The role of supercapacitors in extending the lifetime of lead acid batteries: case study on an isolated hybrid microgrid

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Overview (1/2)

- The synthesis of three-years work, about an improved power flow control system (laboratory-tested) for a remote (military) microgrid with hybrid energy storage and how we linked it to economic parameters, is presented.

- A combination of batteries and supercapacitors (SCs) is managed by a novel control system to increase the battery life by redirecting the higher frequency current that would have to flow in the battery if SCs weren't present (not focus of this presentation).

- The focus today is briefly on how we have formulated the secondary controller law, to give the controller the rules to operate the storage and the energy sources (gensets and PV) by minimizing the fuel consumption

Overview (2/2)

- Another focus is briefly on the methodology we used to evaluate the lifetime of the batteries in each conditions (with a method which proved to be useful for planning purposes)

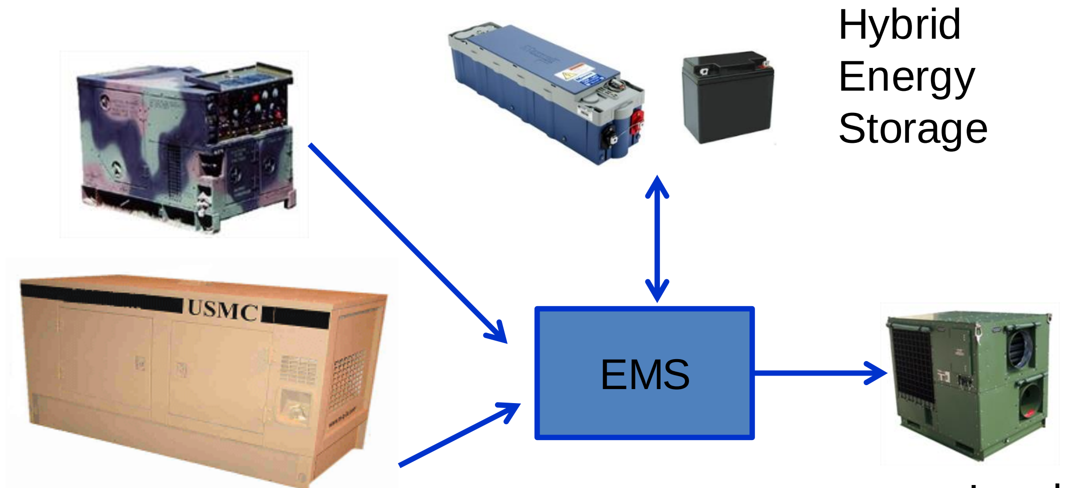
- The new controller allows the independent selection of the low pass filter parameter (alpha) and the number of SCs (beta).

- By making the most out of these two degrees of freedom, we investigate different configurations, identifying the one achieving the best economics of the system, by linking never-linked-before parameters.

Background

- An energy management system (EMS) is a power electronics based controller that monitors power flow and matches load power demand to the available power.
  - Power can be available from the AC grid, various energy sources (including renewables) and energy storage devices.
- An EMS manages the loads in both grid-connected and islanding modes of operation
- The EMS includes primary and secondary controllers to manage the power converters and the microgrid respectively.

EMS in Mobile Microgrids

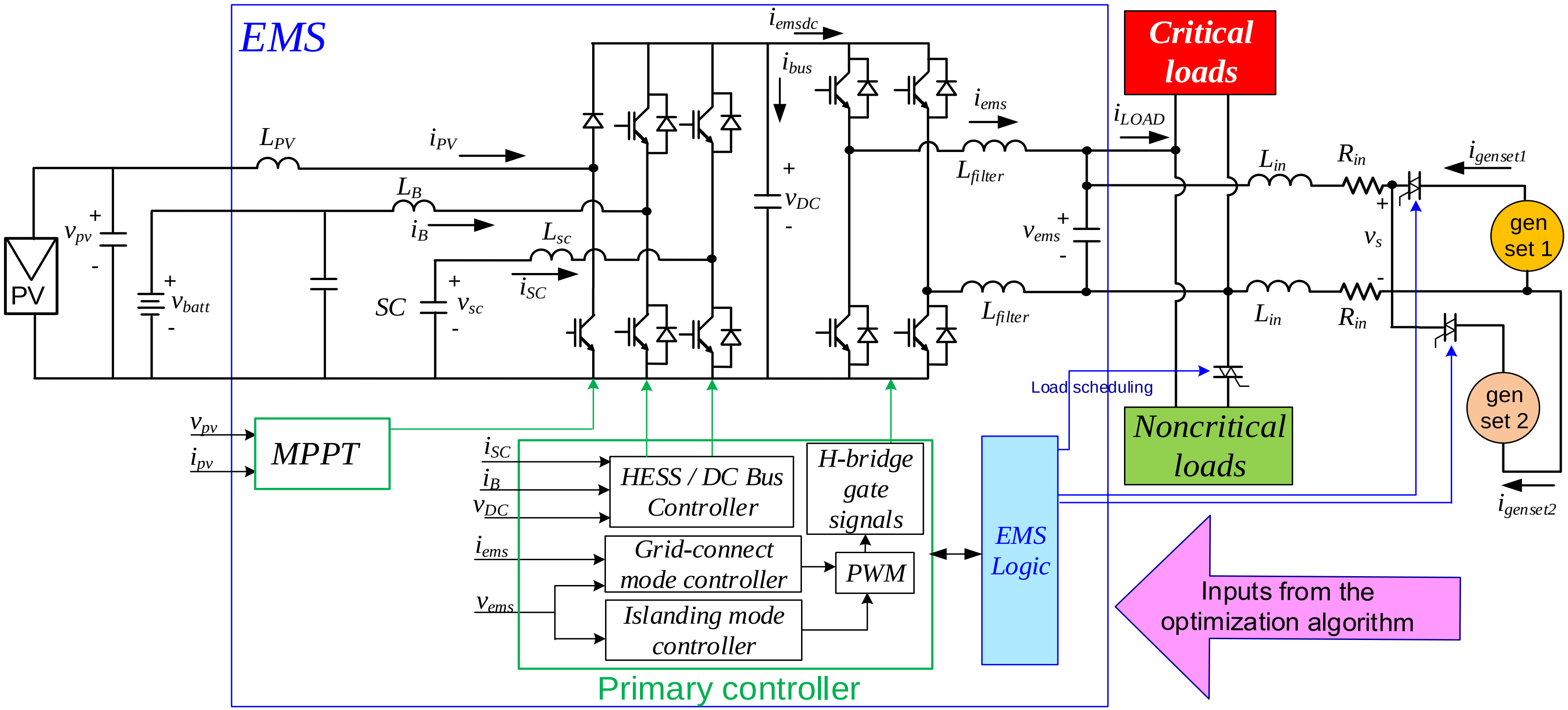


In mobile military installations an EMS can be designed to reduce fuel consumption

R. L. Kelly, G. Oriti, A.L. Julian, "Reducing fuel consumption at a remote military base: introducing an energy management system", *IEEE Electrification Magazine*, vol.1 , no.2, Dec 2013.

