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# A New Supercapacitor Design Methodology for Light Transportation Systems Saving

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## 1. Introduction

Light transportation systems are not new proposals since their utilization started at dawn of electric energy spreading at industrial level. The light transportation systems class includes tramways, urban and subway metro-systems as well as trolley buses. These systems are intrinsically characterized by low investment costs and high quality service in terms of environmental impact and energy efficiency. The vehicle technology, which is continuously improving, allows lighter and economical solutions.
These attractive characteristics has generated a renewed interest of the researchers and transportation companies in trying to obtain better performances of these systems, being foreseeable their remarkable spreading in the next future. However, even though the perspectives appear to be particularly bright, the increase of the electrical power demand associated to the higher number of vehicles circulating at the same time, require to investigate new solutions for optimizing the whole transportation system performance and particularly the energy consumption, also by exploiting the possibility tendered by the advent of technology innovation. The improvement of the energy efficiency is a crucial issue, both in planning stage and during operating conditions, which cannot be deferred. It has to be highlighted that also for already existing light transportation systems, the energy saving can be pursued by integrating new technological components or apparatuses as energy storage systems (Chymera et al,2006), which allow contemporaneously to obtain high energy saving and to reduce the of load peaks requested to the supply system. More specifically, the storage devices employment, which may be on board (Steiner et al,2007), or located at both the substations or along the track (Barrero et al,2008), are attractive means for obtaining contemporaneously energy saving, energy efficiency, pantograph voltage stabilization and peak regularization (Hase et al,2003). Storage devices may play also a fundamental role in enhancing the dynamic response of the overall light transit system, if they are used in combination with properly controlled power converters. All these previously mentioned benefits surely are convincing arguments for persuading to upgrade the existing light transportation systems, all the more that capital costs exhibit very reduced payback periods.
The high energy densities make the supercapacitors attractive means for real time energy optimization, voltage regulation and high reduction of peak powers requested to feeding substations during the acceleration and braking phases. Many solutions have been suggested in the relevant literature, both oriented to the employment of distributed

supercapacitors stationary stations along contact line sections (Konishi,2004) and to the use of onboard storage devices (Iannuzzi,2008). The supercapacitors exhibit energy densities (6 Wh/kg) lower than those of batteries and flywheels but higher power densities (6 kW/kg), with discharge times ranging from ten of seconds to minutes (Conway,1999). This characteristic suggests their utilization for supplying power peaks, for energy recovery and for compensating quickly voltage drop.
The design procedure and management strategy of these innovative systems are often defined on the basis of specific case studies and realized prototype (Hase et al,2002). High difficulties are related to modeling aspects, since the time varying nature of the light transportation system has to be properly performed, this affecting dramatically the identification of a rational procedure for choosing the fundamental characteristics of the storage device.
In the paper, the supercapacitor design problem for light transportation systems saving is handled in terms of isoperimetric problem. Some analytical results can be obtained only with respect to simple case studies, even if they are very interesting because their analyses permit to capture the relationships between fundamental storage device parameters and the transportation ones. For more complex cases, it results quite impossible to have analytical closed solutions. In any case, the design problem can be addressed to a general constrained multiobjective optimization problem which without restrictions is able to handle all the interest cases for deriving the energy management strategies. The optimization procedure results particularly useful for sensitivity analyses, which could be requested also for identifying the optimal allocation and configuration, taking properly into account the timetable. The paper is organized as follows. First of all the fundamental characteristics of supercapacitor devices are described in section II. Some preliminary consideration with respect to optimization methodologies are summarized in section III. Hence the light transportation systems modeling, indispensable for applying the optimization procedure, is derived in section IV, with reference both to the case of the application of stationary storage systems and to the on-board one. The choice of the objective function of the constrained optimization problem, over a prefixed time horizon, is deeply investigated. A numerical application is reported in section V for a case study with two trains along double track dc electrified subway networks, both for stationary and on-board application. The numerical results demonstrate the feasibility and the validity of the proposed systemic design methodology.
The authors will try to tempt in future works to extend the proposed procedure, conceived for the planning stage, to real time control strategy.

## 2. Electrical energy storage system based on supercapacitors device

The Energy Storage System includes the storage unit, i.e. the modules of supercapacitors, a DC-DC, switching power converter whose control system acts in order to exchange regulated power flows between the storage device and the electrical network. The storage unit is realized connecting together several modules of supercapacitors in series and/or in parallel in order to attain the values of voltage and current required for the specific application.

