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General principle of energy recovery and storage in the urban railway transport

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Energy storage in the driving cycle

Current Situation

Braking energy

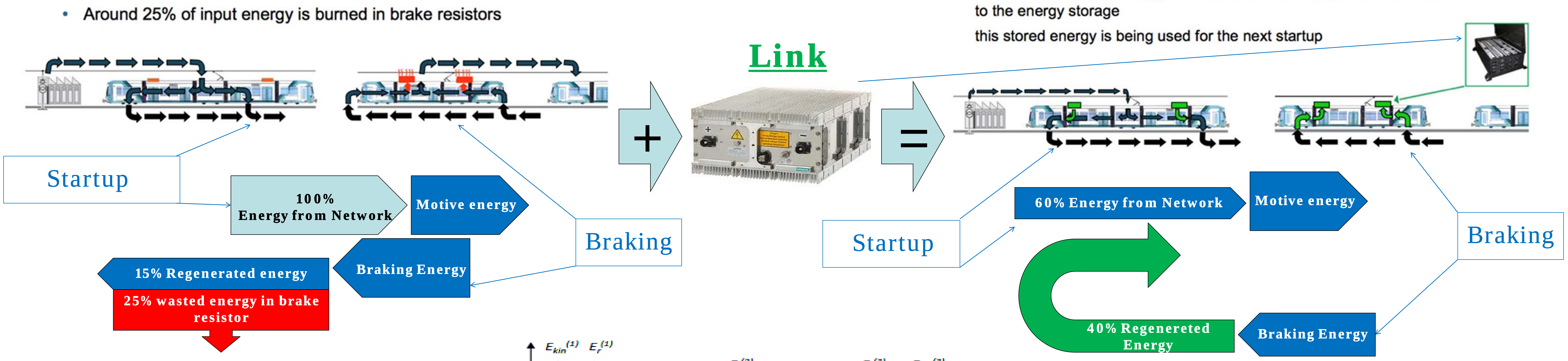
- Only around 15% of total input energy is recuperated in braking mode
- Around 25% of input energy is burned in brake resistors

Future Situation

Energy storage on board of vehicle

Around 40% of input energy is recuperated in braking mode and fed back to the energy storage

this stored energy is being used for the next startup



Startup

100% Energy from Network

Motive energy

Braking

Braking Energy

15% Regenerated energy

25% wasted energy in brake resistor

Link

Startup

60% Energy from Network

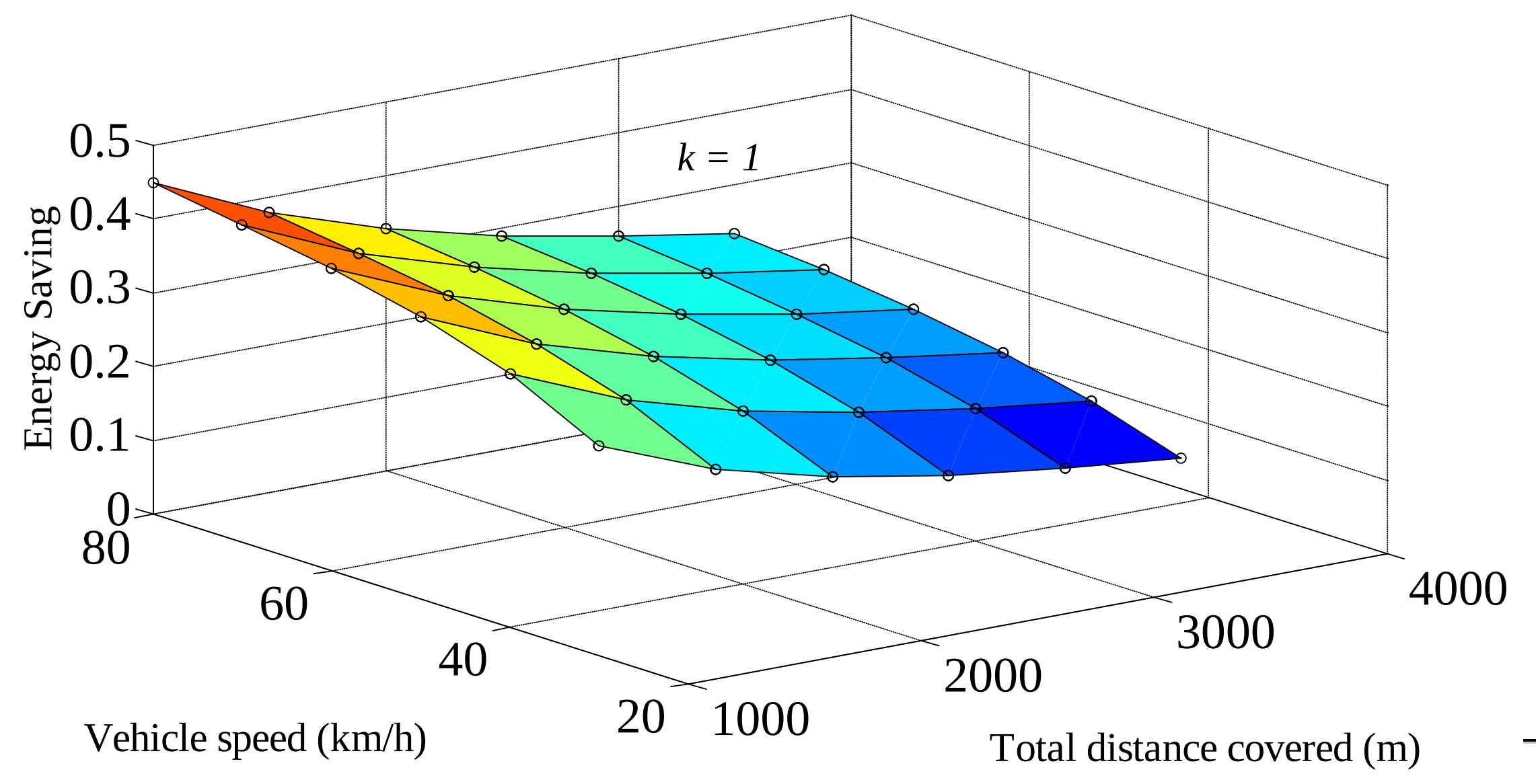
Motive energy

Braking

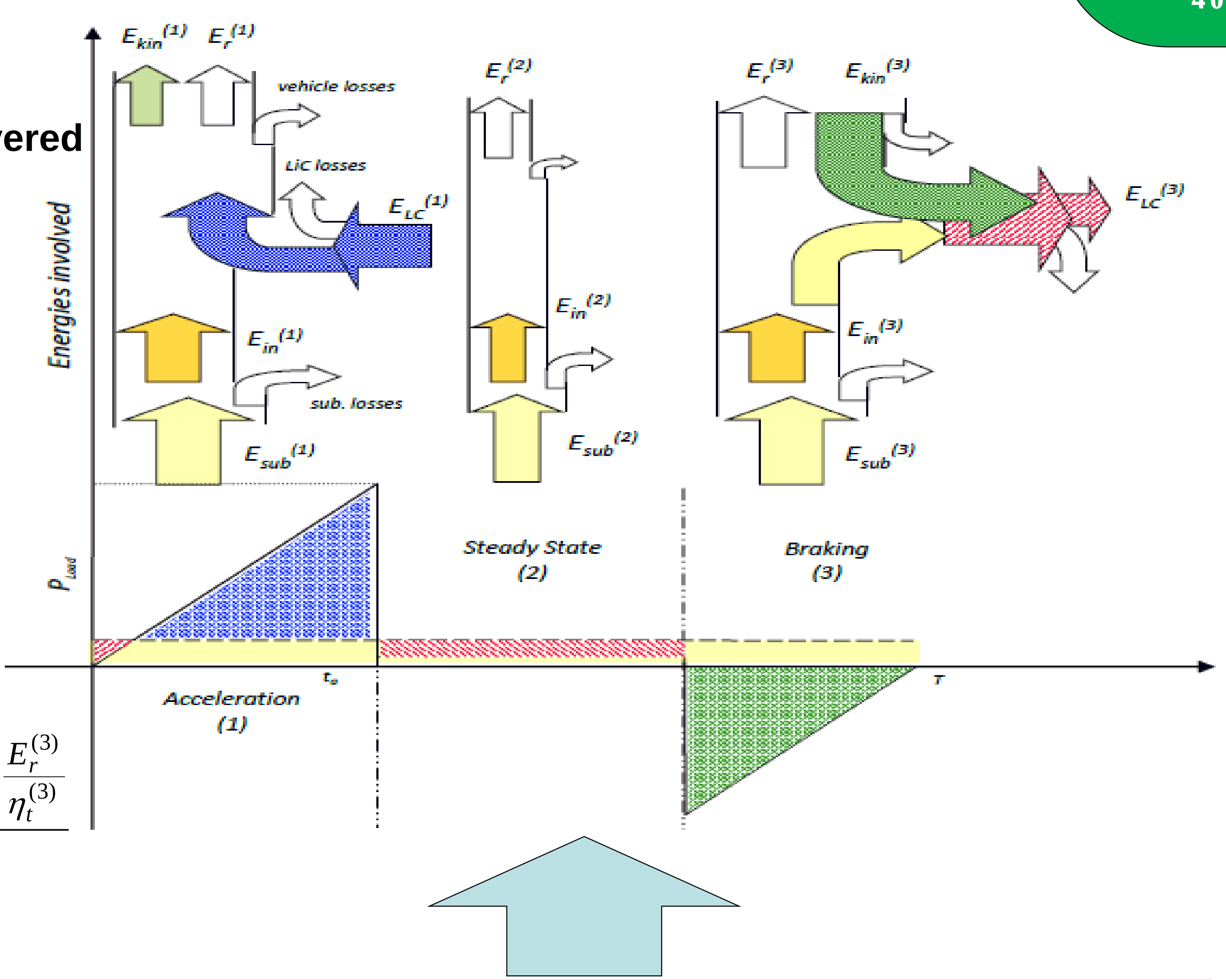
40% Regenereted Energy

Braking Energy

Energy saving vs. vehicle speeds vs. tot. distance covered



$$e_s = 1 - \frac{E_{sub}}{E_{sub}^{(BR)}} = 1 - \frac{E_{LC}\left[\frac{1}{\eta_{sto}^{(3)}} - \eta_{sto}^{(1)}\right] + E_{kin}^{(1)}\left[\frac{1}{\eta_t^{(1)}} - k\eta_t^{(3)}\right] + \frac{E_r^{(1)}}{\eta_t^{(1)}} + \frac{E_r^{(2)}}{\eta_t^{(2)}} + \frac{E_r^{(3)}}{\eta_t^{(3)}}}{\frac{E_{kin}^{(1)} + E_r^{(1)}}{\eta_t^{(1)}} + \frac{E_r^{(2)}}{\eta_t^{(2)}}}$$