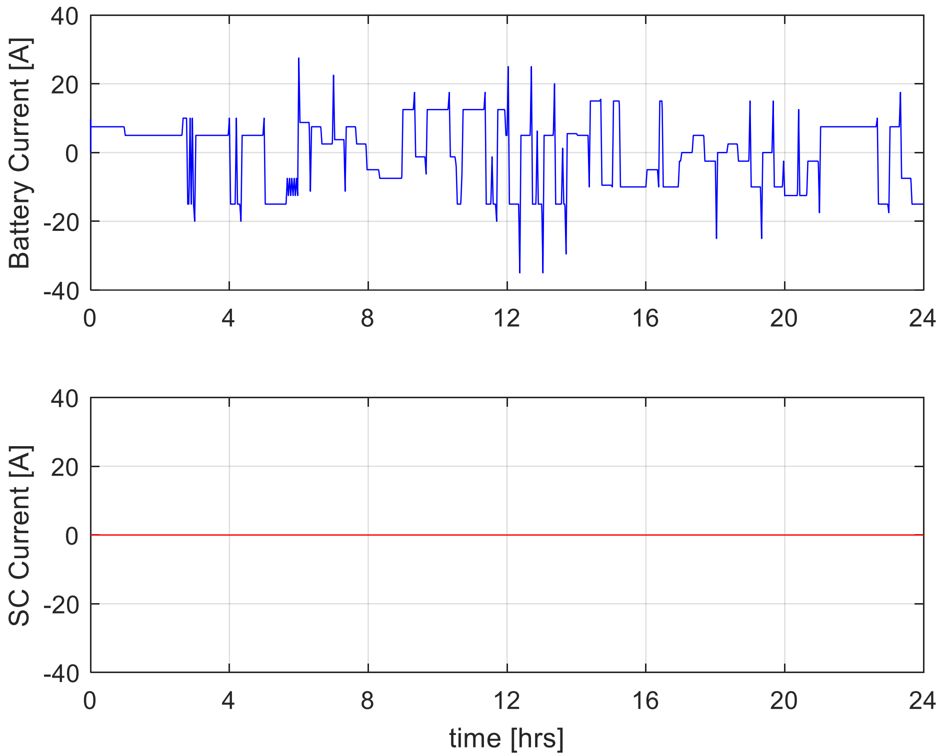
N. Anglani, G. Oriti, M. Colombini, “Optimized Energy Management System to Reduce Fuel Consumption in Remote Military Microgrids”, *IEEE Trans on Industry Applications*, Vol. 53 No.6, Nov/Dec 2017.

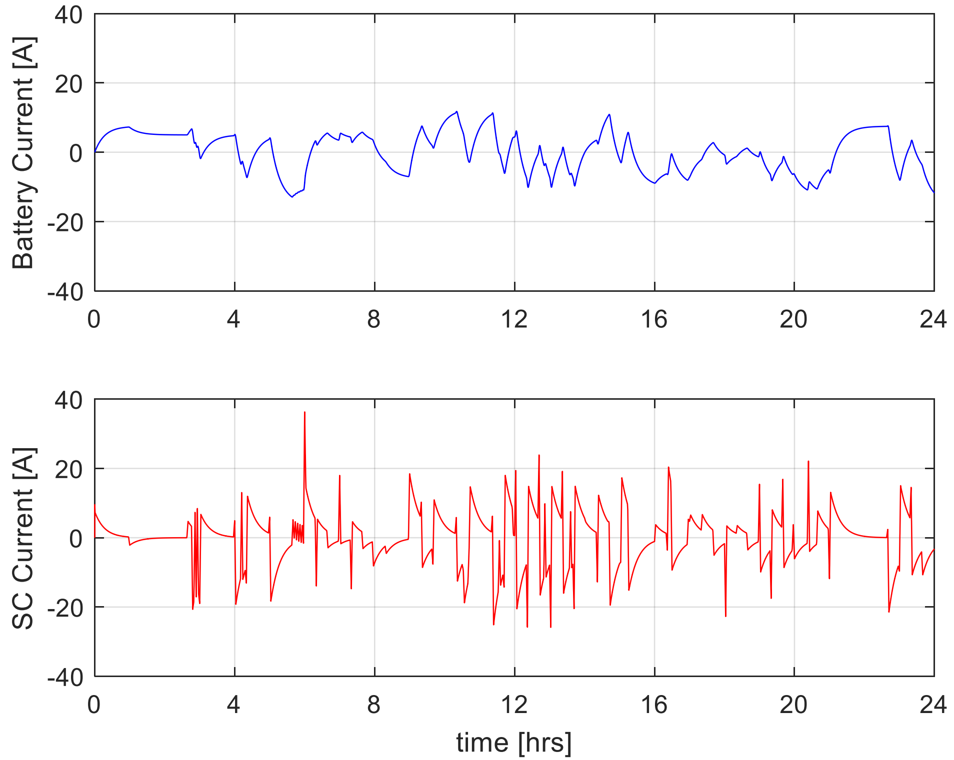
EMS Schematics



EMS functionalities include: energy storage, energy harvesting, peak shaving, load shedding, grid-connected or islanding operation, optimized load management, etc.