### 2.1 Supercapacitors devices

Various papers discuss the physical construction of the double-layer capacitor (DCL). The DLC consists of activated carbon particles that act as polarizable electrodes. These particles, strongly packed, are immersed in an electrolytic solution, forming a double-layer charge distribution along the contact surface between carbon and electrolyte. The physics of the double-layer charge distribution is discussed in (Kitahara et al.,1984) and (R. Morrison, 1990). Three major aspects of the physics of the double-layer charge distribution affect the structure of the equivalent circuit model, as summarized in the following. Firstly, by taking into account the electrochemistry of the interface between two materials in different phases, the double-layer charge distribution of differential sections of the interface is modeled as RC circuit. The resistive element represents the resistivity of the materials constituting the double-layer charge distribution. The capacitive element represents the capacitance between the two materials. As far as the second aspect is concerned, based on the *theory of the interfacial tension in the double-layer*, the capacitance of the double-layer charge distribution depends on the potential difference across the material.

DLC's measurements highlight the same non linear relationship between capacitance and terminal voltage in the device. Furthermore, the measurements put in evidence that, in the interest voltage range of the device, the DLC capacitance varies linearly as function of the capacitor terminal voltage.

By taking into account on the physical aspects and on the basis of the both previously mentioned considerations and the requirement of a practical engineering model, the equivalent circuit can be obtained by employing:

1. RC circuits, by keeping the number of RC elements as low as possible for practical reasons;
2. a non linear capacitance to be included only in one RC element;
3. a parallel leakage resistor.

In order to avoid an arbitrary modeling, a proper choice of the RC circuits number of the equivalent circuit model, depending on the time span of the transient response, is required.

Extensive experiences resulting from measurements have oriented to propose a circuit model exhibiting three RC branches characterized by different time constants, covering the interest time horizon. This choice corresponds to the least number for obtaining a satisfactory degree of accuracy over a time horizon nearly equal to 30 min. The different time constants allow to capture the significant dynamics of the supercapacitor device. The first branch, including the voltage-dependent capacitor (in F/V), dominates the initial time behavior of the DLC, in the time window of seconds order. The second branch, named delayed branch, refers to the slower dynamics in the time window of minutes order. Finally, the third one or long-term branch determines the behavior of time windows longer than 10 min.

For taking into account the voltage dependence of the capacitance, the first branch is modeled as a voltage-dependent differential capacitor. The differential capacitor consists of a fixed capacitance and a voltage-dependent capacitor. A leakage resistor, inserted in parallel to the terminals, is added for representing the self discharge property. The proposed equivalent circuit is shown in Fig. 1.

It has to be highlighted that, however, most of the ultra-capacitor models presented in the literature consider a non-linear (voltage dependent) transmission line or finite ladder RC network (F. Belhachemi et al., 2000), (N. Rizoug et al.,2006). For simplicity of the analysis, the transmission line effect is neglected, and a first order nonlinear model is used (R. Faranda,2007). The internal equivalent resistance $R_i$ is a constant and frequency independent resistance. The ultra-capacitor total capacitance is a voltage-controlled capacitance:

$$C(V_{ci}) = C_0 + k\, V_{ci};$$

where $C_0$ is the initial linear capacitance representing electrostatic capacitance and K is a proper coefficient that takes into account the effects of the diffused layer of the supercapacitor (R. Kotz, et al., 2000).

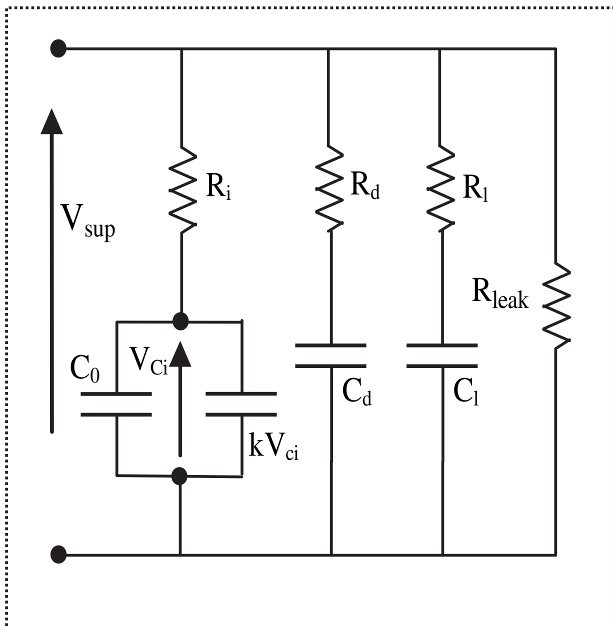


Fig. 1. SC equivalent circuit suggested in (Luis Zubieta et al.,2000)

### 2.2 Dc-Dc power converter and control systems

The switching power converter, for interfacing the storage system and the electrical network is boost type with bidirectional power flow. The bidirectional property allows the discharge and the recharge of supercapacitors. The converter is connected to the contact line and it is able to regulate the voltage at its output terminals, since input and output behave like voltage sources. The converter may be both current-controlled and voltage-controlled. So the duty-cycle may be evaluated on the basis of the reference output current or voltage of the converter itself.

