HYBRID ENERGY MICROSYSTEMS ENHANCED BY SOLAR PV ENERGY

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1. Introduction

PhotoVoltaic (PV) and wind technologies are getting matured and nowadays they provide energy flows for utility power grids. However, it is widely-known that they exhibit strong nonlinear electrical characteristics variable with weather conditions and level of solar light illumination. After the boom of photovoltaic and wind power installations in Europe and in Bulgaria an urgent need of short-term and long-term energy storage is revealed. Power injection in the grid produced by small decentralized power generators occurs as a sharp problem of energy balancing that focus the attention on the stability of power systems and the search for new ways to overcome fluctuations. A simple and intuitive method to mitigate these instabilities is to use energy storage devices in the power system architecture. In recent years, the researchers' emphasis is transferred from energy generation to energy storage importance. Research interests have been focused on innovative hybrid systems with dynamic power flow management - heterogeneous generators with various peak power capacities, new type batteries, hydrogen fuel cells, stacks of supercapacitors or hybrid combinations of them.

Traditional electrical energy storage systems as Sealed Lead-acid and NiCd batteries are less attractive because of heavy weight and a relatively low energy density, and the latter suffers from capacity loss caused by shallow discharge cycles, termed as the memory effect.

On the other hand, supercapacitor technology namely, electrochemical double layer capacitors (EDLC), is a developing and promising technology in the energy storage applications. It is expected to bridge the gap between electrolytic capacitors and rechargeable batteries. Efficient energy storage in EDLC capacitors is a result of highly developed surface area of the electrodes and charge carrier separation in thin layers of macro-, meso- and micro-porous carbon material. The merits of supercapacitors arise from their high power capability based on ultra-low internal resistance, wide operating temperature range of -40oC to +65oC, and high cycling capability (>106 cycles).

The aim of the present work is to test hybrid concepts for energy generation and energy storage in real cases. Two options for decentralized hybrid microsystems are discussed - a hybrid energy system for a building in urban environment and a hybrid bike to move in cities with heavy traffic. The energy management and storage systems contain two elements - an energy storage - battery pack and/or a supercapacitor stack and a renewable generator – solar, wind or human-assisted.

Hybridization concept:

The main target of hybridization of different energy technologies is to improve the system efficiency, to find a way to reduce the environmental pollution from carbon emission and reduce operating costs for transportation systems. The main objective of integrating batteries and supercapacitors is to create a hybrid energy storage system (HESS) with high energy density and power density in vehicular or stationary power system architecture. Efficiency will be improved if peak power demand will be provided by the supercapacitor, while the average power demand will be complete by the battery.

For industrial applications, supercapacitors have become more accepted as high power buffers in combination with conventional lead-acid batteries or advanced chemistry batteries. Unfortunately battery designed to attain maximum energy density in most cases require a sacrifice in power capability. It has been recognized that combining carbon/carbon supercapacitors and batteries would significantly reduce the stress on the batteries in heavy applications in which the batteries are subject to high current pulses in both charge and discharge.

In transportation, the supercapacitors can provide burst power during vehicle acceleration and recover energy during regenerative braking. Similar examples can be found in telecommunications during short transmissions and long stand-by. In the short ranges, the supercapacitors would greatly reduce the power demands on the battery and extend its life cycle.

2. Hybrid energy micro-system for urban building

Recent smart energy systems look beyond the already traditional solar or wind energy applications. More frequently they use several energy sources in one system which means – new Hybrids and higher energy efficiency. We present here small hybrid energy system utilizing solar and wind energy, battery energy storage and grid-connection technologies. The block diagram at Figure 1 below illustrates the main system components. The novelty in this microsystem is the ability to store energy or inject the localy–generated energy into the building grid in a proper moment reducing by this way the office electricity bill.

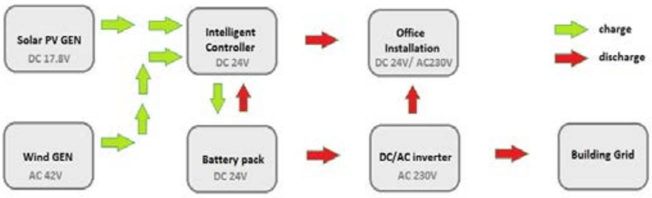

***Fig. 1** Block diagram of Solar/ Wind office microsystem.*

The hybrid prototype is equipped with 720 Wp PV generator, 600W vertical-axes wind generator along with a battery bank of 2.4kWh (100Ah, 24Vdc). The PV rooftop generator consists of 3 standard PV modules (240Wp, c-Si) connected in parallel and protected using additional high-power rectifying diodes and intelligent 24Vdc charge controller. At Figure 2 below photos of the installation are presented.