Previous HESS Controller

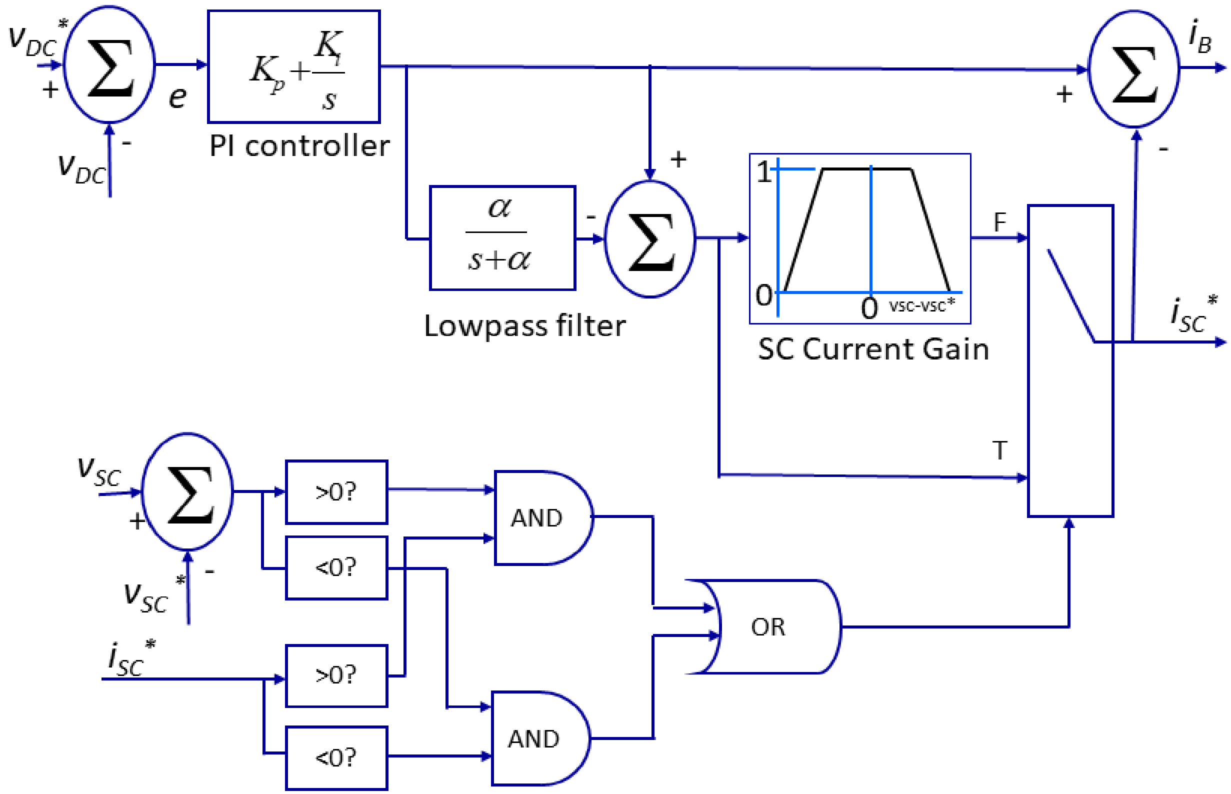




Without HESS – battery only

With HESS – battery and several SCs

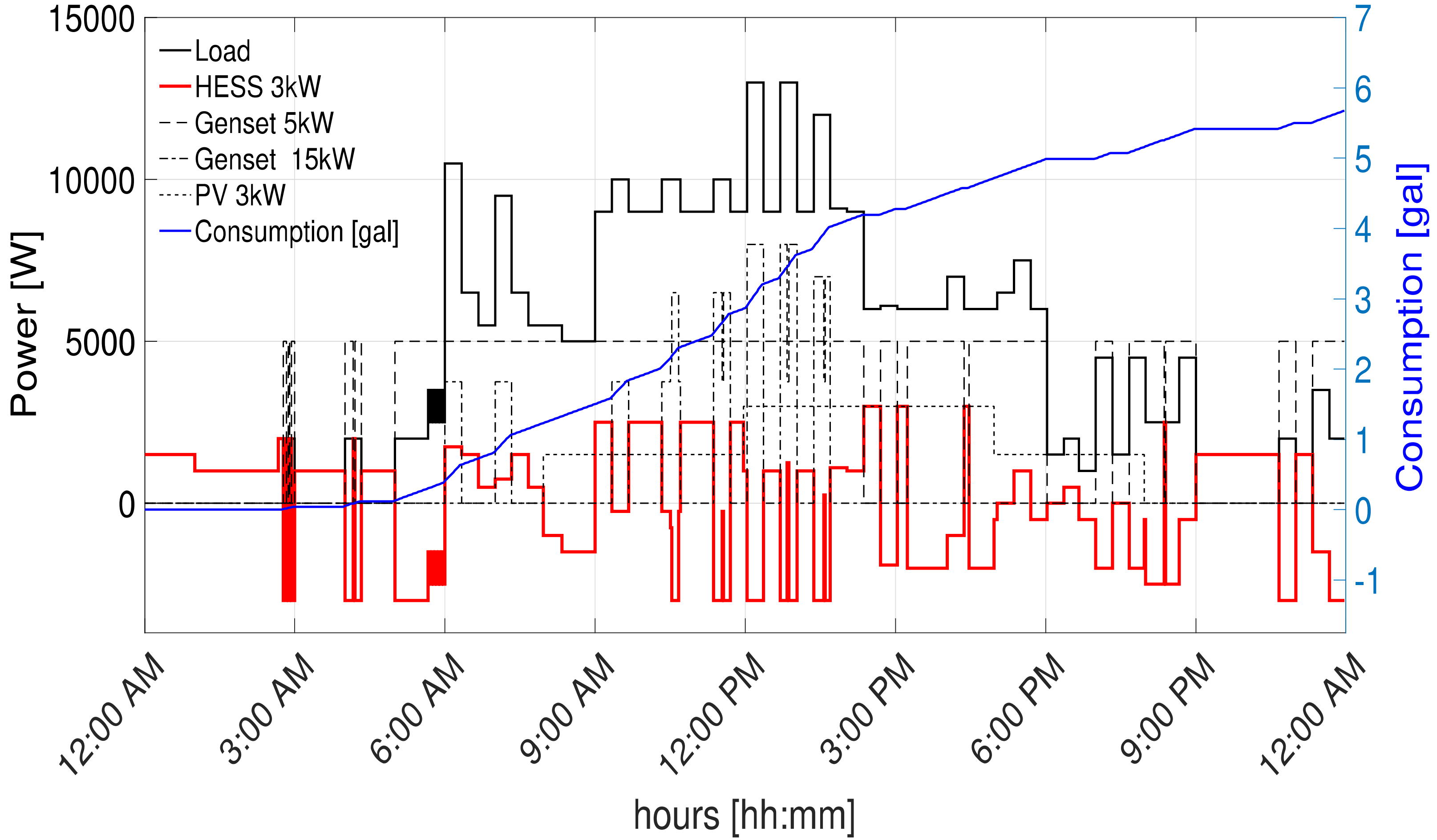
New HESS Controller



When the SCs are not over/undercharged the battery only sees the PI controller output after a lowpass filter. When the SC controller is off then the battery sees the PI output.

Load Profile

In this study we analyze a 24 hour load profile to determine the impact of the HESS over the lifetime of the batteries (lead acid)



Few words on the optimization model for the secondary controller rule

variable /parameter	Description of var./param. and/or Eq.	Equations	#
$x_{1,j}$ - $x_{2,j}$	dominion of decision variables (i.e. load factors)	$x_1^m \le x_{1,j} \le 1$ or $x_{1,j} = 0$ $x_2^m \le x_{2,j} \le 1$ or $x_{2,j} = 0$	(1.2)
	no syncro condition	$x_{i,j} > 0 \rightarrow x_{k,j} = 0 \quad \forall k \neq i$	(1.3)
$x_{3,j}$	HESS load factor dominion	$-1 \le x_{3,j} \le 1$	(1.4)
$P_{i,j}$	power from gen. and from/to HESS at time j (P_{1r}, P_{2r}, P(HESS))	$x_{i,j} = \frac{P_{i,j}}{P_{ir}}$	(1.5)
T, E HESS	time of discharge at rated P(HESS) and capacity of HESS	E(HESS)=P(HESS).T	(1.6)
L_j	Load	$x_{1,j} \cdot P_{1r} + x_{2,j} \cdot P_{2r}$ -$x_{3,j} \cdot$ P(HESS) $+ (P_{PV,j})$=L_j	(1.7)
SOC_j in %	state of charge	$SOC_j = SOC_{j-1} + x_{3,j} \cdot \frac{j}{T}$	(1.8)
	decision var.	$SOC_0 = SOC_{J*}$	(1.9)
	dominion	$SOC^m \le SOC_j \le SOC^M$	(1.10)

Parameters for the 24-hour simulation

Parameter	Value
Supercapacitor (Maxwell BMOD0130P056)	130 F
SC upper limit, V_{max}	56 V
SC lower limit, V_{min}	16 V
SC reference voltage, V_{sc}*	41.2 V
PI controller, K_p	0.004
PI controller, K_i	0.04
Lowpass filter, α in **Case A with 3 SCs**	0.005 rad/s
Lowpass filter, α in **Case B with 1 SC**	0.001 rad/s
Lowpass filter, α in **Case C with 1 SC**	0.005 rad/s

Genesis 150 NP12-12

Table II
NUMBER OF CYCLES VS. DOD FOR LEAD-ACID BATTERIES [?].
INVESTMENT COSTS: $1kW = 3250\$$; $1.5kW = 4125\$$; $3kW = 6750\$$; $5kW = 10250\$$

