the wind turbine power output and the wind speed, and gives power references to the battery and the supercapacitor when needed. The system is connected to the gird through an AC/DC converter.

On fig. 6 the wind turbine power output is presented. With the dotted line is the output of the generator and with solid line is the hybrid system power output. On fig. 7 is presented the power given to the system and received by the Supercapacitor: it can accept or deliver instantaneous power in case of excess or demand.

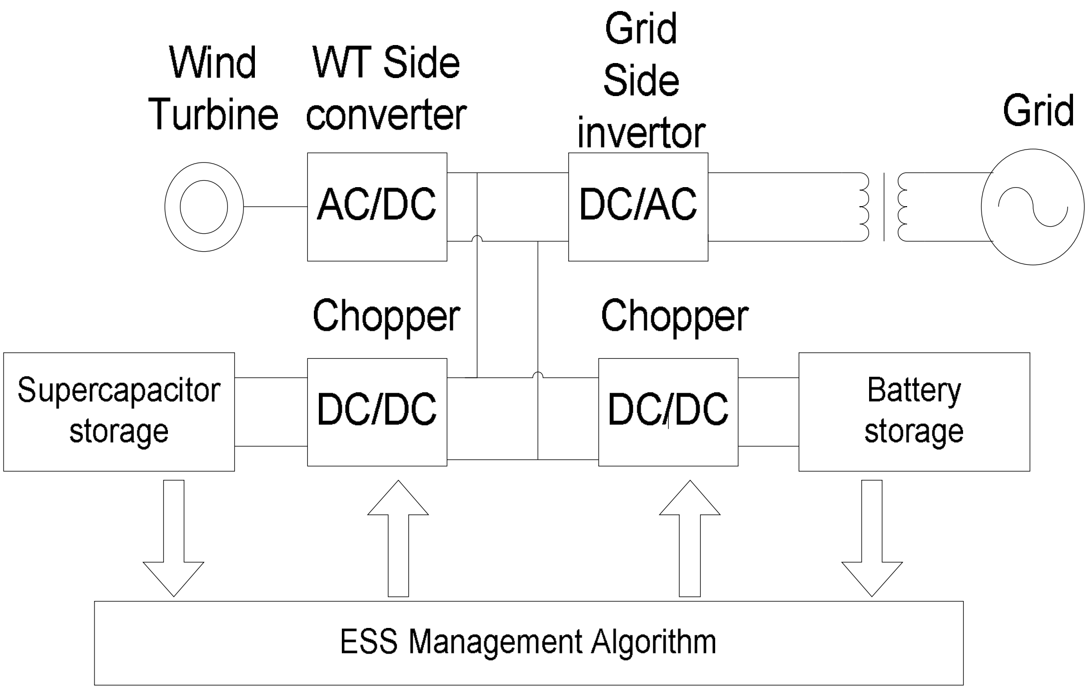

Fig. 5: Block scheme of a wind generator/supercapacitor/battery hybrid system

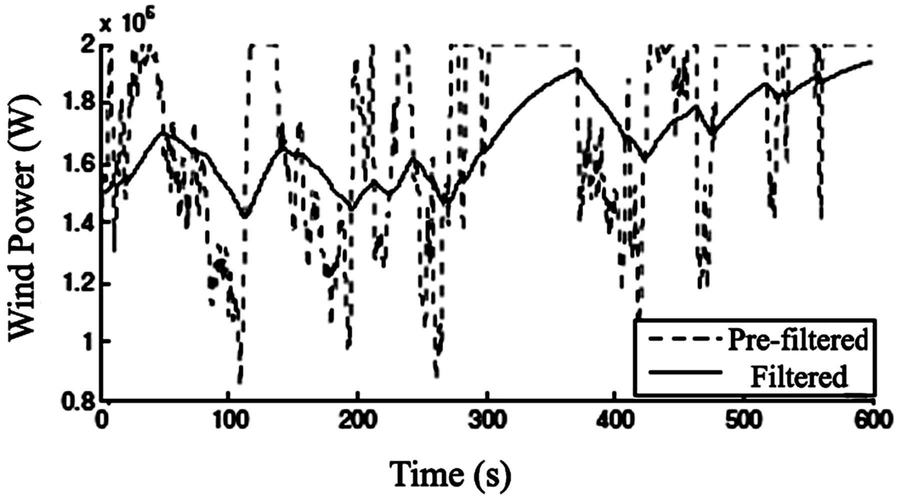

Fig. 6. The wind turbine power output and the power delivered to the grid, filtered by the storage system

