BIDIRECTIONAL DC/DC CONVERTERS FOR SUPERCAPACITOR APPLICATIONS

Research activities on supercapacitor applications at the University of Roma “La Sapienza”

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Outline

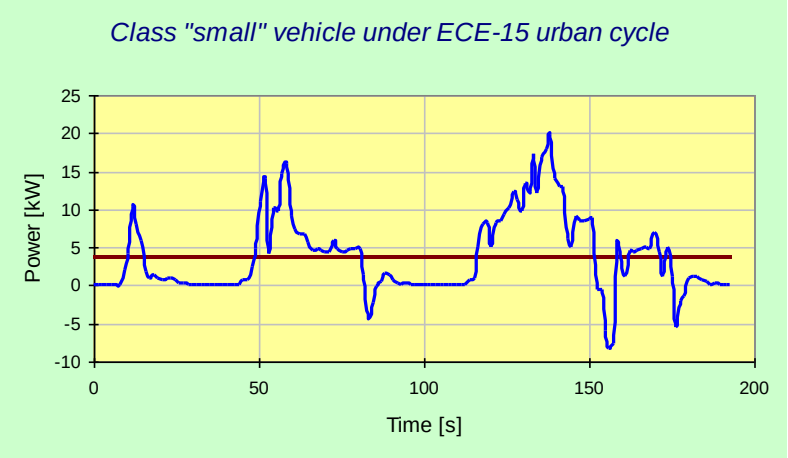
- Introduction
- Need for bidirectional DC/DC converters
- Supercapacitors connections
  - Series layout
  - Cascade layout
  - Parallel layout
- Latest developments
- Control issues
- Conclusions

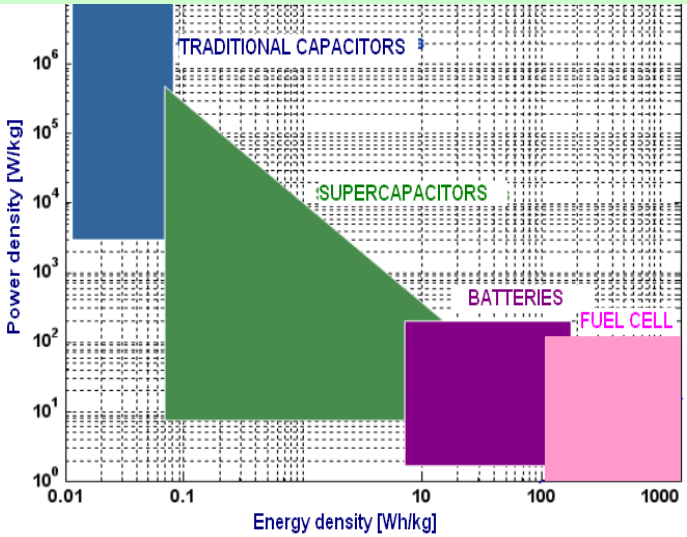
Introduction

- Research on the subject at the Dept. of Electrical Engineering of the University of Roma “La Sapienza” started in 1994 with the acquisition of 24 supercapacitors from Panasonic, rated 2.3V 470F
- Aim of this presentation is to share some of the experience developed along these years

Need for bidirectional DC/DC converters /1

- In many applications (e.g. traction) the peak power is considerably higher than the average power (related to energy)
- Batteries (and fuel cells): ENERGY SOURCES
- Supercapacitors (SCs): POWER SOURCES
- It is possible to combine the two sources to optimize the whole system