Typical driving cycle :
Acceleration – Cruising at constant speed – Braking

Light Railway vehicles

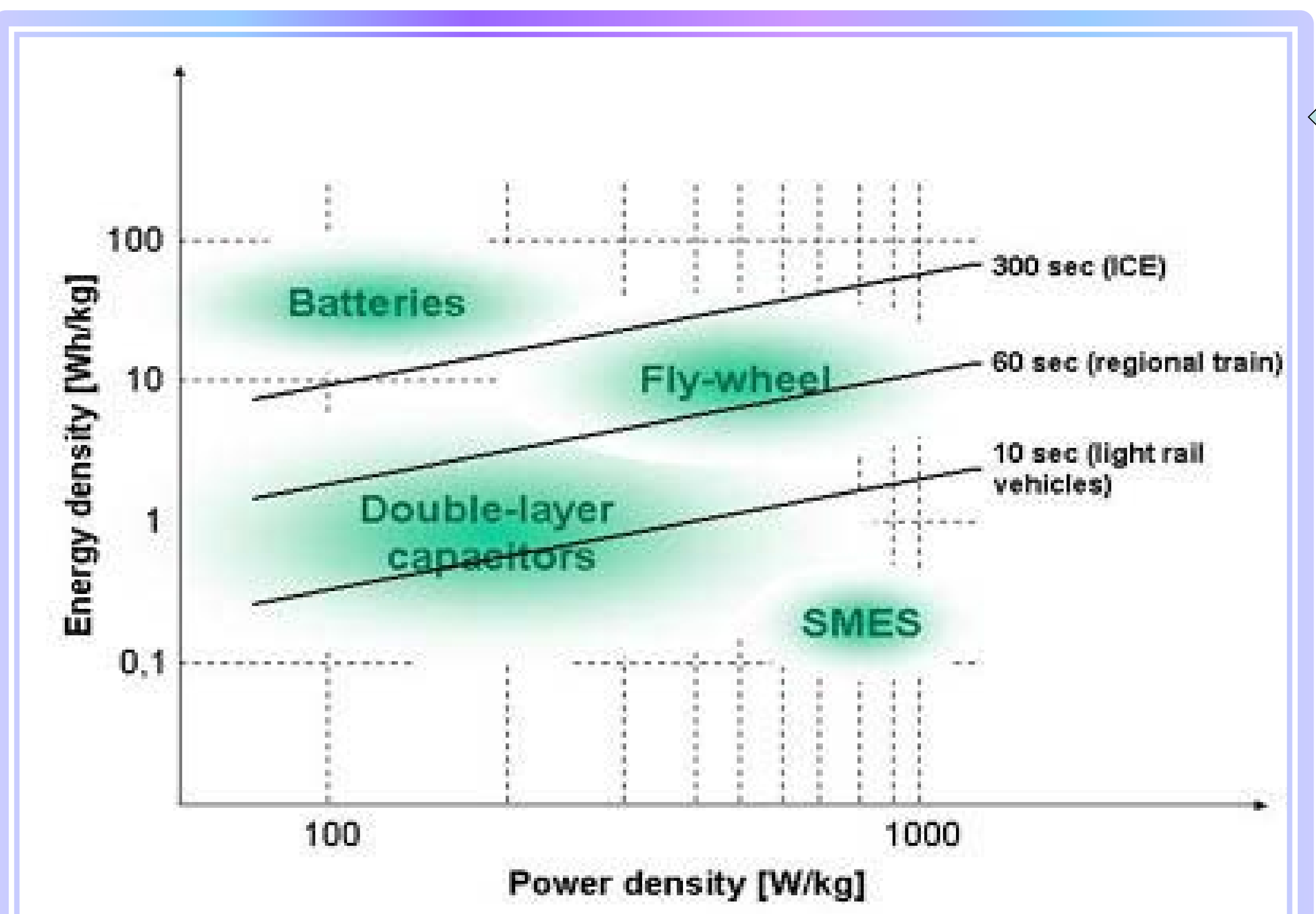
Metro Light Rail

Mass-transit network

Tram-car

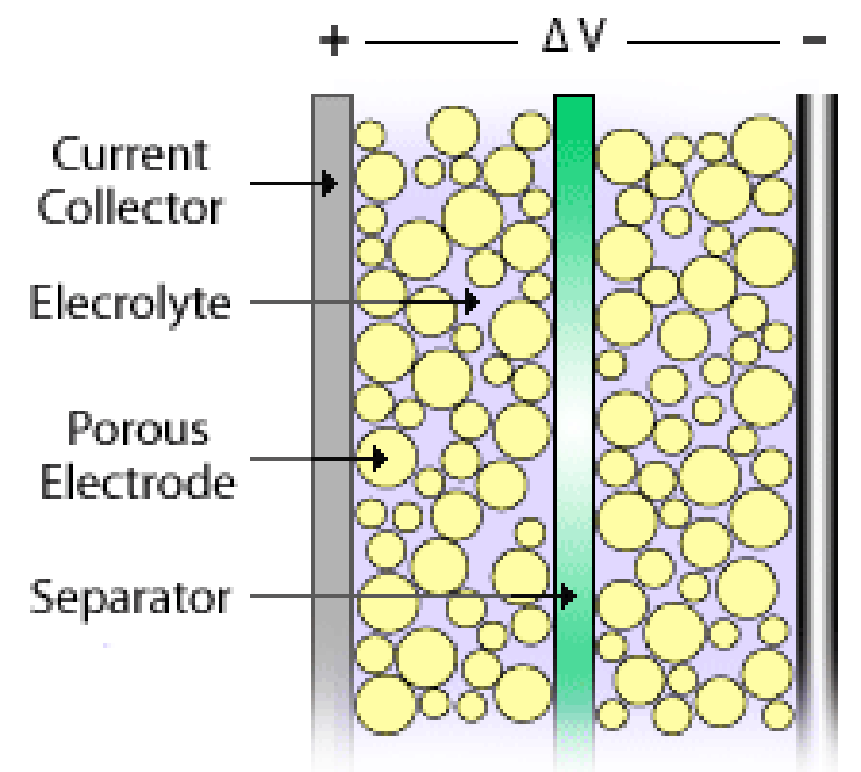
Metro-Train

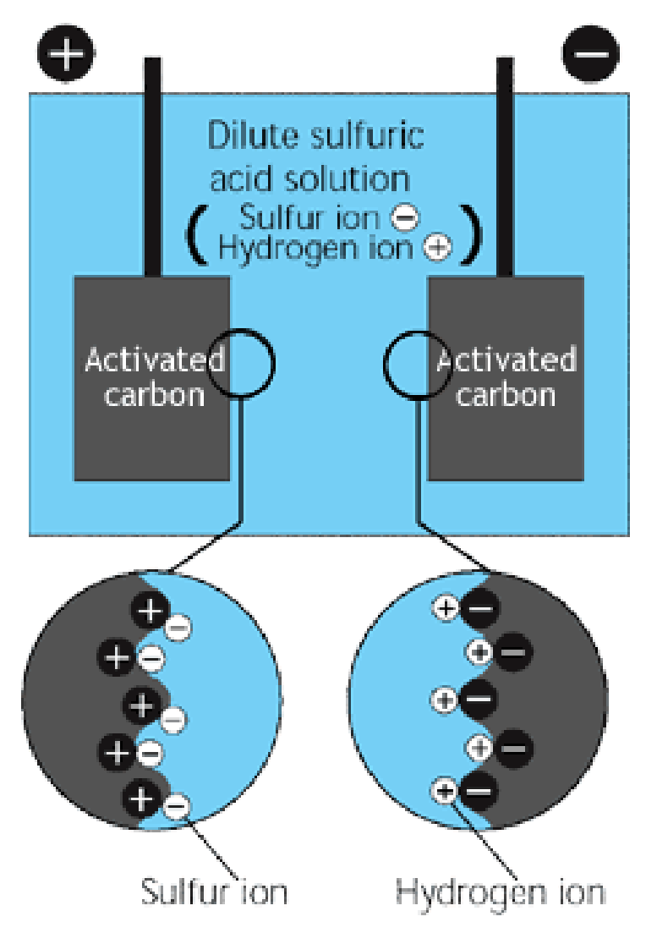
Storage devices: Supercapacitors



Energy Storage Technologies options

Individual Ultracapacitor Cell





Batteries:

+ very high energy density
- bad cycling stability/lifetime
- Electrode material is involved in energy cycling
- Overdimensioning when high numbers of cycles and high peak power are required.

Flywheel Storage

+ high energy density
- expensive
- low peak power

Double-Layer Capacitor

+ enough energy density and high peak power
+ promising price development
+ high numbers of cycles / lifetime
+ simple technical system (reliability)

Double –Layer Capacitor are ready for use

Supercapacitor devices consist of two electrodes to allow a potential to be applied across the cell, and therefore two double-layers are present, one at each electrode/electrolyte interface. An ion-permeable separator is placed between the electrodes in order to prevent electrical contact, but still allows ions from the electrolyte to pass through. The electrodes are made of high effective surface-area materials such as porous carbon or carbon aerogels in order to maximize the surface-area of the double-layer.

High energy densities are therefore achievable in EDLCs due to their high specific capacitance, attained because of this high electrode/electrolyte interface surface-area and a small charge layer separation of atomic dimensions.

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Case study of energy storage supercapacitor integrated on-board and wayside for a real rail system

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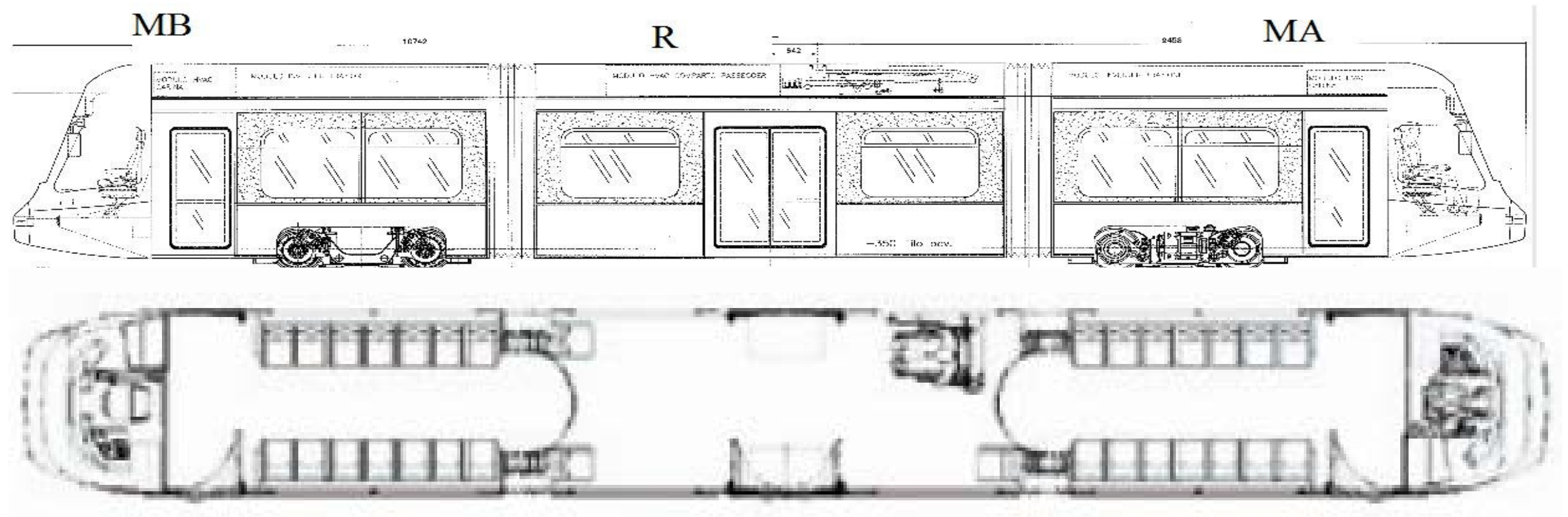
The real system and its parameters

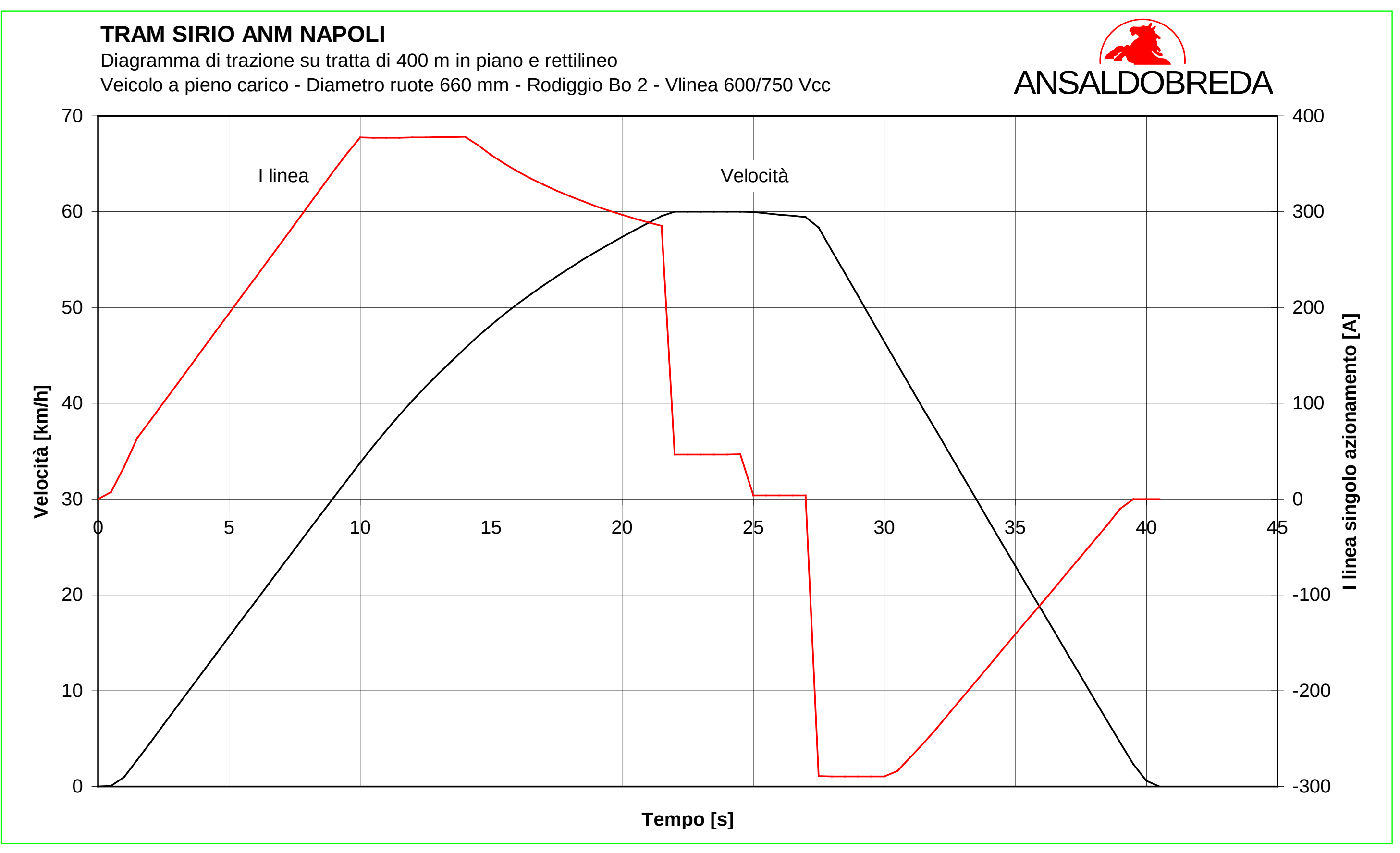
ANM NAPOLI: TRAM "SIRIO"

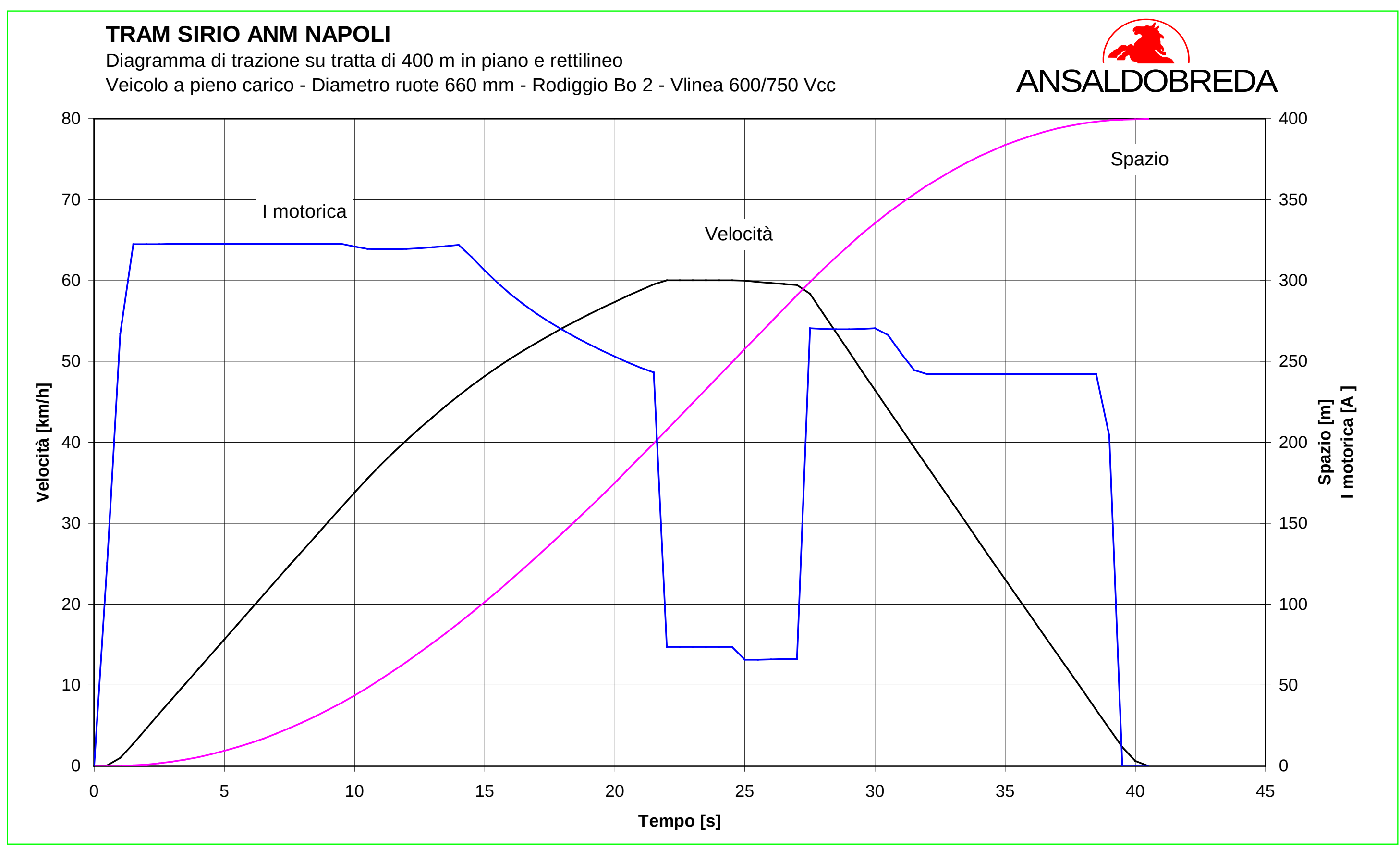


Main technical characteristics of the tram "SIRIO" :

