



Vrije Universiteit Brussel
Department of Electrical Engineering
and Energy Technology (Etec)

Tetra Econocap “gebruik van supercondensatoren met geassocieerde DC-omvormers om energiebesparingen te verwezenlijken in aandrijfsystemen”



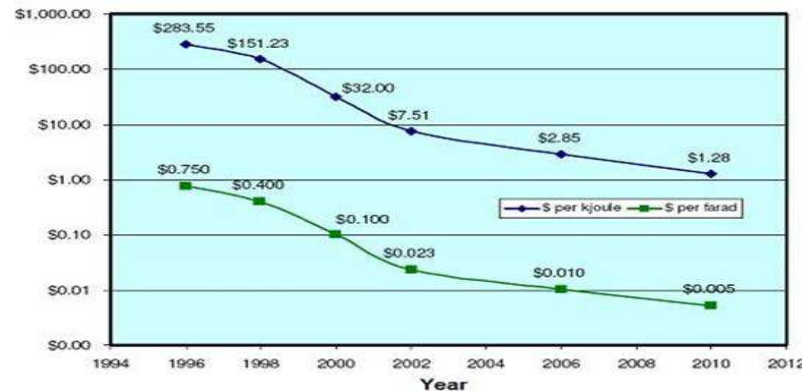
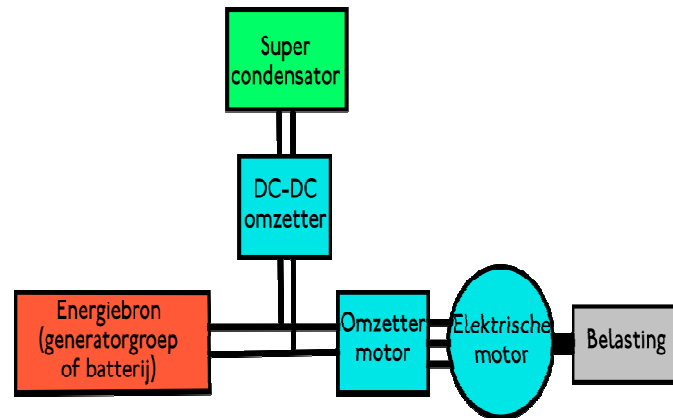
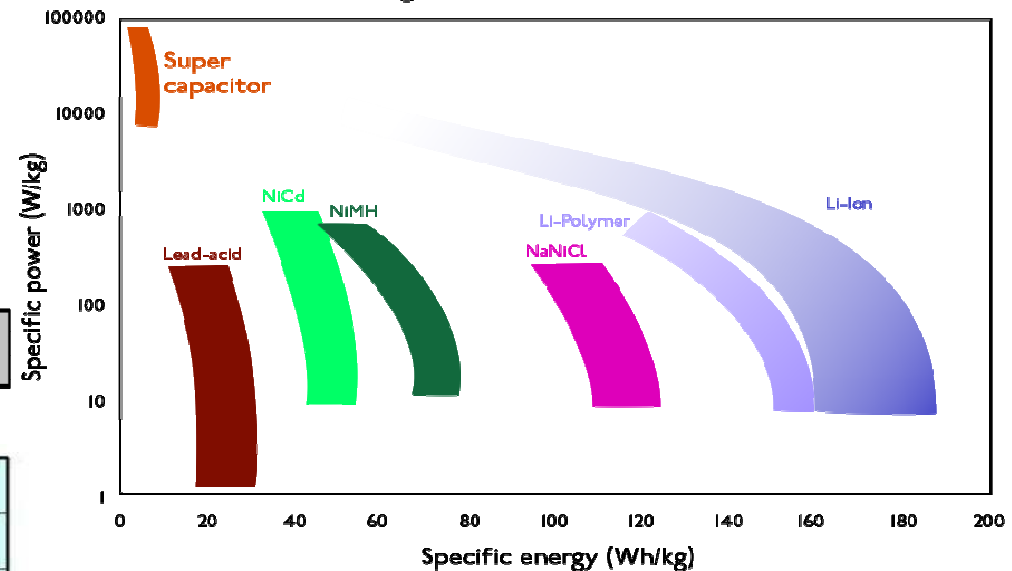
Inhoud

- Technologieverkenning & selectie van potentiële toepassingen
- Modelisatie
- Levensduuranalyse
- Experimentele analyses
- Karakterisatie van # lithium-ion batterijen
- Kosten-batenanalyse
- Conclusie



Technologieverkenning

Ragone chart (cell level)



- R. Kötz, M. Carlen, *Principles and applications of electrochemical capacitors*, *Electrochimica Acta*, The Journal of the International Society of Electrochemistry, ISSN 0013-4686, Volume 45, Number 15, 3 May 2000, pp. 2483-2498(16)
- P. Van den Bossche, F. Vergels, J. Van Mierlo, J. Matheys, W. Van Autenboer, *SUBAT: an assessment of sustainable battery technology*, *Journal of Power Sources*, vol. 162, nr. 2, pp. 7, 2006, Impact factor: 2.770, impact year: 2005



Technologieverkenning

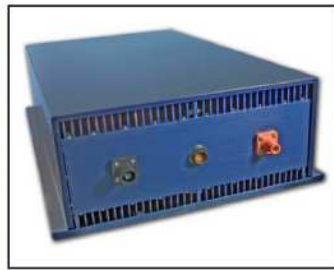


- **Electric rail**
 - SITRAS installations in operation since 2001
 - Up to 250k cycles per year
 - Energy saving and voltage stabilization
- **Fork lifts**
 - Proton Power Systems
 - BOOSTCAPs qualified for fuel cell power fork lifts
 - Fuel cell combined with EDLCs
- **Scania Series Hybrid Bus**
 - Up to 25% fuel saving
 - 90% CO₂ reduction

•R. Kötz, M. Carlen, *Principles and applications of electrochemical capacitors*, Electrochimica Acta, The Journal of the International Society of Electrochemistry, ISSN 0013-4686, Volume 45, Number 15, 3 May 2000, pp. 2483-2498(16)
Rufer A, "A Supercapacitor-Based Energy-Storage System for Elevators With Soft Commutated Interface", IEEE Transactions on industry applications, vol. 38, no. 5, 2002



Technologieverkenning



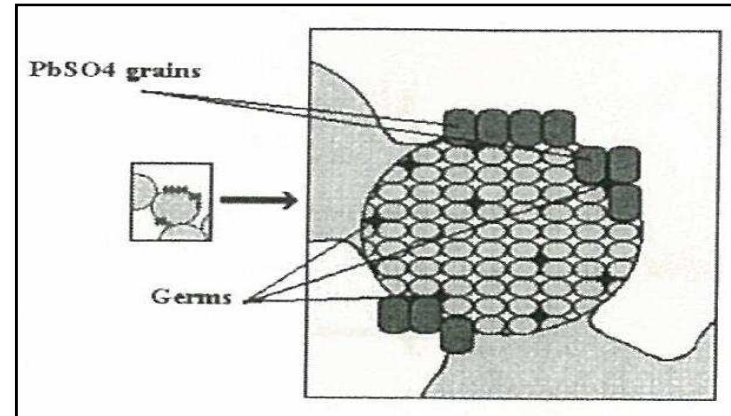
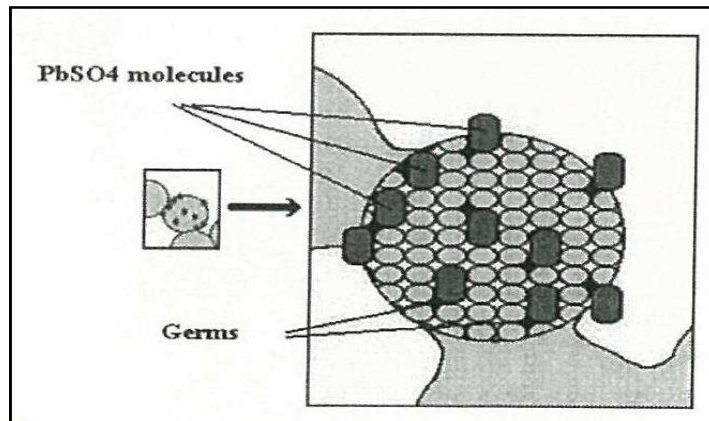
- **Windmills**
 - Burst power to trim blades, since 2003
 - Up to 3 X 128 EDLCs per wind mill
 - More than 500.000 BCAP0350 installed
- **Aerospace**
 - Burst power for door opening
 - 16X56 EDLCs
 - Useful life 25 years, 140.00 flight hours
 - BOOSTCAP passed Airbus qualification testing in 2004
- **On-vehicle recuperation**
 - Braking energy recuperation
 - Up to 30% energy savings allows longer, faster or more trains in the same network
 - Power up to 300kW per system

Scholten J, "Energy Storage on board of railway vehicles", EPE 2005, Dresden
Scholten J, "Energy Storage on board of railway vehicles", ESSCAP, 2006
Gunselmann W, "Technologies for Increased Energy Efficiency in Railway Systems", EPE 2005, Dresden



Modelisatie (heftruck)

- Dynamische piekbelasting
- Batterijpakket overgedimensioneerd
- Beperkt levensduur



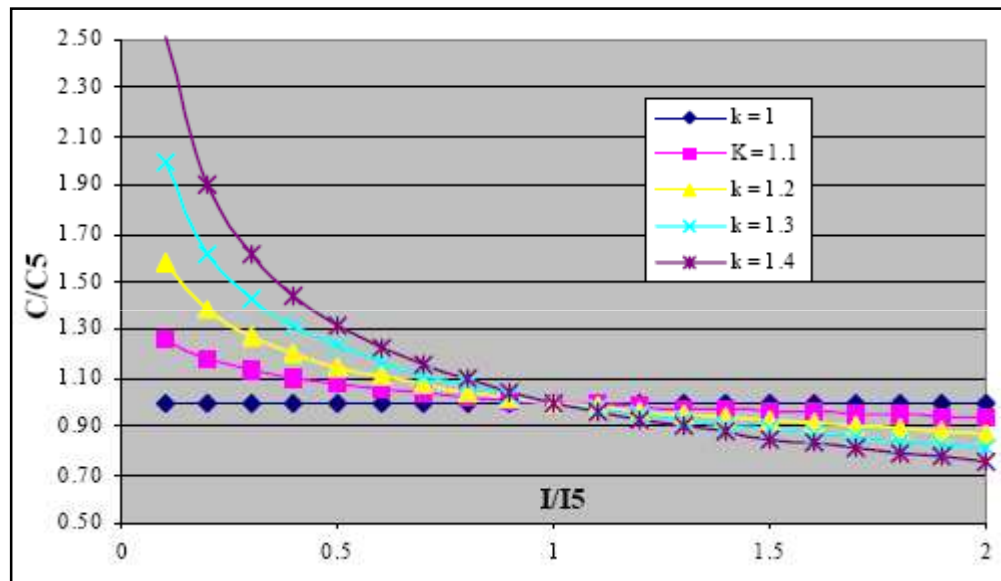
- Verkleining van actieve oppervlakte
- Degradatie van cel