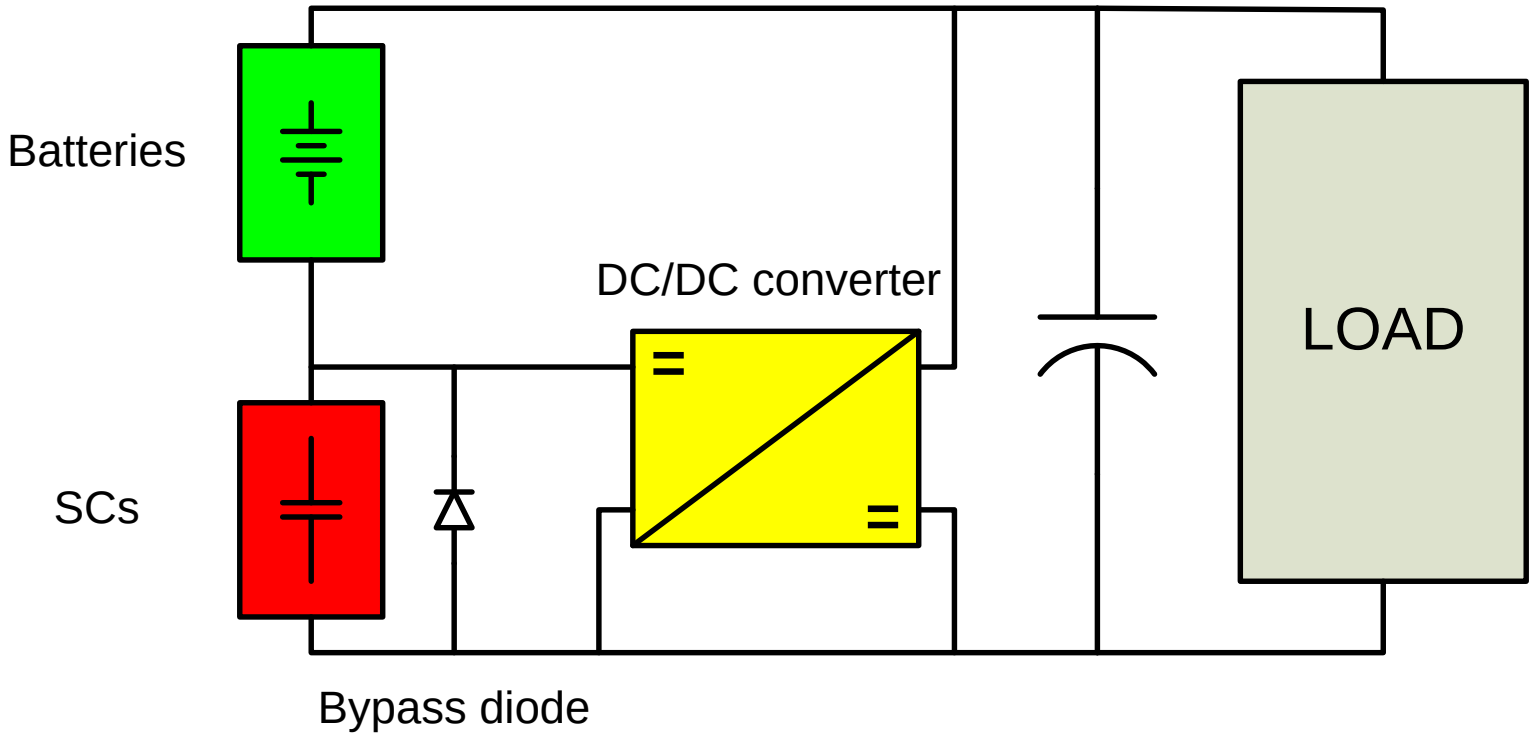




Need for bidirectional DC/DC converters /2

- SCs cannot be connected directly in parallel with batteries:
  - Voltage variation limited by batteries (poor utilization of stored SC energy)
  - SCs and batteries have similar internal resistance (non optimal load sharing)
  - It is not possible to control the power flow
- (Bidirectional) DC/DC converters are an effective way to take complete control of the power flow and sharing between the sources.