Max. Traction Effort ($F_{t,max}$)	41kN
Rated Supply Voltage (v_{line})	750 V d.c.
Total Capacity (Passengers)	156
Mass at max. Load (m_t)	36500 kg
Max. Speed ($v_{t,max}$)	70 km/h
Max. Acceleration/Deceleration rate ($\dot{v}_{t,\max}$)	1 ms^{-1}
Max. Kinetic Recoverable Energy ($E_{kin,max}$)	1.92 kWh
Wheel Diameter ($2*R_{wheel}$)	660 mm
Transmission ratio (τ)	6.541

Traction diagrams of traction and mechanical characteristics during acceleration and braking of the "SIRIO" trams





Energy storage sizing

For the sizing of a storage system, an aspect that must be taken into account is represented by the discontinuity and uncertainty of the power sources availability. The sizing has been referred to the total translating mass and the maximum speed of the LRV.
The storage system is constituted by the several elementary modules of supercapacitors connected in series (N_s) and in parallel (N_p) between them in order to obtain the maximum permissible voltages and currents by the modules.

PARAMETER	Symbol
Mass at maximum load	m_t
Weight of SC modules	m_{sc}
Max speed	$v_{t,max}$
Maximum energy storable in SC	$E_{sc,max}$
Mechanical rated efficiency	η_{mech}
Inverter rated efficiency	η_{inv}
Converter rated efficiency	η_{dcdc}
Electric motors rated efficiency	η_{em}
SC rated efficiency	η_{sc}
Coefficient of SC energy density	α

- $E_{kin,\max} = \frac{1}{2}\left(m_t + m_{sc}\right) v_{t,\max}^2$

$$\alpha = E_{sc,\max} / m_{sc} = 1.75 Wh / kg$$

- $E_{sc,\max} = \dfrac{\alpha\, \eta_{mech}\, \eta_{em}\, \eta_{inv} \eta_{dcdc}\, \eta_{sc}\, m_t\, v_{t,\max}^2}{2\alpha - \eta_{mech}\, \eta_{em}\, \eta_{inv} \eta_{dcdc}\, \eta_{sc}\, v_{t.\max}^2}$

Module features SC: *Maxwell BM0D00063 P125*

Rated voltage $V_{m,max}$ [V]	Equivalent capacitance $C_{sc,m}$ [F]	Equivalent Series resistance $r_{sc,m}$ [mΩ]	Maximum current $I_{m,max}$ [A]	Storable energy @75% SOC $E_{sc,m}$ [Wh]	Module weight [kg]	Dimensions [mm]
125	63	18	750	101.7	58	762 x 425 x 265

- $E_{sc,\max} = 1.048\ kWh$
- $C_{sc} = 47.25\ F$

$$N_s = 4 \qquad N_p = 3$$

$$P_{sc,\max} = \left(m_t + m_{sc}\right) \dot{v}_{t,\max}\, v_{t,\max}\, \eta_{mech}\, \eta_{em}\, \eta_{inv}\, \eta_{dcdc} = 505\ \text{kW}$$

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Stationary vs. On-board Energy Storage

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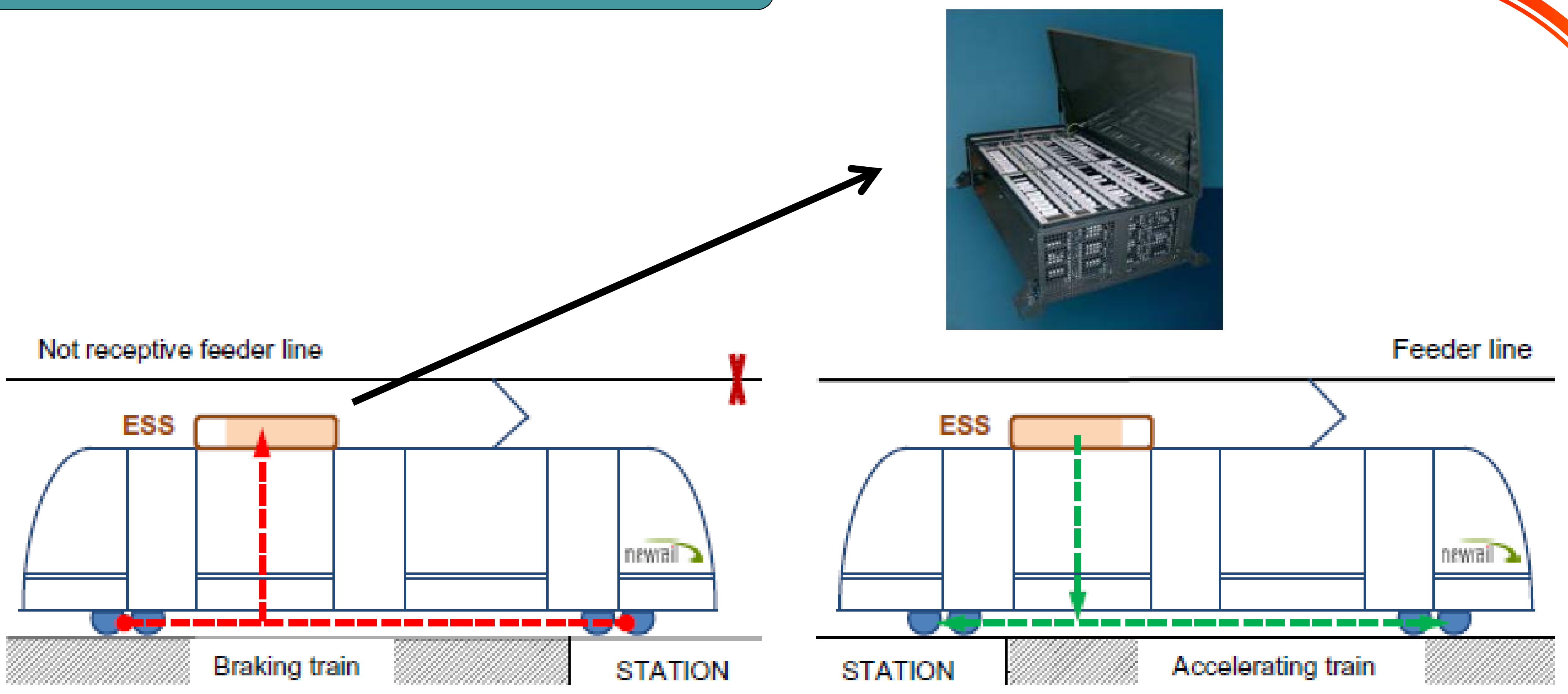
On –Board Energy Storage

▲Advantages

- High efficiency due to reduced overhead line losses, with consequent line voltage stabilization;
- Maximum energy recuperation;
- Energy management easily integrated with traction control and independent on traffic condition;
- Possibility of catenary-free operation (urbanistic integration).
- Potential down-sizing of the onboard braking resistor

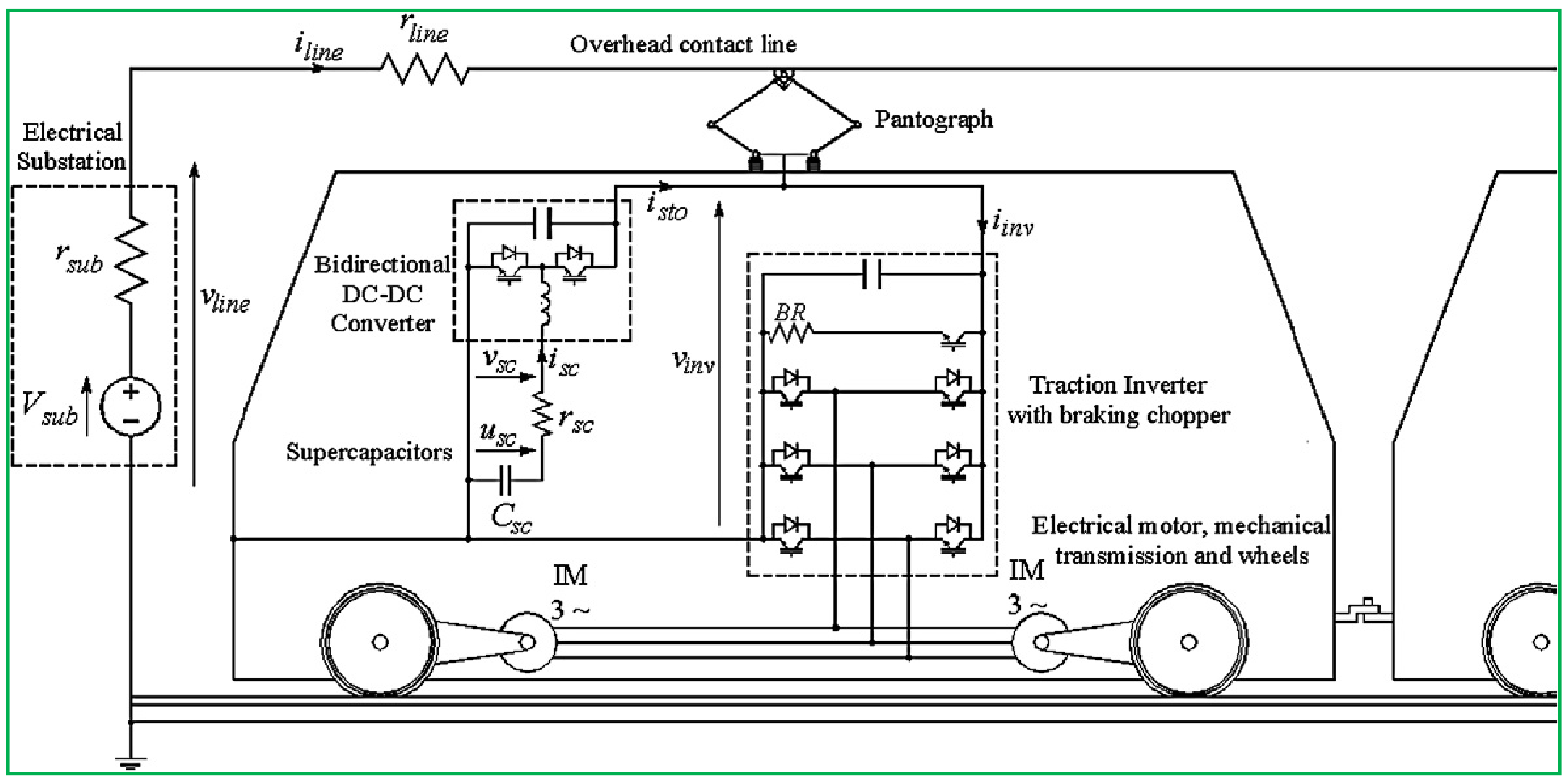
▼Drawbacks

- Space availability and weight constraints;
- Expansive solution, since the installation is not commonly considered when retrofitting existing rolling stock, but when designing new vehicles;
- Higher safety constraints due to passengers onboard.



