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Design of an e-bike with UltraCaps as the only energy source and with regenerative braking

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Abstract

The number of charge/discharge cycles that can be achieved by today's ultracapacitors is almost 1000 times higher than that of classical batteries. From research [1] that was earlier performed by the *Vrije Universiteit Brussel* it is also known that many e-bike users experience the limited battery lifetime as a problem. These 2 facts lead to the design and building of an e-bike without batteries and only using UltraCaps as energy source. By using a newbuilt split-PI converter topology regenerative braking was enabled, and its influence on the range of the e-bike could be investigated. The e-bike is controlled by a twist-grip and all electric quantities can be visualised on a touchscreen. The paper describes the design and shows the first test results of an e-bike with a $250W$ hub motor and a $500F$, $16,2V$ UltraCap module. In the near future, the e-bike will be used as a didactic demo model to analyze power flow during cycling.

bicycle, regenerative braking, wheel hub motor, DC-DC

1 Why an e-bike with UltraCaps only?

In most cases, UltraCaps are rightly used as peak power units. In spite of the low energy density (about ten times less than batteries [2]) it was considered to be an interesting exercise to replace the battery of an e-bike with UltraCaps only. This could deliver us from the limited battery lifetime of many of todays e-bikes, and enables very fast charging. But above all, the e-bike is designed to give students an interesting tool to analyze human and motor power in a familiar way. With the straightforward relation between their leftover energy and leftover voltage (expression 1) UltraCaps seem to perfectly suit that goal.

$$E(V) = \frac{CV^2}{2} \tag{1}$$

The use of UltraCaps as the only energy source implies two important problems:

- The limited energy density of UltraCaps may lead to an even heavier e-bike, while the user's feedback always bring the overweight as the most important disadvantage of e-bikes [3].
- The relationship between the leftover energy in and the voltage over the UltraCaps (expression 1) results in a variable voltage supply for the motor. This problem can be solved by introducing the right power electronic conversion. This will be discussed in detail in section 2.1.2.

The design of the e-bike should show

- whether or not UltraCaps are appropriate to be used as the only energy source for the motor of an e-bike
- that it is possible to build a sofisticated control system for an e-bike with low cost power electronics
- what charge/discharge efficiencies are practically feasible and what advantages are associated with the use of regenerative brakes.

The idea of using a power source of such a limited energy capacity as the applied UltraCap

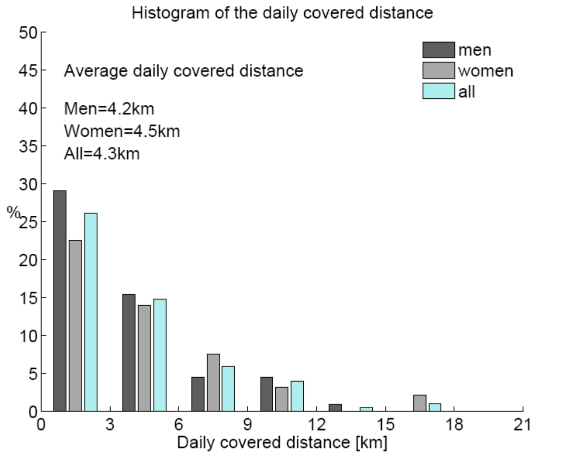

Figure 1: average daily covered distances of 244 test persons [3]

module is maybe not so stupid is it seems at first sight. Fig. 1 shows that the daily covered distance with an e-bike for 244 test persons was less than $6km$ for almost half of the test persons. Fig. 2 shows a recorded 1 hour during commutercycle covered with a conventional bike. The energy required to cover this cycle was calculated to be only $52Wh$. With the energy of the UltraCap module (see expression 2) it is theoretically possible to cover one third of this commutercycle in motor-only operation.