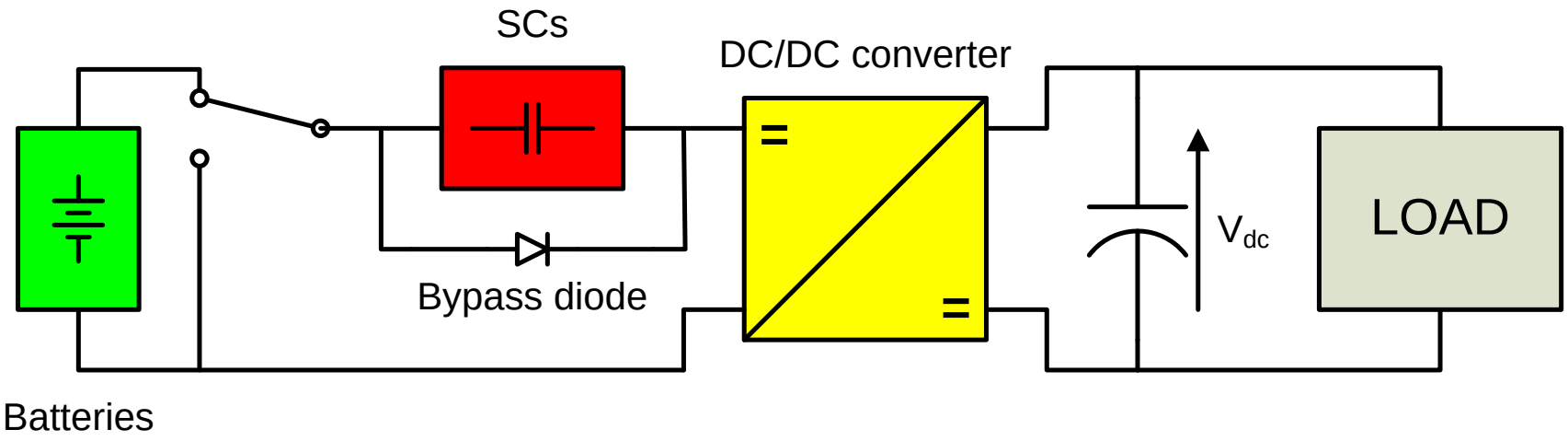
SC connections: series layout /1



SC connections: series layout /2

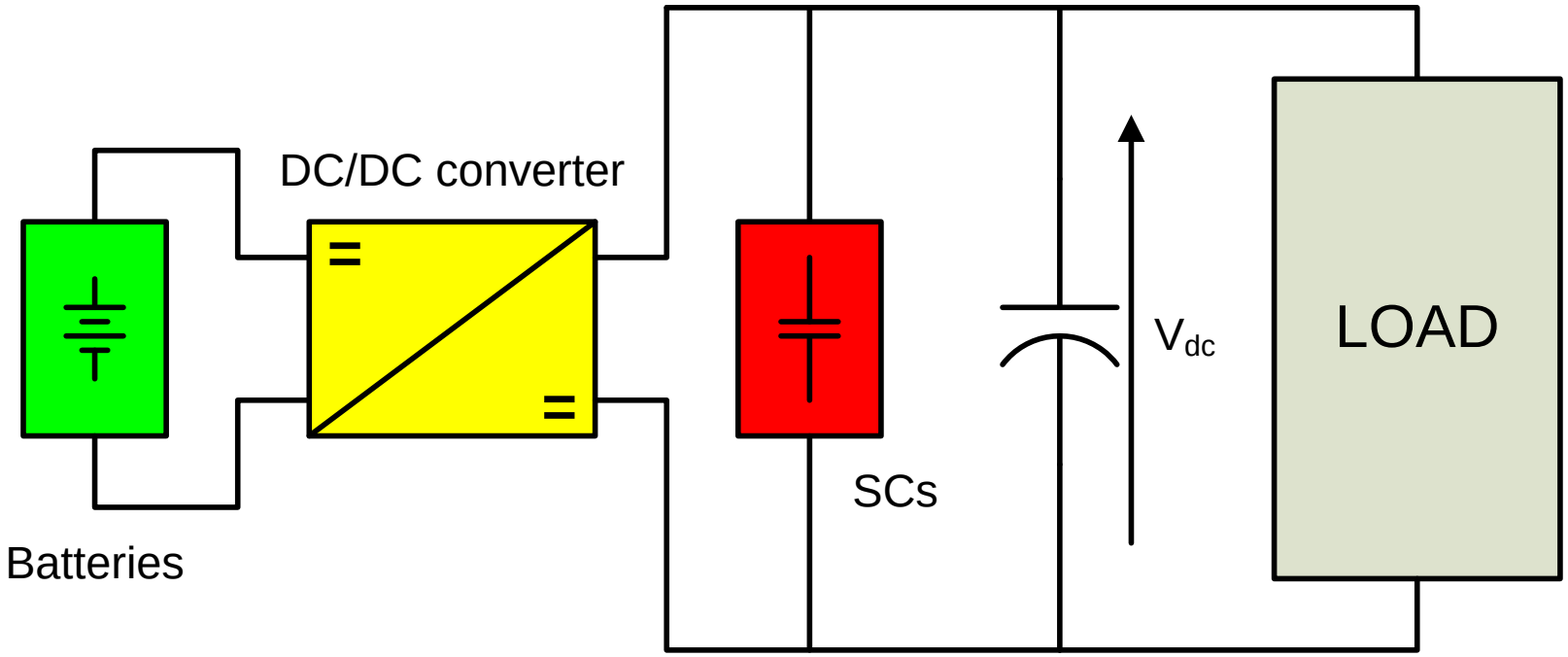
- Advantages
  - Simple layout
  - Independent voltages
  - Full energy utilisation
  - DC/DC converter:
    - Non bidirectional
    - (Sized for peak power)
- Disadvantages
  - Same current in batteries and SC
  - Poor braking efficiency
  - Slow dynamic response
  - Power sharing depends on voltage ratio
  - SCs cannot be charged by the batteries