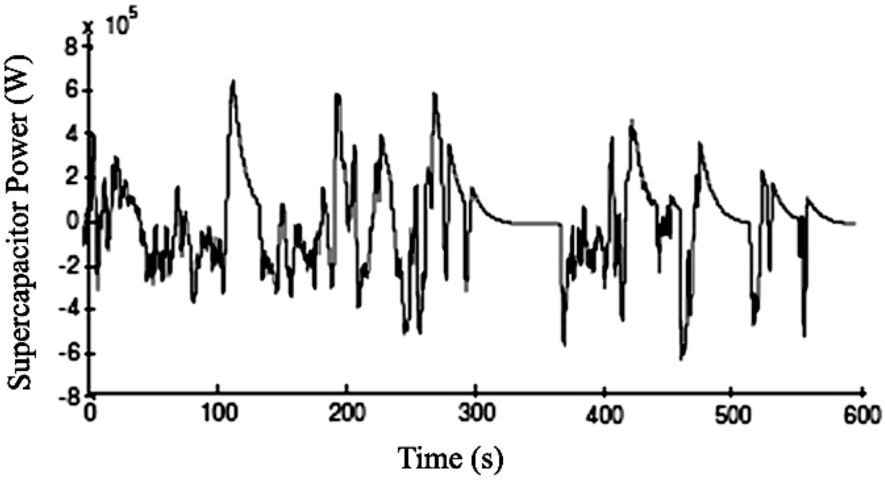

Fig 7. Power, injected into the grid and received by the Supercapacitor

4.2. PV array with supercapacitor and battery

The non-constant character of the primary source is one of the main problems in PV-installations. The photovoltaic panels output power can vary fast, due to clouds or birds passing over the installation. This induces the need of energy storage association to the PV array. From the power system's point of view, a PV installation is a negative load. In the presence of batteries and a supercapacitor, the passive PV-generator can be transformed into an active generator which can follow a constant power reference [25], [26]. The principal schematic of such a hybrid system is presented on fig. 8. The supercapacitor is used for compensating the fast power variations from the PV array and battery is used when long-term power has to be delivered to the system. The system is controlled by a monitoring device which gives power references to the supercapacitor and the battery. The PV array is coupled to a common DC bus with the Supercapacitor and the battery, all of them through DC/DC converters. The hybrid system is coupled to the grid through a DC/AC converter.