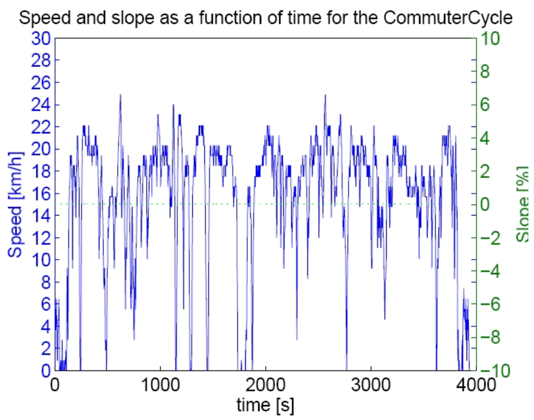

Figure 2: One hour recorded commuter speed cycle covered with a conventional bicycle [4]

$$E_{max} = \frac{CV_{max}^2}{2} = 18,2Wh \qquad (2)$$

Imagine having loaded the UltraCaps at home, many commuters should get at work while using the e-bike as pedelec. With the regenerative braking it would even be possible to use the e-bike as a fitness bike. User-controlled charging of the UltraCaps while cycling, increases the resistance, and so increases the effort of the cyclist to every possible level.

2 The e-bike concept

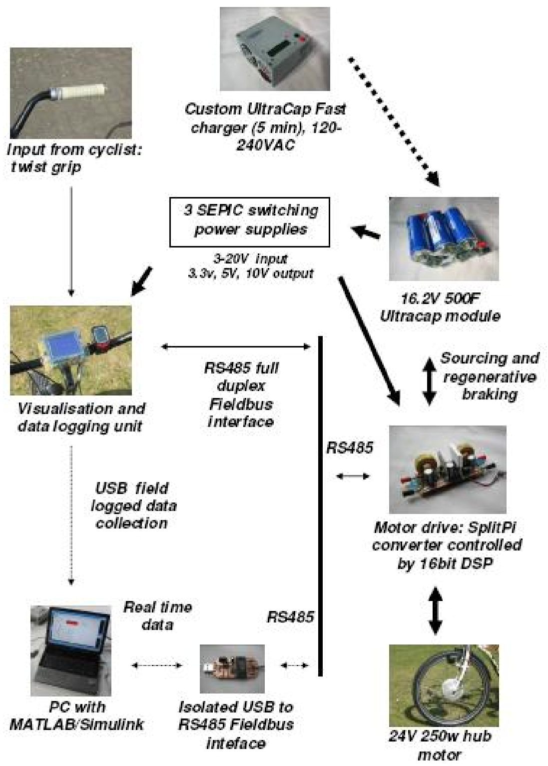

Figure 3: Schematic diagram

An electric bicycle basically has two power sources: the human power from the cyclist and some extra motor power. In opposite to a *pedelec*, the relation between motor and human power for an *e-bike* is not fixed, but is controlled by the cyclist. In this design the cyclist controls the motor power by a twist-grip. The motor is a *Heinzmann front wheel hub motor of* $250W$, with rated voltage of $24V$. The energy for the motor comes from the earlier described *UltraCap module*.

Figure 3 shows that the connection between the motor and UltraCaps is realised by *a split-PI DC-DC converter* (section 2.1.2). To maximize flexibility, the split-PI drive (section 2.1) can be controlled by a second embedded system, which is called *the visualisation and data logging unit* (section 2.2), as well as by a *PC* (section 2.3), all trough the same *RS-485 Fieldbus* [5]. During normal operation on the road the data logging unit receives an analog setpoint for the split-PI converter by *the twist-grip*. When being controlled by a separate emdebbed system, a PC can also be connected to the RS-485 fieldbus to display all variables in real time. This might be interesting during lab excercises.

It is obvious that the UltraCaps are preferably preloaded at departure. Since the maximum voltage of the UltraCaps may not be exceeded while charging, and since charging on a regular lab power supply is slow, difficult and not fool proof, a dedicated *fast charger* for the Ultracap module was also developed. This charger can fully automatically charge the Ultracap module from empty state to its maximum voltage in less then 5 minutes.

Also three separate switching power supplies with different output voltages were built to provide a stable autonomous power source for all electronics on the e-bike. For these additional low power converters the *SEPIC* (single ended primary inductor converter) topology was used [6]. The *SEPIC* topology is distinguished by the fact that its input voltage range can overlap the output voltage[7]. This was necessary to provide a stable output voltage when the voltage of the UltraCap is above and below the output voltage of the individual converters.

With this configuration, a very flexible system has been obtained: The fact that the drive recieves its setpoints from another embedded system or PC even enables the motor drive to be used for a number of other applications then the e-bike including MPP tracking for solar arrays, charging batteries or controlling any type of DC motor.