SC connections: series layout /3



- A. Di Napoli, F. Caricchi, F. Crescimbini, "*Ultracapacitor based bidirectional DC-DC converter prototype for recovery of the braking energy in EV motor drives",* 6th European Conf. on Power Electronics and Applications (EPE'95), Sevilla (Spain), September 1995.

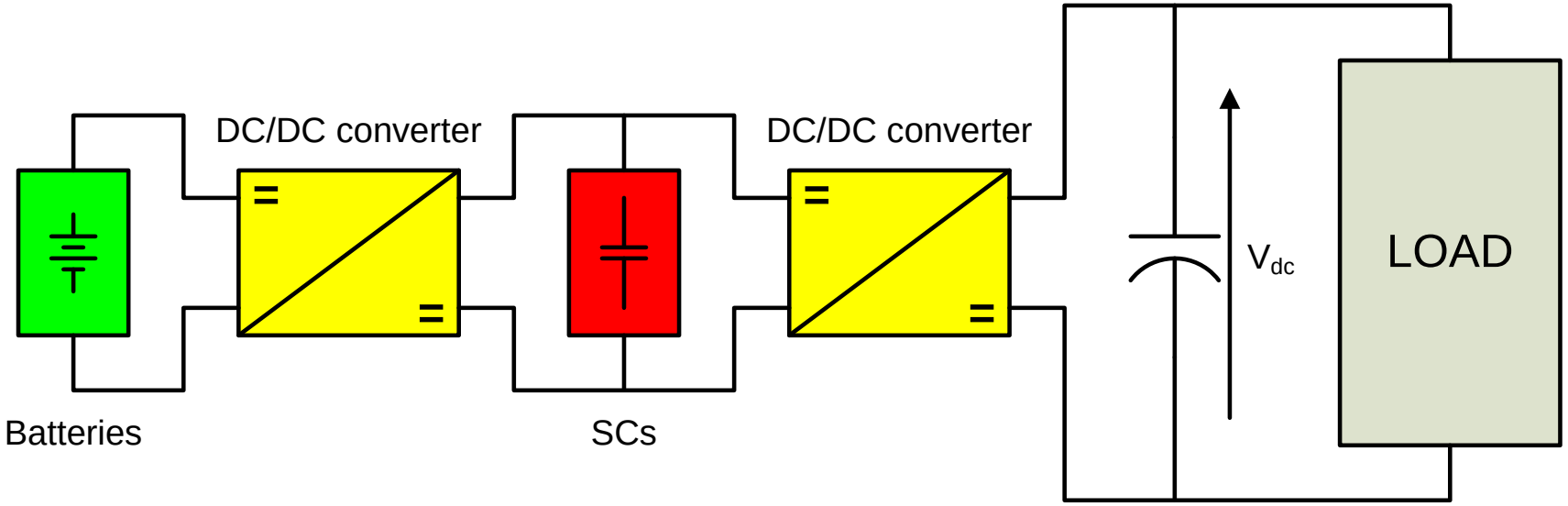
SC connections: cascade layout /1



SC connections: cascade layout /2

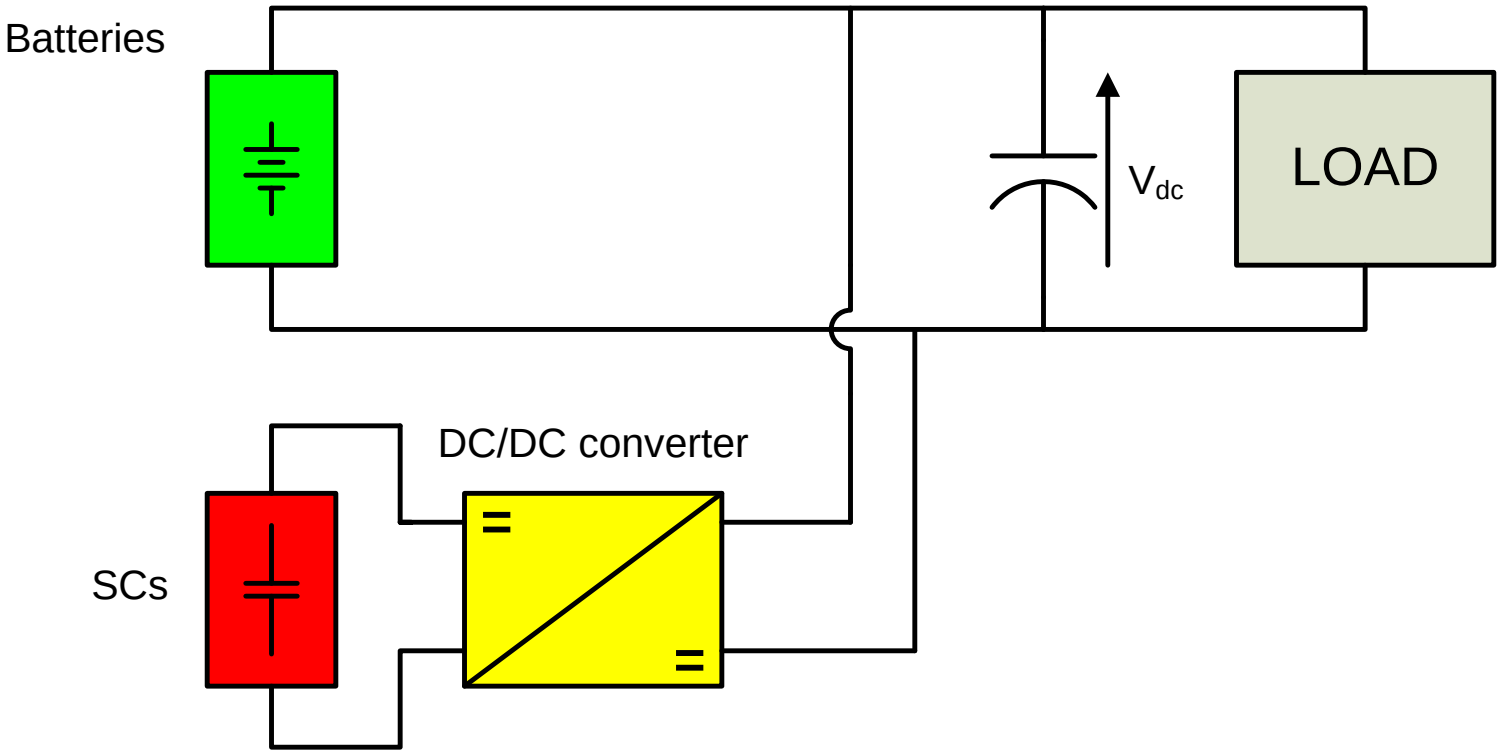
- Advantages
  - Quite simple layout
  - SC charging from both batteries and motor
  - DC/DC converter:
    - Non bidirectional
    - Sized for average power
- Disadvantages
  - Large number of SC connected in series
  - SCs cannot be fully discharged
  - Oversizing of the SC tank

SC connections: cascade layout /3



- G.P. Barra, P.A. Genova, P. Morhet, G.P. Brusaglino, P. Rena, "*Supercapacitors for EV, results, trends and industrial perspectives",* 13th Electric Vehicle Symposium (EVS-13), Osaka (Japan), October 1996.
- P. Mestre, S. Astier, "*Application of supercapacitors and influence of the drive control strategies on the performances of on electric vehicle",* 15th Electric Vehicle Symposium (EVS-15), Bruxelles (Belgium), October 1998.

