Powering Business Worldwide

Supercapacitor Technology for Peak Power Storage

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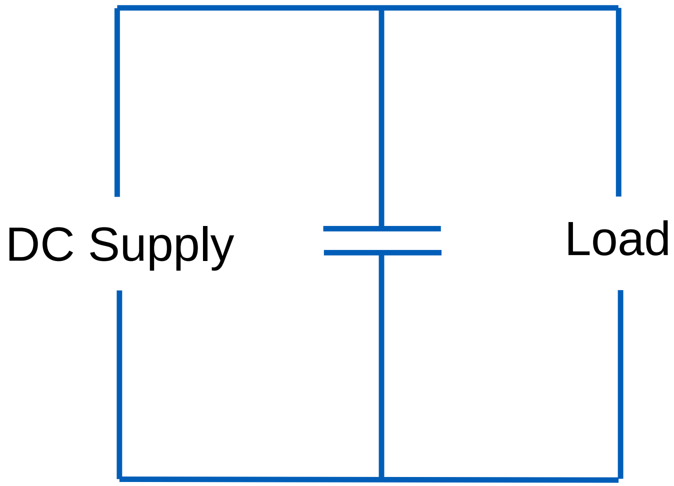
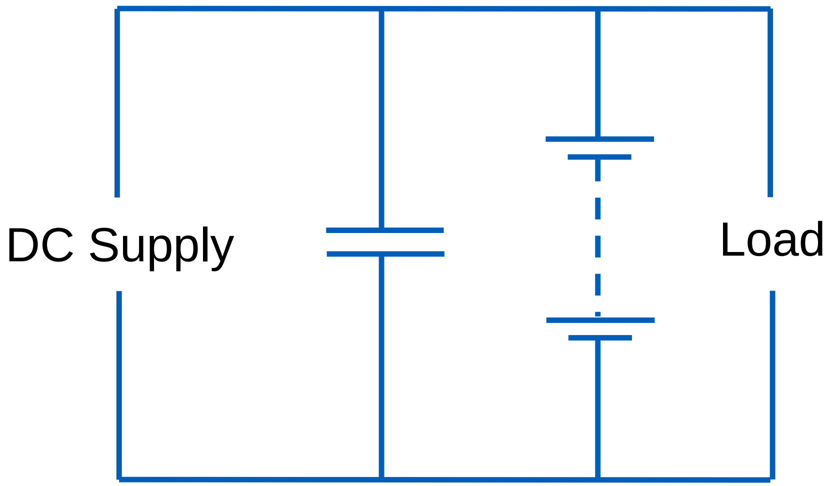
Outline

- Supercapacitor Implementation
- Supporting Batteries for Peak Power
  - Simulation Approach
  - HESS Example
  - HESS Summary
- Supercapacitors ESS
  - Traction Examples
- Features & Benefits of Supercapacitors

Supercapacitor Implementation



Supercapacitor Energy Storage System



Hybrid Energy Storage System (HESS)

High peak power for short durations, typically <30s but can be as high as one minute. Light weight, long life, maintenance free solution.

High peak power plus high energy, long duration operation. Supercapacitor reduces peak current stress on the battery, prolonging the battery maintenance life.

Hybrid Energy Storage System

- Supporting Batteries for Peak Power
  - Simulation Approach
  - HESS Example
  - HESS Summary

Battery Life Estimation

- Validate model of cell and battery pack
- For a given *DoD* time history, expected (average) number of cycles-to failure is

$$EN(N_f) = \sum_{1}^{k} n_i\, p_i \approx \sum_{1}^{k} \frac{n_i}{N_{fi}} = 1$$

- If D_N is number driving cycles per day, life in years

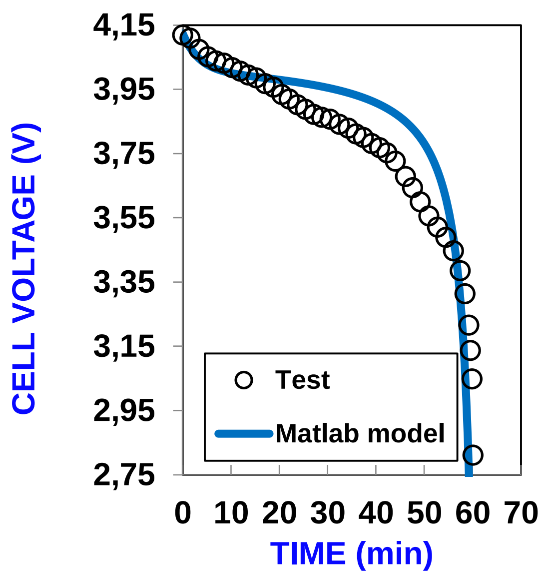
$$L = \frac{1}{EN\ D_N\ 365}$$

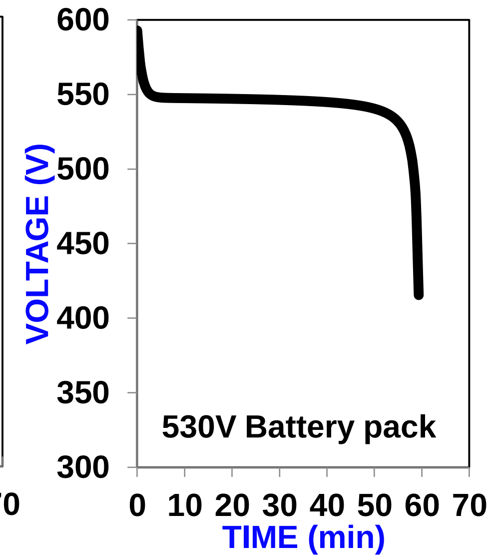
n_i Expected cycles of charge/discharge for peak DoD_i by Rainflow counting

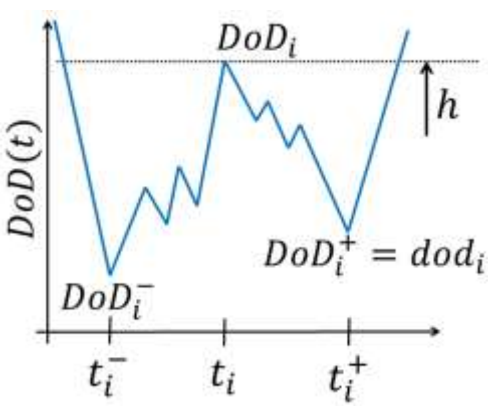
$p_i = \frac{1}{N_{fi}}$ Probability of incremental damage measure

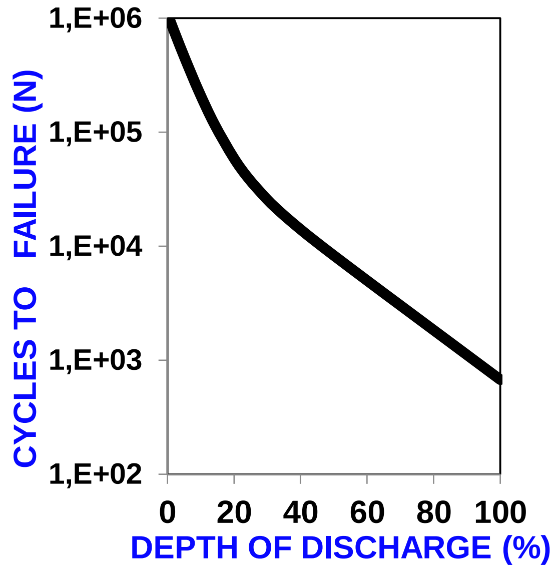
$$N_f = a_1 e^{(a2\ DoD)} + a_3 e^{(a4\ DoD)}$$