Depth of Discharge	# cycle (approx.)
100%	250
50%	550
30%	1200
10%	4100

$$V_{sc}^{*} = \sqrt{\frac{(E_{\max} + E_{\min})}{C_{sc}}}$$

where

$$E_{\max} = \frac{1}{2} C_{sc} V_{\max}^{2}$$

and

$$E_{\min} = \frac{1}{2} C_{sc} V_{\min}^{2}$$

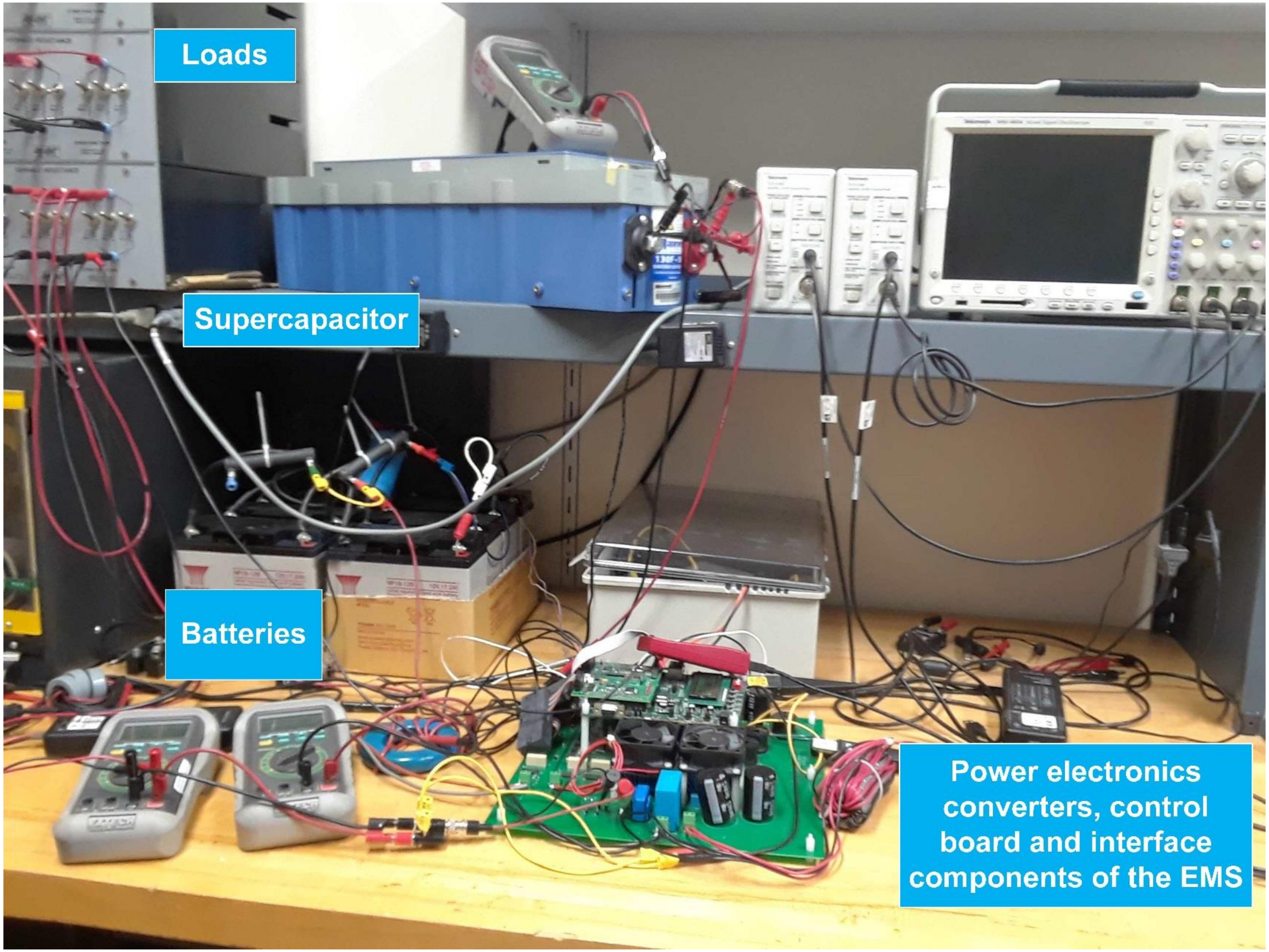
Experimental Verification

- The proposed control system has been implemented in a laboratory prototype

- The controller is entirely programmed into a field programmable gate array (FPGA) using the Xilinx System Generator software.

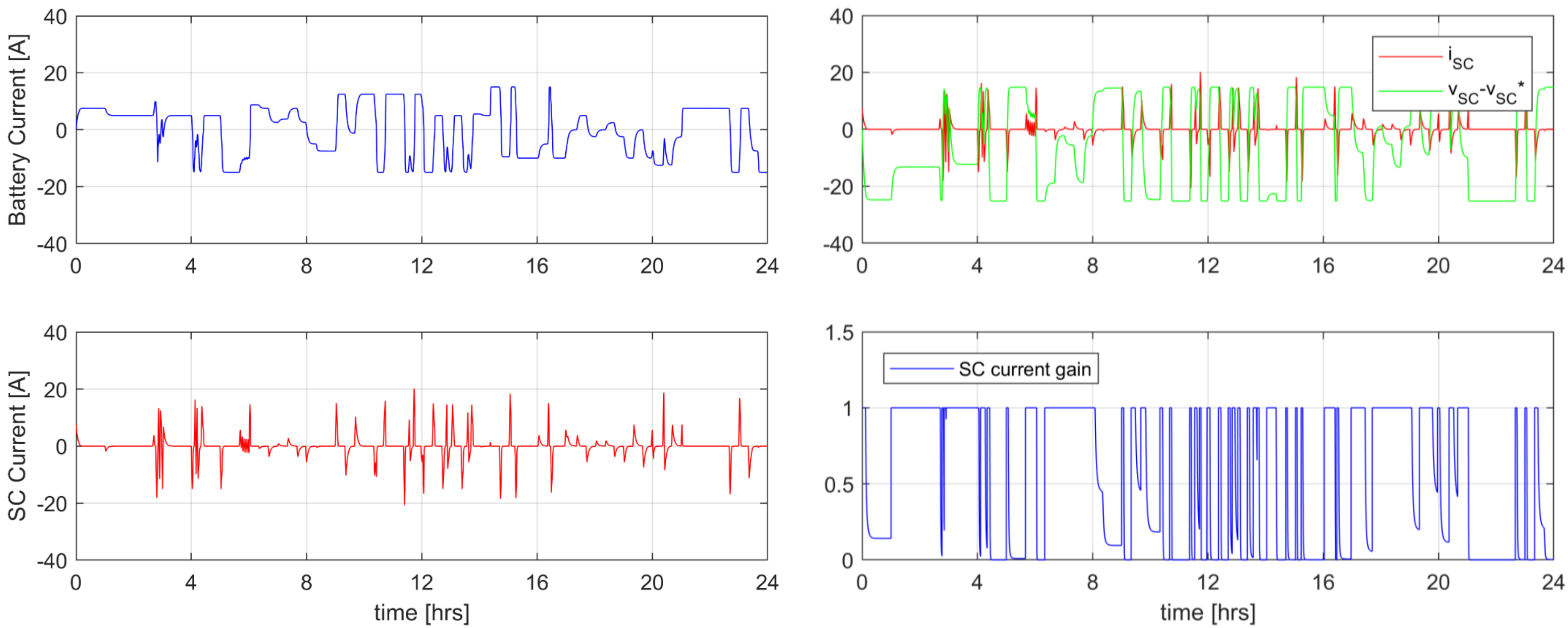
- The EMS hardware includes an FPGA development board and two custom printed circuit boards (PCBs) with power converters, sensors and interface devices