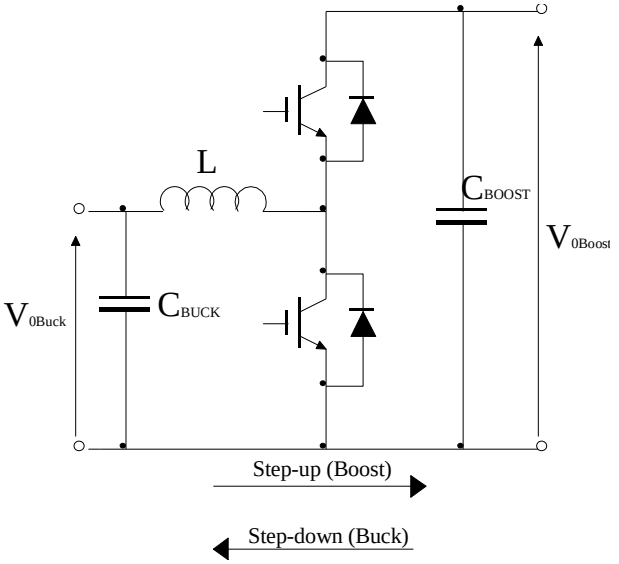
SC connections: parallel layout /1



SC connections: parallel layout /2

- Advantages
  - Reduced number of SC connected in series
  - SC charging from both batteries and motor
  - Almost full energy utilisation
  - High efficiency during regenerative braking
- Disadvantages
  - Need for a power relay to disconnect the batteries
  - DC/DC converter:
    - Bidirectional
    - Sized for peak power

SC connections: parallel layout /3



- High converter efficiency (up to 98%)
- Input/output working voltage ratio as far as 0.3 (reduced SC tank size)
- Very effective load sharing

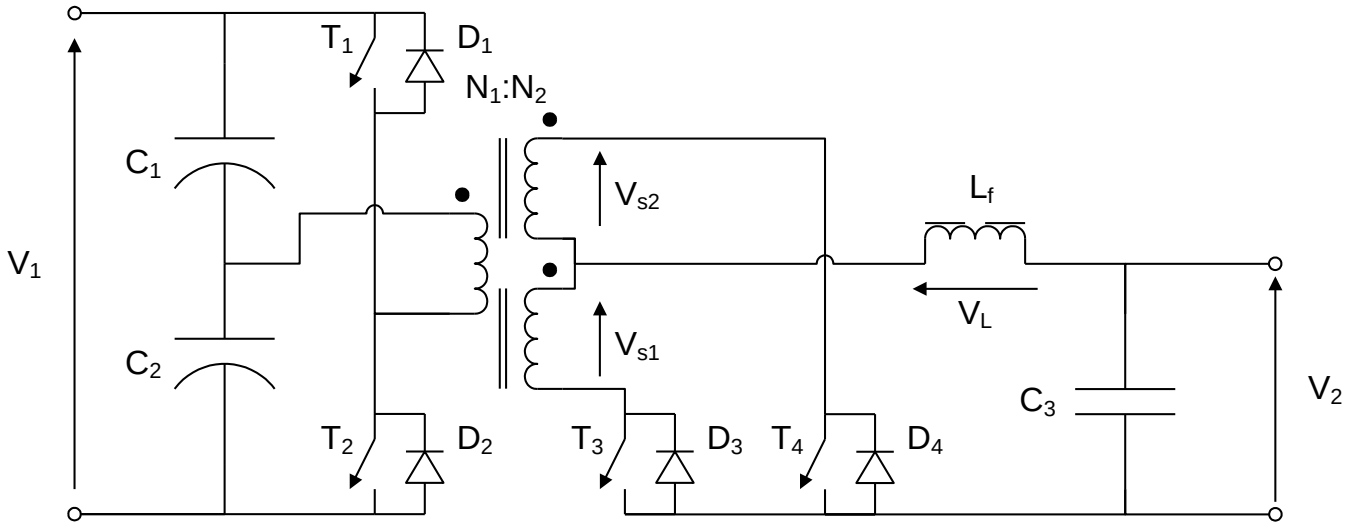
- M. Schmid, "*Electric Double-Layer Capacitor in a Hybrid Vehicle - Basic Considerations and Simulation Results*", 13th Electric Vehicle Symposium (EVS-13), Osaka (Japan), October 1996.
- F. Caricchi, F. Crescimbini, F. Giulii Capponi, L. Solero, *"Ultracapacitors employment in supply systems for EV motor drives: theoretical study and experimental results",* 14th Electric Vehicle Symposium (EVS-14), Orlando (Florida, USA), December 1997.