a_1, a_2, a_3 and a_4 are found to correlate to baseline field data



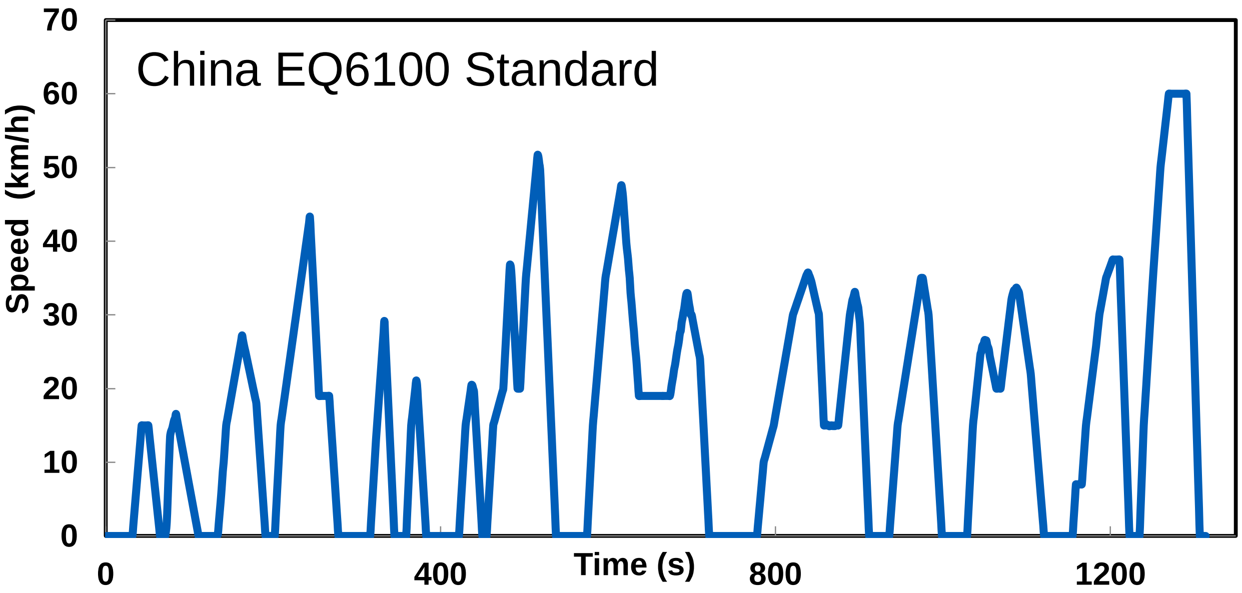






Electric Bus Drive Cycle

- Wuhan city is a typical major metropolis in China.
- Accounts for crowded street and vehicles and uneven roads.
- Driving distance approximately 6 km.
- The idle time is 373 sec, 28.4% of the total cycle.
- Average battery life of electric buses is 4 years.



Maximum speed = 62 km/h

Average speed = 16.5 km/h

Average acceleration = 0.39m/s^2

Average braking = −0.48m/s^2.

Total distance = 6 km.

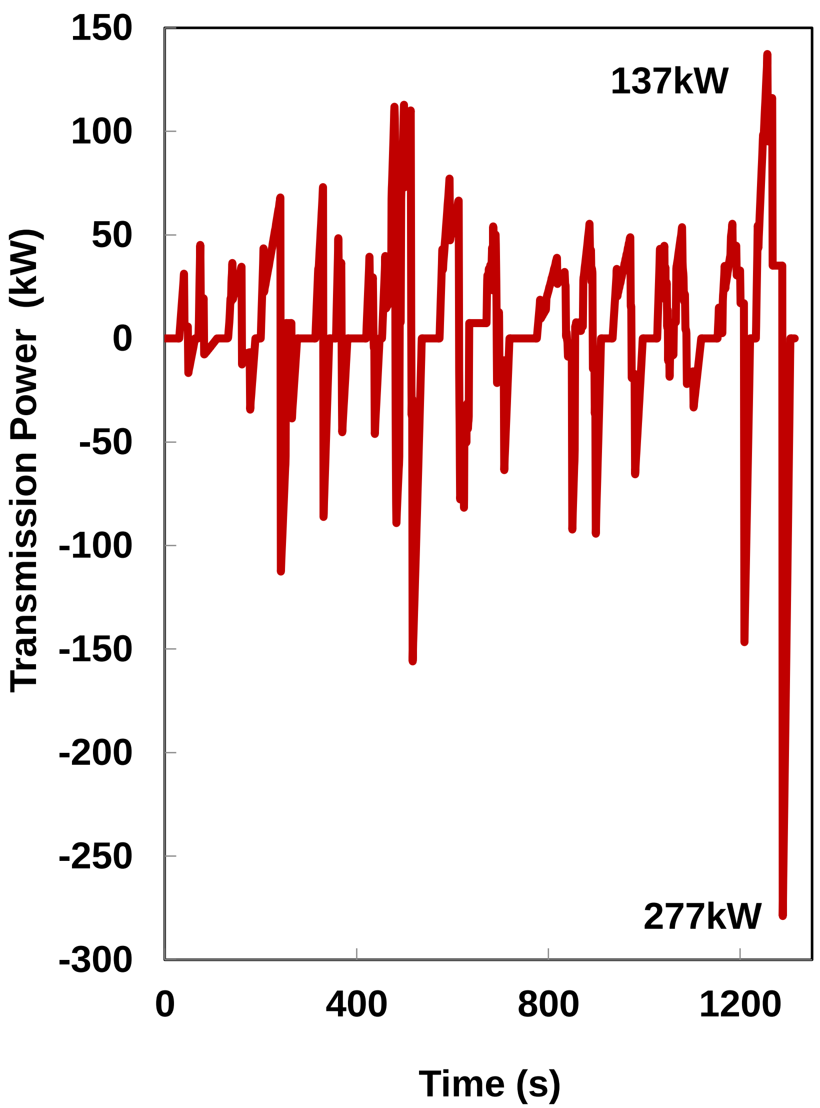
Duration = 1314 sec

Idle time: 373 sec, (28.4%)