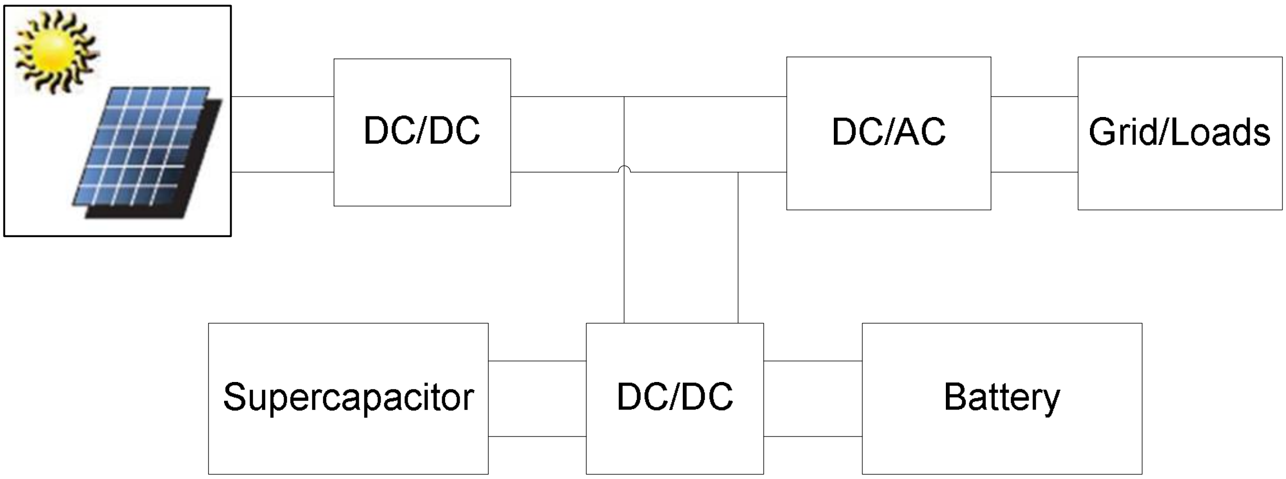

Fig. 8. Block scheme of a PV/Supercapacitor/Battery hybrid system

4.3. PV/Supercapacitor/Micro gas turbine hybrid system.

In this application, each system's component is controlled by the supervisory control through a communication bus. The supervisory control monitors the PV power production and the load power demand and sends power references to the micro gas turbine and the supercapacitor. The micro gas turbine has a response time of about 30 seconds to increases in power demand. Thus, the supercapacitor is used as a power buffer to compensate PV power fluctuations and the micro gas turbine response time. The system bloc scheme of this is presented on fig. 9. In this application the sources (PV, micro gas turbine, supercapacitor) are coupled to a common AC bus.

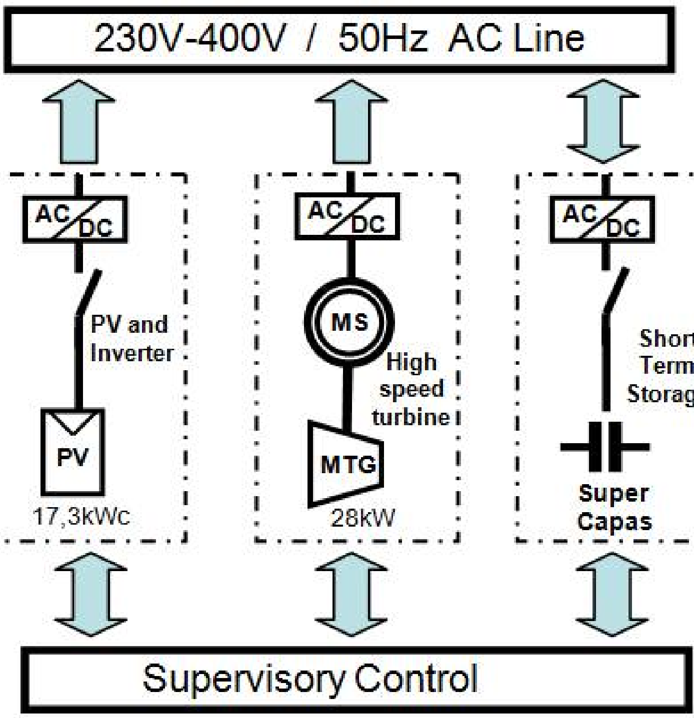

Fig. 9. Block scheme of a PV/Supercapacitor/Micro gas turbine hybrid system

From the difference between the load power demand and the PV power output, the reference for the supercapacitor and the micro gas turbine is deduced. This reference passes through a low pass filter and is send to the micro gas turbine. The fast fluctuations are used as a reference to the supercapacitor [27].

4.4. Fuel cell and supercapacitor hybrid system

The fuel cells represent a great interest to research as low-carbon emissions power source. They can be used in hybrid systems for power supply, as well as in the electric transport. In combination with a hydrolyser they can be used for energy storage in the form of hydrogen. One of the main disadvantages of fuel cells is their slow response on load changes. This can be compensated by using a supercapacitor in combination with the fuel cell, as presented on fig. 10. The fuel cell is connected to the system via a DC/DC converter, because the fuel cell output voltage has a low value. Then, the supercapacitor is coupled in parallel on the DC bus. The load is satisfied through another DC/DC converter for DC consumers or a DC/AC converter for alternative ones. On fig. 11, the fuel cell and supercapacitor power output are presented. The supercapacitor compensates the slow response of the fuel cell, thus supplying constant power to the loads [28], [29] [30] and [31].