1.O. Caumont, P. Le Moigne, C. Rombaut, X. Mureret, P. Lenain, "Energy Gauge for Lead-Acid Batteries in Electric Vehicles", IEEE transactions on energy conversion, VOL. 15, NO. 3, September 2000. p. 354-360



Modelisatie

- Peukert fenomeen

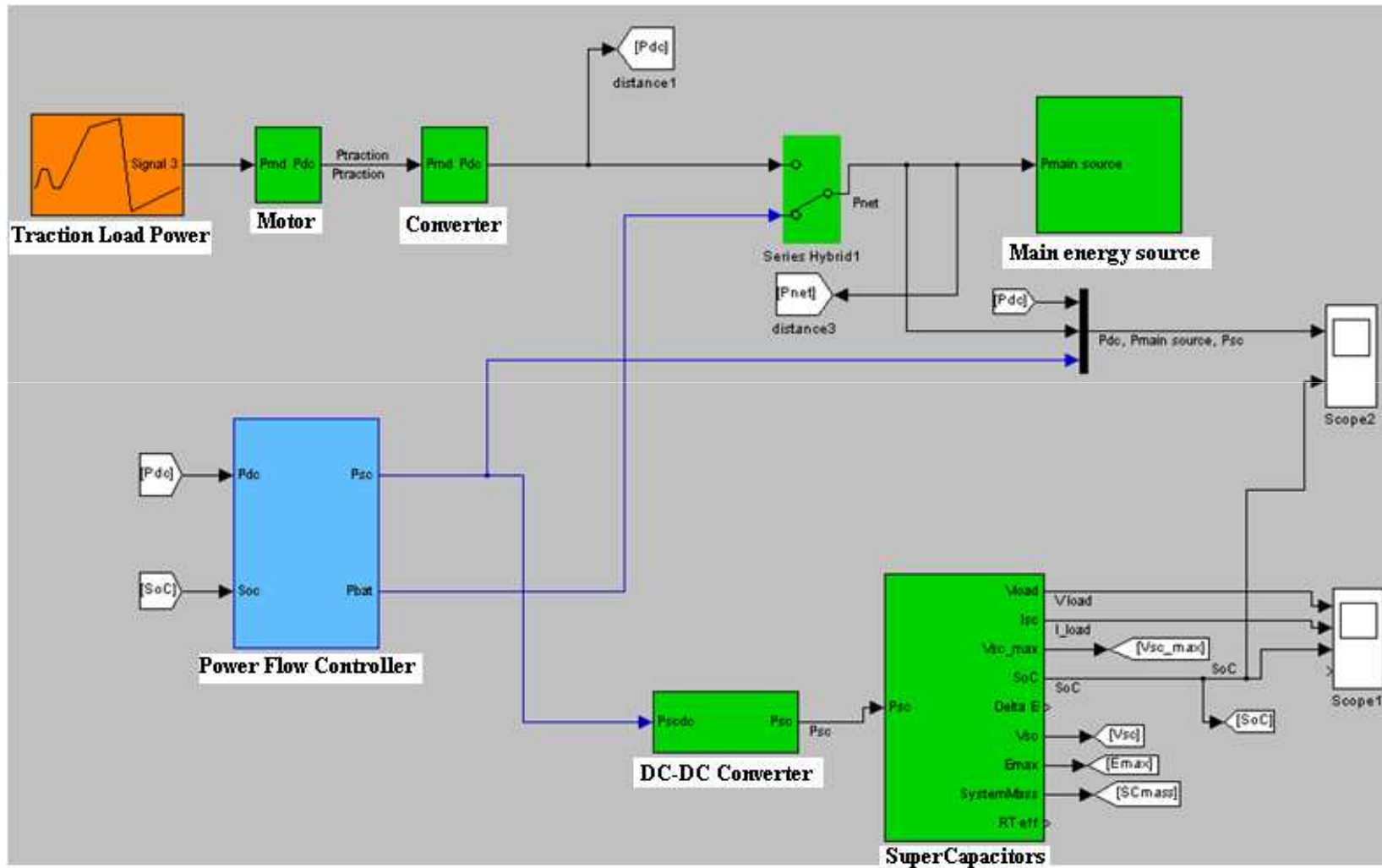


- Meer capaciteit bij kleine stromen

1. "Cursus milieuvriendelijke voertuigen", Joeri Van Mierlo, 2009, VUB, België



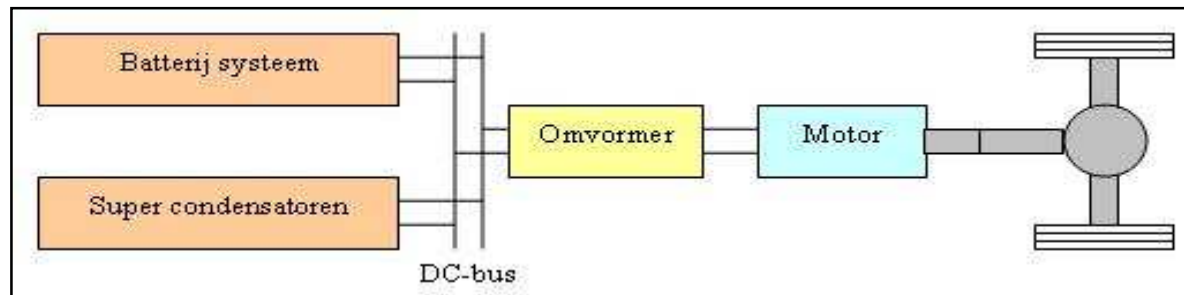
Model



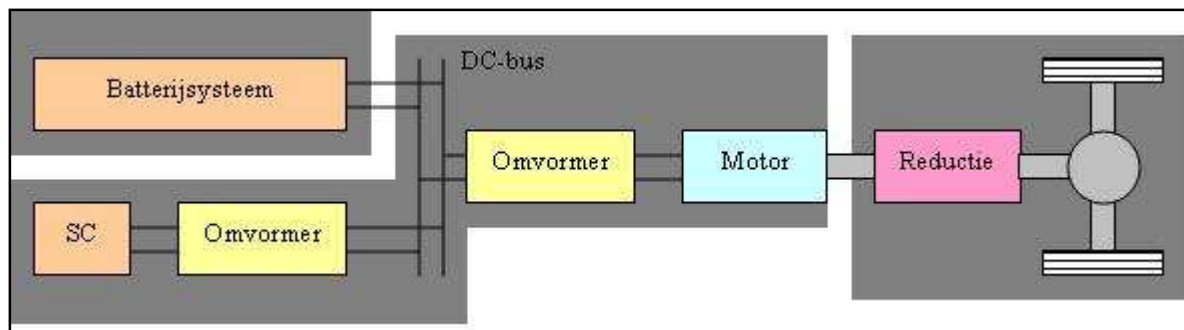


Topologieën

- Parallelschakeling van EDLC met batterij zonder omvormer