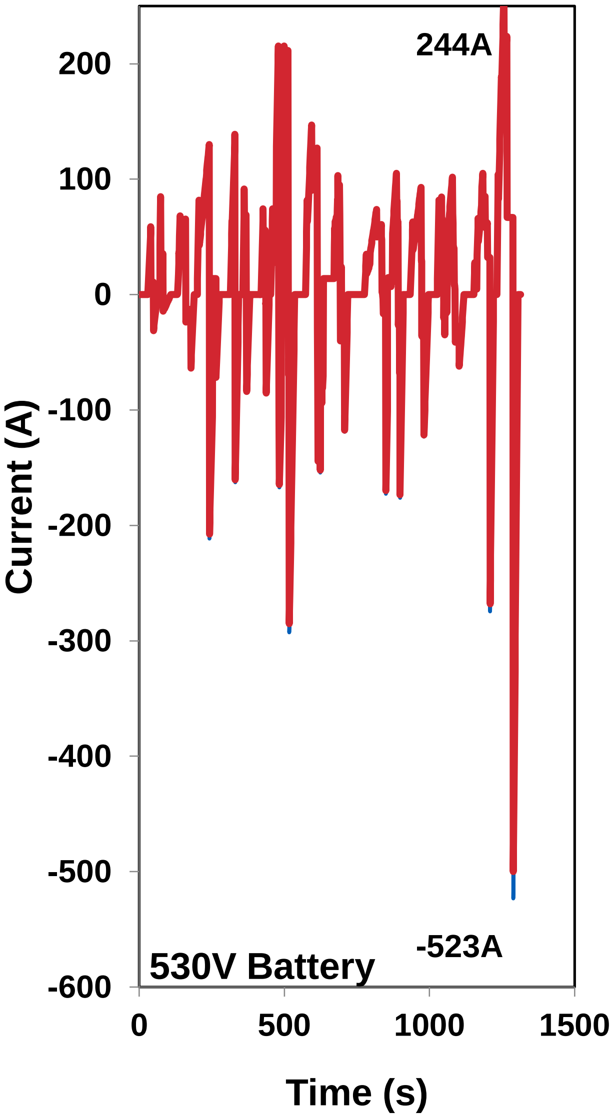
Battery Life without Supercapacitors

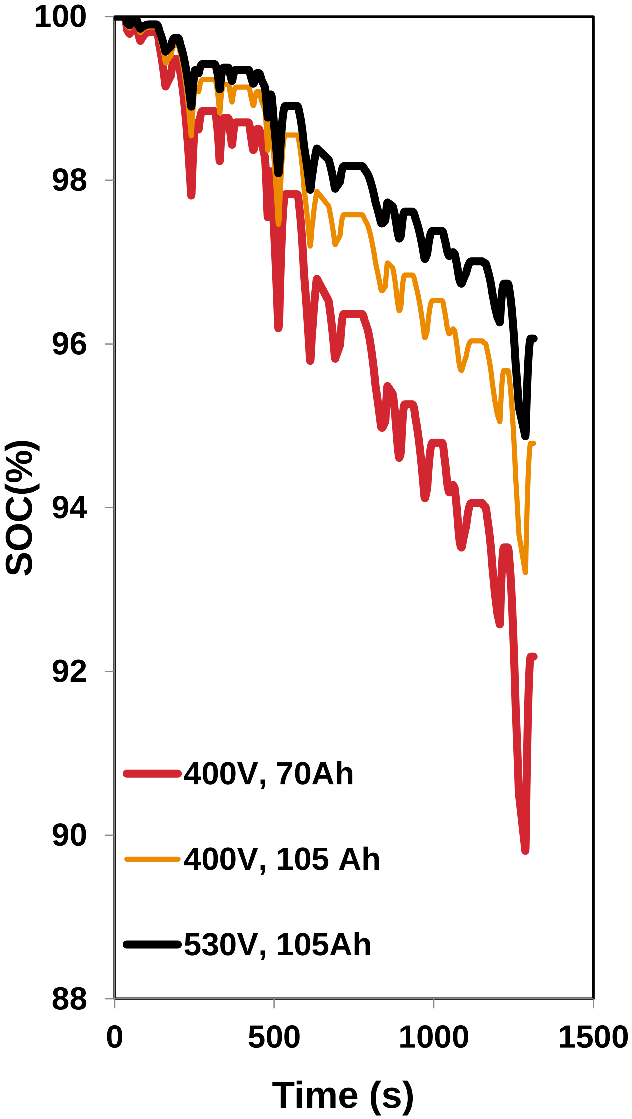
Lithium-ion batteries for the study

Parameter	Battery 1	Battery 2	Battery 3
Battery voltage (rated)	400V DC	400V DC	530V DC
Battery capacity	70Ah	105Ah	105Ah
DC bus operation voltage range	380 -750V DC	380 -750V DC	460 ~640V DC
Electric network	450 ~720V DC	450 ~720V DC	450 ~720V DC



Battery Life without Supercapacitors





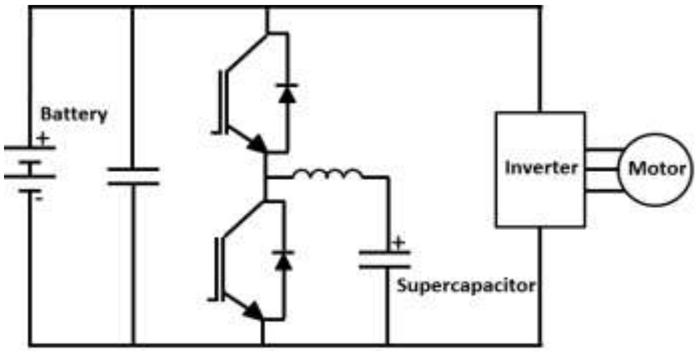
Battery Life (Years) for 200km per day drive cycle

Battery	Field Data	Simulated
400V 70 Ah	~4.0	4.09
400V 105Ah	--	4.25
530V 105Ah	--	4.32

Life extension of 5.6% from 400 V to 530V battery system

HESS Architecture

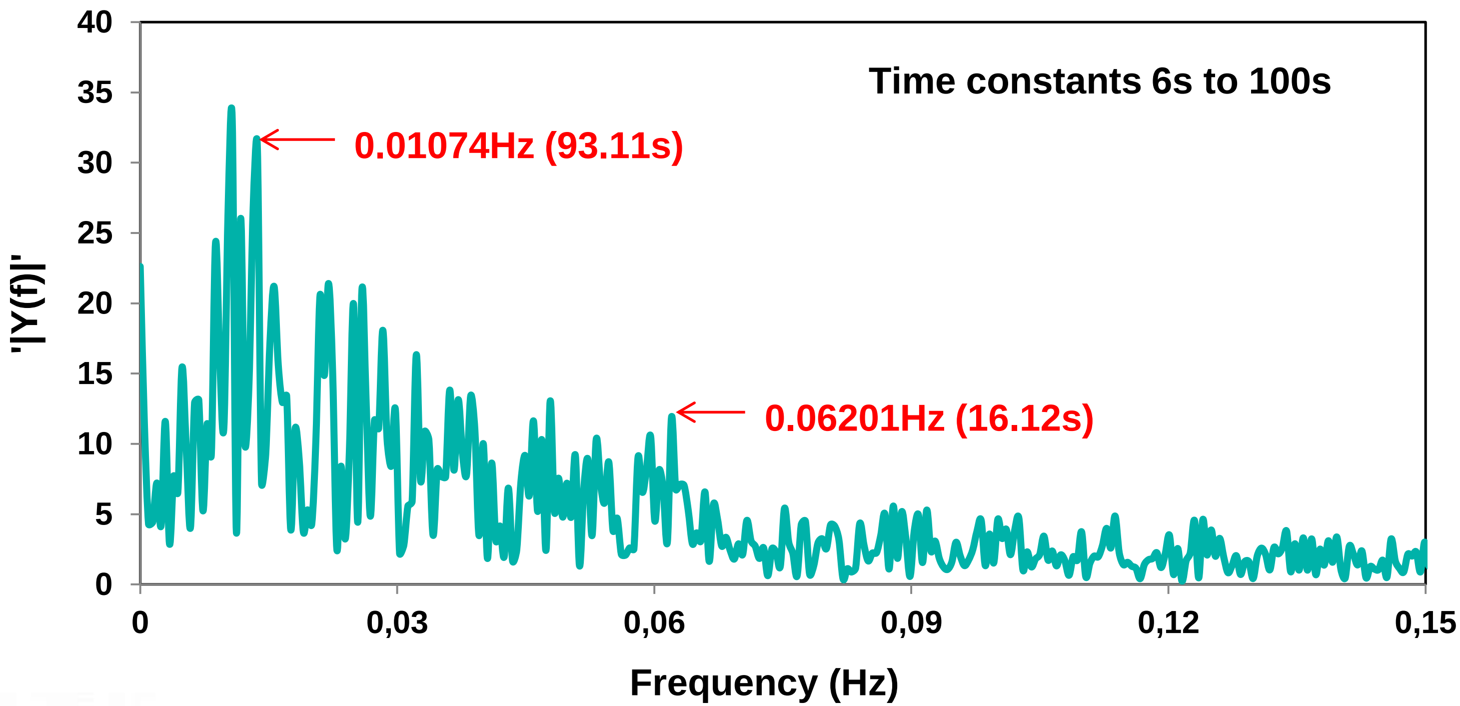
- Configuration
  - Battery on the high-voltage side directly connected to DC link; SC module is on the low-voltage side
  - Flexible SC module voltage selection for optimum performance, weight, cost and life extension
  - Bi-directional boost converter can charge and discharge the SC module
  - Capacitance of SC module sized to meet instantaneous power demand and maximize SC module utilization.
- Simulation
  - Matlab Simulink model consisting of digital high pass filter, a digital hysteresis comparator and PI controller† are employed.
  - Current control model and controller strategy† is employed.
  - Simulation is carried out for various capacitances and SC voltages.