SCs sizing considerations

- Usually, SC tank size does not depend on the required power, but on the energy to be stored during transients
- In any case, usually a low voltage SC tank can meet the requirements
- Moreover, it is desirable to connect them in parallel rather than in series (cell balancing)
- On the other side, the dc link voltage V_{dc} is usually fixed around 300-500 V
- In order not to oversize the SC tank, bidirectional DC/DC converters with high voltage ratios are needed
- The conventional solution, the up/down bidirectional converter shows:
  - Poor SUR at high voltage ratios
  - In any case, voltage ratio is limited to ~4

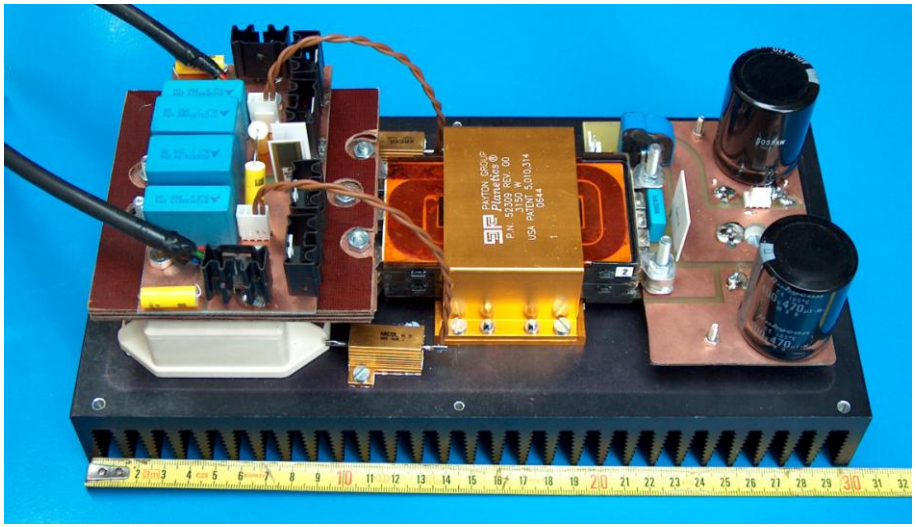
Latest developments /1

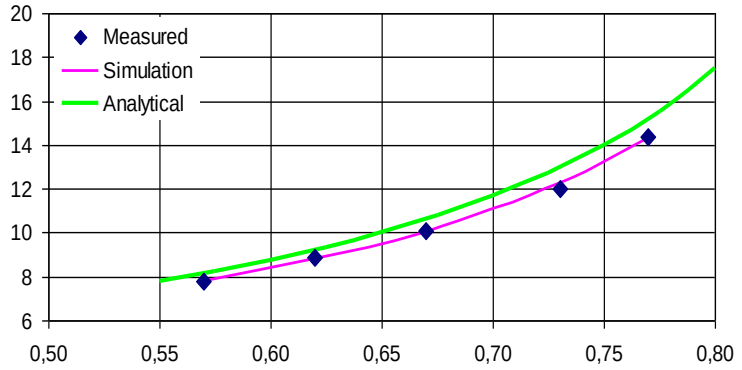
HBCS (Half Bridge Current Source) Converter



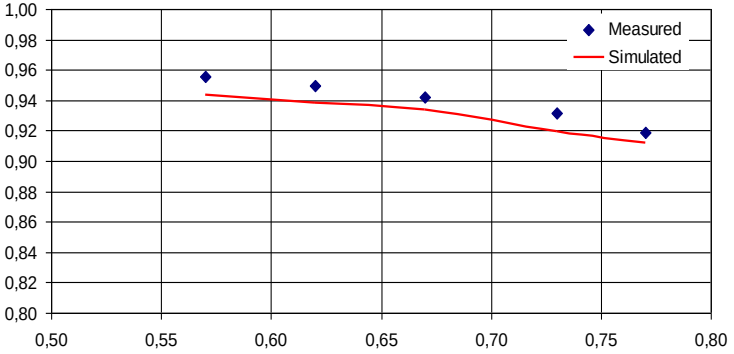
- This converter configuration is very suitable when high voltage ratios are required (better sizing of the converter and high efficiency)