Laboratory Hardware



Case A

3 Supercapacitors, α= 0.005 rad/s



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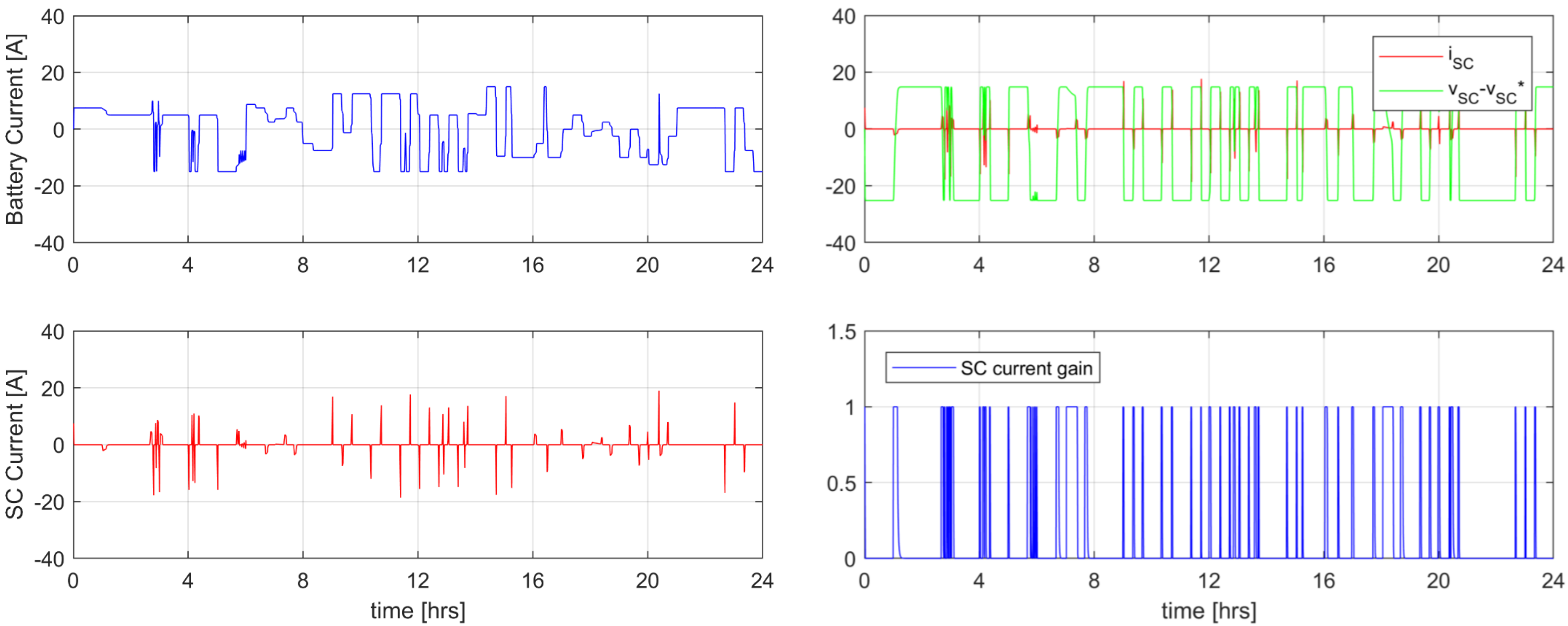
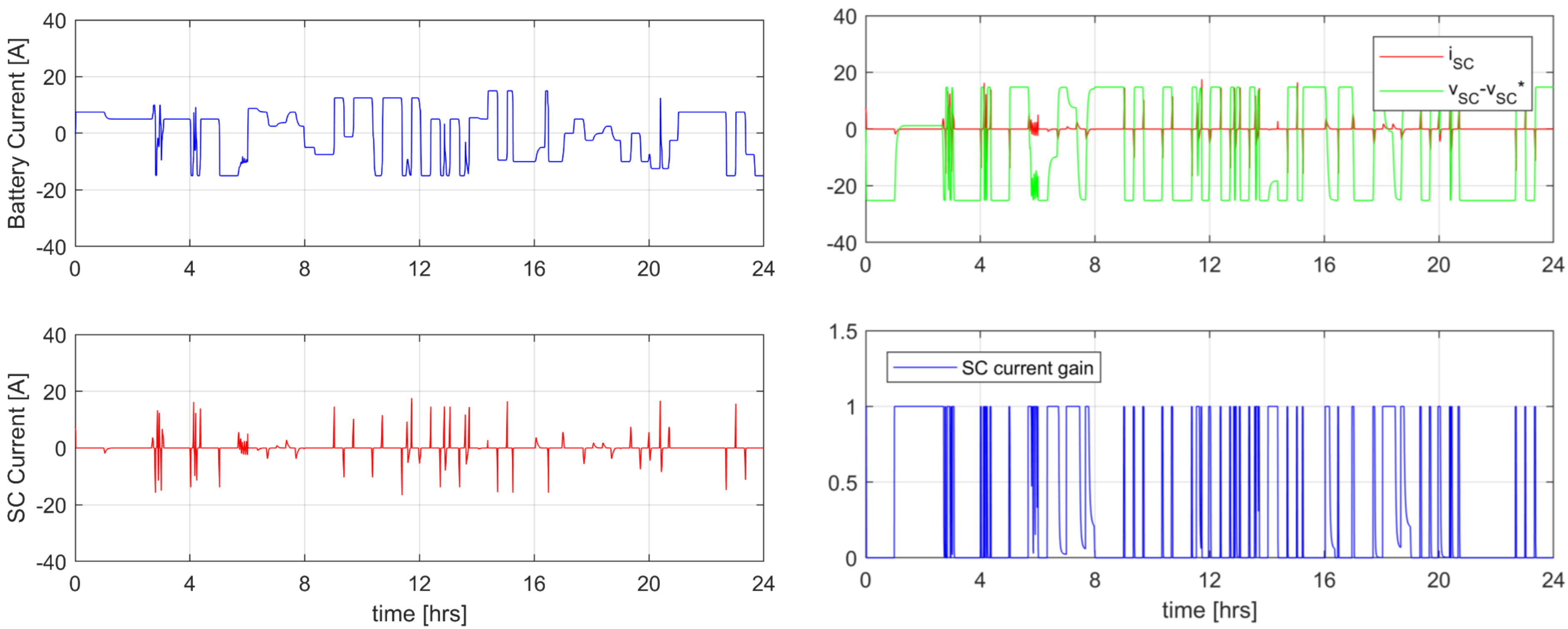
Case B