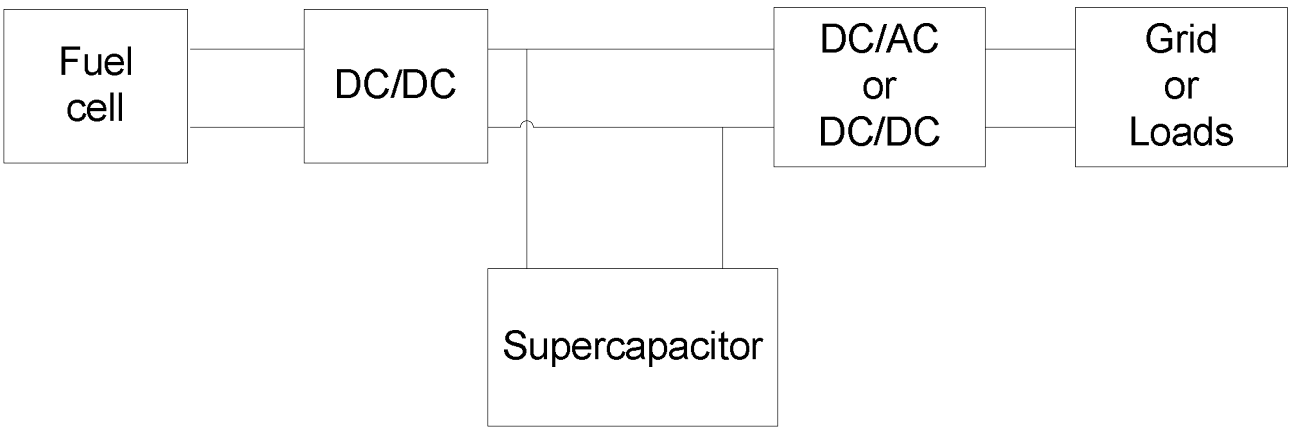

Fig. 10. Block scheme of a PV/Fuel cell hybrid system

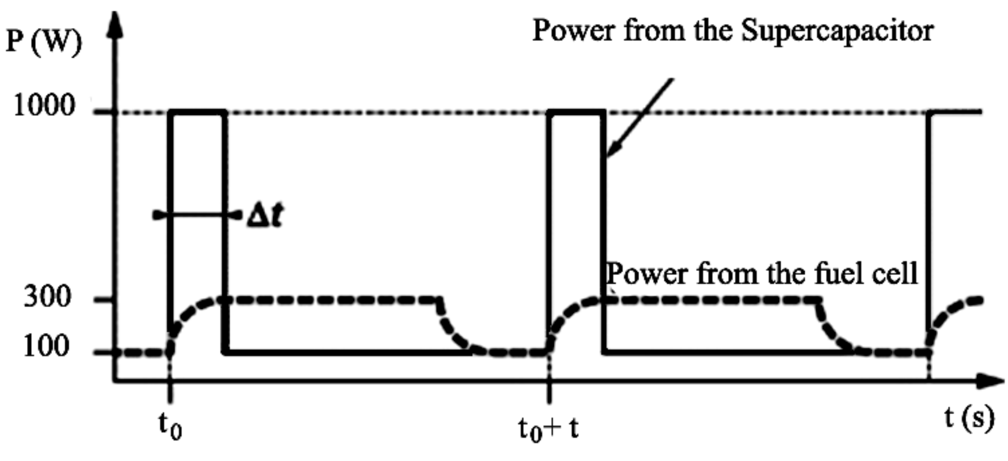

Fig. 11. Fuel cell and Supercapacitor power output

4.5. Starting system for internal combustion engine

The internal combustion engine starting needs a high current, which decreases the battery life. The supercapacitor can supply this current, thus facilitating the battery operation and increasing its life cycle. Moreover, the engine will start easier in low temperatures, due to the supercapacitor high power density and its capability to supply high currents for short time [32], [33]. On fig. 12 is presented the system bloc scheme. The generator and the battery are used to charge the supercapacitor and the supercapacitor supplies power to the engine starter. If the supercapacitor is already charged, the engine can be started immediately. If it isn't charged, the battery has to charge the supercapacitor for some 30 seconds and the engine can be started. The advantage of this system is that the battery can charge the supercapacitor for longer period than starting the engine, thus the current consumed from the battery is lower than the direct supply to the engine starter.

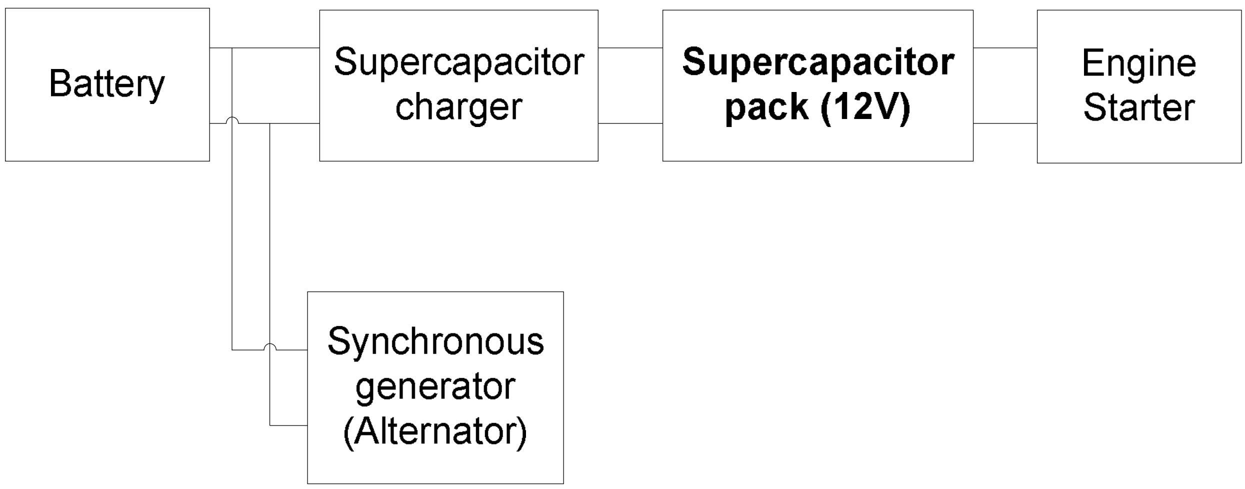

Fig. 12. Block scheme of a system for starting an internal combustion engine by using supercapacitor

5. Conclusions

In the last years, the supercapacitors and their applications are subject to intensive research. In this paper emphasis was given to the use of supercapacitors in hybrid systems with renewable energy sources. The supercapacitors main parameters, equivalent circuits and applications were highlighted.

Numerous studies based on the supercapacitor equivalent circuits are made. Other researches focus on new materials (carbon nanotubes, carbon/metal oxide), which will decrease internal losses in supercapacitors or increase their energy density to reach values similar to the new batteries technologies (Li-Ion, Li-Polymer, VRB). At this moment, supercapacitors have power density, and life cycle greater than all battery technologies. They can be charged and discharged much faster than batteries which is an advantage in applications needing fast buffering.

In hybrid systems with renewable energy sources, supercapacitors are used to compensate the fast-changing stochastic character of the renewable energy sources output power. Supercapacitors are used as a power buffer, because of their high power density and instantaneous reaction time. These characteristics are most useful in a hybrid system with wind turbine and supercapacitor or PV installation and supercapacitor. They are also used to compensate the high fuel cells time constant.

The supercapacitors are also applied in systems such as: mobile communications power supply, UPS devices and internal combustion engine starting devices.

At this moment the main disadvantage of supercapacitors is their high price.

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