HESS Topology for the battery life extension study

†Gyawali et al. Battery-ultracapacitor Based Hybrid Energy System for Standalone Power Supply and Hybrid Electric Vehicles – Part I: Simulation and Economic Analysis, Rentech Symposium Compendium, Vol 4, 2014.

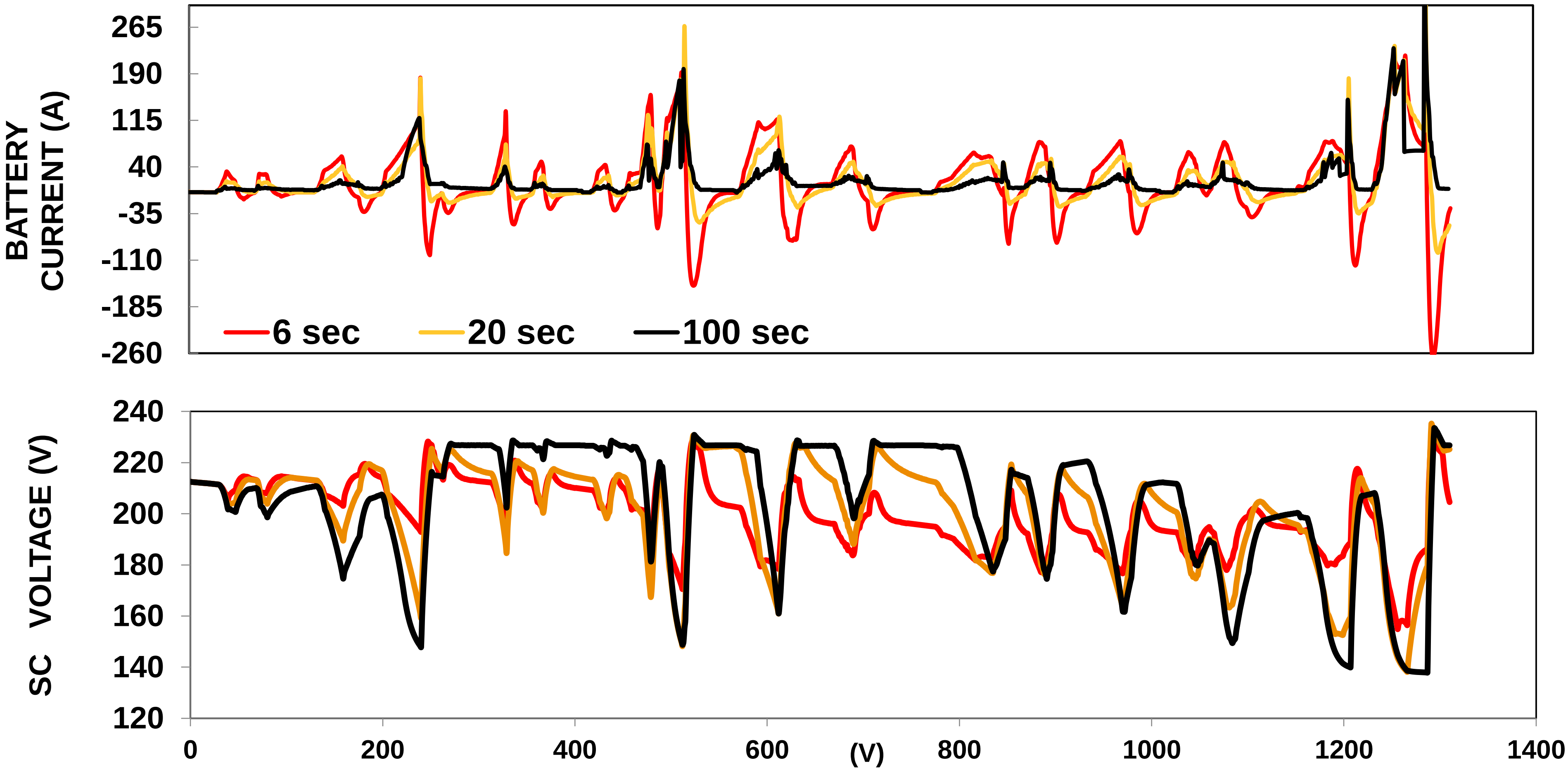
Battery Life with Supercapacitors



XL60 2.7V SC cells 3000F, maximum energy storage capacity of 10,935J, ESR 0.2mΩ

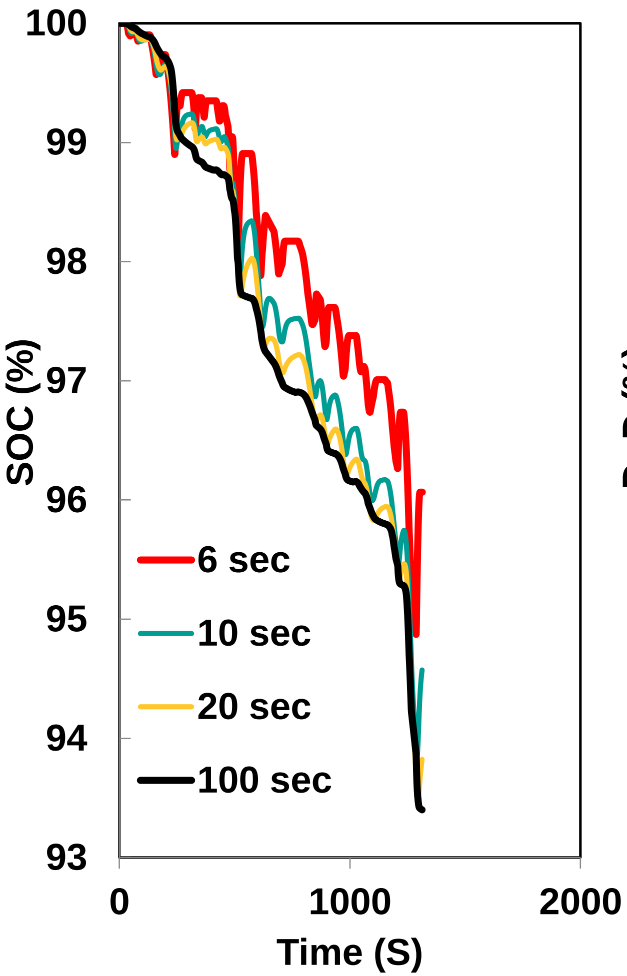
	1	2	3	4	5
# Series SC cells	67	84	134	168	202
# parallel SC cells	2	2	2	2	2
# Total SC Cells	134	168	268	336	404
Voltage (V)	180	210	335	420	505
Capacitance (F)	89.5	71.43	44.78	35.71	29.7
Weight (kg)	67	84	134	168	202

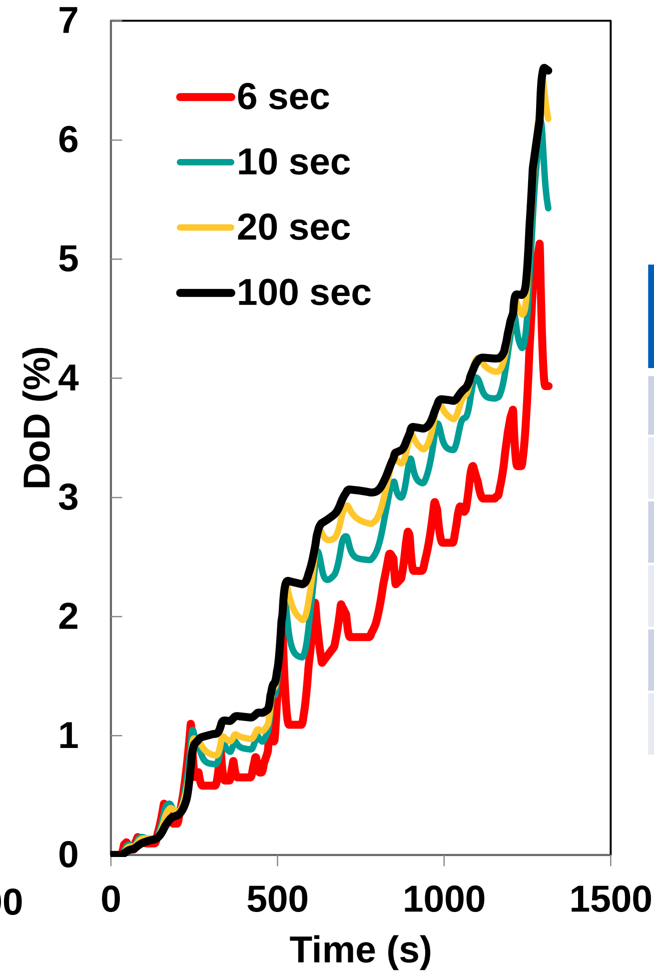
Battery Life with Supercapacitors



- Supercapacitor module responds to faster dynamics
- Battery current peaks are reduced substantially during charging
- With increase in time constant, battery charging cycles are reduced