1 Supercapacitor, α= 0.001 rad/s



Case C

1 Supercapacitor, α= 0.005 rad/s



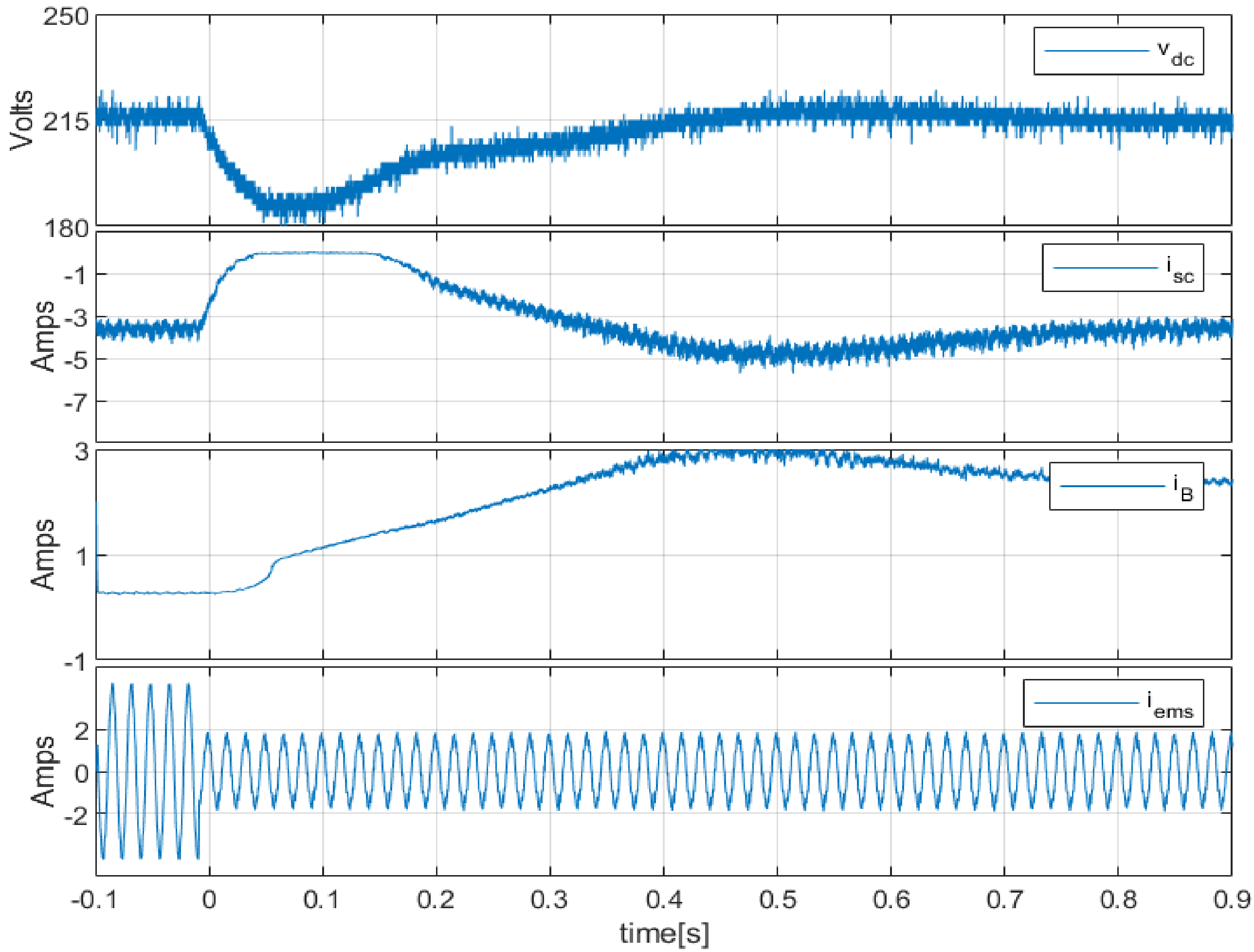
Experimental Measurements

DC bus Voltage

SC Current

Battery Current

EMS Current



HESS Controller ON

Load step up and γ=1.

Steps of the Economic Analysis

- Formulate the optimization problem over 24h, where the load factors of the two diesel generators are calculated as well as the active power from the HESS to keep the daily diesel consumption to the minimum (>>savings)

- Give the global value of the HESS power to the primary controller and get the share of power from the battery and from the SCs, according to different SCs and alpha LPF

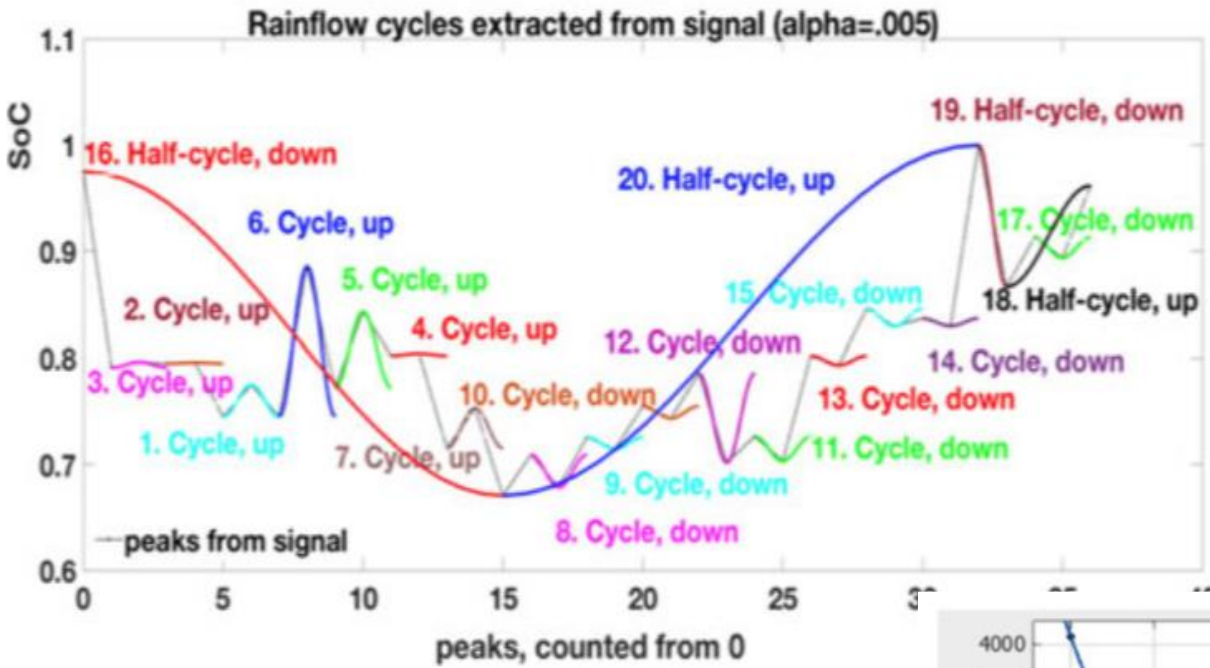
- Assess the battery lifetime (i.e. days to failure), connected to the controller parameters, functional to the assessment of the NPV (net present value) of the investments over 5 year time

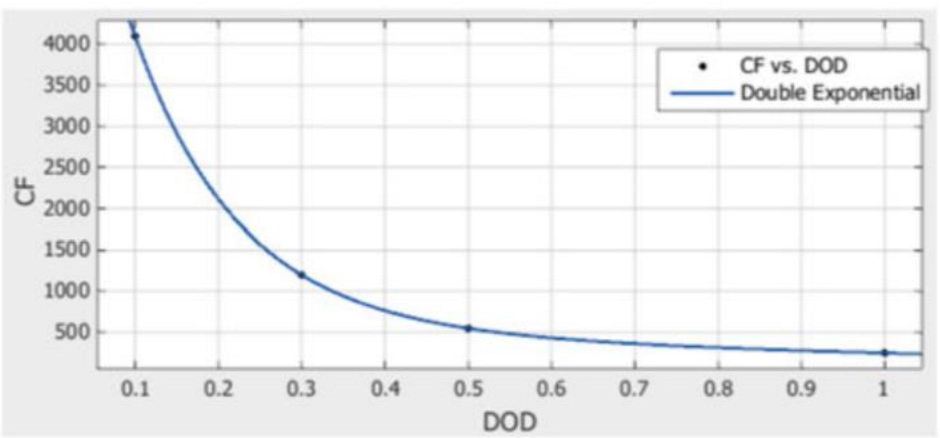
Outlines of the Rainflow Counting (1/2)

- The Rainflow Counting algorithm provides information on the amplitude (related to the Depth of Discharge) and frequency of cycles presenting the same amplitude on a set time horizon, from the SoC_{bat} knowledge. The life expectancy of the battery is related to the Cycle to Failure, with 1/CF being the life fraction. We assess D, the inverse of the lifetime, as

$$D = \sum_{i=1}^{m} \frac{N_i}{CF_i}$$

Outlines of the Rainflow Counting (2/2)





Economic Analysis following the optimization problem

$$NPV(\alpha,\beta,r) = \sum_{i=1}^{N} \frac{S}{(1+r)^i} - I_0 - \sum_{i=1}^{N} \frac{I_i(\alpha,\beta)}{(1+r)^i}$$

Net present value (NPV) is the difference between the **present value of cash inflows** (i.e. the savings we realized with the optimization) and the **present value of cash outflows over a period of time**.