2.1 The motor drive

2.1.1 Requirements for the motor drive

The relationship between the leftover energy and the voltage over the UltraCaps (expression 1) poses an extra challenge when designing power electronics for an UltraCap e-bike. The UltraCap module is specified as a $16.2V$, $500F$ module. The hub motor used, however, reaches its nominal speed at a back EMF of $24V$. Using a motor with lower back EMF or using a higher voltage UltraCap bank only solves part of the problem: the voltage drops quickly over the UltraCap bank, and the deeper the power electronics allow the UltraCap to discharge, the more energy can be drawn from the UltraCap bank. In this context it is worth mentioning that 75% of the energy is found in the reduction of the UltraCap voltage from V_{max} to $V_{max}/2$.

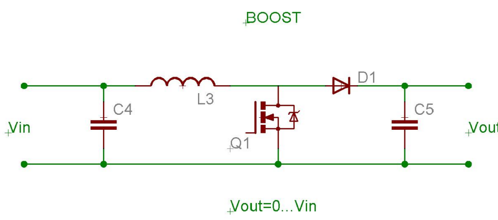

Figure 4: Topology of a classic boost converter

Since the motor has to be able to run at nominal speed during the whole discharge cycle, a boost converter (see Fig. 4) is required to boost up the UltraCap voltage to $24V$, no matter what the voltage of the UltraCap module is. Practical lower limits of the minimum boostable voltages at given power levels are imposed to prevent high currents.

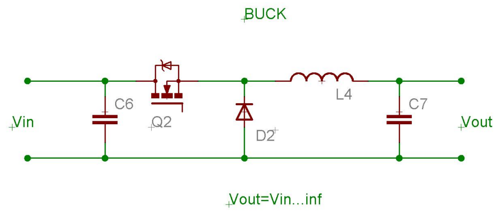

Figure 5: Topology of a classic buck converter

However, to control the motor speed, the voltage of the motor should be controlled, which also implies the use of a buck converter (see Fig. 5).

Variable regenerative braking when the motors back EMF voltage E is higher then the UltraCap voltage V_c implies the use of a buck converter in the opposite direction. Variable regenerative braking when $E < V_c$ implies the use of a second boost converter in the opposite direction. These 4 requirements, with their own converter topologies, combined together may lead to the split-PI topology [8]. This topology will be explained in section 2.1.2.

2.1.2 The split-PI converter

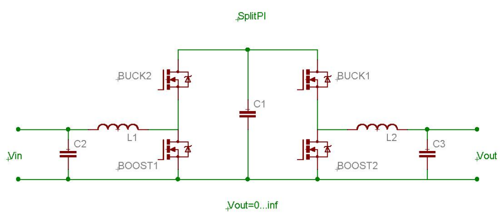

Figure 6: Topology of a split-PI converter

The split-PI topology enables the four operation modes described in section 2.1.1. These modes are schematically presented in Fig. 7.
The split-PI promotes optimisation of passive and active component mass to provide direct current (DC-DC) up and down (boost, buck) voltage conversion with the ability to seamlessly sink and source electrical current with identical forward and reverse transfer characteristics. In other words, this topology allows us to precisely control the power flow from/to the motor, no matter what the UltraCap voltage V_c or motor back EMF E is.