The wind turbine is Maglev-type [1],[2] Vertical Axis Wind Turbine (VAWT) which combines magnetic levitation AC motor with S-type of Savonius rotor and 3 air-foil Darrieus blades to maximize the electrical output performance. Maglev generators use magnetic suspension technology based on NdFeB magnets. As can be seen at Figure 3, it creates frictionless, efficient, far-out-sounding motors which provide excellent rotational stability, eliminating vibration, typical wobble, shaking and noise. All these factors are important for noiseless urban building applications.

Fig. 2 *General view of hybrid (solar and wind) system.*

The solar and wind generator are working in complimentary regime because typically the solar peak generation is in daylight while the wind has e maximum generation in nighttime. Hence, the resultant combined energy generation covers the energy needs of a small office in urban area.

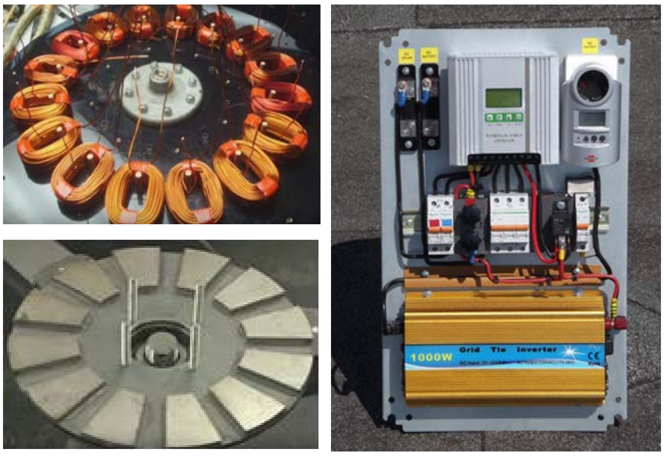

Fig. 3 *BLDC motor, charge controller and grid-connected inverter.*

In the application the produced energy is store in battery block and later injected in the building grid intentionally, depending on the needs of the office equipment and labor force. In Table 1 results on power generation in three typical days is summarized.

Table 1: *Solar/Wind power generation.*

CASE STUDY: Three case studies were conducted to determine the effect of amount of battery power drawn during typical sunny day, windy day and cloudy day to determine a suitable amount of battery power for real case studies.			
Case	***Into Grid (9.00 - 17.00h)***	***Averages PV prod.***	***Averages Wind prod.***
Case 1: (high solar, no wind) PV and batteries are connected to the system. The demand limit occurs for 3 hours from 17:00 to 20:00. To keep the total consumption below demand limit, the EM algorithm has reduced non-critical loads.	3.6 kW	448 W/h	2 W/h
Case 2: (low solar, small wind) PV and batteries are connected to the system but the battery is not charging. The inverter still injects into the grid. The use of RE system in this case resulted in lower amount of load reduction for shorter periods.	2.0 kW	226 W/h	24 W/h
Case 3: (no solar, middle wind) PV, Wind turbine and batteries are connected to the system but the battery is not charging. The inverter still injects into the grid. The use of RE system in this case resulted in lower amount of load reduction for very short periods.	1.2 kW	20 W/h	128 W/h

The basic result of power generation in urban area for our climatic conditions pointed out that the effect of wind power generation is below 19% while the solar PV generates approx. 81% of the total amount of produced electricity.

In future developments, the office microsystem will be enhanced by web-connected energy management systems (EMS) to control the power injection into the grid only at moments of “peak price” tariff.

3. Hybrid urban e-BIKE

Many e-bike users experience the limited battery lifetime as a problem for more wide range applications. Our e-bike is designed to give students an interesting tool to analyze human, solar and motor power in a complimentary way. This part of the paper describes the design and shows the first test results of a hybrid energy storage e-bike with a 5kW hub motor, a 50Wp c-Si PV module, a 60V,18Ah battery and a 500F,16V superCaps stack.