On the basis of type of control adopted (voltage or current mode control) the whole system of supercapacitors and converter can be modeled as an ideal voltage or current source. In the case of current source, the control system consists of a supercapacitors side current control on the basis of actual value of the supercapacitors current and state of charge of supercapacitors. The set-point of supercapacitors current depends on the energy strategy adopted. For example, in the case of on-board application, the set-point for the supercapacitors charge and discharge is calculated on the base of kinetic energy of the train, thanks to the knowledge of actual value of train speed. In Figg. 2, and 3 simple schematic current and voltage mode control are depicted.

## 3. Light transportation system and modelling

### 3.1 Physical system

A light transportation system characterized by double line track, depicted in Fig.4, is investigated. The system represents a large class of actual systems and the analyses performed can be easily generalized to more complex transportation systems.

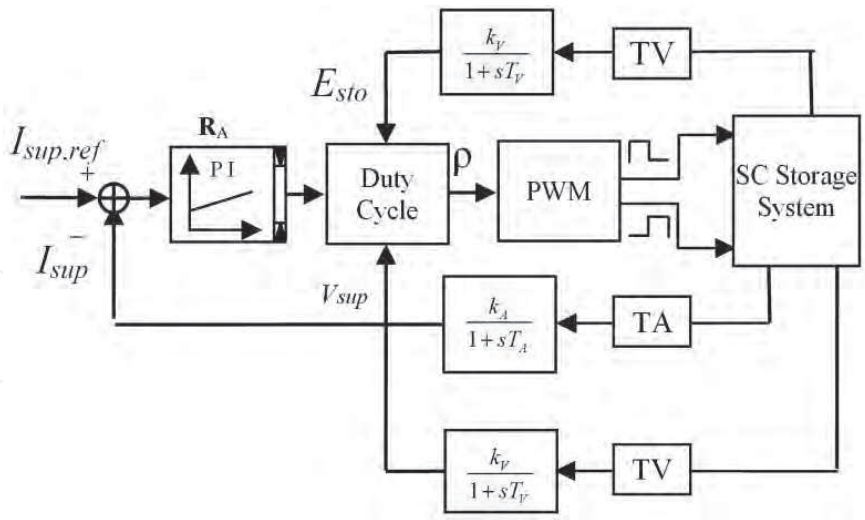


Fig. 2. Supercapacitor current-mode control diagram block

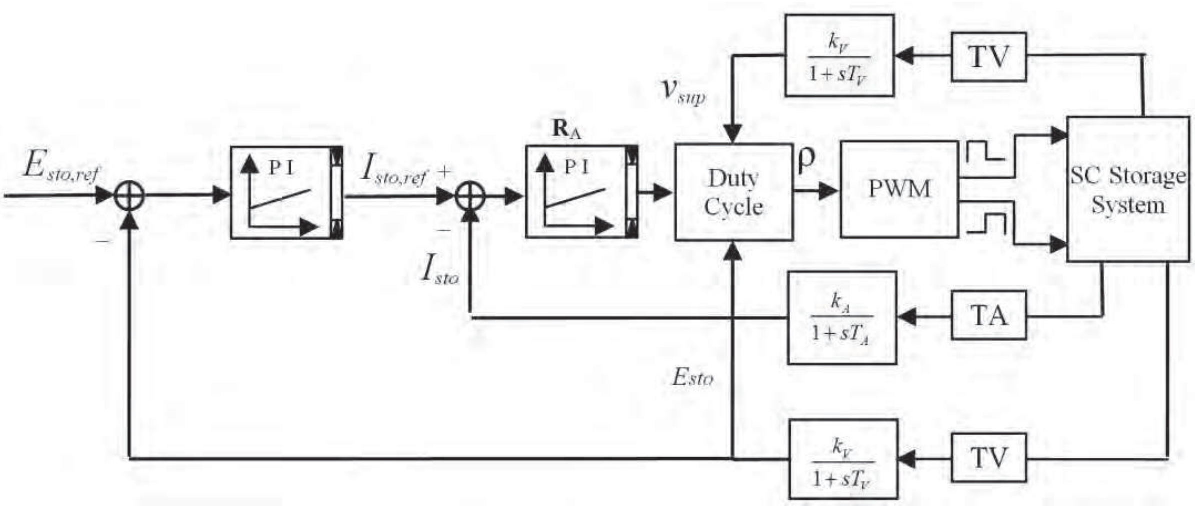


Fig. 3. Storage voltage-mode control diagram block

The overhead contact line consists of one main wire having a section of 120 mm² for each direction of the vehicles, as depicted in Fig. 4. In Tab. I the main parameters of the test system are listed. For simplicity, the simulated track in the paper refers to a branch of 1.5 km with two regular stops and two trains traveling in different direction. The system during operating conditions may be affected by high pantograph voltage drop consequent to the train peak powers, this strongly