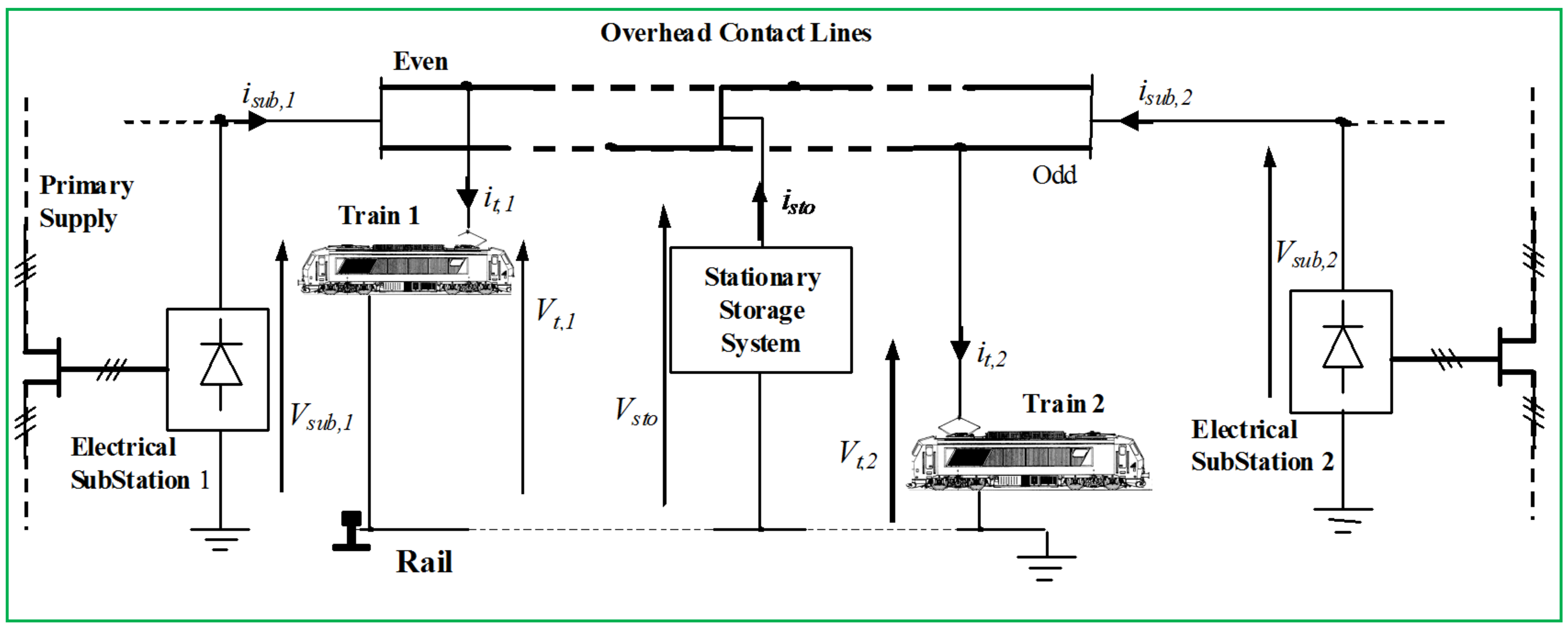
Charging mode **Discharging mode**

Equivalent electrical drive



Wayside Energy storage

Equivalent electrical network



▲Advantages

- The stored energy can be used all vehicles running on the line, resulting in a more active system;
- Might eliminate the need of additional feeding substation to compensate the voltage drops typically associated to weak points of the line (without upgrading the electrical network);
- Reduction of the waste heat, which avoid warming tunnels and stations;
- Fewer restriction in terms of weight and required space.
- Might enable trains to reach the nearest station in case of failure of the power supply, increasing the system security.

▼Drawbacks

- Fine-tuned analysis for sizing and for choosing the right locations, which strongly depends on the scenario
- Generally less efficient, due to overhead line losses increasing with the distance of the vehicle;
- Place availability in the substations or along the line.

Application of On-board/Stationary supercapacitor energy storage a reduced-scale light railway vehicle simulator

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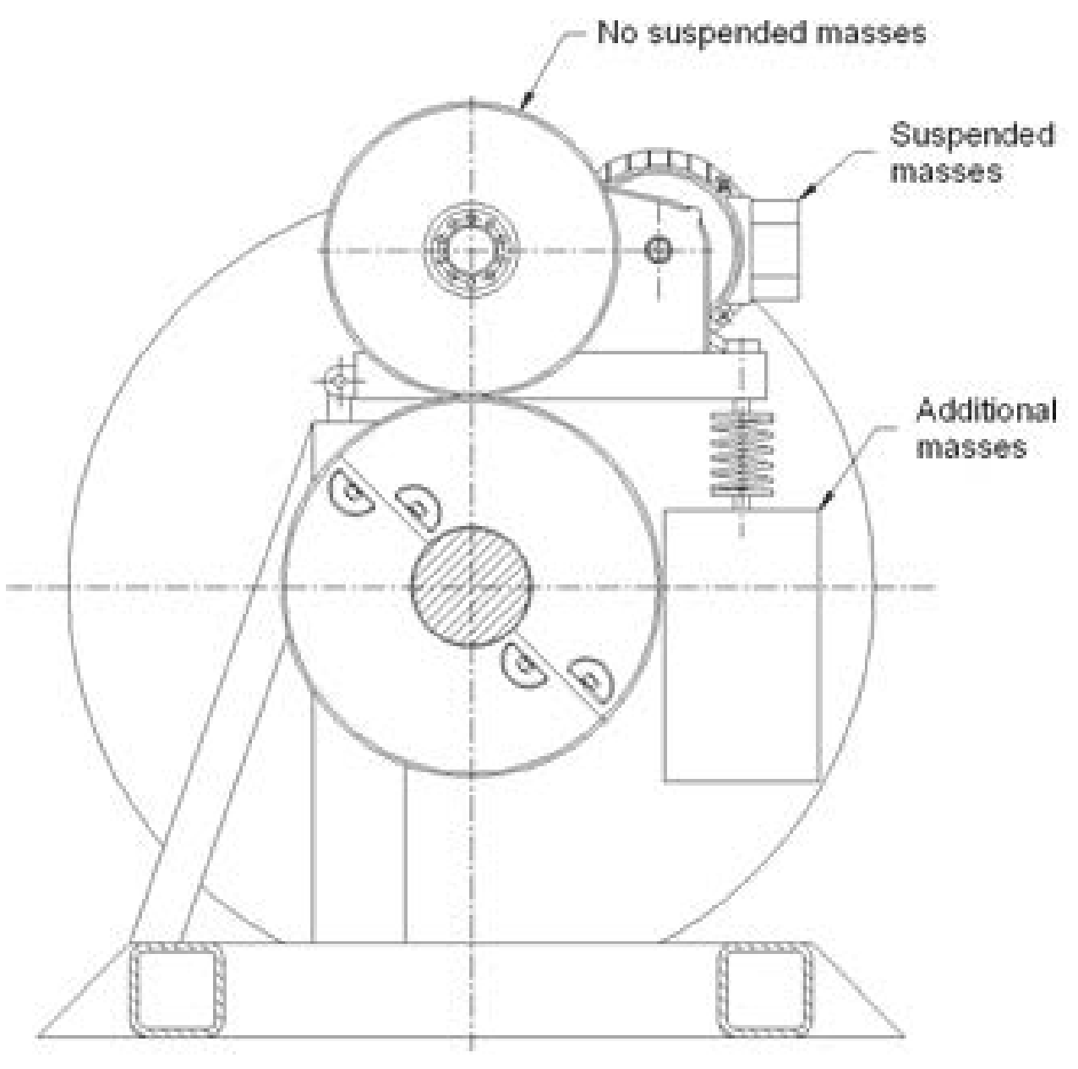
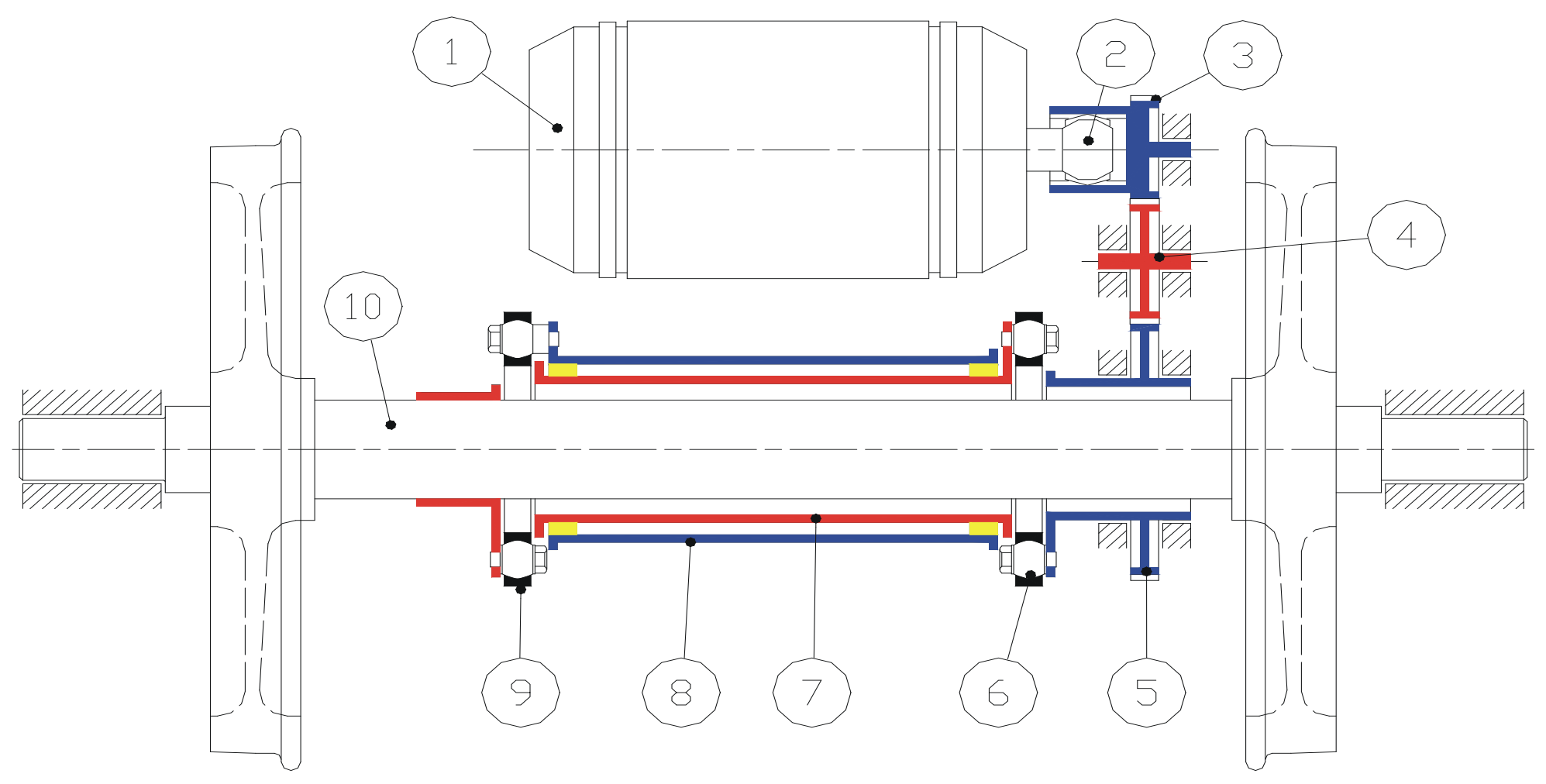
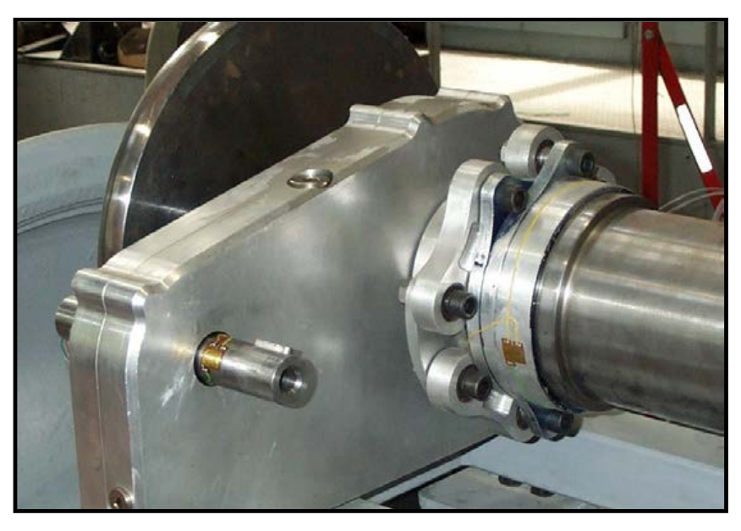
Why choose reduced-scale system?

In the study of physical phenomena is often useful to consider a different system than real and that its behavior with regard to a particular phenomenon, allows us to trace the behavior of the real system, using a set of proportionality constants.

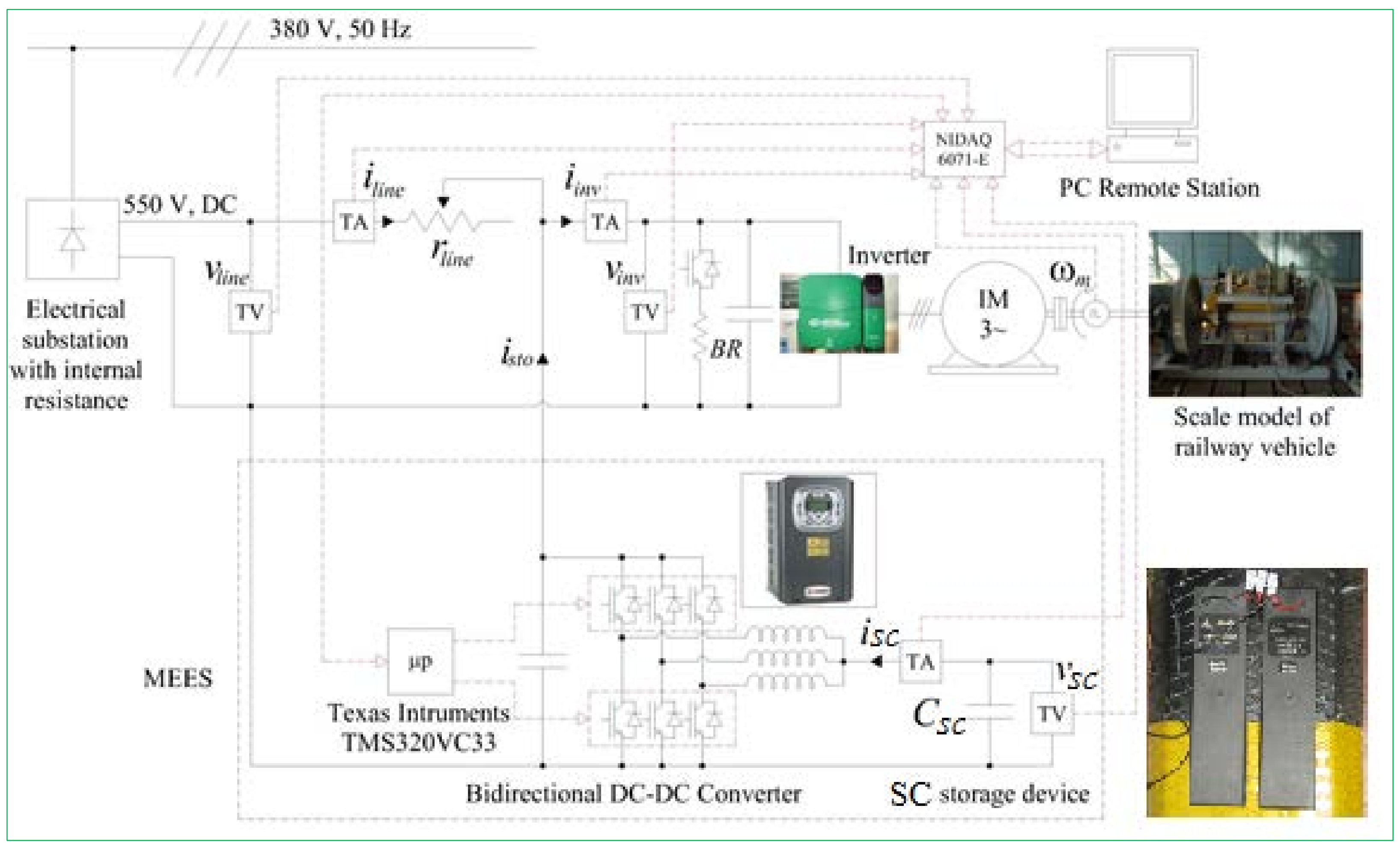
Parameters of the simulator	
Rated DC voltage (v_{line})	**550 [V]**
Total line resistance (r_{line})	**3.3 [Ω]**
Rated power of induction motors ($P_{m,1}$; $P_{m,2}$)	**5.5 ; 7.5 [kW]**
Voltage source inverter DC-AC (P_{inv})	**22 [kW]**
DC-DC converter power	**20 [kVA]**
Max current referred to SC side ($i_{sc,max}$)	**150 [A]**
SC Module equivalent capacitance (C_{sc})	**1.65 [F]**
SC Module rated voltage ($v_{sc,max}$)	**150 [V]**
SC Module Storable energy ($E_{sc,max}$)	**5 [Wh]**
Total eq. inertia ref. to the 1st motor axle ($J_{t,1}$)	**3.7 [kgm²]**
Total eq. inertia ref. to the 2nd motor axle ($J_{t,2}$)	**0.9 [kgm²]**
Max motor angular speed ($\omega_{m,1}$; $\omega_{m,2}$)	**800 ; 1500 [rpm]**
Equivalent gear ratio (τ_1 ; τ_2)	**3.27 ; 1**