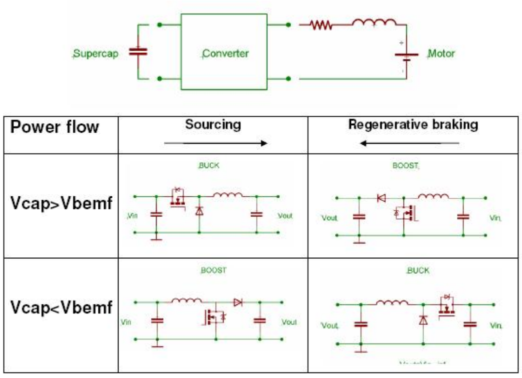

Figure 7: 4 converters in one topology

2.1.3 Practical implementation

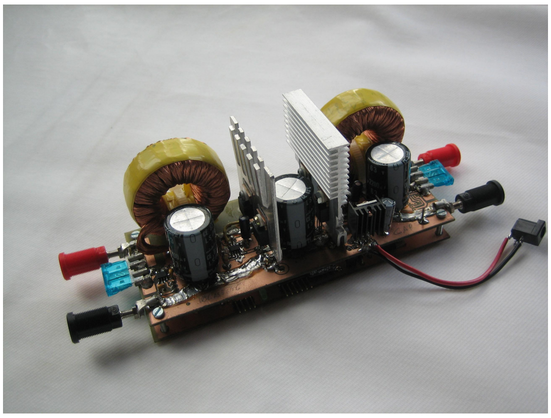

Figure 8: The designed split-PI converter

Figure 8 shows the built split-PI converter. The split-PI topology is not an easy topology to control. The PWM waveforms are complex and hard to integrate in a discrete digital circuit. Therefore a Digital Signal Processor (DSP) with 16-bit RISC (Reduced Instruction Set Computer) architecture was used. The DSP does not only generate the PWM pulses for the MOSFET bridge, it also monitors the voltage and current on both sides on the bridge trough a fast simultaneous sampling Analog-Digital Converter (ADC), and communicates trough a RS-485 full duplex interface. Various systems are software implemented to protect the MOSFET bridge from overcurrents and voltages.
Trough the RS-485 interface the DSP can receive its setpoints from a PC (section 2.3) with a custom MATLAB/Simulink model running or another embedded controller (section 2.2). The DSP also sends its realtime current and voltage measurements over this bus, which can be used by the PC or embedded controller for visualisation and logging.
The electronics are built modular to make it easy to swap power stage modules when a higher voltage or current rating is needed.

2.2 Visualisation and datalogging unit.

Figure 9: Visualisation and datalogging unit

2.2.1 Features

The visualisation and data logging unit on the steering column enables the user to monitor all voltages and currents, and check the state of the DSP and mosfet bridge. It is based on an 8-bit microcontroller with a 128×64 graphic LCD with touch screen interface. The unit also logs data on a SD flash memory card which can be later imported into Microsoft Excel trough the USB interface. This is implemented to make it easier for students to analyze the power flows during cycling.

2.2.2 Controlling the DSP trough the visualisation and datalogging unit.

The visualisation and datalogging unit converts the analog setpoint from the twist grip to a digital setpoint, and sends it to the DSP trough the RS-485 Fieldbus. It receives real time voltages and currents from the DSP, and displays them on the graphic LCD. With the Touch screen the user can customize the controller (see Fig. 10).

Figure 10: The touchscreen

2.3 Controlling the motor drive with MATLAB/Simulink

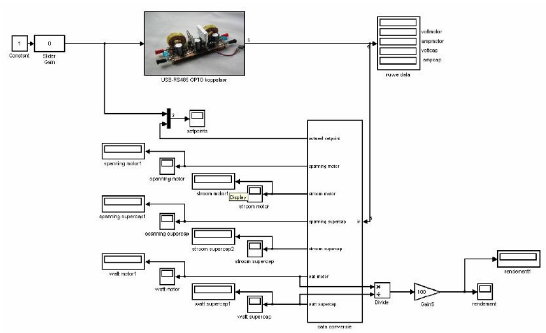

Figure 11: MATLAB/Simulink model

In lab conditions, the e-bike can be controlled by a laptop running MATLAB[9]/Simulink[10]. Setpoints can be generated on the PC or can come from the visualisation and datalogging unit via the twist-grip. The MATLAB/Simulink model can easily be modified by the user to accomodate different kinds of tests. Setpoints are now generated by a slider gain, but this can be easily adapted to S-curves or preprogrammed trajectories by using standard Simulink blocks. The current MATLAB model logs voltage, current and power at both sides of the bridge, and calculates the efficiency of the power converter. The intuitive MATLAB interface makes it easy to monitor and evaluate all parameters after or during the tests.
The connected PC is fully galvanically isolated from the e-bike's electronics for additional safety by a custom developed isolated USB to RS-485 fieldbus interface (see Fig. 3). Only one free USB port is required on the computer, which enables it to work with almost any PC.

2.4 The Fast charger

2.4.1 Charging Ultracaps

Charging UltraCaps is different from charging batteries. Since UltraCaps behave essentially just like normal capacitors, basically, all a charger has to do is putting *electric charge* on the UltraCaps. However there are 2 important points that ask special attention.

1. The UltraCaps may not be overcharged! Therefore the applied power supply should limit the maximum voltage over the UltraCap module.

2. A complete discharged UltraCap module has an output voltage of $0V$ and a low equivalent series resistance (ESR).
   This might be a problem when charging from a power supply that behaves like a voltage source: some of these power supplies will shut down at these short circuit conditions, others are able to limit the current by folding back the voltage. The last technique is the one that was used in our laboratory DC power supply.