Battery Life with Supercapacitors





530V Battery

Filter Time	SC Min V	Bat. Min V	Life Yrs
6	154.8	540.6	4.32
10	140.5	494.2	5.10
20	138.2	488.8	5.44
40	138.3	483.4	5.83
60	137.9	479.6	7.88
100	93.4	479.6	15.15

Life extension of battery can be as high as 3x, designed by properly selecting time constant of low pass filter

HESS Summary

- For electric buses, life extension of battery is only marginal with increasing voltage and Ah rating of battery pack.
- SC module are high-power-density devices which respond faster for high transient loads reducing the peak currents in the battery while charging (braking).
- With SC, the number of charge/discharge *DoD* cycles can be reduced increasing the life of the battery.
- Life extension of battery can be as high as 3x with 210V SC module, designed by properly selecting time-constant of low pass filter
- SC module on the low side voltage of the HESS provides flexibility to determine voltage rating for optimum performance with lower weight and cost.
- Battery life model can be easily integrated to the HESS simulation model and allows quick estimation which is useful in optimizing the battery pack size with SC module for weight and cost.

Supercapacitors ESS

- Supercapacitors ESS
  - Traction Examples

Traction Applications

Increasing electrification across Europe's rail networks is encouraging the adoption of energy storage technologies, for both on-board and line-side applications. This is enabling rail operators to embrace smarter energy architectures, leading to more sustainable operations with lower carbon emissions, and new opportunities for cost savings.

One of the main application for this energy storage is regeneration of breaking energy, which requires an energy storage system that can reliably handle repetitive high current charge & discharge.

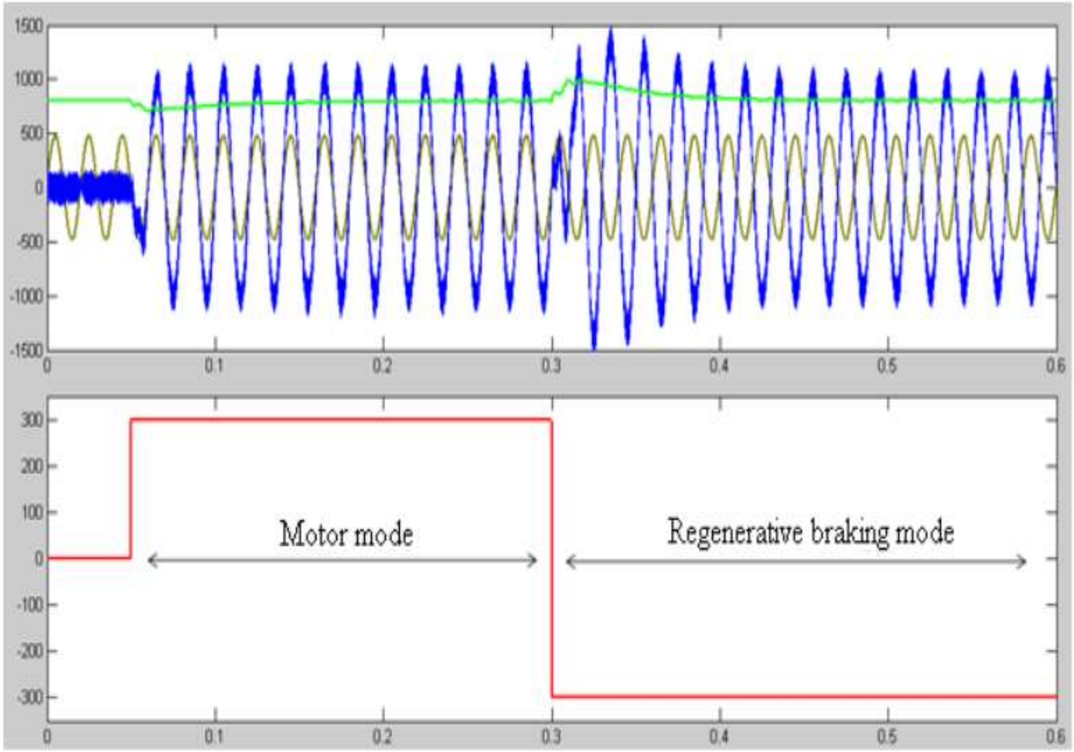
Advantages of using Energy Regeneration

- *Reduces peak power demand on the utility supply*
- *Stabilises the supply voltage*
- *Lower running costs*
- *Significantly less heat generated during braking*
- *Reduced maintenance compared with mechanical braking*

Braking Energy Regeneration

Energy regeneration looks to be very simple, putting the energy generated by the electric motors during the braking phase back to the power lines

Brown: $V_{\text{commercial grid}}$
Blue: $I_{\text{commercial grid}}$
Green: $V_{\text{traction power line}}$
Red: $I_{\text{traction power line}}$