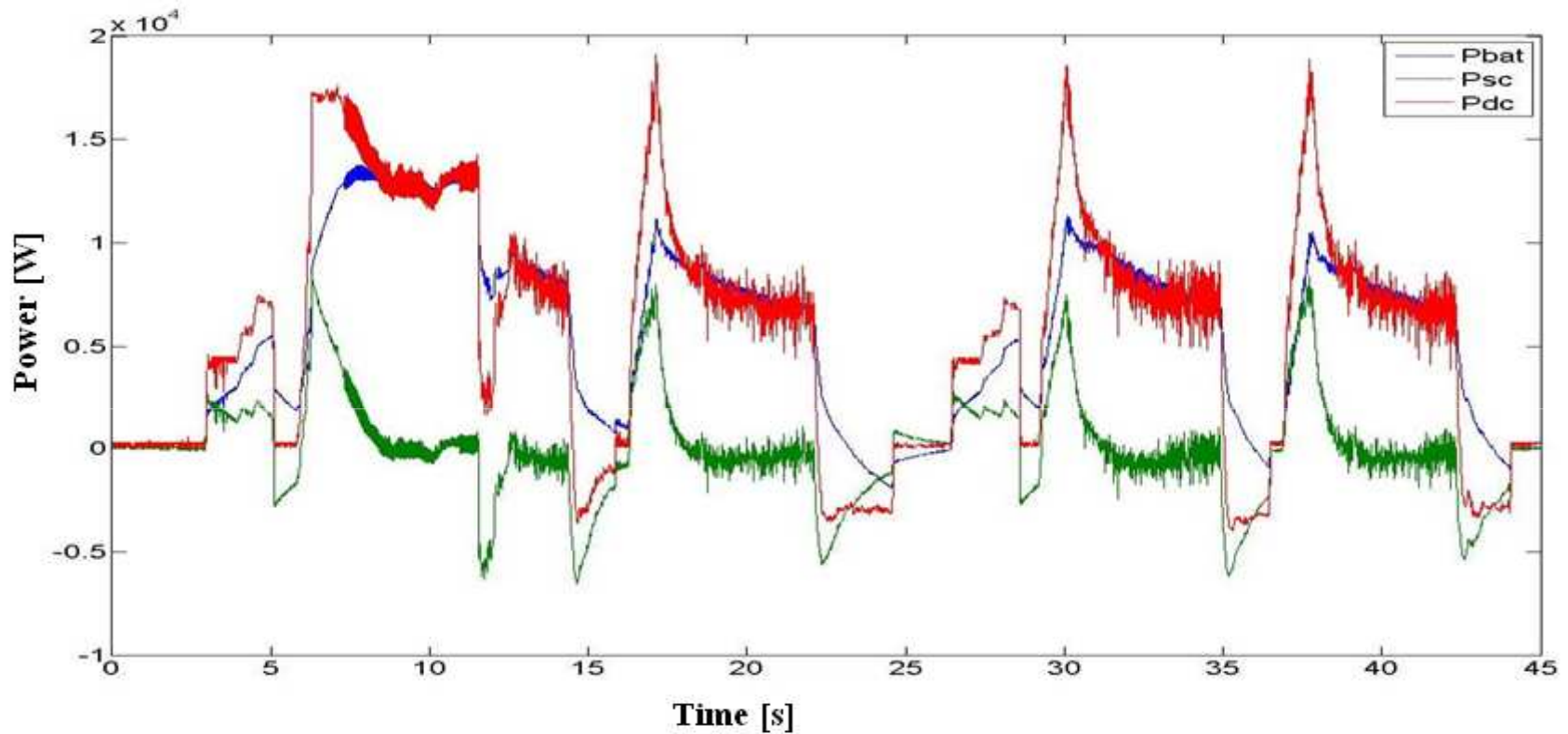


- Met gelijkstroomomvormer





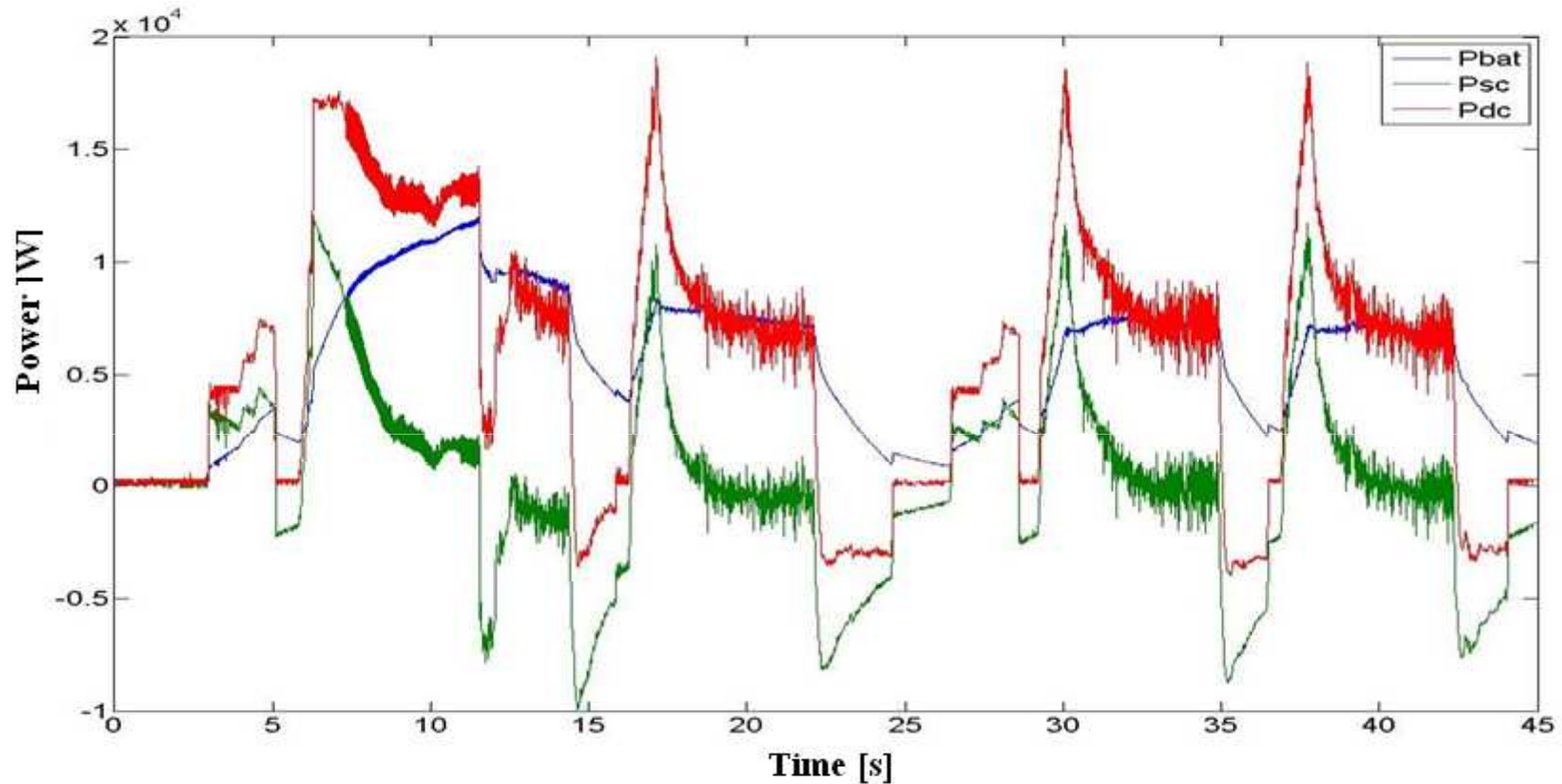
Resultaten



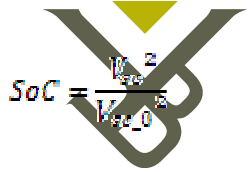
- 1 stack (18 cellen 650F)
- Ontlastingspercentage: 24%
- Gewicht EDLCs: 3.6kg



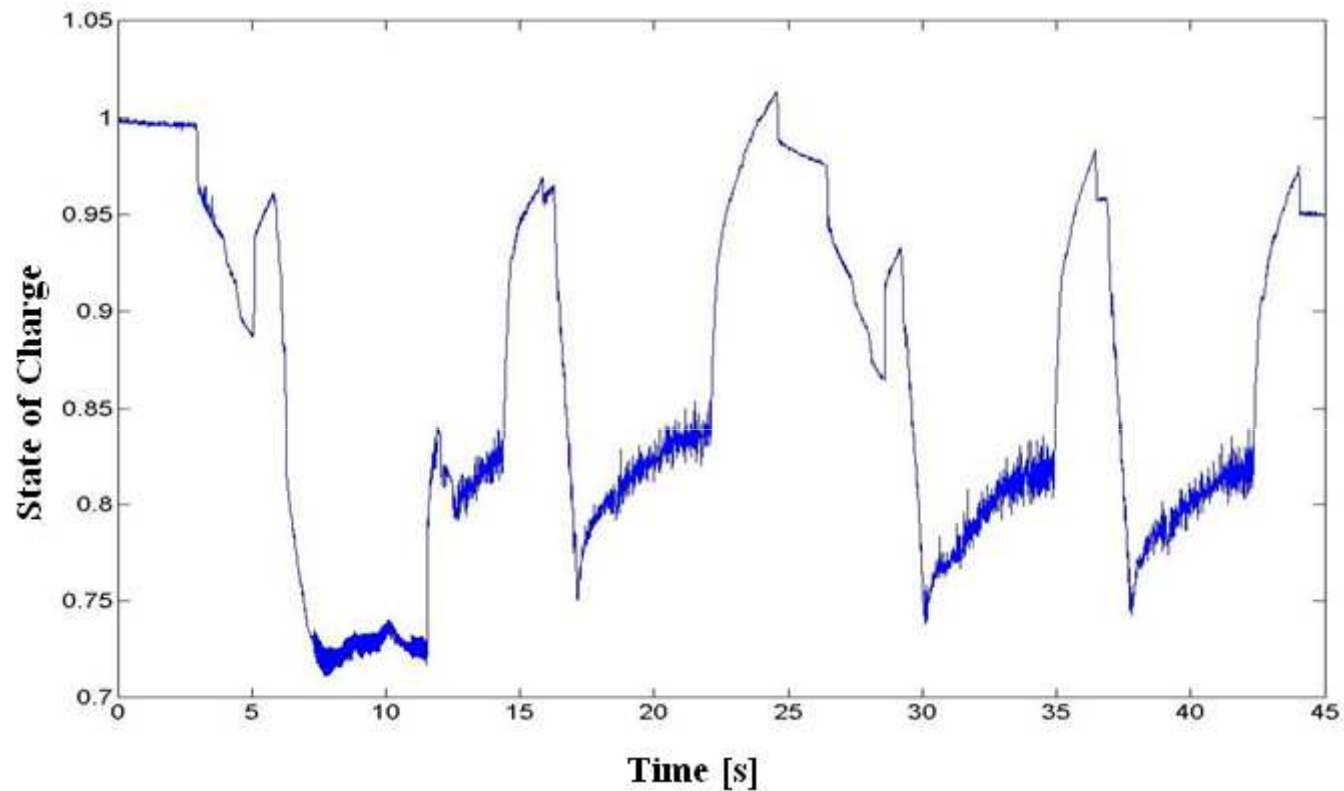
Resultaten



- 2 stacks (18 cellen 650F)
- Ontlastingspercentage: 27%
- Gewicht: 7.2kg



Resultaten



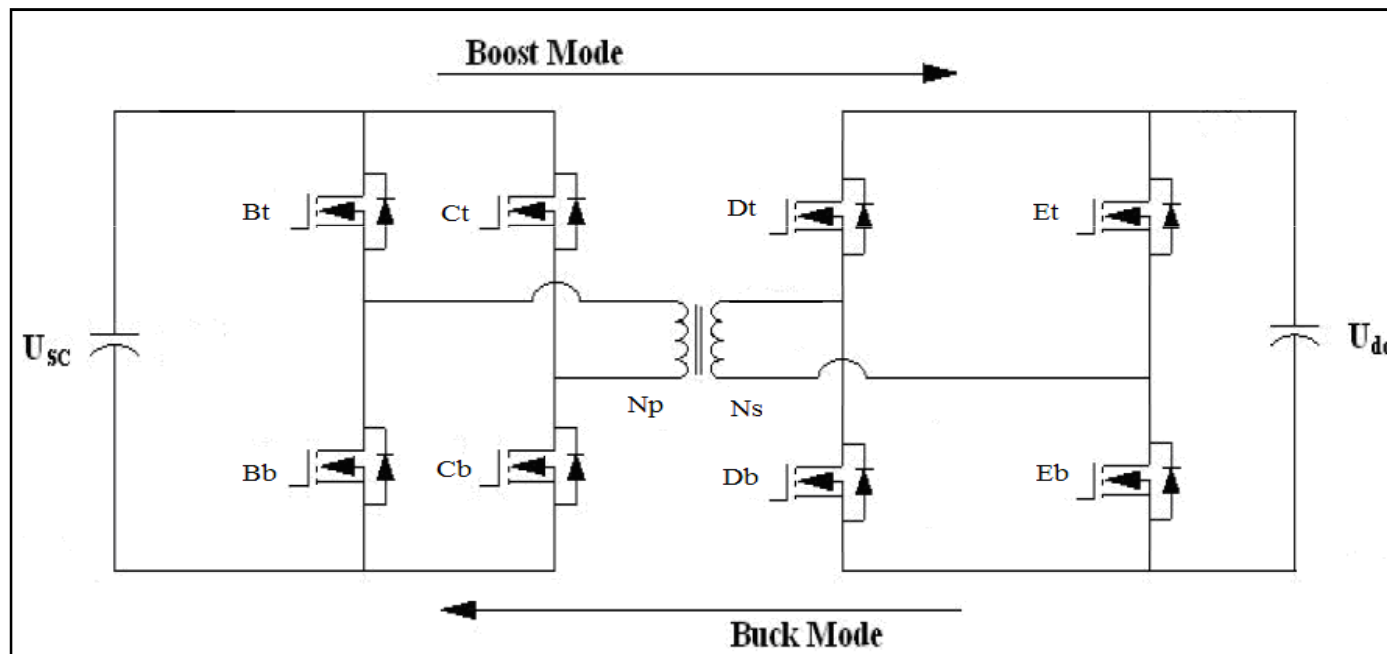
- Beperkte benutting van EDLCs inhoud: 30% SoC

$$E = \frac{1}{2} C \cdot V_{max}^2 - \frac{1}{2} C \cdot V_{min}^2 \quad SoC = \frac{V_{sc}^2}{V_{sc_0}^2}$$