However, by using this lab power supply some practical problems occurred. When the empty UltraCap module was connected to the lab power supply, only gradually increasing the supply voltage could prevent the power supply from shutting down. Unfortunately this manual technique left lot of space for errors: the voltage might be set too high by the user, resulting in blowing the UltraCaps, or the current might be too high by increasing the voltage too fast, resulting in the damage of the series regulator of the power supply. Other drawbacks of the lab power supply were the speed of charging and the heavy weight, which complicated the mounting on the e-bike.

Figure 12: The Ultracap fast charger

2.4.2 Design of a fast charger

Based on a modified power stage of a PC power supply, a fast charger was developed which is able to charge the UltraCaps in less then 5 minutes. It is very compact and light due to the modern half bridge isolated flyback technology used nowadays in most modern PC power supplies. It is so small and light it can be mounted on the bike itself, allowing to fully recharge in only 5 minutes at any 50/60hz 240/120VAC wall socket. The charging proces is microprocessor controlled and monitored. The charger is essentially a current source which limits the charging voltage to 16.2volts, the maximum voltage of the UltraCap module. The user can see the charging currrent and voltage and an indication of the charge time left on the 16×2 character display mounted on top of the supply. Further development may still increase the charging current capabilities of the supply.

3 Test results

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.

- With one full UltraCap charge, the initial test showed the e-bike has a range of $1.4km$ on UltraCap power only. The average speed during this test was $14.6km/h$, maximum speed was $27.1km/h$, without pedalling!
- At $27.1km/h$ the motor produces a back emf of $30V$, and delivers a maximum power of $307W$. This is well above the maximum continuous rated power of the hub motor.
- The maximum speed without help from the cyclist decreases as the UltraCap voltage decreases, because the current levels in the boost converter are limited.
- The range of the e-bike may seem very small, but will be drastically increase when speed is lowered, or when the electric bicycle is used as a pedelec.
- The regenerative braking system also proved to work well from speeds above $5km/h$. At lower speeds the back emf voltage is too low to brake effectively. Further testing will have to be done to explore the limits of the braking system.

4 Conclusions

Figure 13: The UltraCap e-bike prototype

A stable platform to test the use of UltraCaps in electric bicycles has been succesfully developed. When using Ultracaps a special power converter topology is neccesary to get as much energy as possible from the UltraCaps. The Split-Pi topology is very well suited to get the maximum potential out of the Ultracaps. A split-PI motor drive controlled by a DSP, SEPIC converters to supply the electronics, a fast charger for the UltraCaps, a data logging and visualisation unit,... were all developed from scratch, only using low cost power electronics.
Ultracaps do not pack as much energy as battery technologies, but have vast advantages when it comes to fast charging and long life. For an e-bike a long range is not so important when you can recharge in less then 5 minutes.
In spite of the promising first tests, thorough testing of the e-bike still has to be done. In the near future the evaluation of the UltraCap e-bike concept for daily use and the evaluation of the efficiency of regenerative braking will be started.

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Authors

Jan Cappelle graduated in 1999 as electro-mechanical engineer at the Katholieke Universiteit Leuven. In 2008 he obtained a PhD in engineering sciences at the Vrije Universiteit Brussel. His PhD thesis was an objective and subjective study of the performance of electric bicycles. At the KaHo Sint-Lieven engineering department in Ghent, he is a full-time lecturer in electric power systems. His research is mainly in the domain of intelligent energy management, autonomous photovoltaics and spectral responses of solar cells.

Niels Polfliet is graduating this year as an control and automation engineer at the engineering department of KaHo Sint-Lieven in Ghent. This paper is mainly based on work that was done in the framework of his master thesis. His main interests are embedded software developement, Permanent Magnet Brushless DC motor developement and power electronics in general.

Jean-Marc Timmermans graduated in 2003 as an Electromechanical Engineer at the Vrije Universiteit Brussel. His master thesis dealt with the development of a test bench for electric bicycles. As an academic assistant, he was involved in projects about the evaluation of the environmental impact of both conventional and alternative vehicles and was also involved in the development and evaluation of electric bikes for postal delivery use. Further research goes to the evaluation and optimization of hybrid electric drive trains for vehicles.