3.1 E-bike concept

The authors are inspired by conceptual all-weather bike designed by Torkel Dohmer (2008). The developed e-bike platform consists of a motor, battery stack, solar generator, superCAPs stack and corresponding DC-DC converters [3], [4]. During normal operation on the road, DC energy from battery supplies a rim-incorporated BLDC motor. The battery is charged in motion by additional solar PV module. Other innovative feature is regenerative braking through supercapacitor energy storage [5]. Regenerative braking recovers much of the kinetic energy of the vehicle. It is an option for additional charging, because in fact the reverse current could not be fully used due to charging limits of the battery. Excess current could be absorbed by superCAPs. User-controlled charging of superCAPs while cycling improves charging fluctuations and increases the e-bike efficiency.

3.2 SuperCAPs energy storage

Charging process of superCaps is different from charging batteries. The superCAPs may not be overcharged! The applied power supply should limit the maximum operating voltage over the superCAP module. The other reason is the supercaps are difficult to charge in SOC =0% by conventional chargers but the PV module fits well to charge them in nearly zero voltage at Isc point of operation. Typical industry load voltages are 3.3, 5, and 12 V while the largest supercapacitors have cell voltages of 2.7 V. Reaching industry voltage levels would require multiple supercapacitors in series. Supercapacitors in series require a protection circuit for voltage balancing, so called battery management system (BMS), during charging to prevent internal breakthrough. This irreversible degradation is caused by the overvoltage across a capacitor exceeding the rated voltage of 2.7V on the cell.

3.3 Design and implementation of hybrid e-bike (velo-EV)

The focus of this design is a low-cost hybrid-e-bike to be created that can be repeated easily. Only system performance is discussed without details on underneath software and hardware technologies. This application of solar PV module combined with supercapacitors is designed to show their versatility and feasibility as a power source for any portable system.

The velo-EV used in this experimentation is a two wheels prototype designed and realized in research units of Bulgarian Academy of Sciences. A drawing and a photo of the implemented velo-EV are presented at Figure 4.

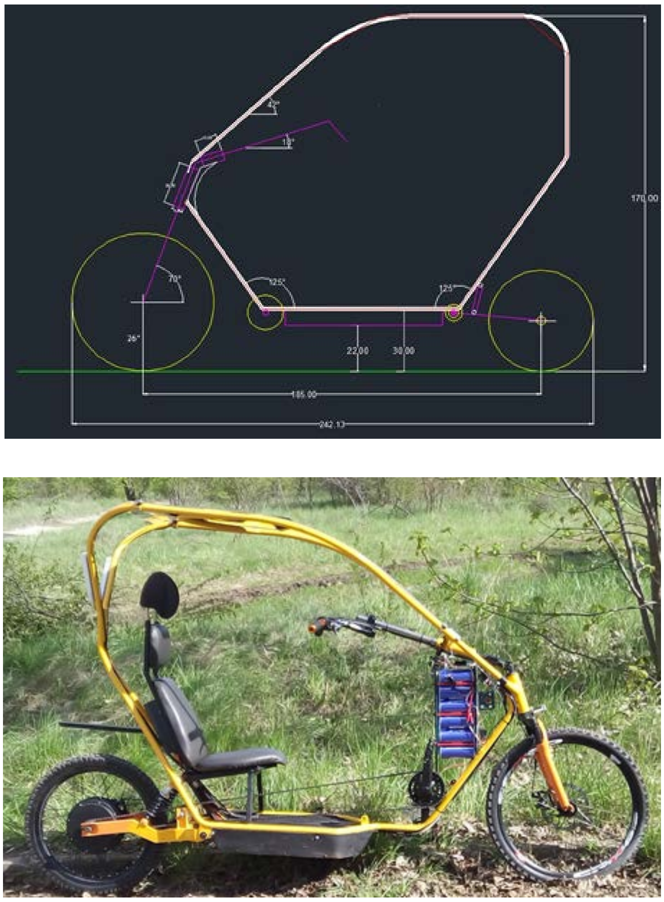

***Fig. 4** Solar e-Bike concept and prototype.*

The starting configuration is a thin iron-tube chassis with a roof, rim-integrated BLDC motor, AGM lead-acid batteries and a supercapacitor stack. The battery block is mounted at the bottom of the platform between the wheels in order to be charged or replaced easily. The lower location of the battery increases the mechanical stability during bike motion. Highly efficient PV module (50Wp, 22% eff) consisting of back-contact c-Si solar cells is mounted on the roof. With this configuration, a very flexible hybrid energy system has been obtained.

A summary of specifications of the BLDC motor, presented at Figure 5, and controller can be found below in Table 2 and Table 3. Brushless DC motor attached into the wheel use a rotating permanent NdFeB magnets in the rotor, and stationary electrical magnets on the motor housing. A motor controller converts DC to AC driving impulse trains. The control strategy is based on current regulation loop using a powerful DSP and high-power n-channel MOSFETs.