Modelisatie

- Analyse # DC-DC omvormers
- Buck-Boost, Full Bridge en Interleaved multi-channel

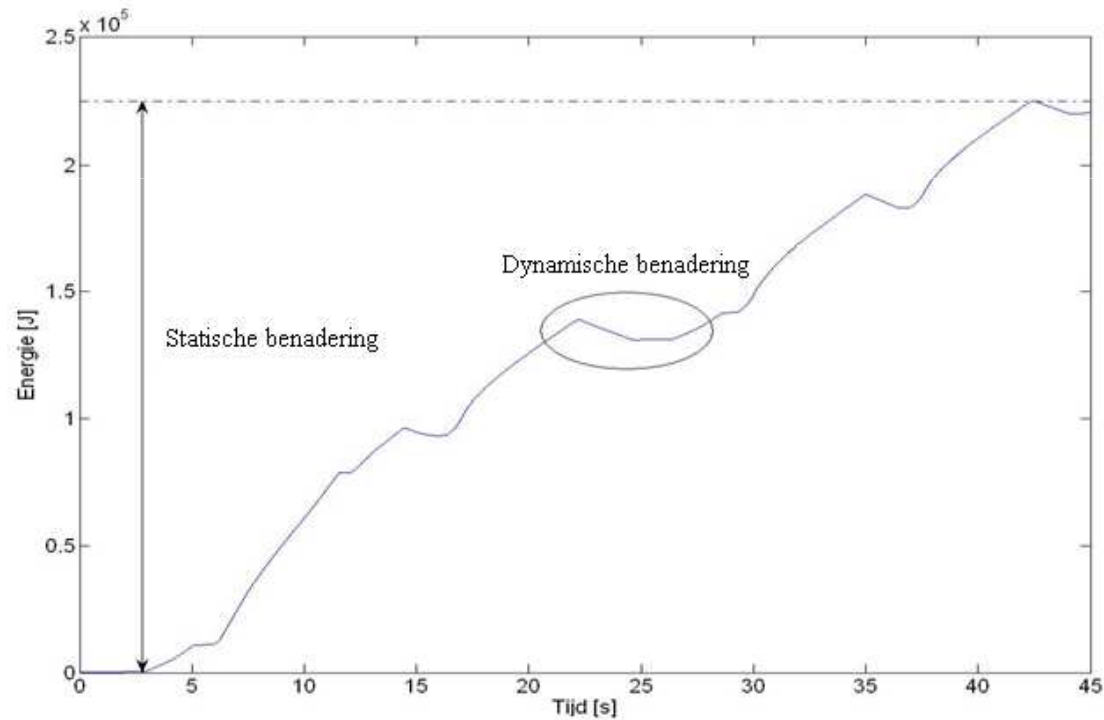


M. Al-Sakka, J. Van Mierlo, H. Gualous, Ph. Lataire, Power Electronics and Applications, 2009, EPE 2009, Barcelona



Modelisatie

- Dimensioneren van het supercondensatorpakket
- Statische en dynamische benaderingswijze



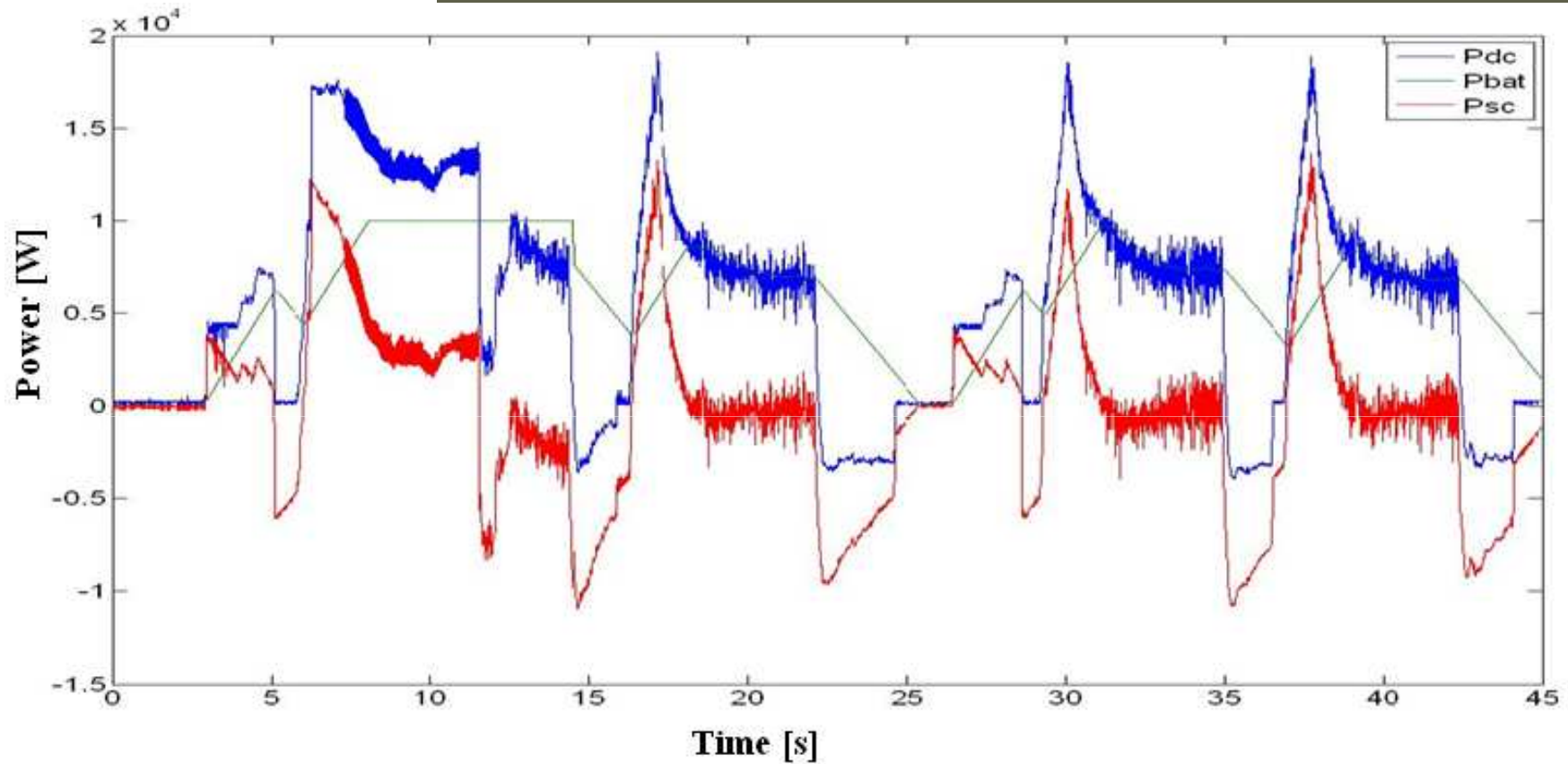


Modelisatie

- 18 cellen in serie (BCAP0650 P270)
- Moving average controle strategie
- Batterij levert gemiddeld vermogen
- EDLC levert piekvermogens