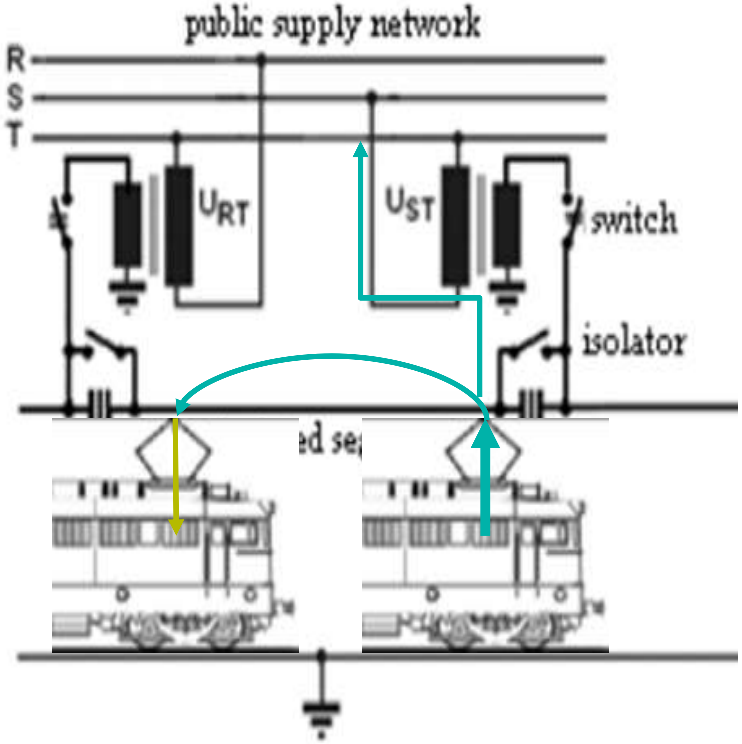


Source: BME

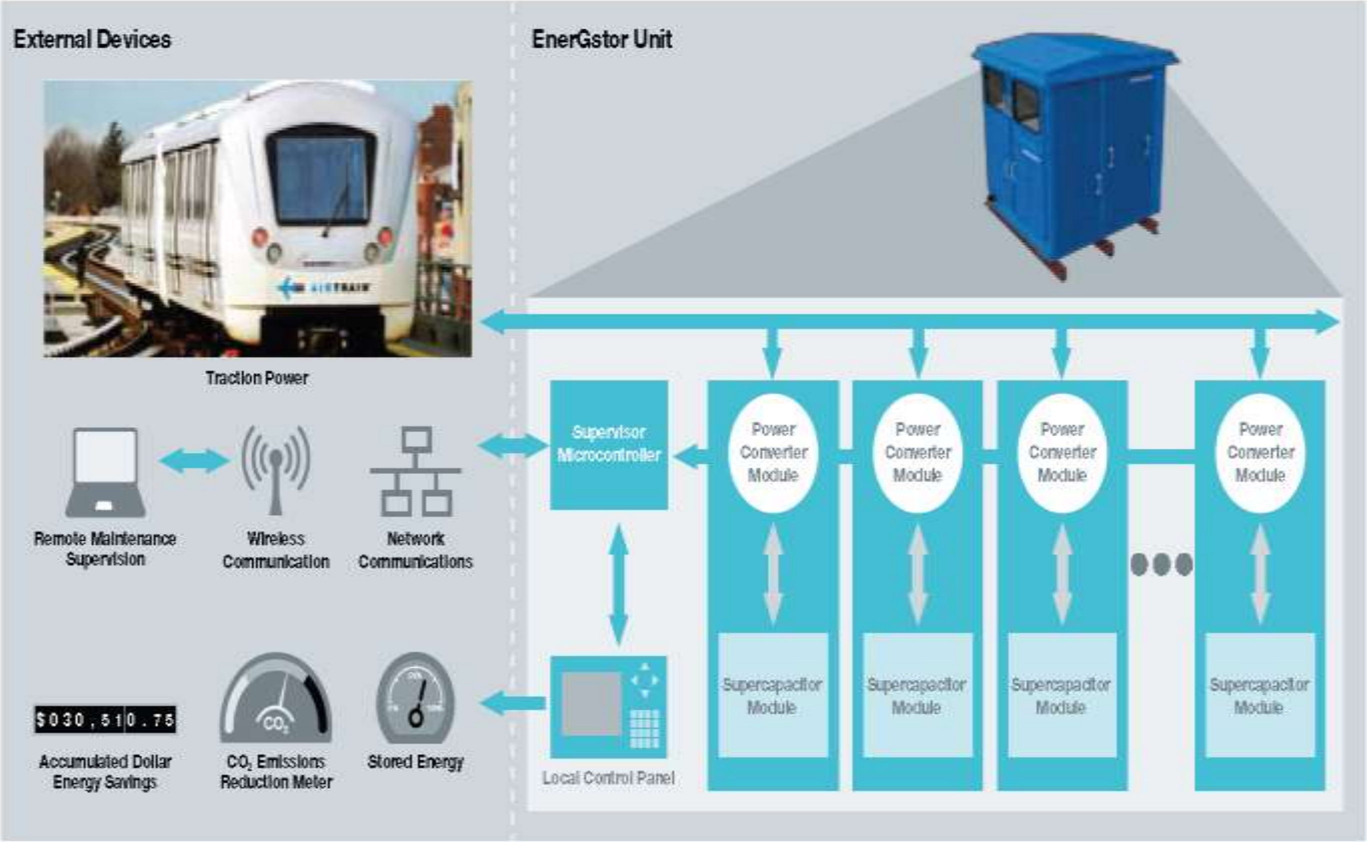
Braking Energy Regeneration

Challanges with traction energy regeneration:

- Previous simulation assumes that the power line section transformers have reversible rectifiers...very expensive and many constraints feeding back the energy to the commercial grid...plus difficult to track the saved energy, so the train operator makes no saving.
- In case the regenerated energy is not supplied back to the commercial grid, it will increase the power line's voltage unless there is an other vehicle using the same line section. This is mostly unpredictable.
- Ideal solution is store the regenerated energy and supply back on demand



Wayside Energy Regeneration

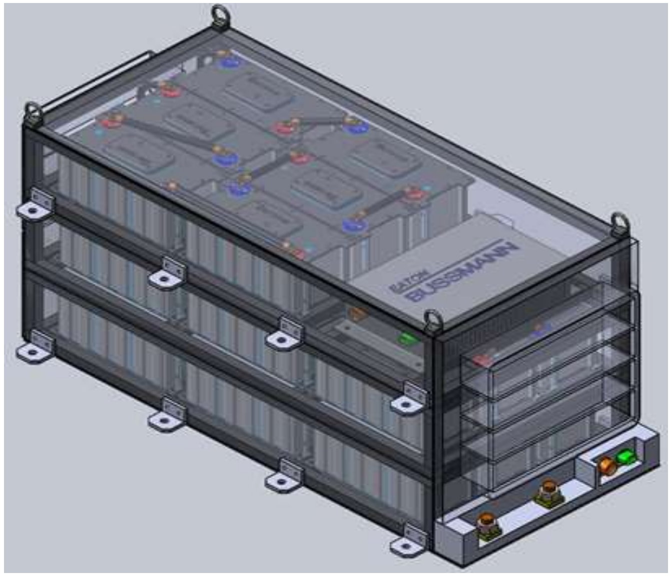


Source: Bombardier Germany

Wayside Energy Regeneration

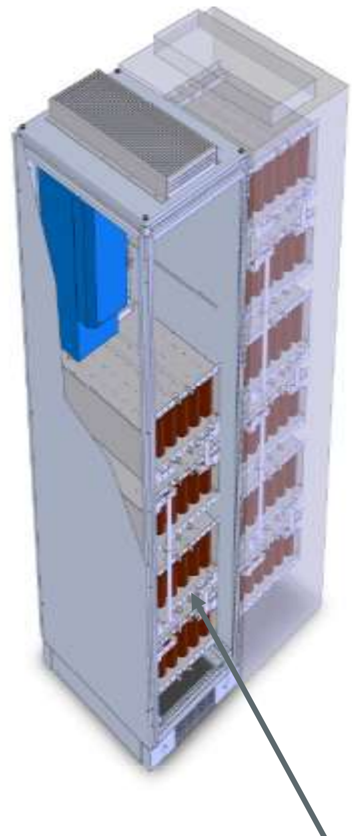
Advantages of the system:

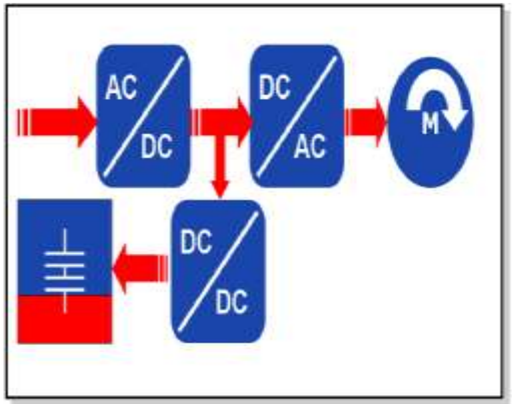
- Recovering breaking energy
- Doesn't add weight to the vehicles
- Level power flow – voltage stabilization over a specific timeframe and improve line voltage at critial track positions
- Reduces peak current demand on substations
- Reduce the waste heat during breaking – important in tunnels

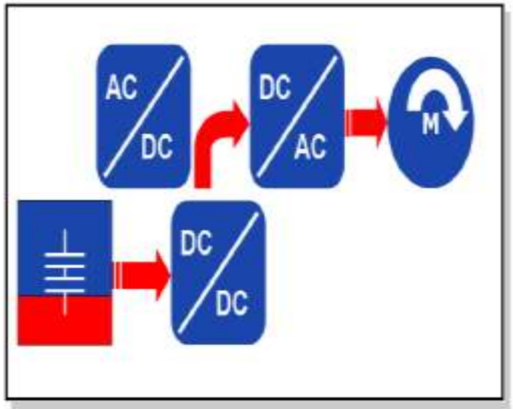


On Board Energy Regeneration

- Suitable for small trains, trams, subways and trolleys
- 10-280kW capable using purely supercaps
- 3-6s backup or regeneration at high power
- Customizable for any traction/vehicle systems