***Fig. 5** Rim-integrated BLDC motor.*

***Table 2:** Electrical specifications of BLDC motor*

Max voltage & power	Windings	Max torque	RPM
72Vdc, 5000W	4T x20, 180^0C Cu	190 N.m	700@72V
Max loading	Max speed	Rotor Position control	Net weight
150 kg	70km/h	2 x Hall sensors head	11.0 kg

***Table 3:** Electrical specifications of drive controller*

Voltage range	Max DC current	FET drive current form	Speed limit
48-72V	120A, programmable	True -sine	Soft controlled
Soft Access	Gear control	Max Reverse Brake current	Weight
Cable & Bluetooth	Electronic switch	200A, programmable	2.5 kg

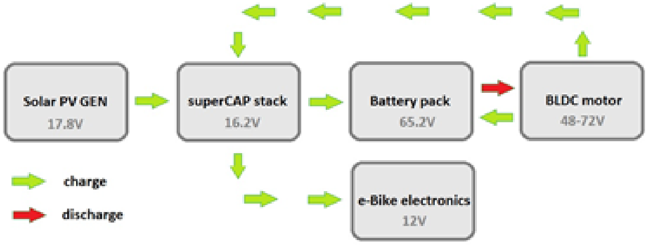

***Fig. 6** Solar e-Bike block diagram.*

The velo-EV, with approx. weight of 42 kg has been equipped with a BLDC electrical motor with permanent magnets operating at 48-72V and 5 kW of peak power. The battery system is composed by 5 units of AGM-12v, with 65.2V in total and capacity of 18 Ah and the total energy is 108 Wh. The main specifications of AGM lead-acid batteries per unit are weight of 5.97kg, internal resistance - 20 mOhms. The batteries can operate in any orientation excluding upside-down with a max discharge current - 10s - 119A, 5 min - 89A, 60 min - 20A.

The chosen supercapacitors are six MAXWELL 2.7V, 3000 farads Boostcap3000P® ,connected in series and protected by battery management system (BMS), as can be seen in Figure7.

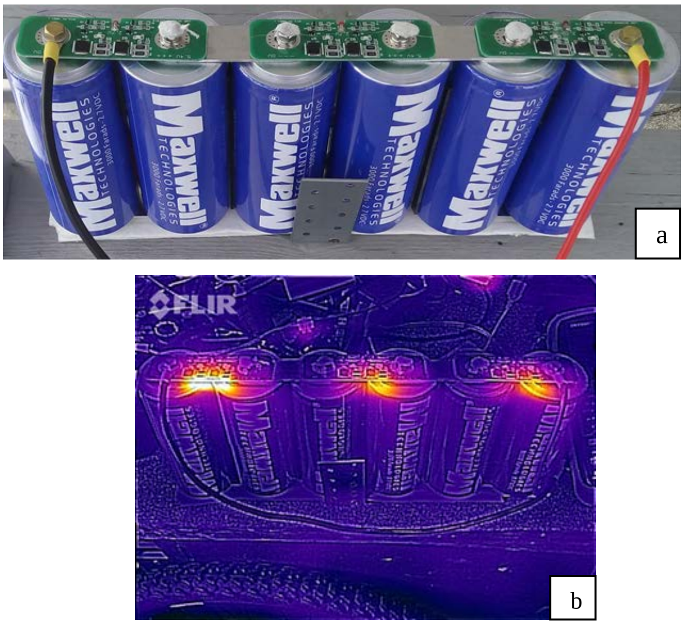

Fig. 7 *Photos of SuperCAPs stack (a) and infrared image of overvoltage BMS activation (b).*

Due to the absence of chemicals, supercapacitors can charge and discharge faster and without degradation [6],[7]. They can withstand temperature changes, shocks, and vibrations better than most batteries.

Cmax= 3000F/2.7V Emax = (Ceq x Umax2) / 2 =>Emax = 10.93 kWh Eeff= 3.28 kWh

Cblock = 500F/ 16.2V =>Emax = 65.61 kWh Eeff= 19.69 kWh

ESR= 0.4 mOhms Pdischarge = Umax2/ 4ESR => Pdischarge= 164 kW

DoD = 33% Umin = (1-DoD) Umax

Uncharged supercapacitors (U_{min}=0) appear as a virtual short to voltage-fed power supplies, not allowing to be directly charged by connecting them to conventional CC/CV power chargers. Having the stack voltage of 16.2V exceed the standard12V options will benefit the output power manipulation and DC-DC converter's efficiency.