NPV is used in capital budgeting to understand the profitability of a projected investment.

α → low pass filter cutoff frequency

β → number of SCs

r → discount rate for energy investments

i → years

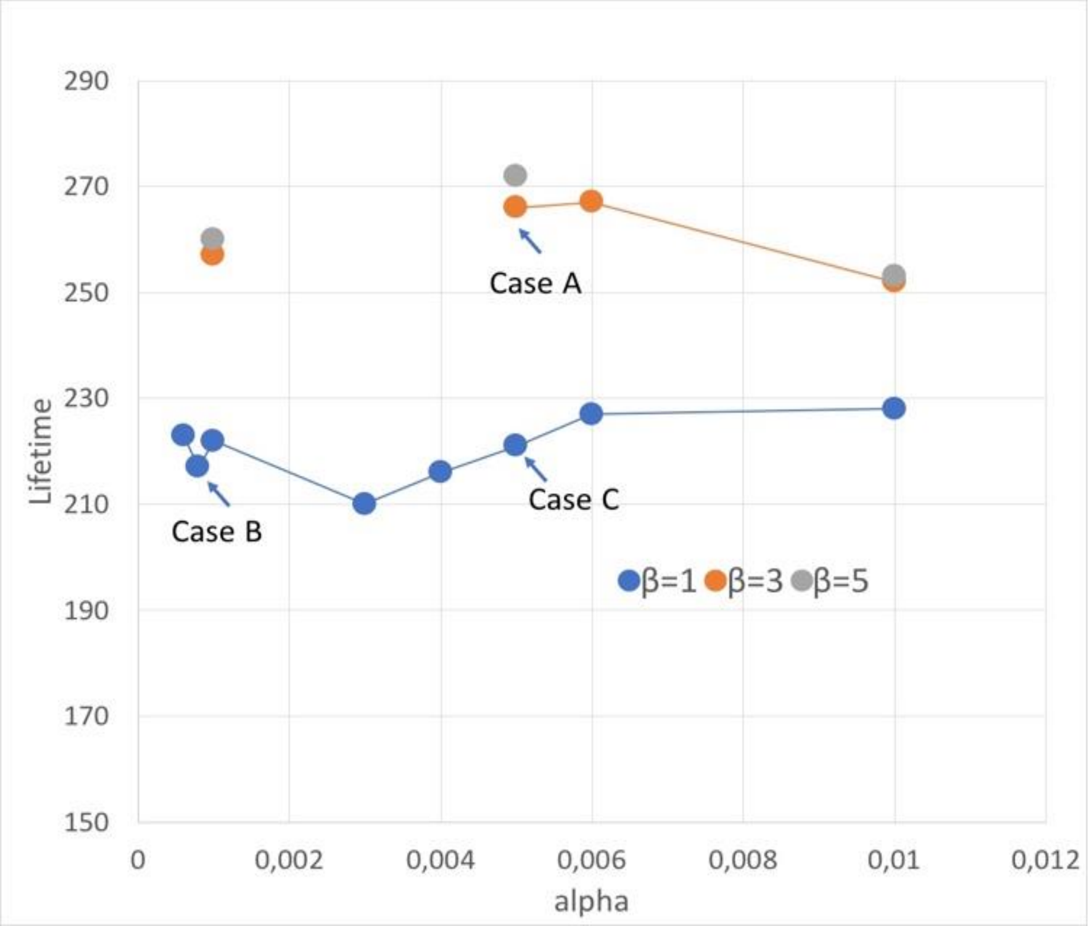
N → horizon (5 years)

S → annual fuel savings, due to the results of a preceding optimization

I_o → investment at year zero

I_i → investment in new batteries due to failure after the estimated days

Battery Lifetime vs. α, β



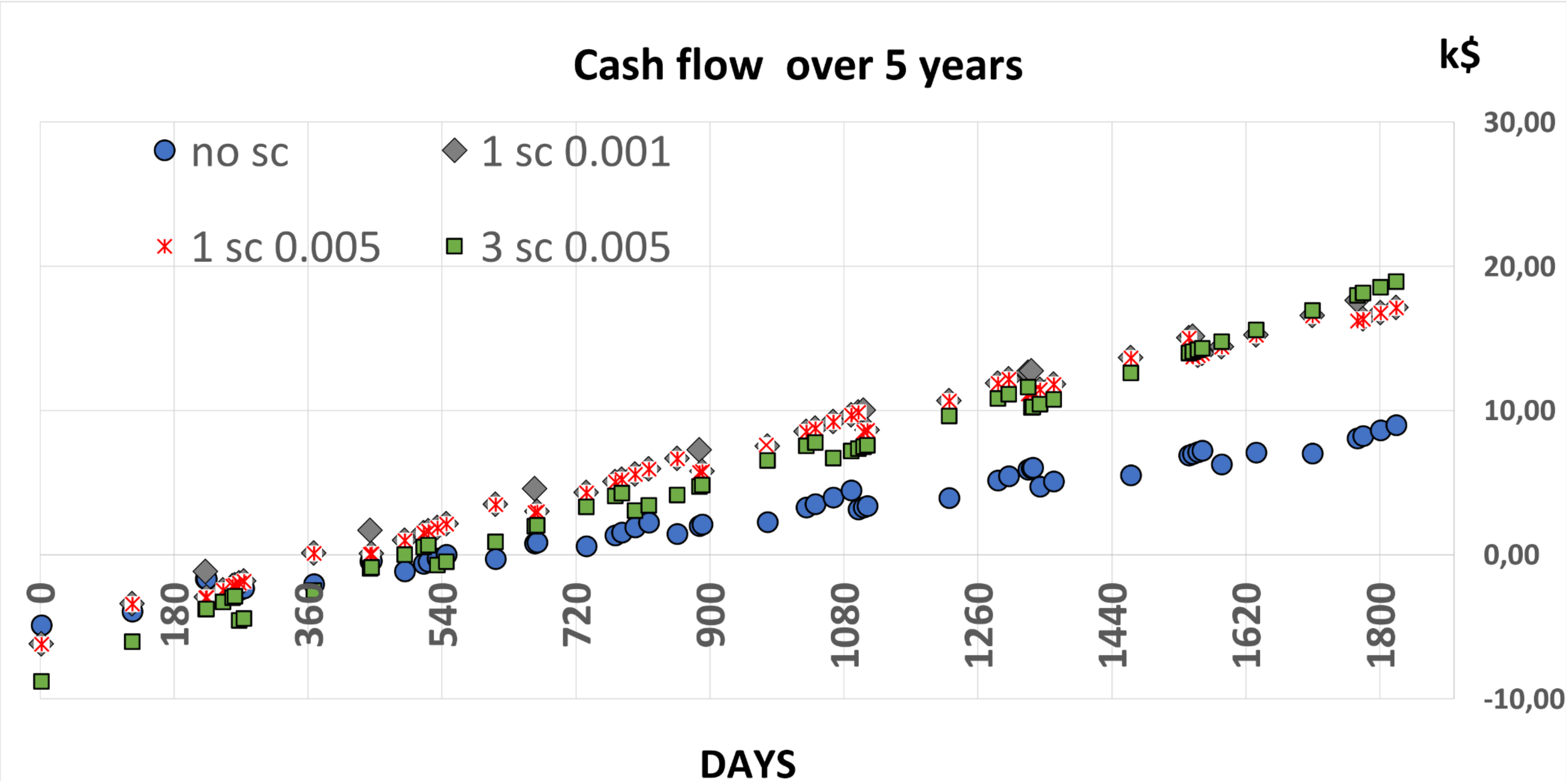
We chose to keep β not higher than 3 because of economic considerations