Source: MSc Finland

On Board Energy Regeneration

Advantages of the system:

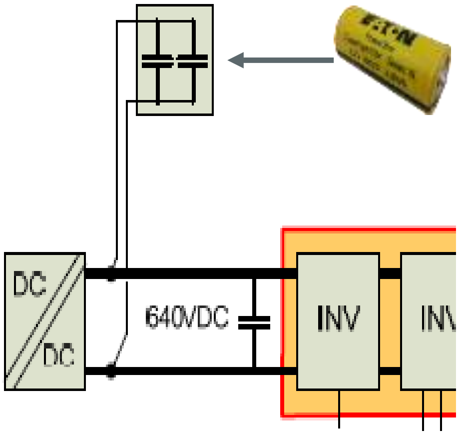
- Efficient energy recovery, close connection between regeneration system & storage.
- Stored energy can be immediately reused.
- Allows catenary, 3rd rail free, operation for several hundred meters for:
  - Loss of supply
  - Crossing none electrified junctions

Power Conversion in Traction Vehicles

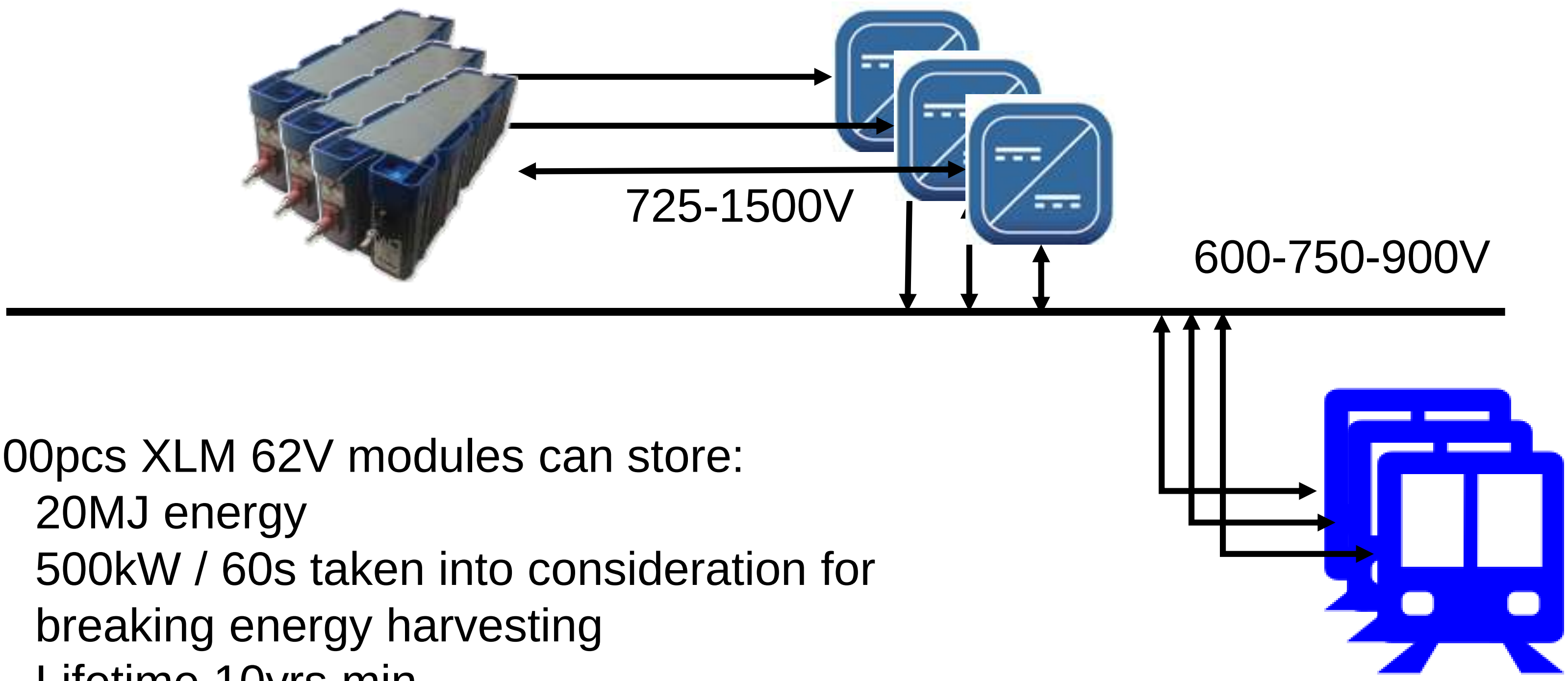
- Typcially wire contact supply lines are powered by the commercially available 3 phase AC grid and connected to the traction network via transformers to give a 600-1500V DC supply or 25kV AC supply.
- The power lines consists of isolated segments typically 1 segment per 10-15km for DC lines and 1 segment per 20-50km for AC lines.

- Large portion of running trains, trams, subways are still using dynamos to convert power for the auxiliaries.
  - Advantage - as long the train moves it produces power
    Disadvantage - efficiency ~50%, weight, maintainance & battery
- New high power IGBTs allow to convert power directly from the power lines
  - Advantage - better power control, higher efficiency, smaller size and weight, longer lifetime
  - Disadvantage - when there is a dead track or interruption in the power line (isolation between sections or tunnel entrance, low height overhead bridges).
- Ideal solution: IGBT power converter with supercaps bridging the gap between power lines. Typcially 1.5-3s bridging time is required.