During normal operation - driving mode - the battery stack is discharged by BLDC motor. The charging cycle is ensured by SolarGen and superCAP stack or by motor charging during regenerative braking. There are 3 levels of DC voltages and 3 types of DC-DC converters for energy flows corresponding to 3 energy sources - PV module, superCAPs and Battery stack. Separate DC_DC converters with different output voltages were built to provide energy flows and a stable autonomous power source for all electronics on the hybrid e-bike.

In stationary mode the charging process could be performed by solar PV and by external 72V DC charging station.

The SolarGen, superCAP stack and Battery stack voltages are monitored in 3 different displays during bike driving. The digital communication among components is implemented as an open LAN which consists of three main subsystems: motor controller monitoring, currents flow supervision and Bluetooth communication.

During normal operation on the road a data logging unit receives sensors signals from the BLDC motor inverter, the battery and the PV module. Real-time data can be displayed to an Android tablet using Bluetooth or to a Windows laptop using USB link.

3.4 Design considerations

Three foreseeable obstacles became apparent: - mechanical stability of the frame construction, superCAPs charger and DC-DC converters circuits safety.

General schematics look nice on paper or on screen but may not be feasible on a testing field/board.

The motor has enough power to drive the vehicle, the driver and carry relevant equipment but mechanical vibrations occur in the front suspension of the bike. Due to weight of the battery block frame construction and front brake should be reinforced.

High voltage spikes occurred in the cables between motor and drive controller which deteriorate the power supply of electronics. Hence, the charging circuit had to be redesigned and manually tested for functionality and performance.

The supercapacitors used in the stack are heavily charged and they can produce sparks if not isolated properly. This meant creating a safe and portable enclosure around the supercapacitors and power circuitry had to be taken into account.

3.5 Charge testing

Due to virtual short in empty supercap it is hard to provide enough voltage to the stack. Initially overcoming this problem involved attaching an external charged battery to the supercapacitor stack and draining the battery into the stack. For our proof of concept we chose to test our supercapacitor stack using PV module. In principle, the short circuit condition in PV module is not dangerous for the module because the internal current generator is limited and the generated power is dissipated. We attempted connecting uncharged supercap stack directly to the MPPT charge controller of a solarPV module. We tested successfully the charge/discharged cycle in a sunny day with high level of sunlight illumination.

3.6 Drive testing

Testing of the vehicle was performed at Research complex II of the Academy in Sofia. A photo of the first driving is presented at Figure 8. Unfortunately, at the moment of writing, the completed e-bike has not been tested thoroughly yet. Some initial tests have been performed, and the initial results look promising.

Fig. 8 *First test driving.*

The maximum speed during our test was over 35.0 km/h, without pedaling! With one full superCap and battery charge, the initial test showed the e-bike trip has a range of 54 km. Further testing will have to be done to explore the limits of the braking system recharge. In the initial tests reverse brake has been switched-off by the software.

The driving cycles are acceleration phase, mild drive, deceleration phase. Speed and distances have been measured by external Android phone @ GPS applications.

Two additional tests have been performed for the battery storage (BS) and the hybrid storage-Battery / Supercapacitors (HESS). The difference in terms of range is about 37 km BS versus 54 km with HESS. Higher values of internal resistances of lead-acid batteries lead to higher voltage drop during accelerations and shorter drive distance. These are much smoothed with SuperCAPs. The implementation of superCAPs in the power system has provided significant performance improvements. Totally, a 1.2V voltage drop of the battery pack has been observed after 45 min round trip test.

Conclusion

The hybridization of small power generators and energy storage devices has reached a level for daily use and offers new energy-efficient solutions in power engineering. Small Solar/Wind generators can be incorporated in the existing urban infrastructure.

A stable open EV platform to test the use of superCAPs in e-bike has been succesfully developed. The hybrid bike, nor the energy storage systems, exhibited any problems under the test conditions. The use of superCAPs together with the lead acid battery of velo-EV has the advantage of improving the behavior of the lead-acid batteries. SuperCAPs have vast advantages when it comes to acceleration, fast charging and long life. The effect of PV roof is observable on SuperCAPs charging. A fast charger for the superCaps, a data logging and visualization unit were all developed from scratch, only using low cost power electronics. In the near future the evaluation of the superCap e-bike concept for daily use will be started.

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