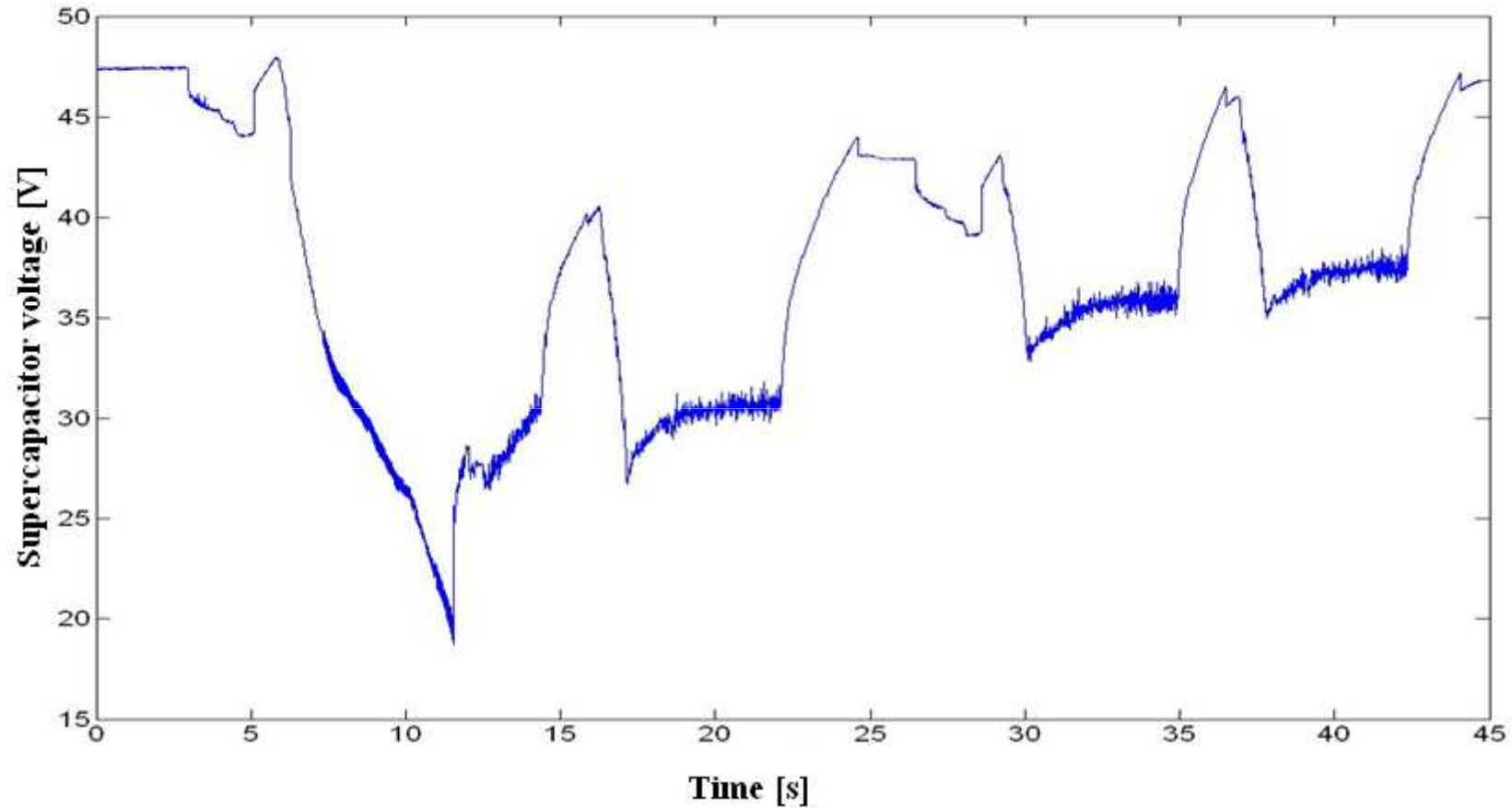
Resultaten



- Ontlastingspercentage: 42%
- Dimensionering van batterijpakket mogelijk



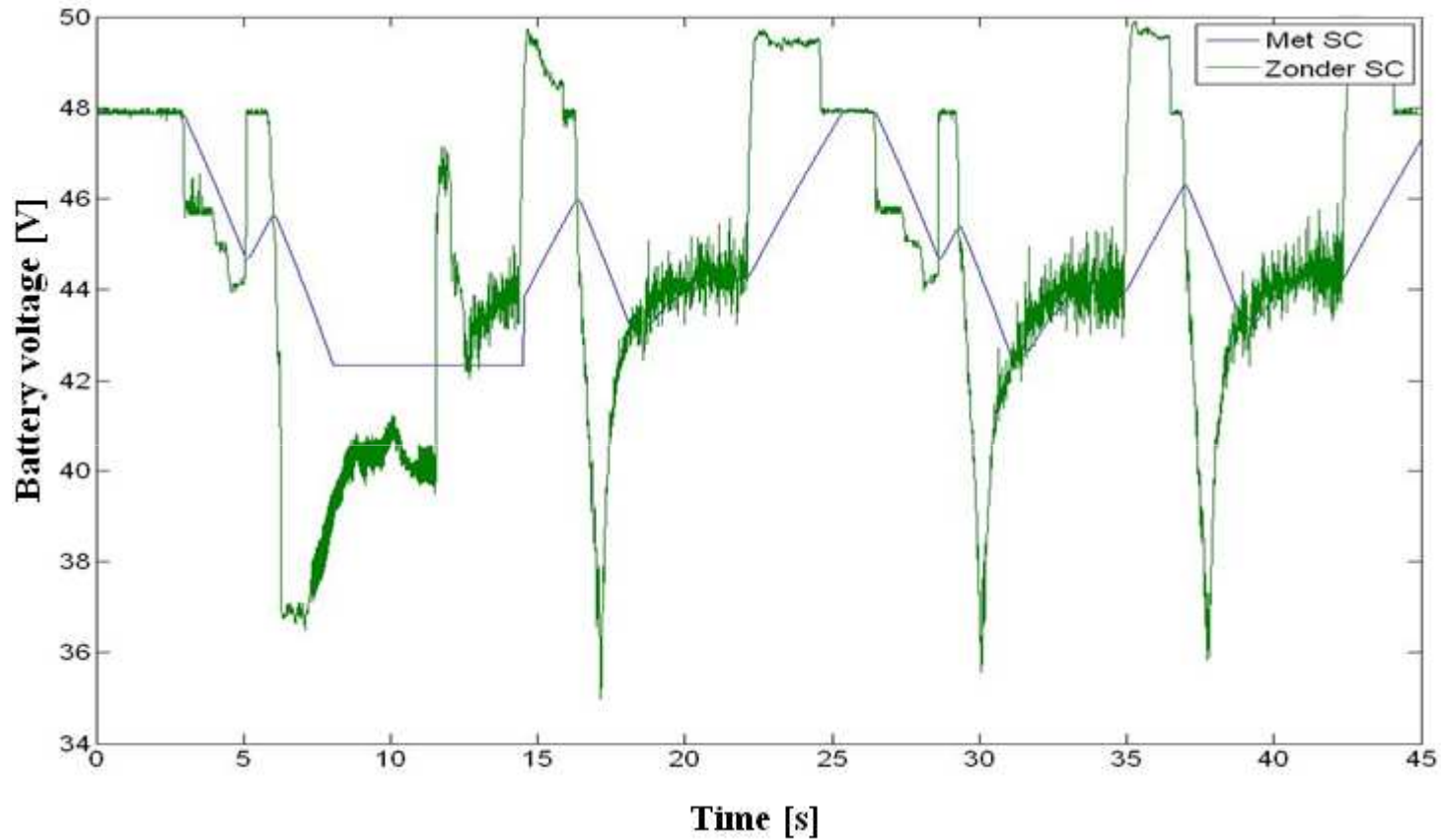
Resultaten



- Maximale benutting van EDLC inhoud



Resultaten

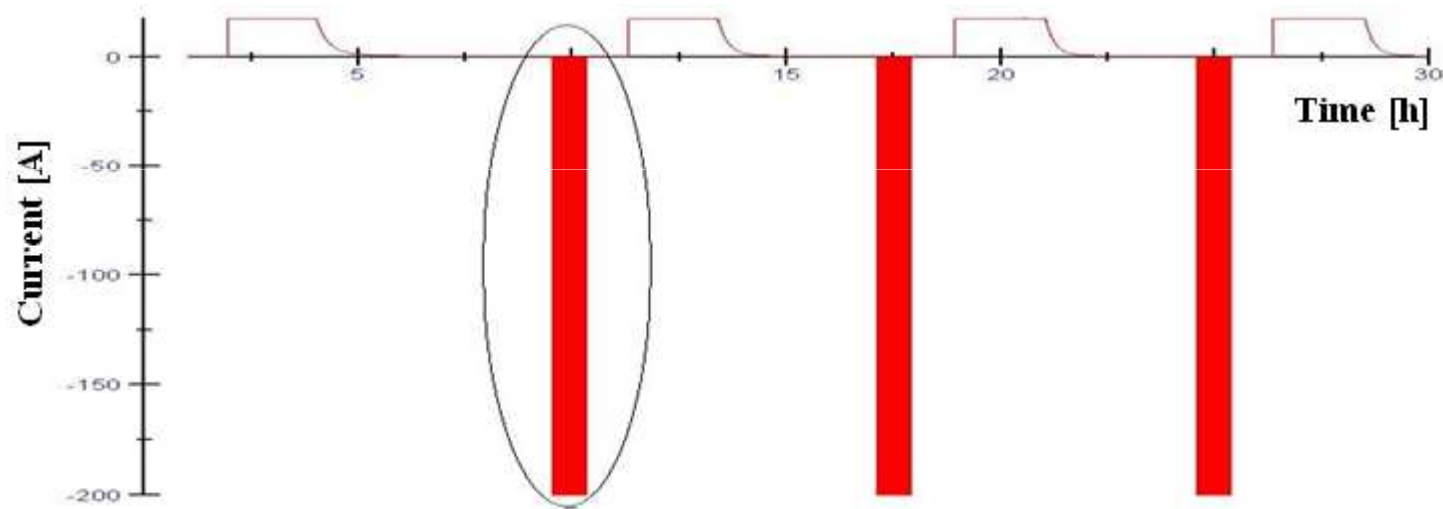


- Geringe spanningsvariaties
- Langere autonomie
- Hogere energie-efficiëntie



Levensduuranalyse

- Twee PC1500 57Ah batterijen
- 2 stacks, 6X600F cellen in serie
- IEC 61982-2
- Versnelde test



- Hoge stroom I_{dh} om : acceleratie (10 s),
- Lage stroom I_{dl} : constante snelheid (20 s),
- Geen stroom : rust periode (30 s),



Levensduuranalyse

- Zonder EDLC: 50 cycli
- Met EDLCs: 65 cycli
- 30% verlenging
- Verschil?
- Capaciteitsverhoging t.g.v. EDLCs: 0.80Ah

	Met EDLCs		Zonder EDLCs
# cycli	Capaciteit [Ah]	# cycli	Capaciteit [Ah]
1	49.9	1	39.8
65	39	50	31.9