200-300pcs ultra low ESR 650-3000F caps are suitable for the bridging



Wayside Energy Regeneration - Example

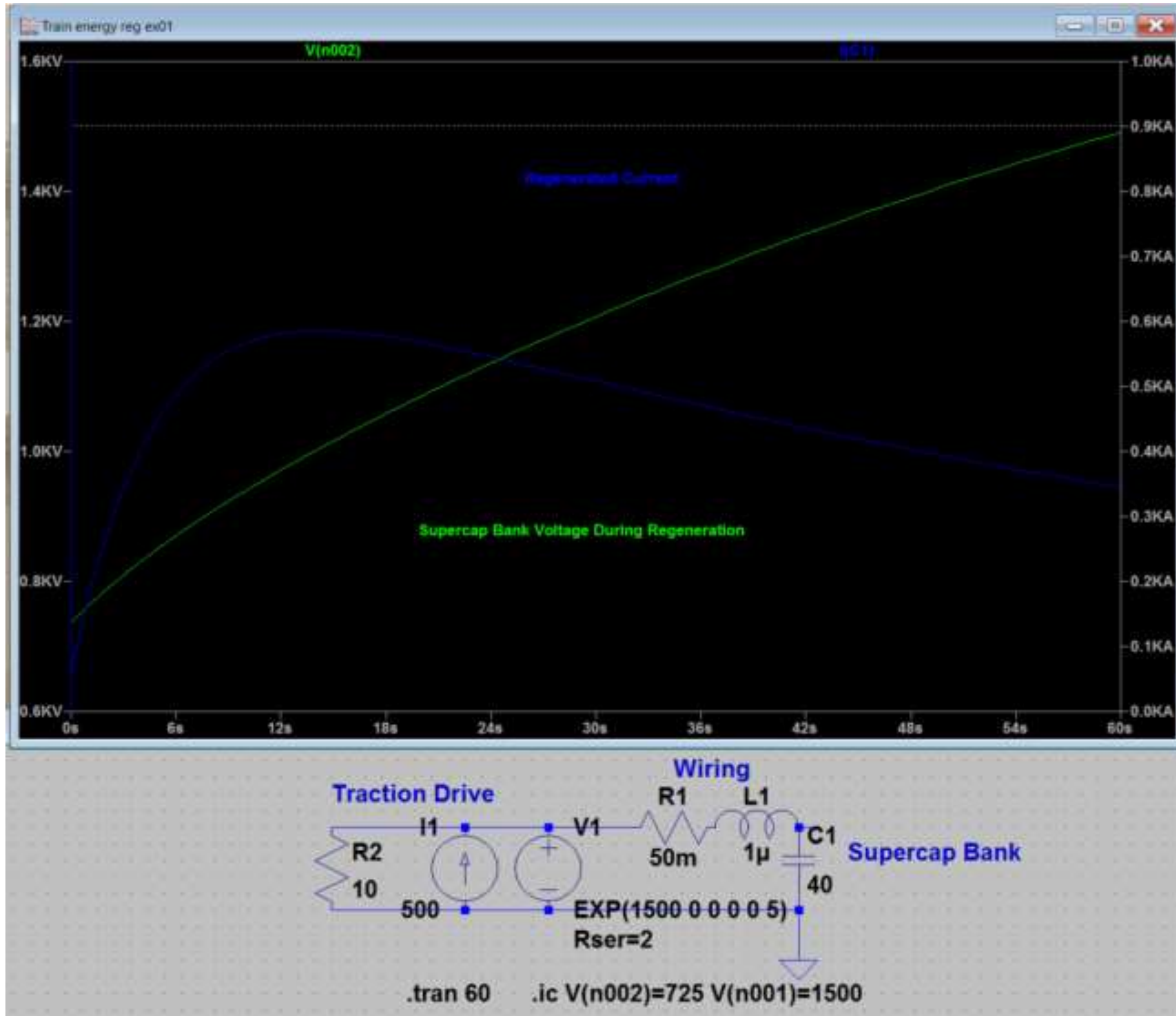


200pcs XLM 62V modules can store:

- 20MJ energy
- 500kW / 60s taken into consideration for breaking energy harvesting
- Lifetime 10yrs min
- Total size would be incl cabinets
  ~ 5.4m x 1m x 2m = 11m^3

Brake Energy Regeneration Cycle

Supercap bank is charged to full in 60s

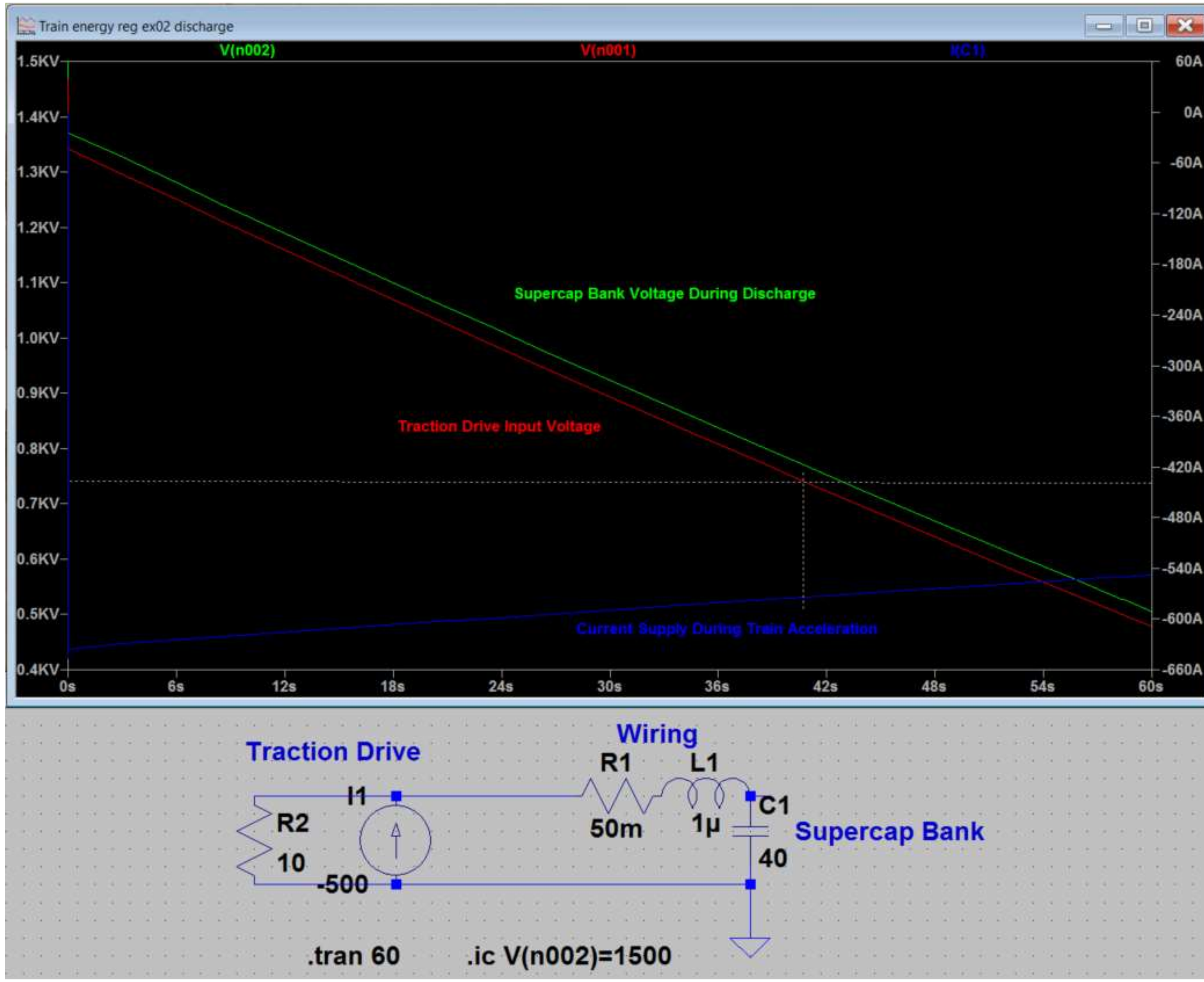


Energy Return Cycle

Supercap bank returns energy to the catenary line for up to 41s before getting discharged.

The energy lost compared to the charge cycle is due to the inefficiencies resulted by typically:

- 98% supercap efficiency
- 85% converter efficiency
- 3% wiring losses



Returned Energy During Lifetime

- Average returned energy per train stop cycle is 22.85MJ (6.35kWh)
- In case the train frequency on the station is 6x/hr (every 10min) for 12hrs per day the expected energy saving in 10yrs is 1.6GWh
- Total savings of energy cost per train station calculated with 0.2EUR (EU average) is 320.000EUR in 10years

Supercapacitors vs. Batteries

Key Characteristic	Units	Supercapacitor	Batteries
Voltage	V	2.5 – 5V	1.2 – 4.2
Cold Operating Temp	°C	**-40**	-20
Hot Temperature	°C	**+70 (85)**	+60
Cycle Life		**>500,000**	300 – 10,000
Calendar Life	Years	**5-20**	0.5 – 5
Energy Density	Wh/L	1 – 10	**100 – 350**
Power Density	W/L	**1000 – 10,000**	100 – 3,000
Efficiency	%	**>98**	70 - 95
Charge Rate	C/x	**>1,500**	<40
Discharge Time		Sec / Minutes	**Hours**





Key Advantages of Supercapacitors

- Long calendar life (up to 20 years) and high charge/discharge cycles (millions)
  - No replacement
  - Maintenance free
  - Predictable wear out/time to end of life
  - Simple monitoring & voltage balancing
- High power, high efficiency, low resistance
- Wide temperature range: -40 to +85C
- Light weight
- Environmentally friendly
  - No heavy metals
  - No thermal runaway
  - Industrial waste disposal
- Scalable with modular configuration

Ideal for Energy Storage Systems with High Current Load Cycling

Large Supercapacitor Modules

- XLM-62R1137A-R
- 130F / 62V
- 6.7mOhm ESR
- Passive voltage balancing
- Plastic housing for stationary applications (IP20)

- XLR-48R6167-R
- 166F / 48V
- 5mOhm ESR
- Active voltage balancing
- Ruggedized construction for harsh enviromnents (IP65)