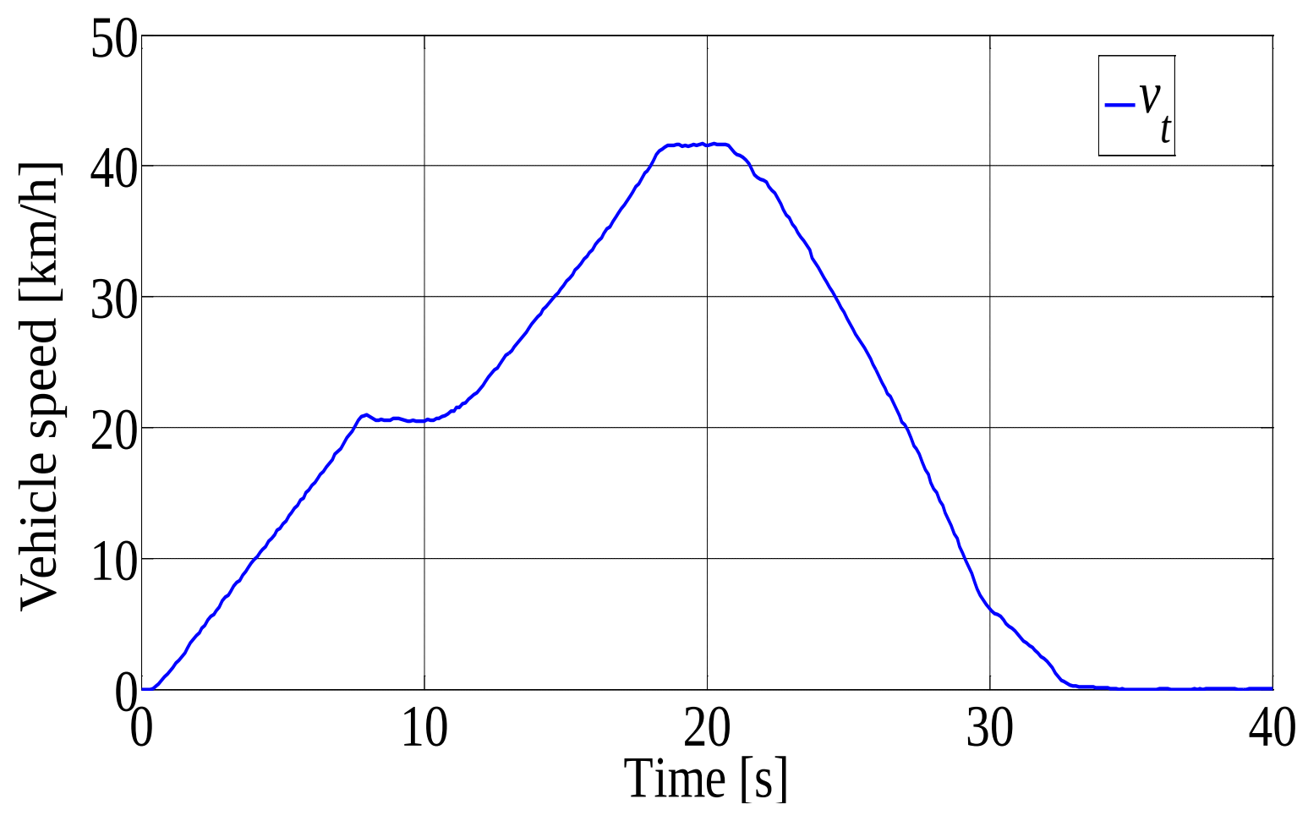


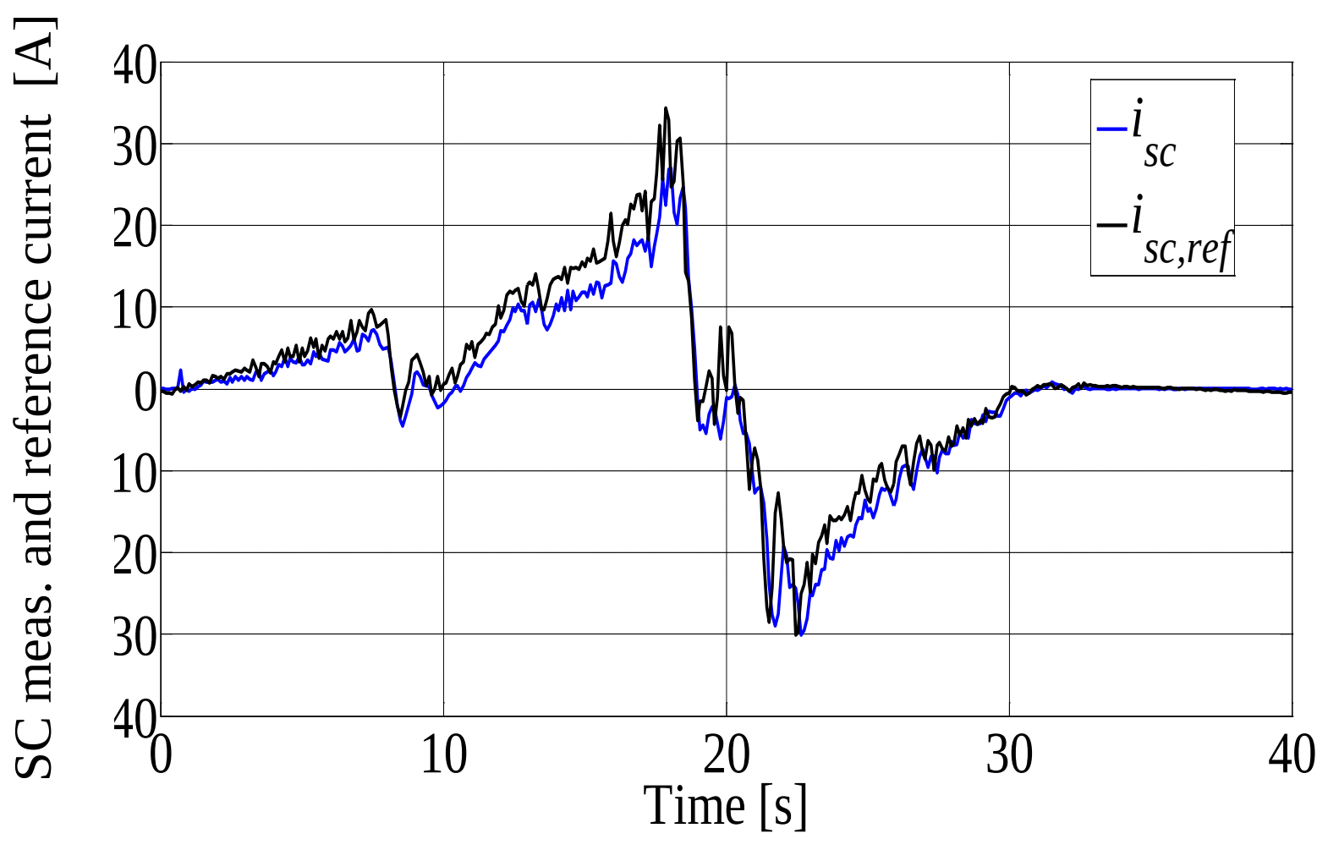


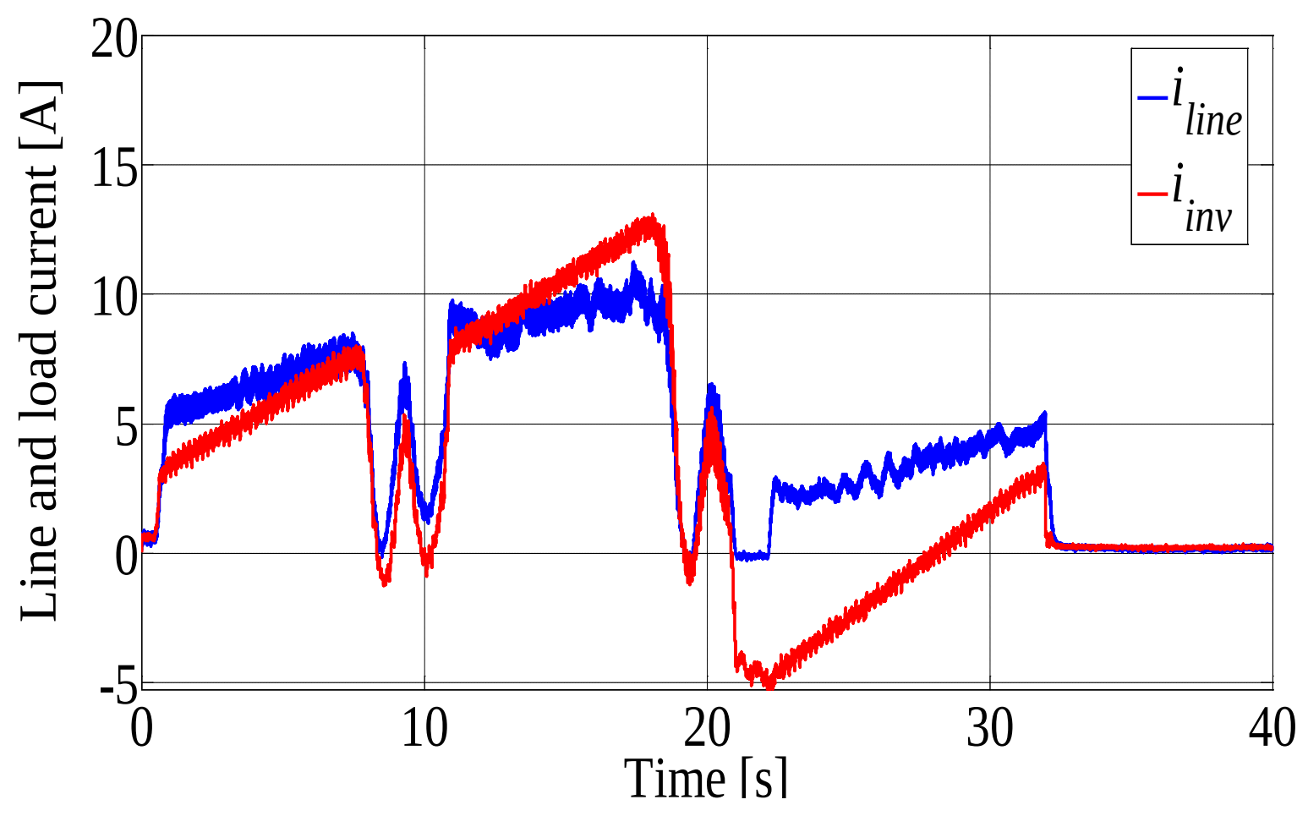
On–board Energy Storage configuration

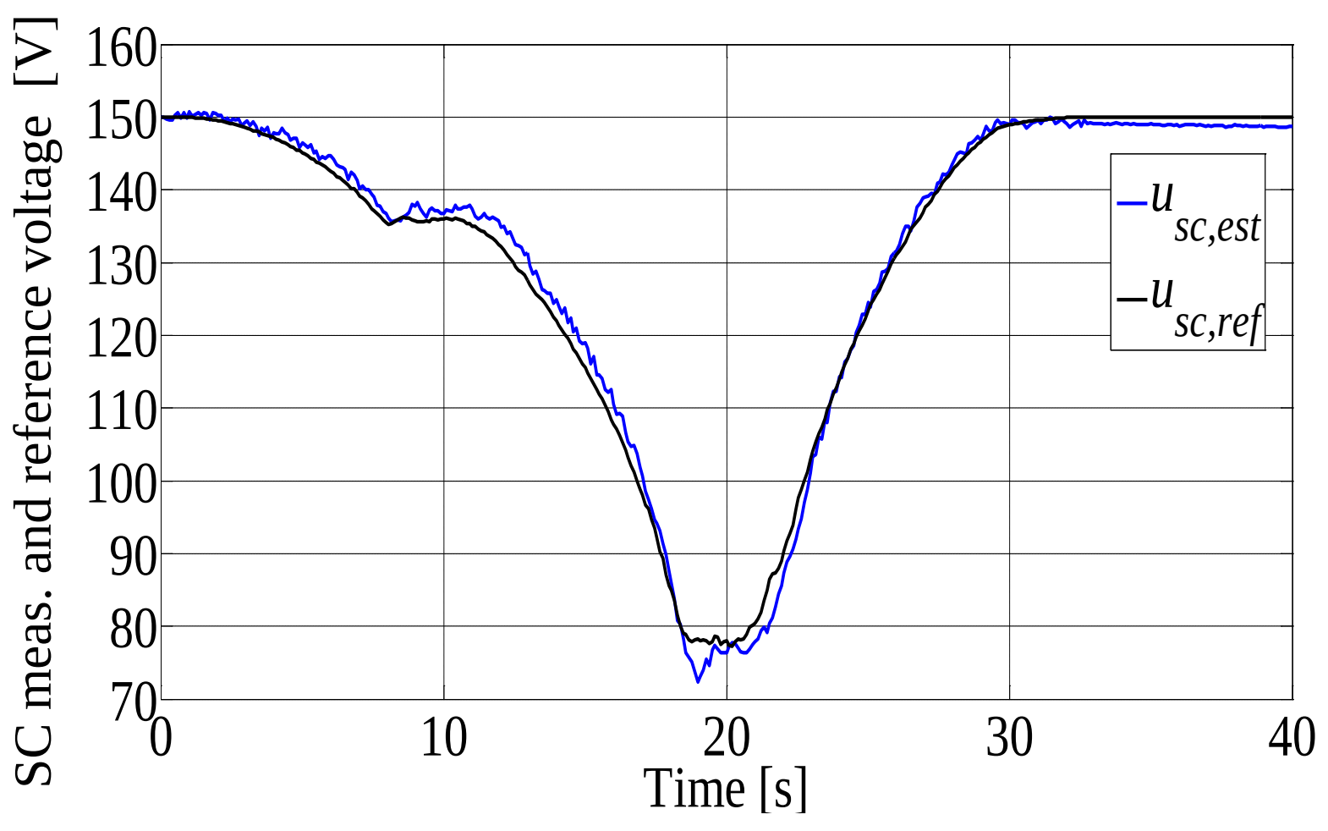


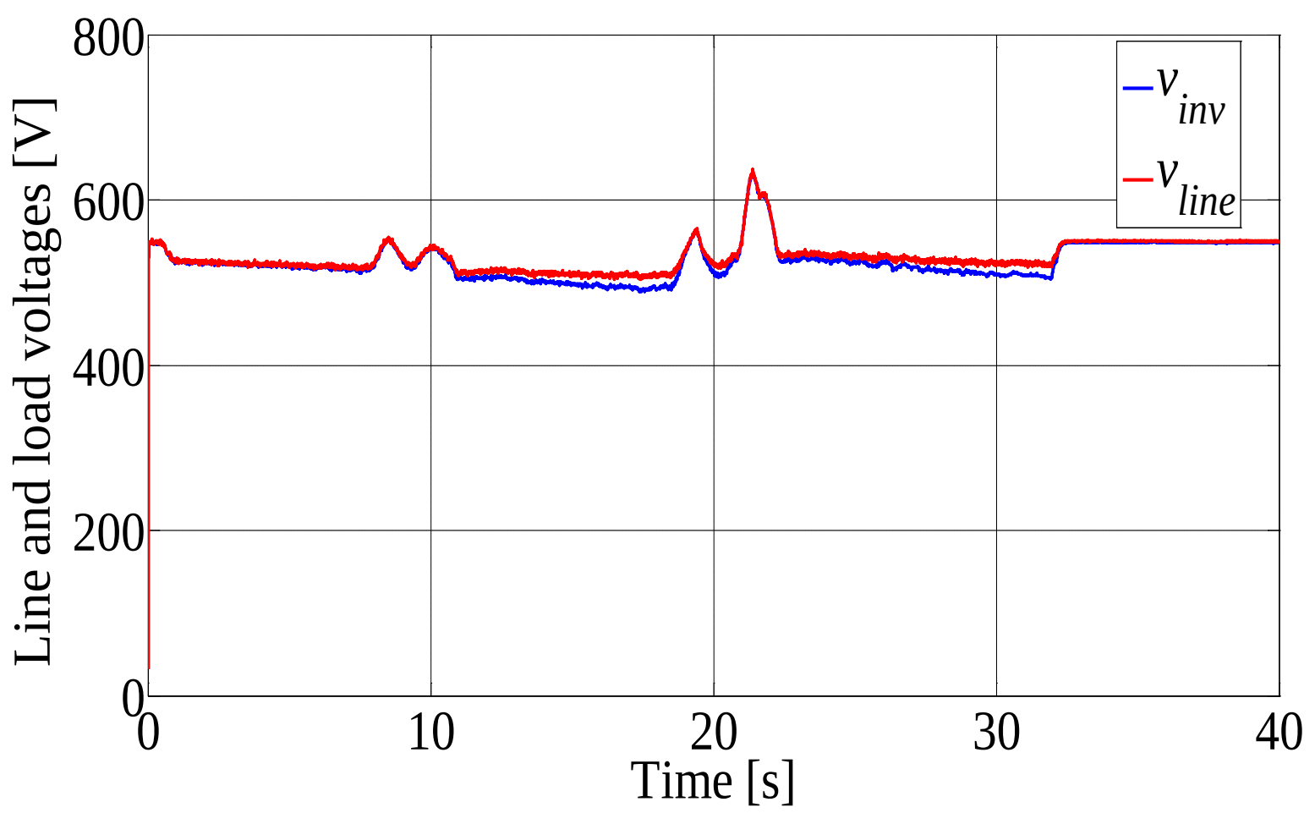
Performance Parameters	
Energy saving	**$e_{\%}$ = 11% of 24.22 Wh (24.21Wh)**
Maximum voltage drop reduction	**$r_{\Delta v\%}$= 28.9% of 83 V (59 V)**
Max line current reduction	**$r_{isub\%}$= 18.9% of 12.7 A (10.3 A)**