- Peukert fenomeen $C_p = I^k \cdot t$

	Peukert constante
Met EDLCs	1.17
Zonder EDLCs	1.22



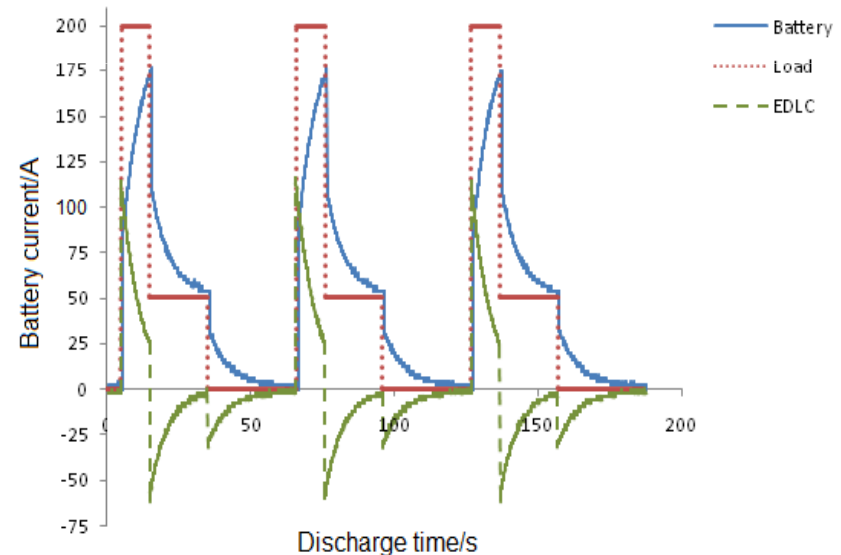
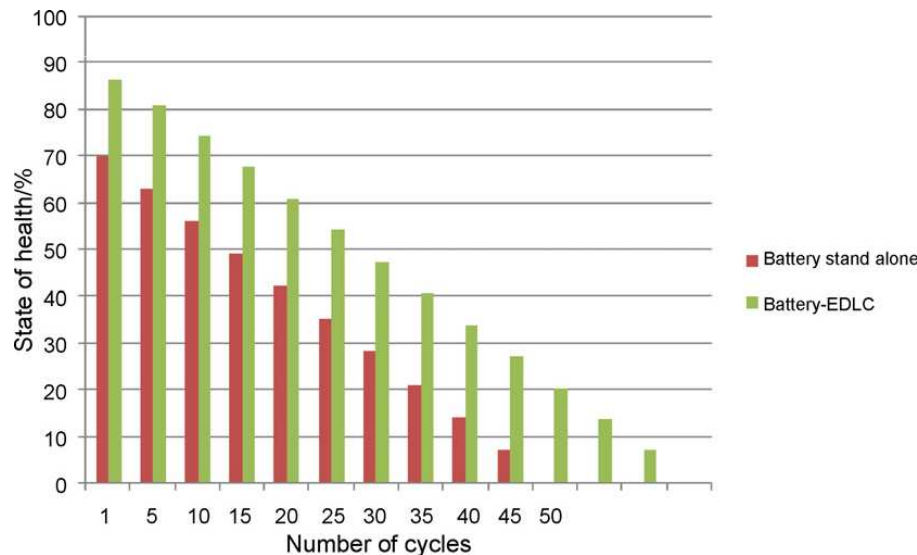
Levensduuranalyse

- Introductie van nieuwe definities als:

Battery stress

$$\text{Stress Factor} = \frac{1}{2} \left[\frac{I_{peak}}{I_{load_peak_ref}} (\%) + \frac{\frac{di_B}{dt}}{I_{load_ref}} (\%) \right] + DoD(\%)$$

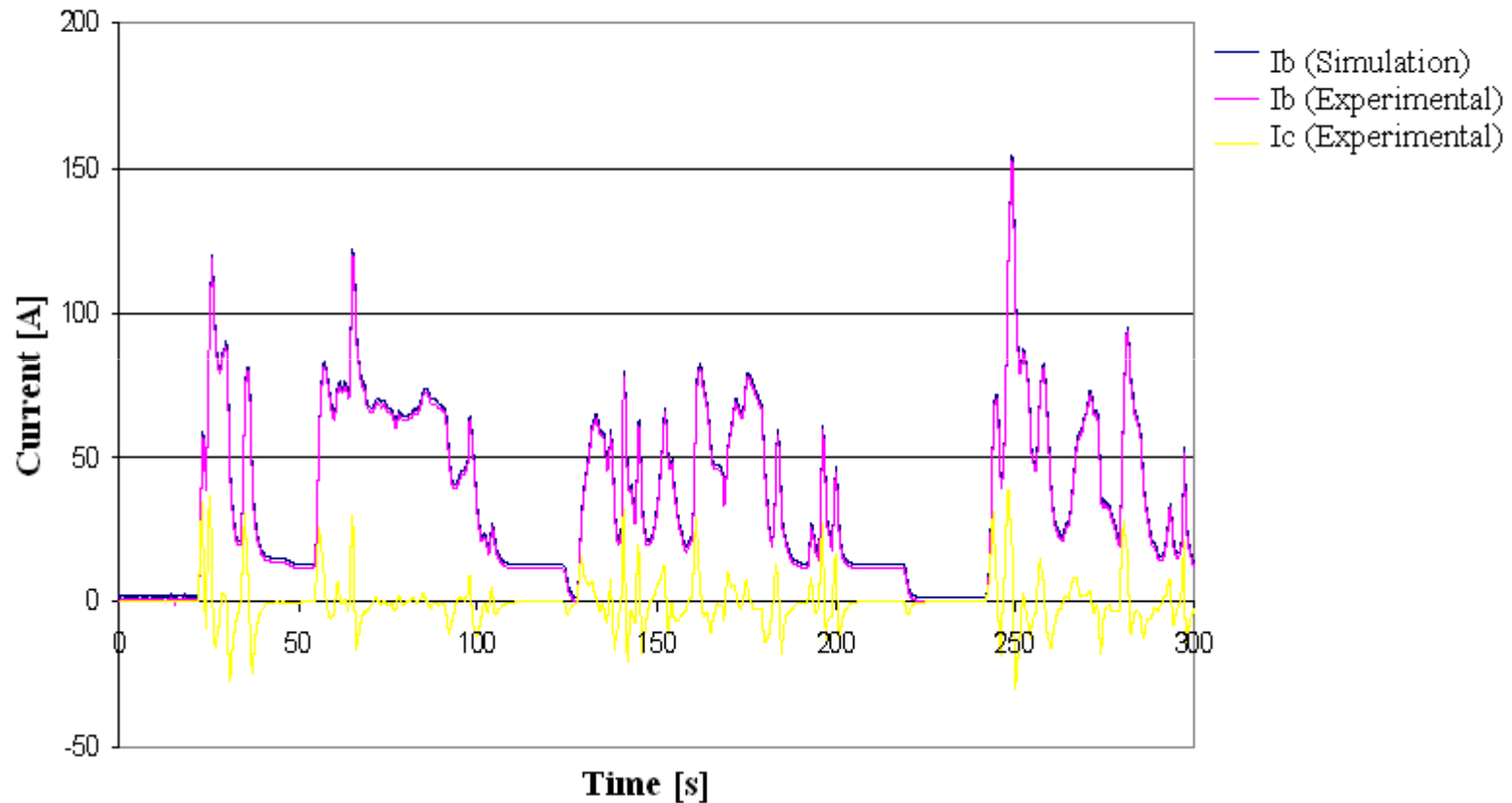
State of health



N. Omar, B. Verbrugge, P. Van den Bossche, J. Van Mierlo, Power and Life Enhancement of Battery-Electrical Double Layer Capacitor for Hybrid Electric and Charge-Depleting Plug-in Vehicle Applications, Journal of the International Society of Electrochemistry, 2010, ISBN-ISSN 0013-4686



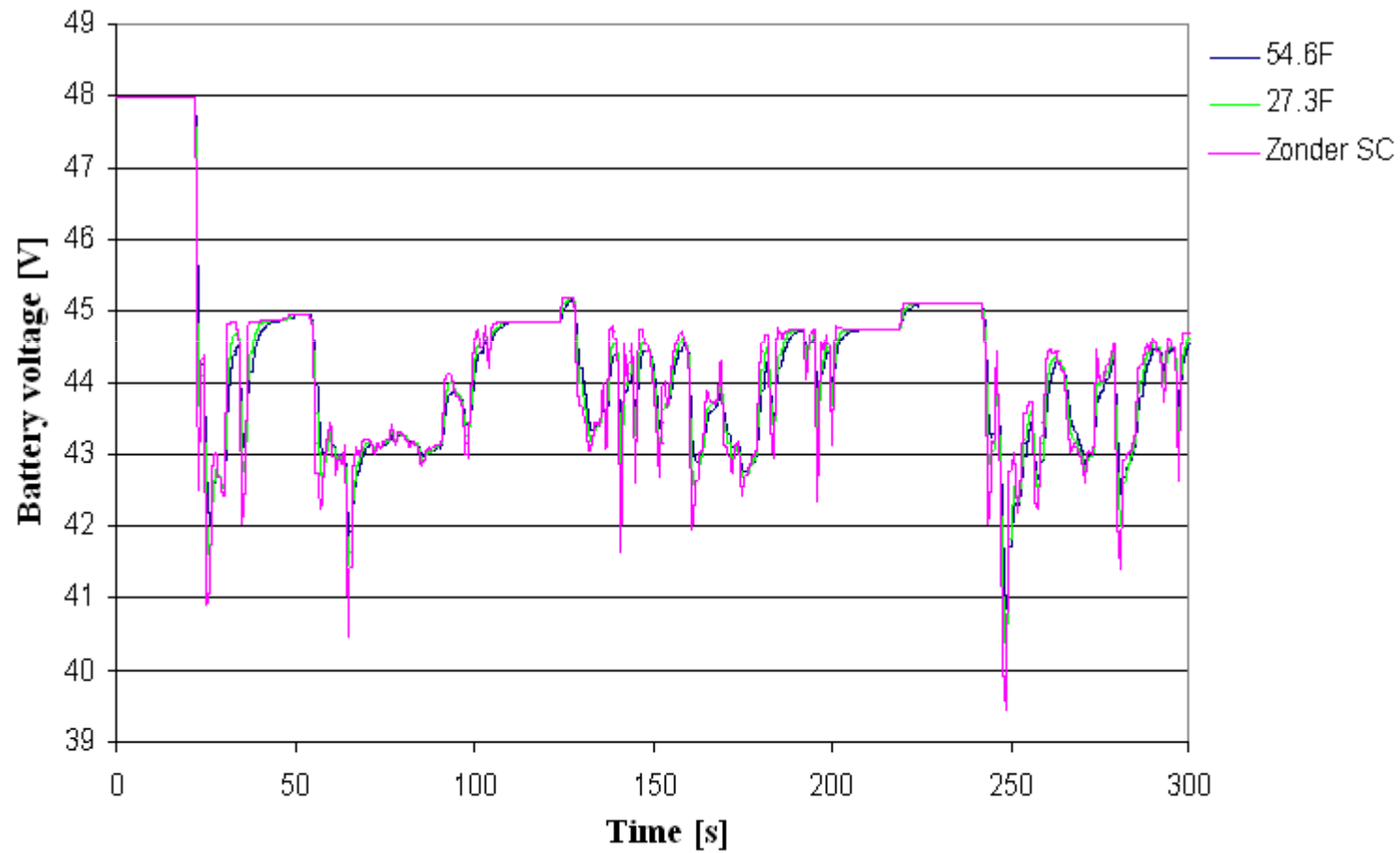
Experimentele analyse



N. Omar, F. Van Mulders, P. Van den Bossche, J. Van Mierlo, Assesment of behaviour of Super Capacitor-Battery system in Heavy Lift, Journal of Asian Electric Vehicles, Volume: 7, N° in volume: 2, pp: 1277 - 1282, ISBN-ISSN: 1883-6038