Results (1/3)

		case B	case C	case A	
		α = 0.001	α = 0.005		
Description/#SC		**1**	1	3	no SC
set SoCmin	p.u.	0,5	0,5	0,5	0.2
Lifetime	days	222	221	266	122
Investment on SC at year 1	$	1300	1300	3900	0
Investment on PV at year 1	$	3000	3000	3000	3000
Investment on battery at year 1	$	1800	1800	1800	1800
Annualized investment on batteries at the end of 5th year	$	$12.403	$12.403	$9.434	$21.836

** Fuel cost = $4/gal

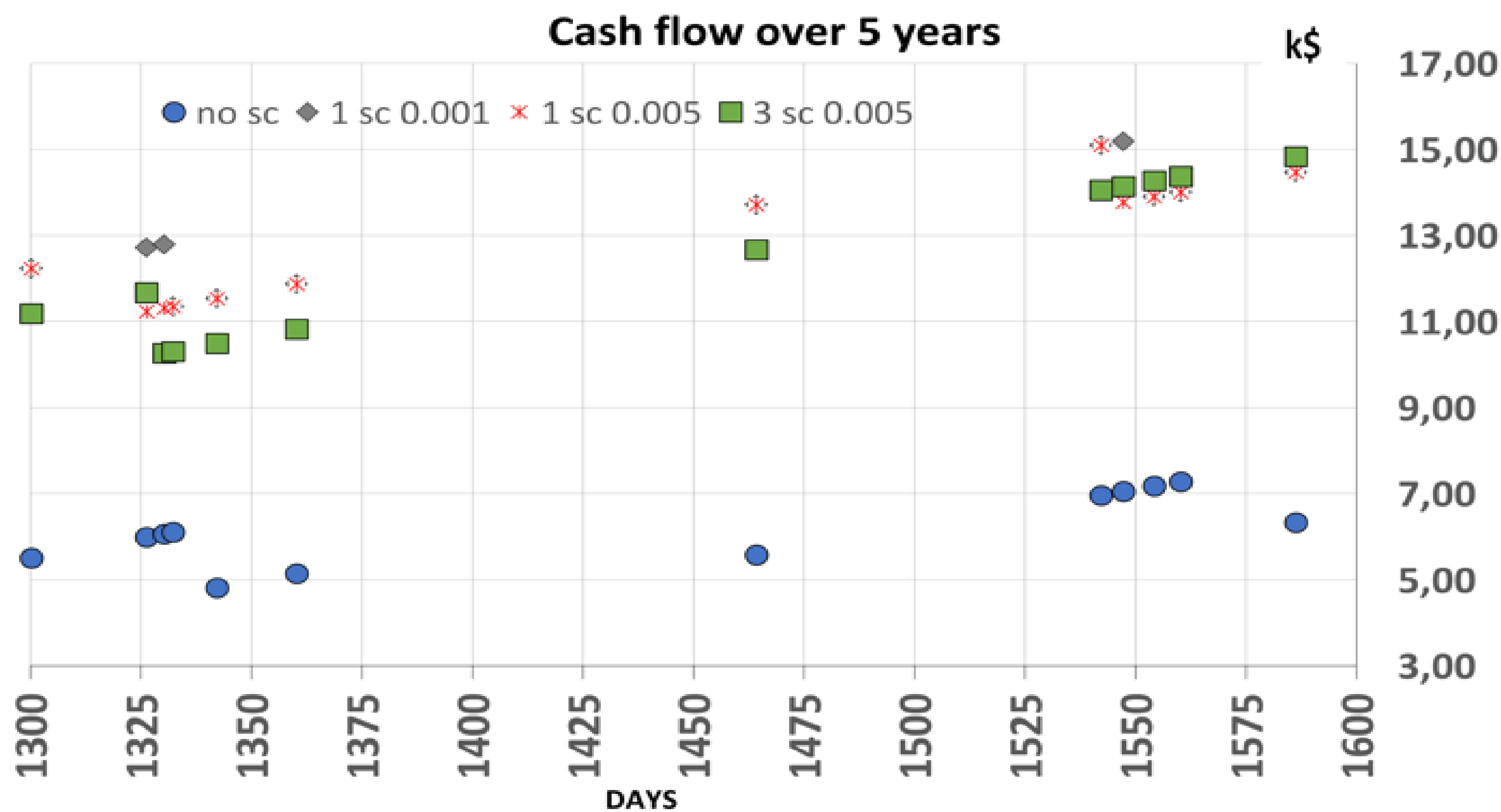
Results (2/3)



The addition of supercapacitors (SCs) to the energy storage system of a FOB is cost effective after about 200 days of operation. The best configuration for ~ 4 years operation is 1 SC with α=0.001, onwards the best configuration is with 3 SCs and α=0.005.

Results (3/3)

Enlargement between day 1300-1600



Case A, with 3 SCs (square green markers) and alpha= 0.005

Case B with 1 SC (diamond grey markers) and alpha = 0.001

<u>The greater the NPV, the greater the economic convenience</u>

Sensitivity on Investment Costs of Batteries vs SCs

			case A	case B	case A	case B	no SC
	Investment cost for SC [$]	Investment cost for a battery pack [$]	Cashflow at day 1554 [$]	Cashflow at day 1554 [$]	Cashflow at the end of the 5th year [$]	Cashflow at the end of the 5th year [$]	Cashflow at the end of the 5th year [$]
Inv SC/Inv batt = 0.72	**1300**	**1800**	14269	15310	19094	17314	9181
	1260	1745	14689	15698	19514	17788	9903
	1220	1689	15114	16092	19939	18270	10638
	1180	1634	15535	16480	20360	18744	11360
	1140	1578	15960	16874	20785	19226	12096
	1100	1523	16380	17262	21205	19700	12818
	1060	1468	16801	17649	21626	20174	13540
	1020	**1412**	17226	18044	22051	20656	14276
Inv SC (-20%) / Inv batt =	1260	1800	14389	15350	19214	17354	9181
	1220	1800	14509	15390	19334	17394	9181
	1180	1800	14629	15430	19454	17434	9181
	1140	1800	14749	15470	19574	17474	9181
	1100	1800	14869	15510	19694	17514	9181
	1060	1800	14989	15550	19814	17554	9181
	1020	**1800**	15109	15590	19934	17594	9181

- When Inv_{SC} and Inv_{B} both decrease Case A always better at the end of the 5th year, case B better up to day 1554
- Same behavior occurs even when SC investment cost decreases (up to -20%) and battery's remains constant: the case A (3 SCs) shows to be more profitable only after 1554 days

Conclusions

- We have proposed and tested a way to link the controller parameters with the economic evaluations of a remote isolated (and temporary) microgrid

- The proposed control system manages the state of charge of the SCs and increases the (alleged) lifetime of the batteries.

- Based on a specific load profile for a remote camp, results are analyzed by investigating under which conditions (i.e. changes in control parameters) the optimal solution to minimize fuel consumption remains the same.

- Three scenarios are analyzed to set the boundaries of the best configuration. The configurations are chosen according to the most suitable number of SCs and the best low pass filter parameter alpha values.

- For the future, different kind of batteries (and SC) will be tested to such control and evaluated always under this peculiar standpoint

Thanks for your kind attention

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