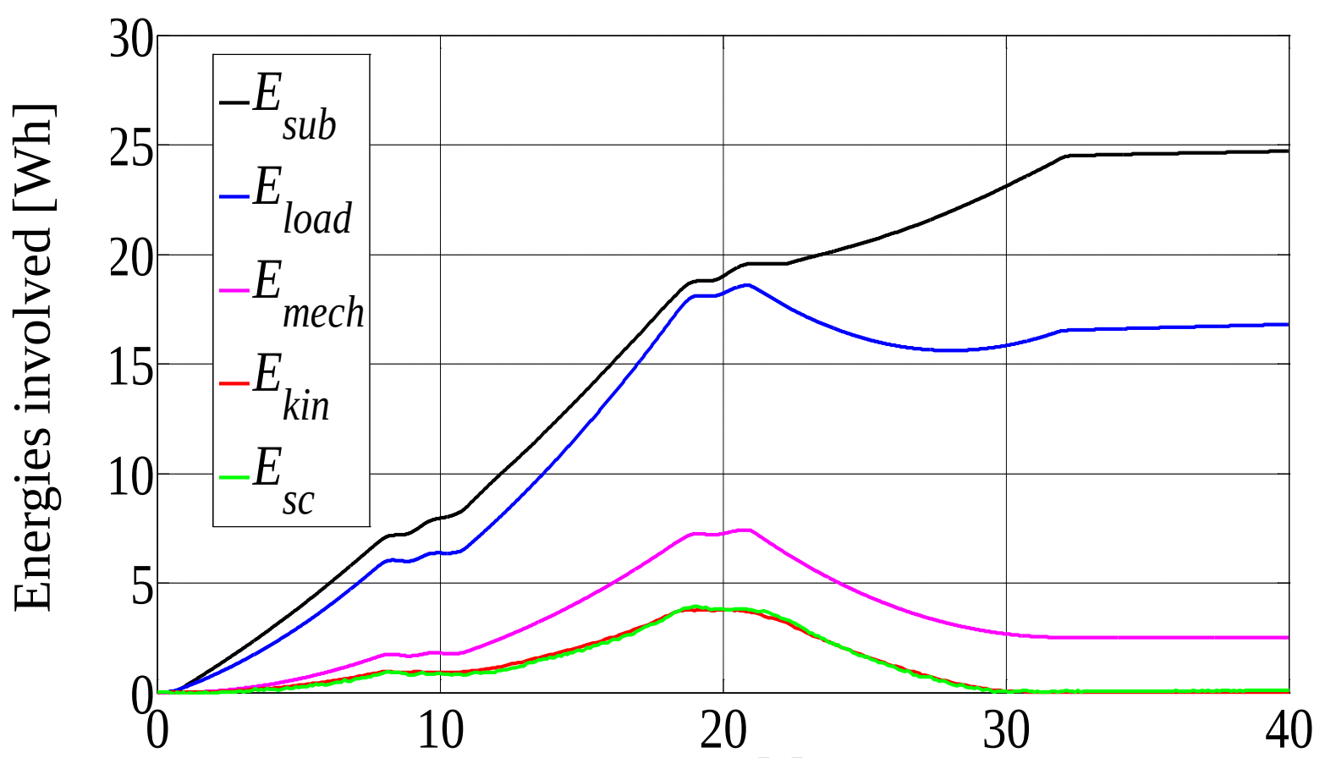




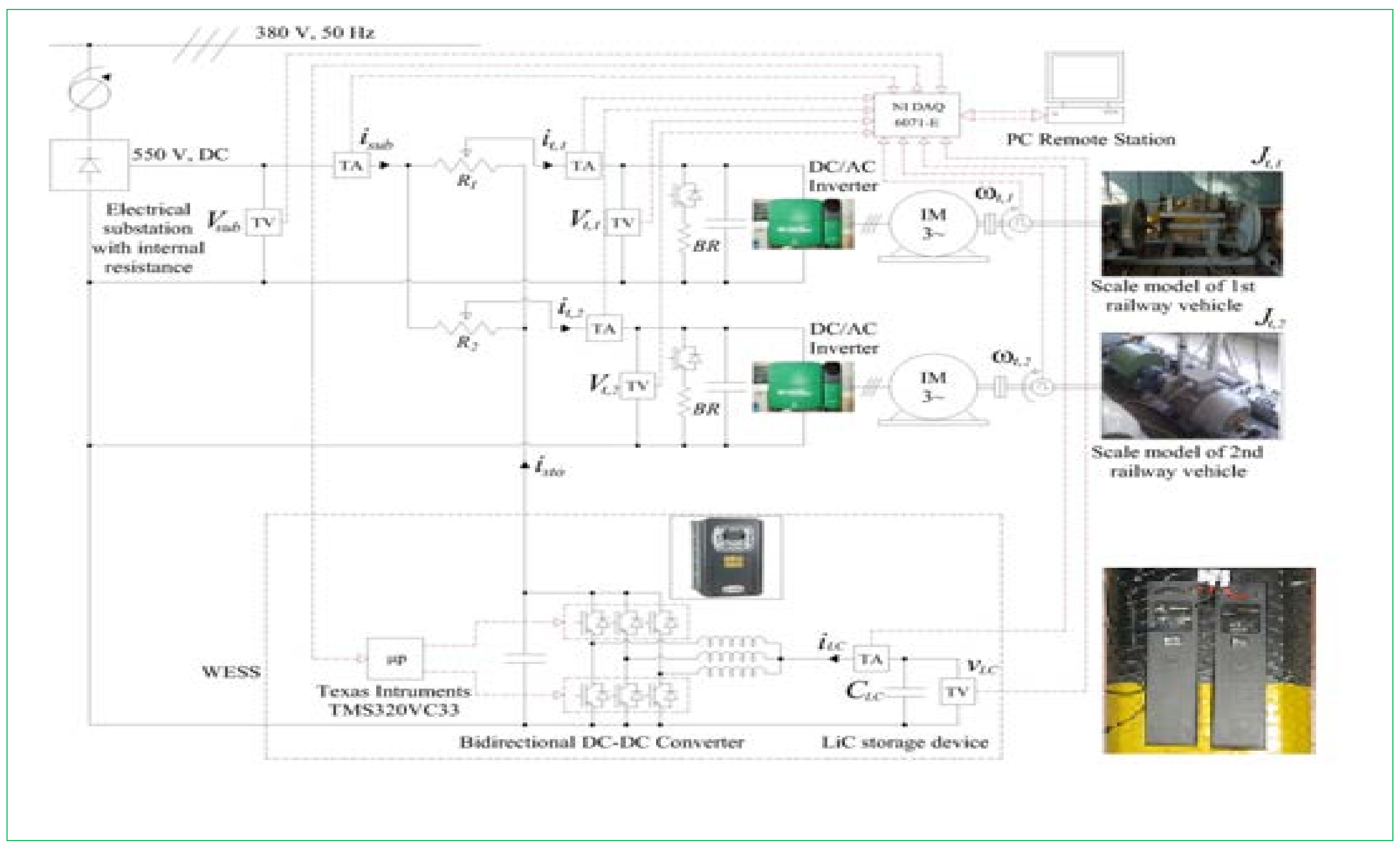




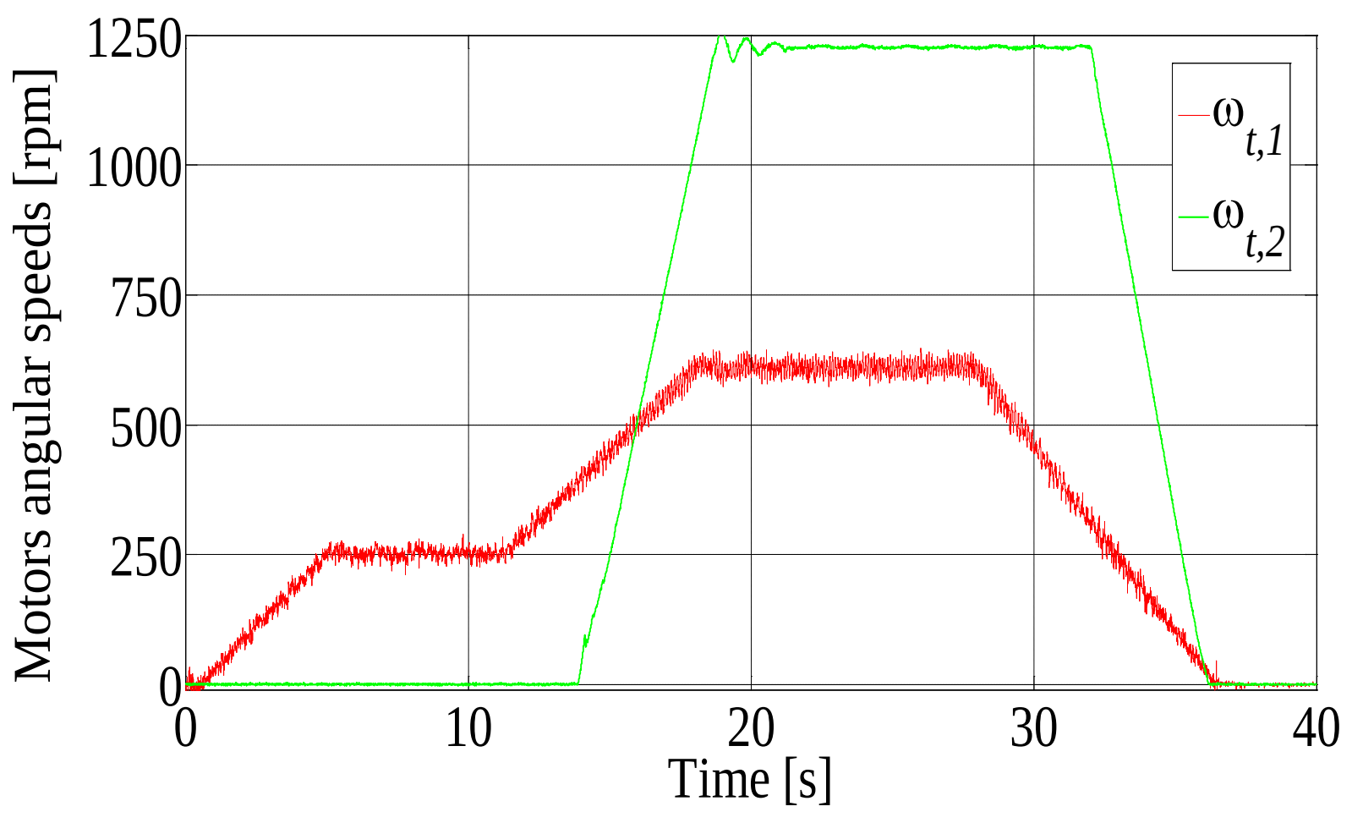


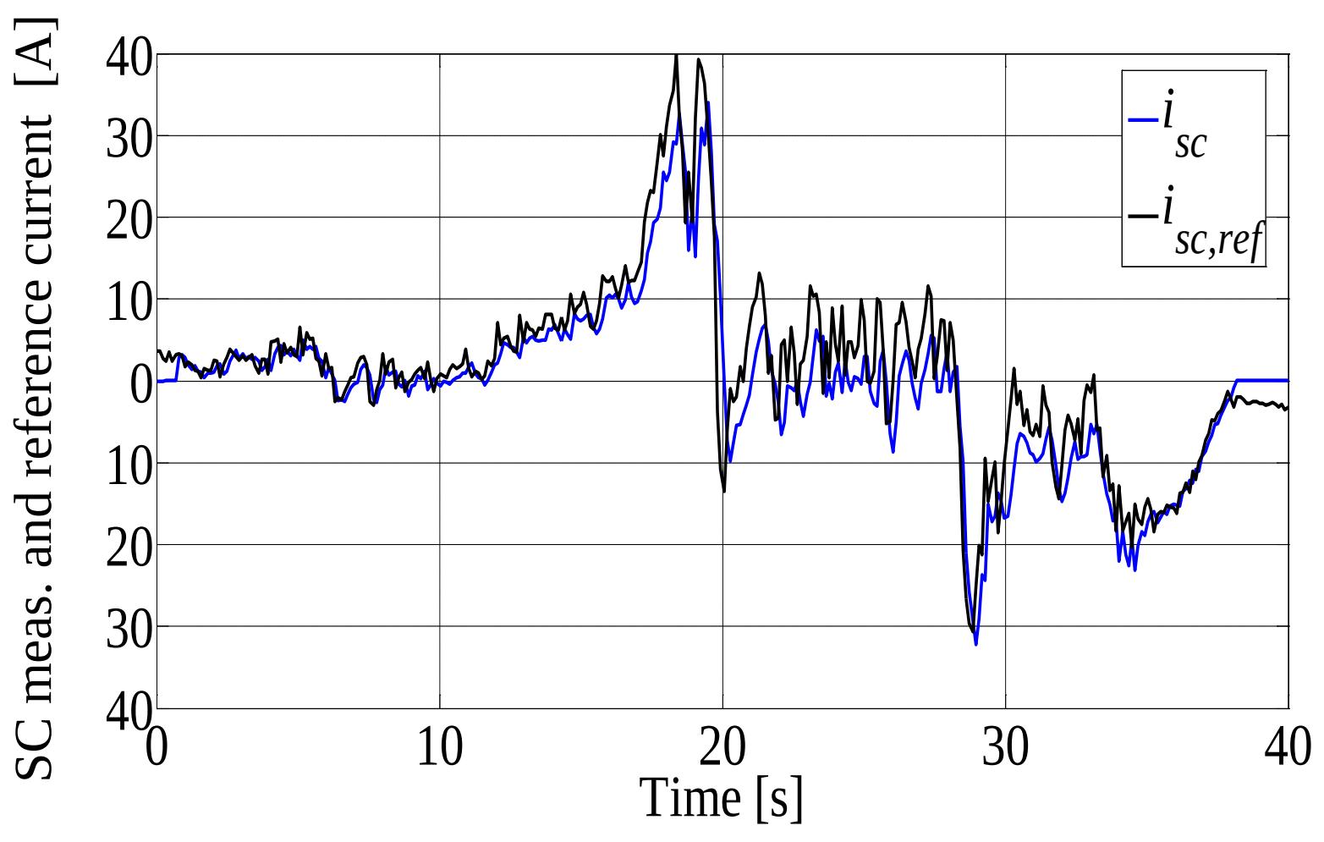


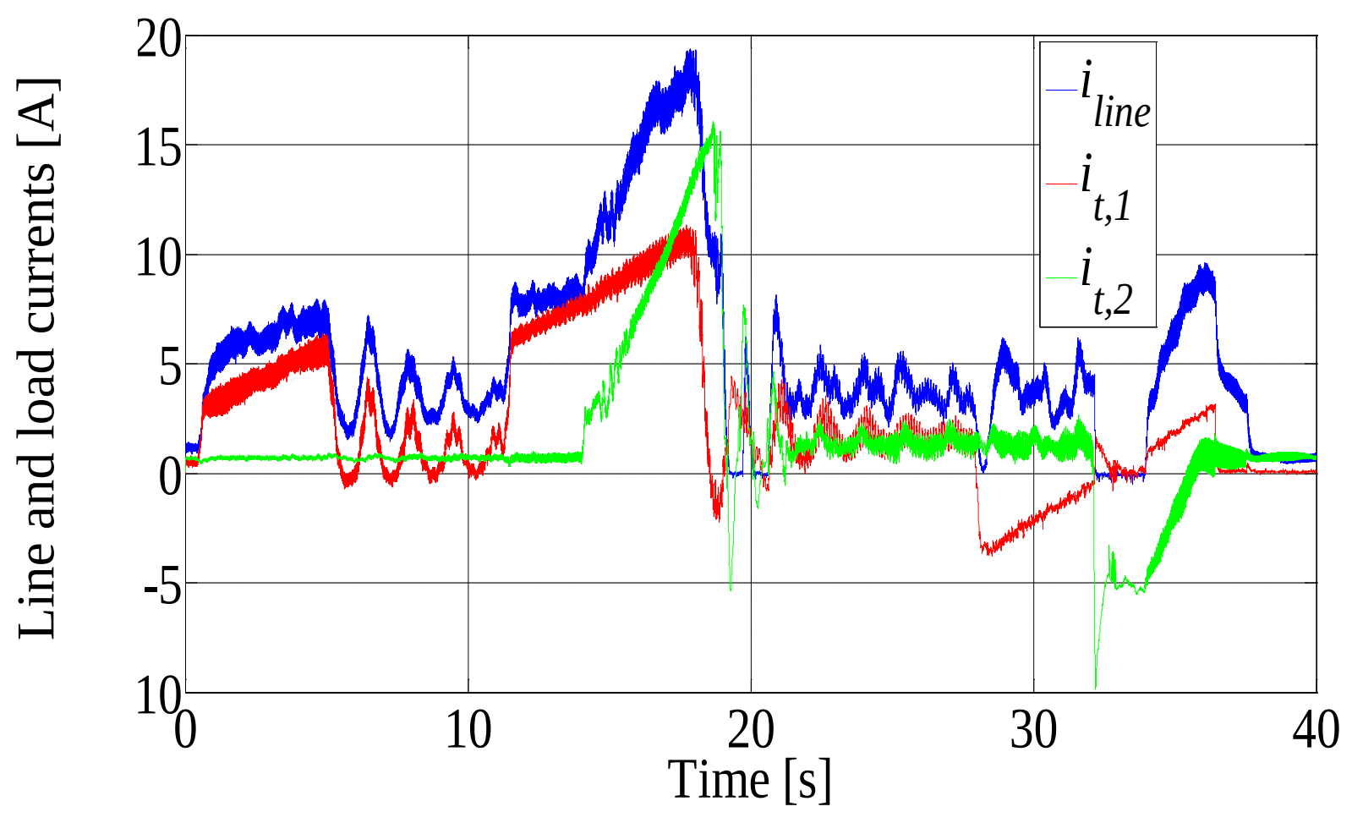
Stationary Energy Storage configuration

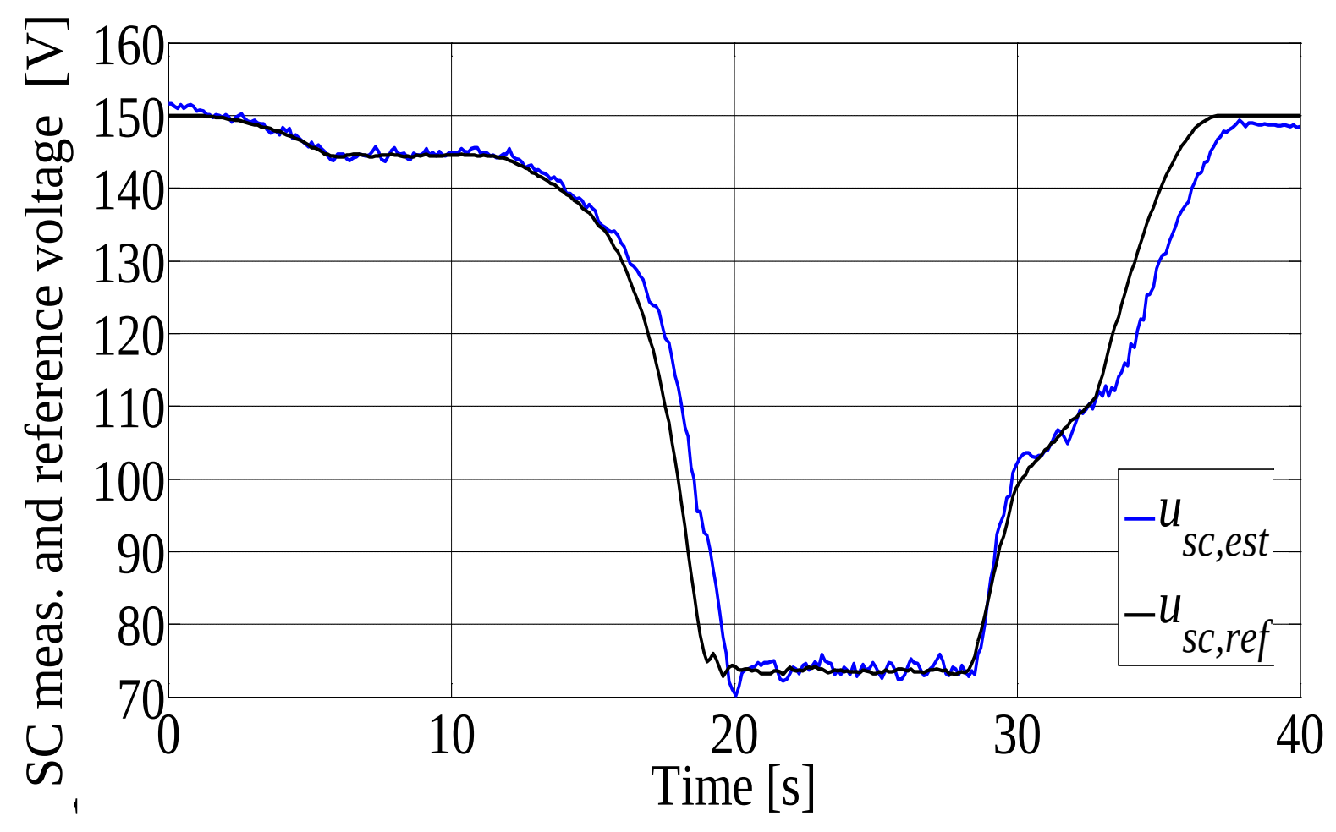


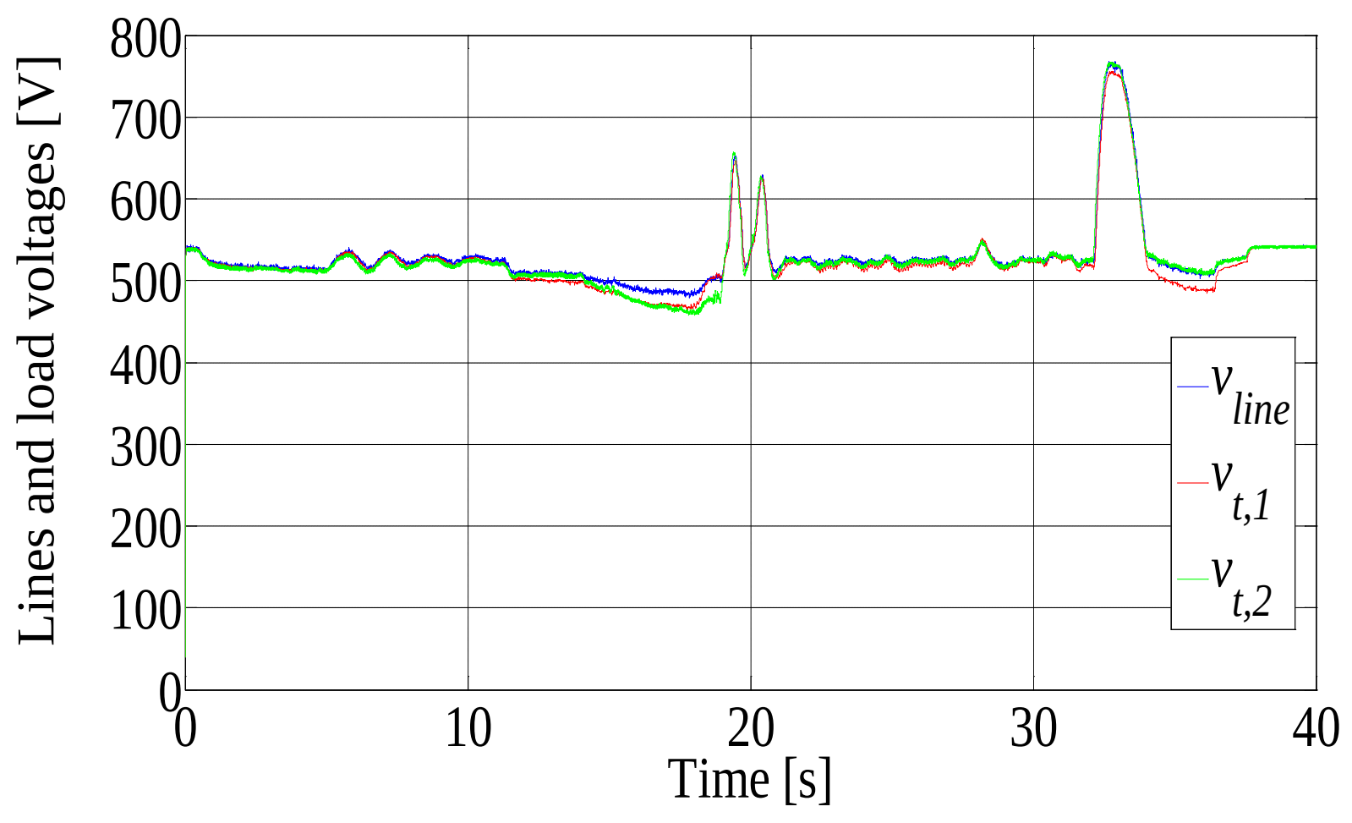
Performance Parameters	
Energy saving	**$e_{\%}$ =11.2% of 33.3 Wh (29.56Wh)**
Maximum voltage drop reduction	**$r_{\Delta v\%}$=17.5% of 97 V (80 V)**
Max line current reduction	**$r_{isub\%}$=24.6% of 23.6 A (17.8 A)**

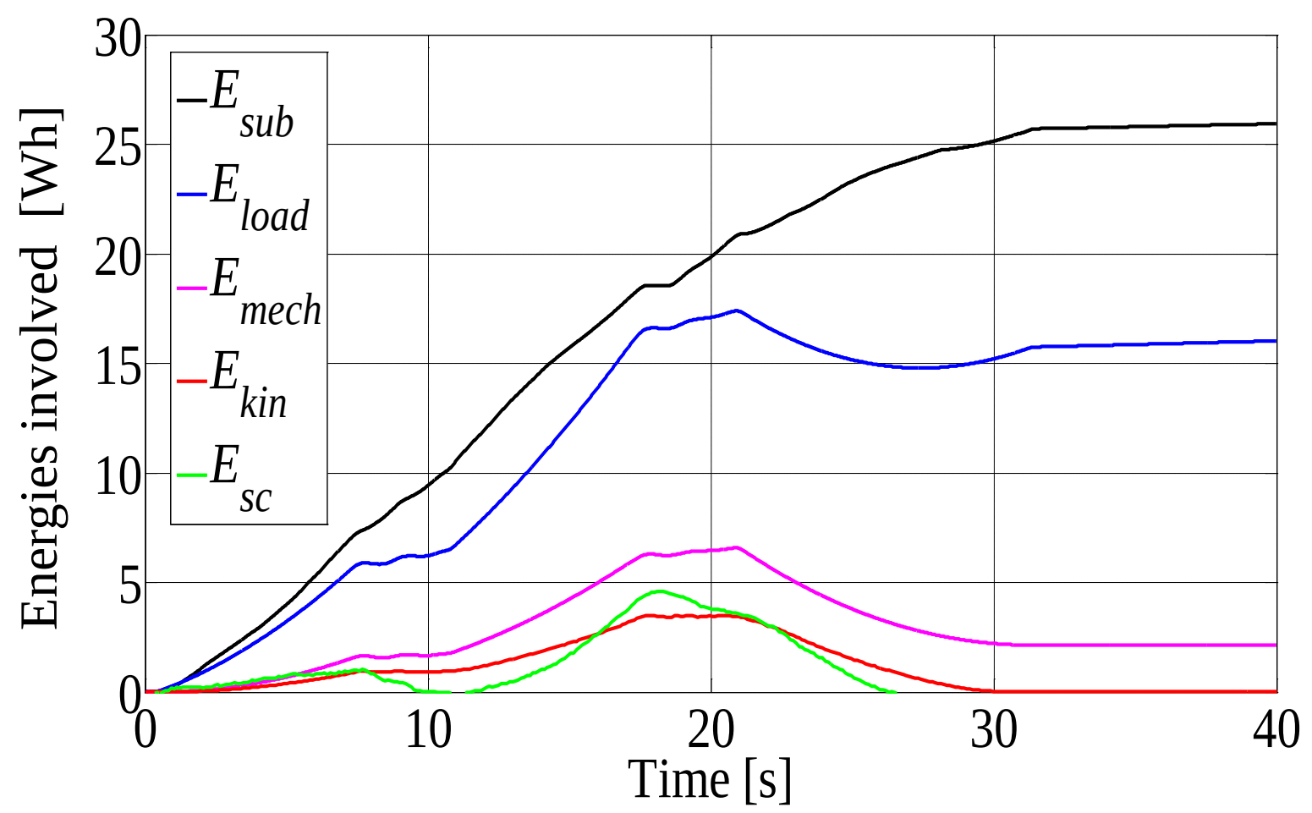












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Energy Management control algorithm

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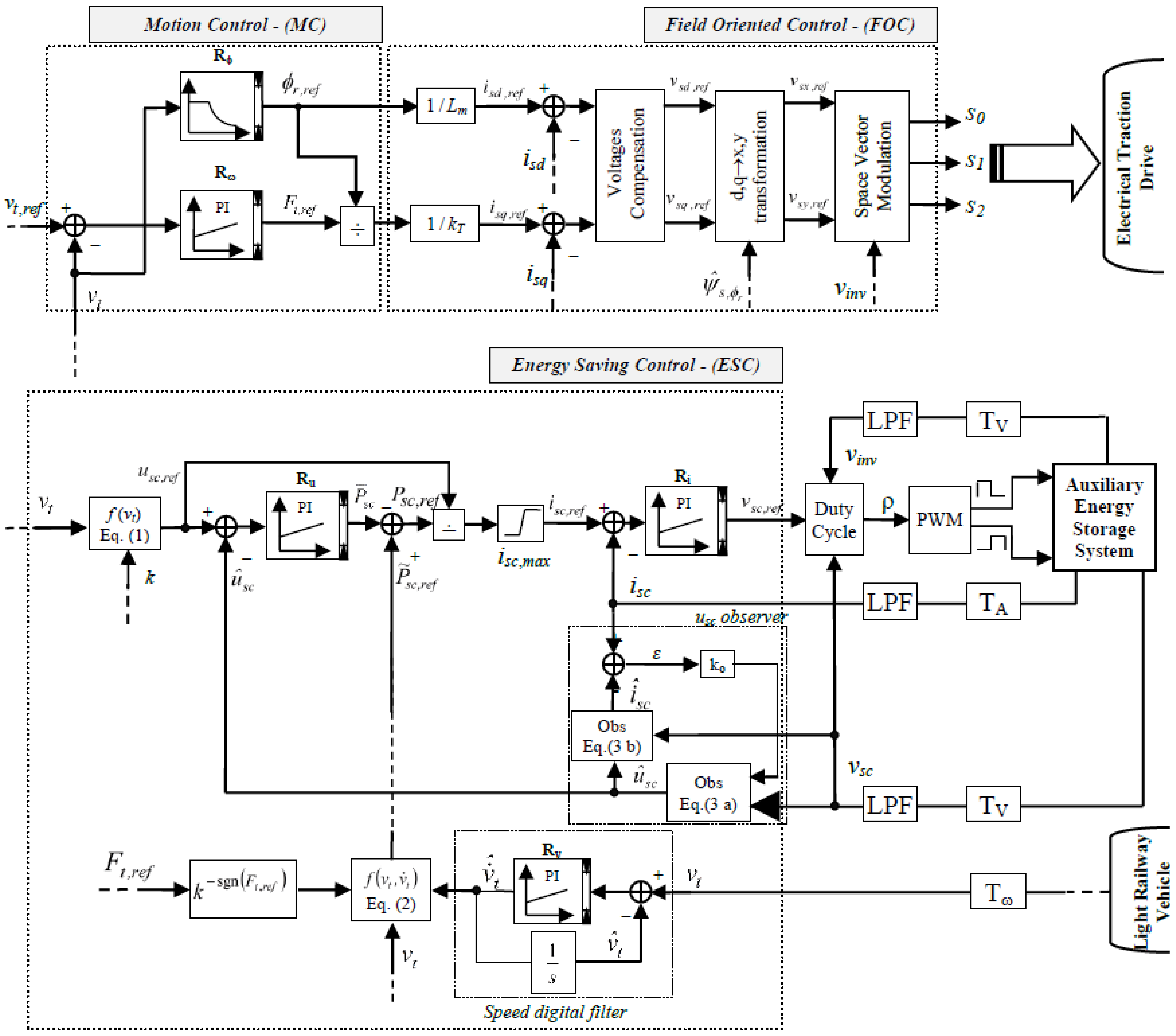
Maximum Energy Recovery algotirthm

The proposed control algorithm evaluates analytically the SC reference current on the basis of the actual train kinetic energy, which is properly taken into account by measuring the actual vehicle speed. The efficiencies of the different subsystems have also been considered. Therefore, on the basis of the size selected for the storage device, the control is capable of recovering the electrical energy during the braking of the train for recharging completely the SC units and dissipating the extra energy on the braking resistor.