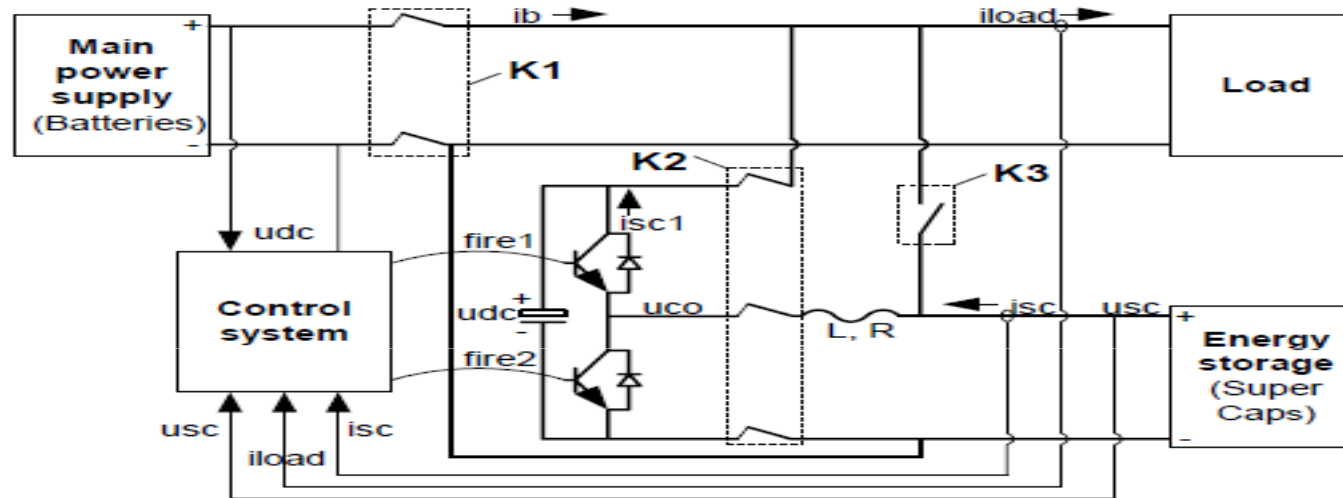
Experimentele analyse



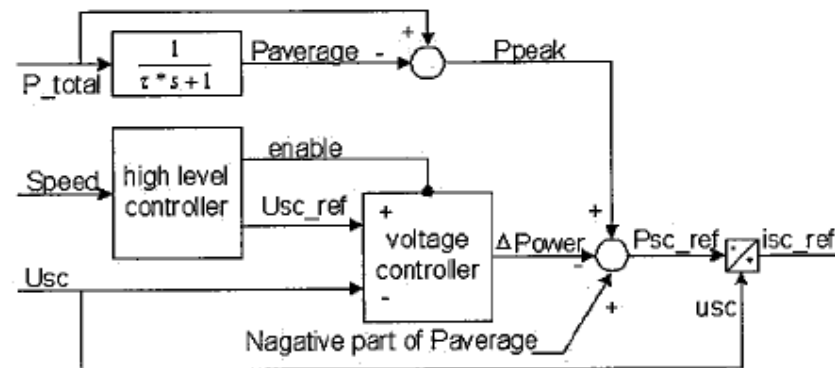


Experimentele analyse

- Testopstelling met DC-DC omvormer

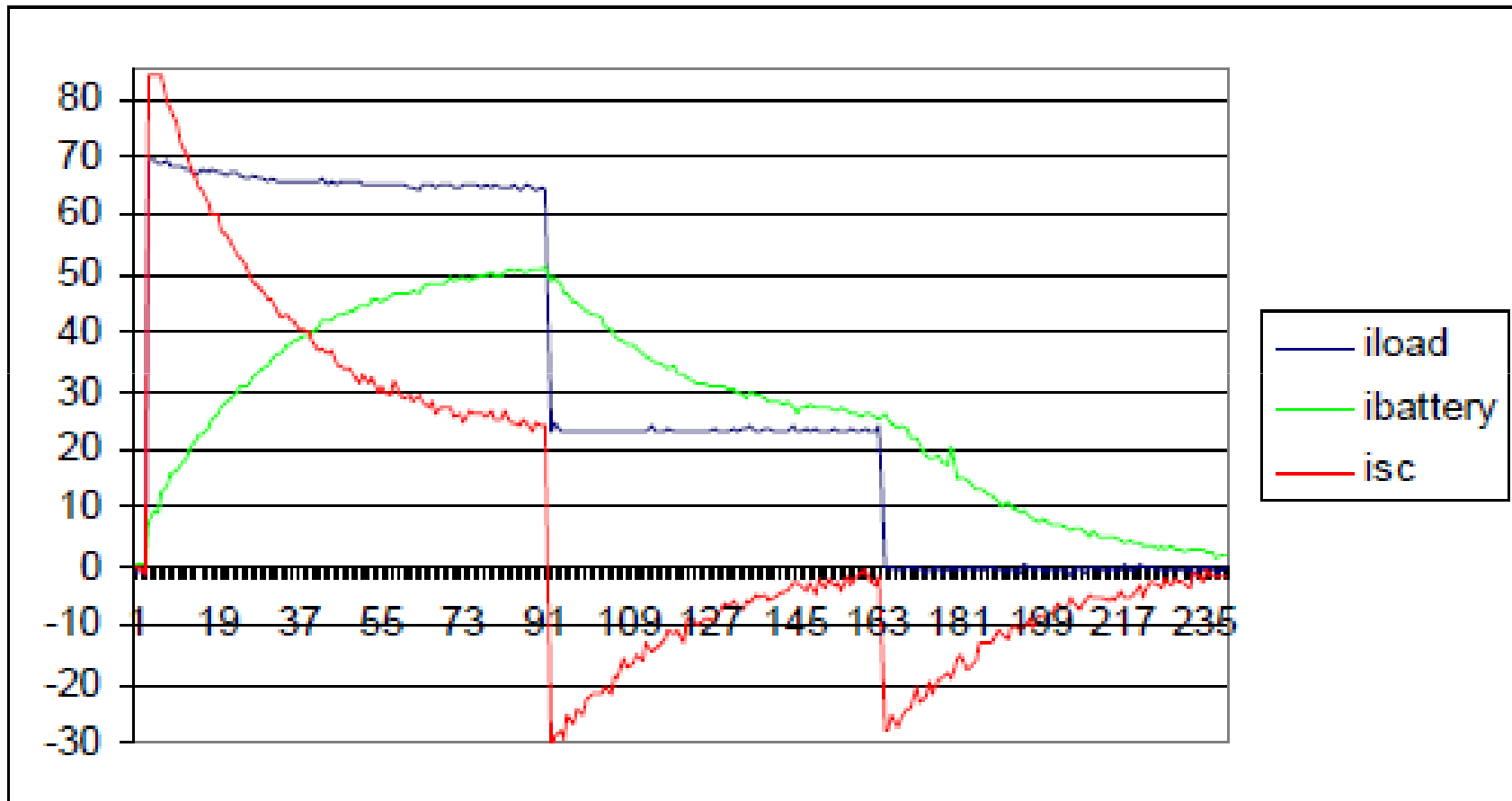


- Controle strategie



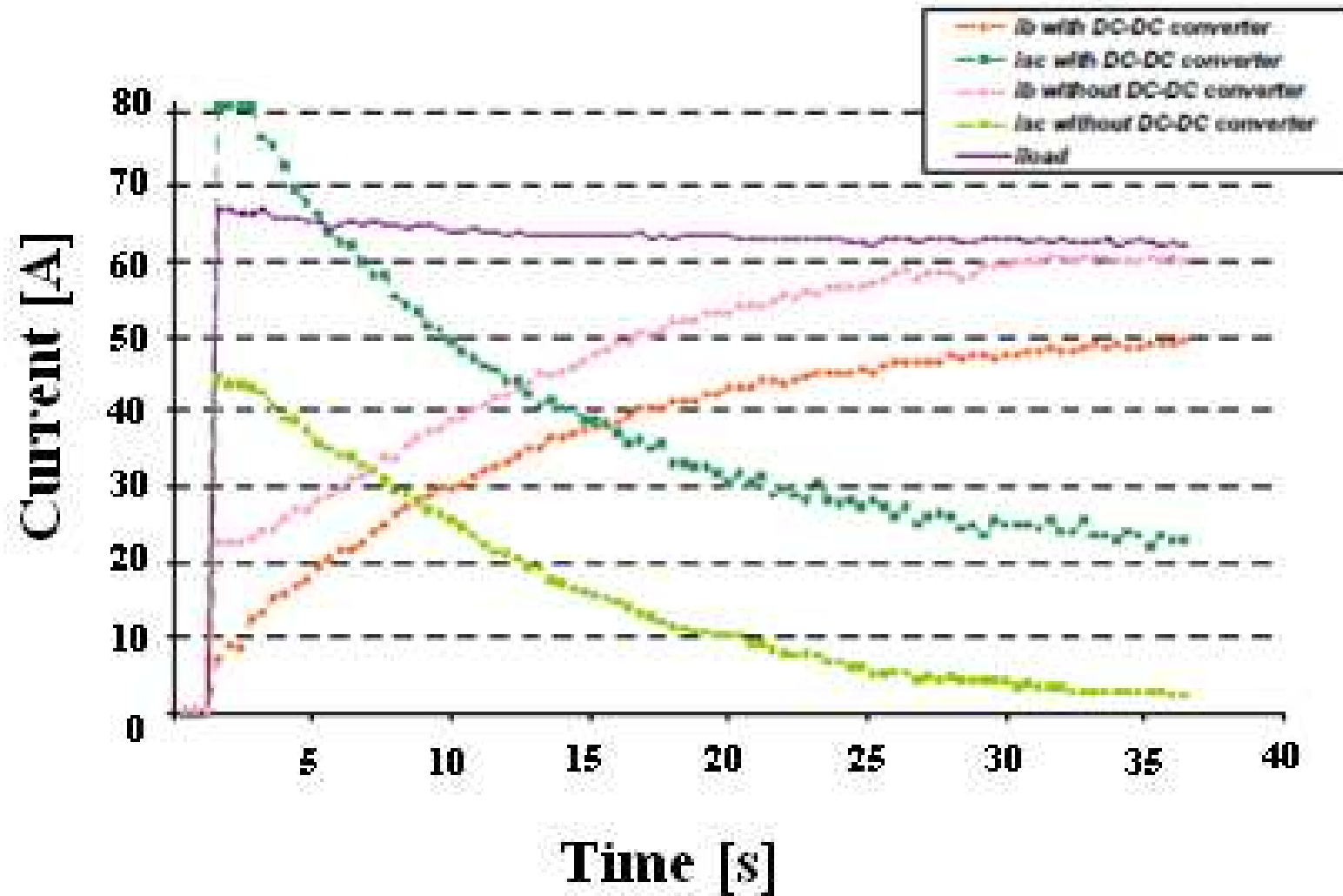


Experimentele analyse





Experimentele analyse





Kosten-baten analyse

Zonder DC-DC omvormer

- Kost EDLCs: 234 EUR
- Kostprijs batterijpakket: 4000 EUR
- Winst: 30% verlenging batterij levensduur (1200 EUR)