Latest developments /2





Voltage ratio vs. duty cycle



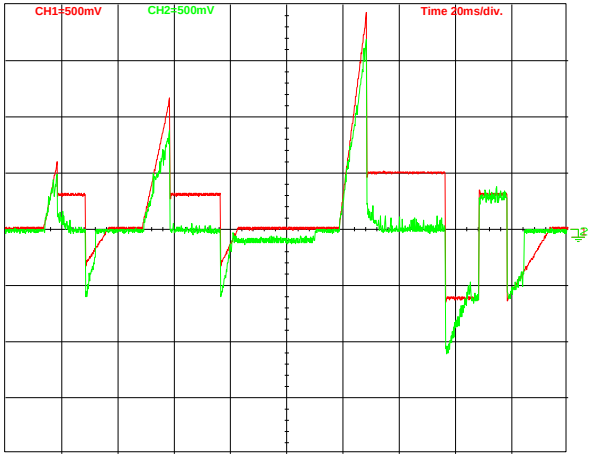
Efficiency vs. duty cycle

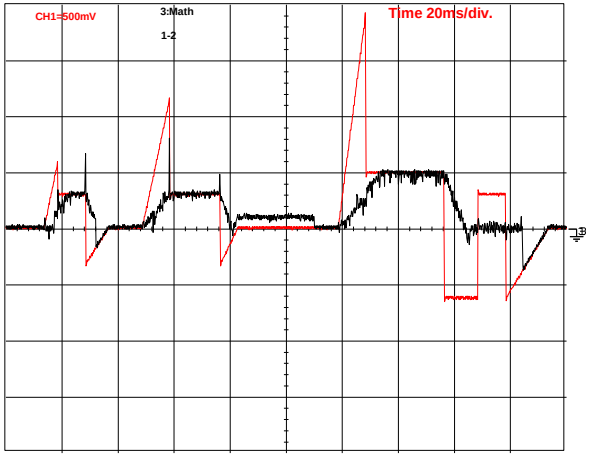
- F. Giulii Capponi, P. Santoro, E. Crescenzi, *"HBCS Converter: A Bidirectional DC/DC Converter For Optimal Power Flow Regulation in Supercapacitor Applications".* Proc. of IAS 2007, New Orleans, LA (USA), 23-27 September 2007.

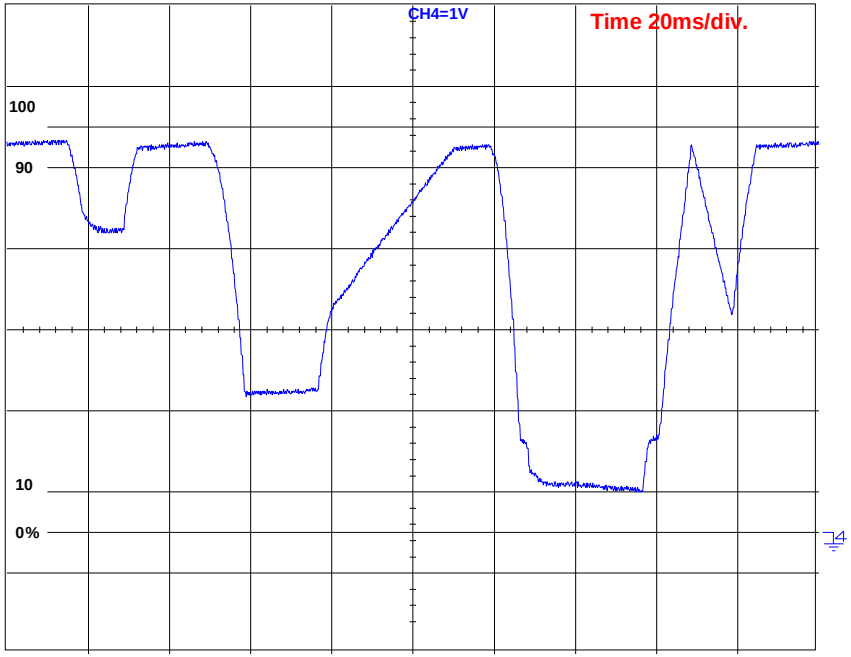
Control issues

- Hypothesis: V_{dc}= const.
- Then power is proportional to current
- $P_{load}=P_{SC}+P_{batt} \rightarrow I_{load}=I_{SC}+I_{batt}$
- Control strategy:
  - Define admissible battery current (I_{batt}^*)
  - $I_{SC}^*=I_{load} - I_{batt}^*$
  - Control the current in the converter such that $I_{SC}=I_{SC}^*$
- In these conditions, the power required by the load is always balanced by the combination of P_{SC} and P_{batt} (initial hypothesis is verified)
- Attention must be given to management of limit conditions (SOC of SC must be monitored)

Control issues







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Potential research areas

- Applications
  - Elevators
  - Satellites
  - UPS and feeding of critical users
- Testing and modelling
  - Effect of aging
  - Effect of charge/discharge current
  - Modelling to enhance power flow control