Physical system model

$$
\begin{cases}
V_{sub} - (r_{sub} + r_{line})\, i_{line} = v_{inv} \;, \\
i_{line} = i_{inv} - i_{sto} \;, \\
i_{inv} = \dfrac{P_{inv}}{v_{inv}} \;, \\
i_{sto} = \dfrac{v_{sc,ref}\; i_{sc,ref}}{v_{inv}} (\eta_{dcdc})^{\mathrm{sgn}(F_t)} \;, \\
i_{sc} = -(C_0 + 2C_1 u_{sc}) \dfrac{d\,u_{sc}}{dt} \;, \\
v_{sc,ref} = -r_{sc}\, i_{sc} + u_{sc} \;, \\
r_{line} = \dfrac{R x_t}{L} \;, \\
u_{sc}(0) = V_{sc,max} \;,
\end{cases}
\qquad
\begin{cases}
F_t - F_r = (m_t + m_{sc}) \dfrac{d\,v_t}{dt} \;, \\
\dfrac{d\,x_t}{dt} = v_t \;, \\
F_r = c_0 + c_1 v_t^2 \;,
\end{cases}
$$

Electrical drives model

$$P_{inv} = F_t \; v_t (\eta_{el}\, \eta_{mech})^{-\mathrm{sgn}(F_t)}$$

$$
\begin{cases}
F_t = \displaystyle\sum_{v=1}^{N_m} \frac{T_{m,v}\, \tau}{R_{wheel}} \;, \\
v_t = \dfrac{R_{wheel}\, \omega_{m,v}}{\tau}
\end{cases}
$$

Only a part of the vehicle kinetic energy can be recovered due to friction and electrical losses, which have been taken into account by means of the coefficient *k*. The balance (1) allows to evaluate the SC unit reference internal voltage $u_{sc,ref}$ that depends explicitly on the vehicle speed.

$$\frac{1}{2} C_0 \left(V_{sc,\max}^2 - u_{sc,ref}^2\right) + \frac{2}{3} C_1 \left(V_{sc,\max}^3 - u_{sc,ref}^3\right) = \frac{1}{2} k \left(m_t + \frac{E_{sc,\max}}{\alpha}\right) v_t^2 \qquad (1)$$