Met DC-DC omvormer

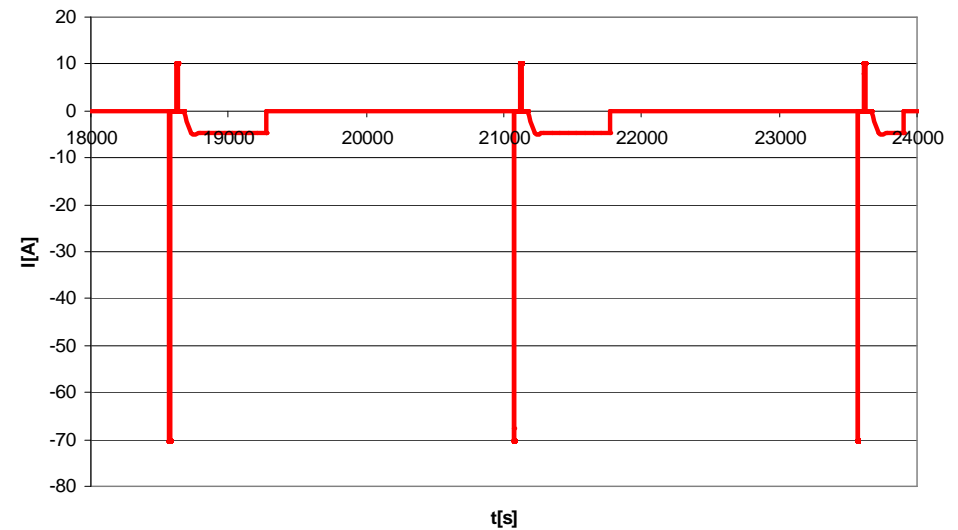
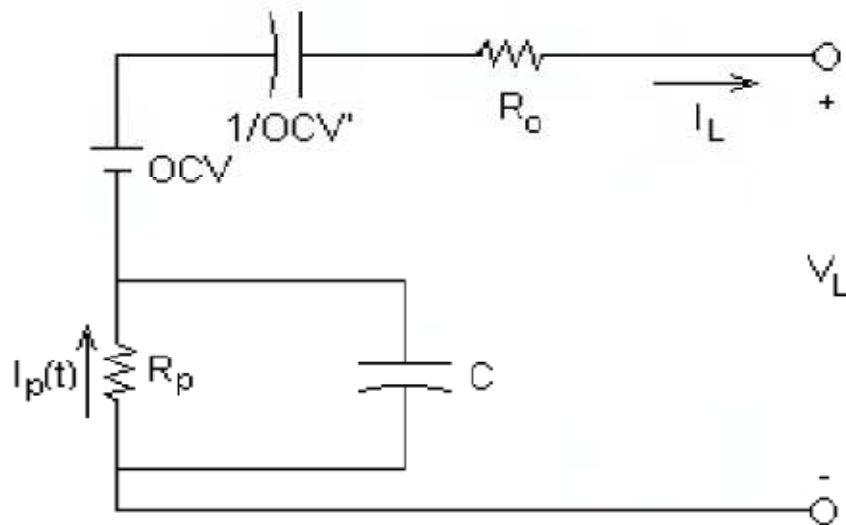
- Kost omvormer: 1500 à 3000 EUR
- Kost EDLC: 117 EUR
- Winst: $\approx 55\%$ verlenging batterij levensduur (2200 EUR)



Karakterisatie van # lithium-ion batterijen

	Type 1	Type 2	Type 3
Spanning [V]	3.3 (3.6...2)	3.3 (2...3.65)	3.3 (3.8...2)
Capaciteit [Ah]	2.3	3.5	10
Max. lont. [A]	70	35	80
Max. lop. [A]	10	3.5	30
Interne weerstand [mΩ]	10	19	6
gewicht [g]	70	82	365

- Pre-conditioning Test
- Capaciteitstesten
- Dynamic Discharge Performance Test
- Hybrid Pulse Power Characterization Test



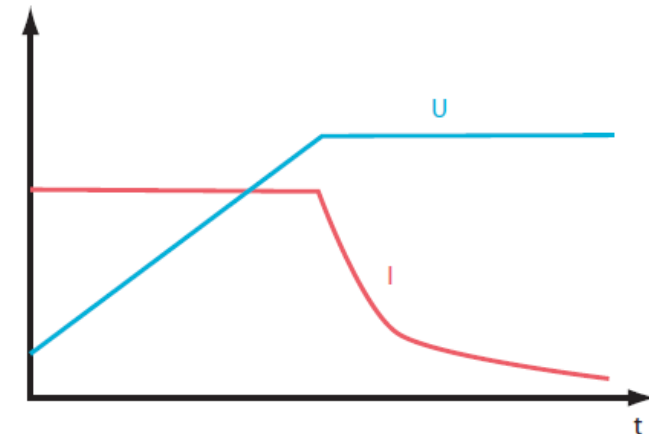
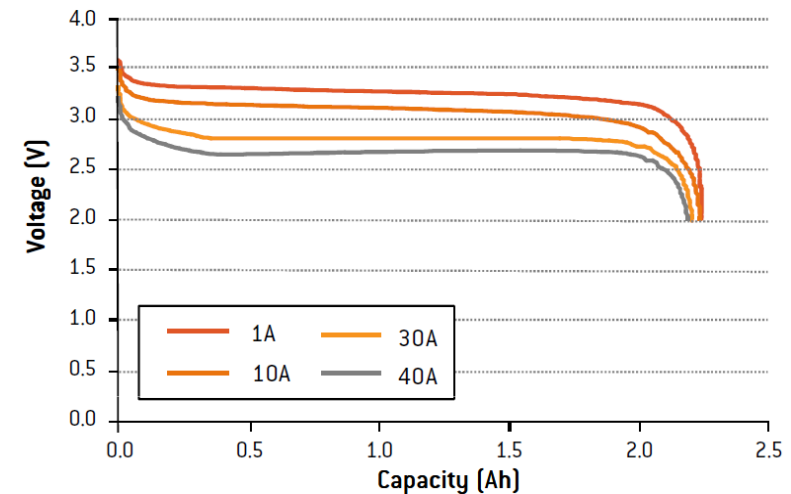


Karakterisatie van # lithium-ion batterijen

Batterijperformanties

	Type 1	Type 2	Type 3
Cap. 1C [Ah]	2.2	3.6	9.5
Cap. 5C [Ah]	2.1	3.5	9.5
Cap. 10C/8C [Ah]	2.1	3.5	9.4
Peukert	1.0	1.0	1.0
Eff. 1C [%]	95.0	90.0	87.0
Eff. 5C [%]	85.0	80.0	75.0
Eff. 10C/8C [%]	80.0	75.0	70.0
temp. 5C [°C]	34.0	33.0	46.0
temp. 10C/8C [°C]	29.0	31.0	57.0
SoC@CV, 1C	96.0	81.0	84.3
Energie dichtheid [Wh/kg]	95.5	84.0	80.2
Vermogen dichtheid 5C 50% [W/kg]	510.0	692.7	383.8
Internal resistance [mΩ]	10.0	20.0	6.0
St. Dev. [%]	0.2	0.3	0.5

Discharge Characteristics, 25 deg C





Conclusies

- Verschillende topologieën geanalyseerd
- EDLCs ontlasten batterijen van pieken
- Parallel (zonder omvormer): beperkte ontlasting van batterijpieken
- Met omvormer: grotere ontlasting van pieken
- Levensduurtesten: langere batterijlevensduur door EDLCs
- Testmethodologie voor karakterisatie van Li-Ion batterijen
- Introductie van een nieuwe topologie door VUB zonder omvormer



Publicaties

- N. Omar, B. Verbrugge, P. Van den Bossche, J. Van Mierlo, Power and Life Enhancement of Battery-Electrical Double Layer Capacitor for Hybrid Electric and Charge-Depleting Plug-in Vehicle Applications, Journal of the International Society of Electrochemistry, 2010, ISBN-ISSN 0013-4686
- N. Omar, F. Van Mulders, P. Van den Bossche, J. Van Mierlo, Assesment of behaviour of Super Capacitor-Battery system in Heavy Lift, Journal of Asian Electric Vehicles, Volume: 7, N° in volume: 2, pp: 1277 - 1282, ISBN-ISSN: 1883-6038
- N. Omar, F. Van Mulders, P. Van den Bossche, J. Van Mierlo, Effectiveness evaluation of a Supercapacitor-battery parallel combination for Hybrid Heavy Lift Trucks, EVS24, Stavanger, May 13-16, 2009
- G. Maggetto and J. Van Mierlo, 2001, Electric vehicles, hybrid vehicles and fuel cell electric vehicles: state of the art and perspectives, Annales de Chimie – Science des materiaux; Thematic issue on "Material for Fuel Cell Systems"; ISSN 0151-9107, VOL 26 N.4, 2001; pg. 9-26
- J. Van Mierlo, G. Maggetto and Ph. Lataire, Which energy source for road transport in the future? A Comparison of battery, hybrid and fuel cell vehicles, Energy Conversion and Management, 2006 Elsevier Ltd
- Y. Cheng, J. Van Mierlo, P. Van den Bossche, Ph. Lataire, Super Capacitor based Energy Electric Vehicles, PEMD 2006, Ireland
- Y. Cheng, J. Van Mierlo, P. Van den Bossche, Ph. Lataire, Energy sources control and management in hybrid electric vehicles, EPE-PEMC2006, Slovenia
- J. Van Mierlo, G. Maggetto, Vehicle simulation program: a tool to evaluate hybrid power management strategies based on an innovative iteration algorithm, Proceedings of the Institution of Mechanical Engineers Part D-Journal of Automobile Engineering, I Mech E, SAE and IEE, ISSN 0954-4070, VOL 215, NO D9, Pg. 1043-1052, 2001



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