The actual value of SC voltage, u_{sc}, cannot be directly measured since the terminal voltage, v_{sc}, differs from u_{sc} for So an identification procedure has been applied for the estimation of u_{sc}. In particular, a Luenberger observer (2) has been considered:

$$
\begin{cases}
\dfrac{d\hat{u}_{sc}}{dt} = -\hat{u}_{sc} \dfrac{1}{r_{sc} C_{sc}(\hat{u}_{sc})} + v_{sc} \dfrac{1}{r_{sc} C_{sc}(\hat{u}_{sc})} + k_0 \left(i_{sc} - \hat{i}_{sc}\right) \\
\hat{i}_{sc} = \dfrac{\hat{u}_{sc} - v_{sc}}{r_{sc}}
\end{cases}
\qquad (2)
$$

From the mathematical model of SC it's obtained the unit power reference output of SC $\tilde{P}_{sc,ref}$ that has to be evaluated on the basis of (3):

$$\tilde{P}_{sc,ref} = k v_t \left(m_t + \frac{E_{sc,\max}}{\alpha}\right) \frac{dv_t}{dt} \qquad (3)$$

The SC voltage controller (R_u) processes the error between the SC reference internal voltage given by (1) and the actual estimated one given by (3). The out put of the regulator R_u is a compensating term $\tilde{P}_{sc}$, which takes into account the error in the model parameters:

$$\tilde{P}_{sc} = k_{p,u} (u_{sc,ref} - \hat{u}_{sc}) + k_{i,u} \int_0^t (u_{sc,ref} - \hat{u}_{sc})\, dt$$

The optimal SC current set-point can be finally determined on the basis of the actual value $P_{sc,ref}$

$$i_{sc,ref} = \frac{\tilde{P}_{sc} + \tilde{P}_{sc,ref}}{u_{sc,ref}}$$