depending on driving cycles and their diplacement, load dynamic behaviours and network characteristics. The optimal design of storage devices based upon supercapacitors is deeply investigated in the following at the aim of obtaining contemporaneously energy saving, energy efficiency, pantograph voltage stabilization and peak regularization.

Two case studies will be considerd considered: the first one refers to a storage system based upon supercapacitors (SC) employment, located at the end of line and the second with supercapacitors installed onboard.

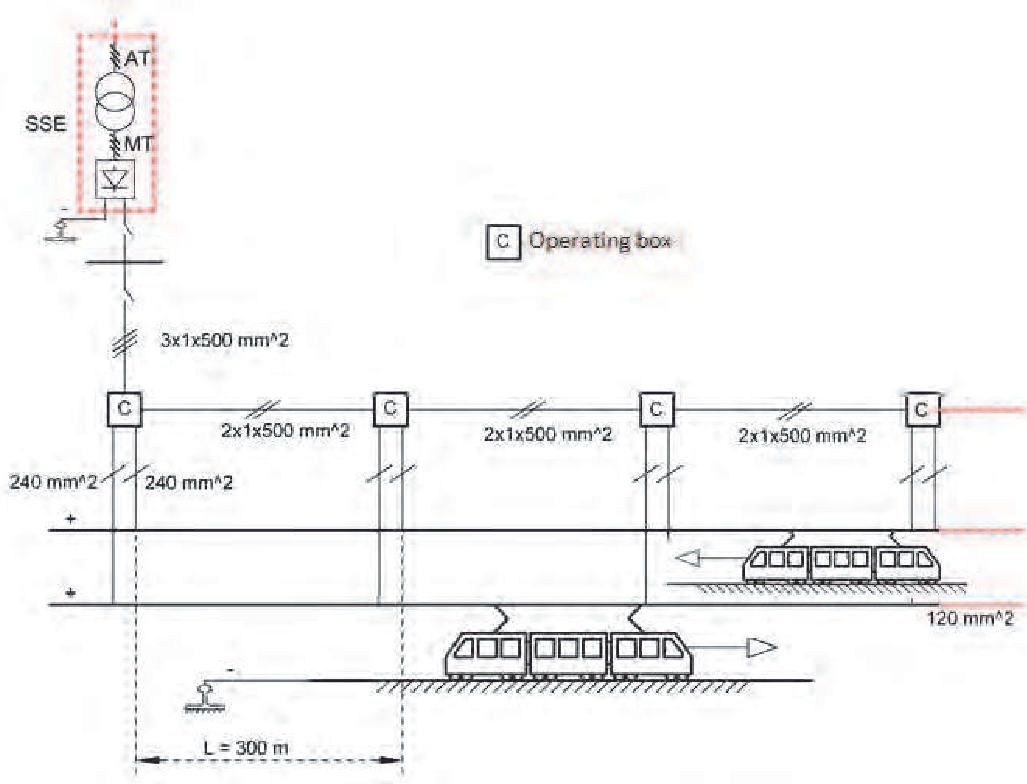


Fig. 4. The light transportation system under study

| Parameter | Unit | Quantity |
|---|---|---|
| Track Length | [km] | 1.5 |
| Contact Wire Resistance (Copper 150 mm$^2$) | [Ω/km] | 0.125 |
| Rail resistance | [Ω/km] | 0.016 |
| Substation internal Resistance | [mΩ] | 20 |
| Rated Voltage | [V] | 750 |
| N° Substations | - | 1 |
| N° Trains | - | 2 |
| Average Train acceleration/deceleration | [m/s$^2$] | 0.7/0.9 |
| Maximum Train Power | [kW] | 800 |
| Maximum Braking Power | [kW] | 400 |
| Train Mass | [T] | 60 |

Table I. Light Transportation system Parameters

### 3.2 Electrical network modeling with stationary ESS

The equivalent circuit of the traction system and the energy storage system located on end of the line are shown in Fig. 5 in which the subscripts odd and even refer respectively to the traction system parameters (contact wire resistance, track resistance, train currents and pantograph voltages) of both the odd and even tracks. In particular contact wire resistances will vary as a function of trains positions with respect to the feeding substations. The railway electrical system can be considered, broadly speaking, as a distribution system.

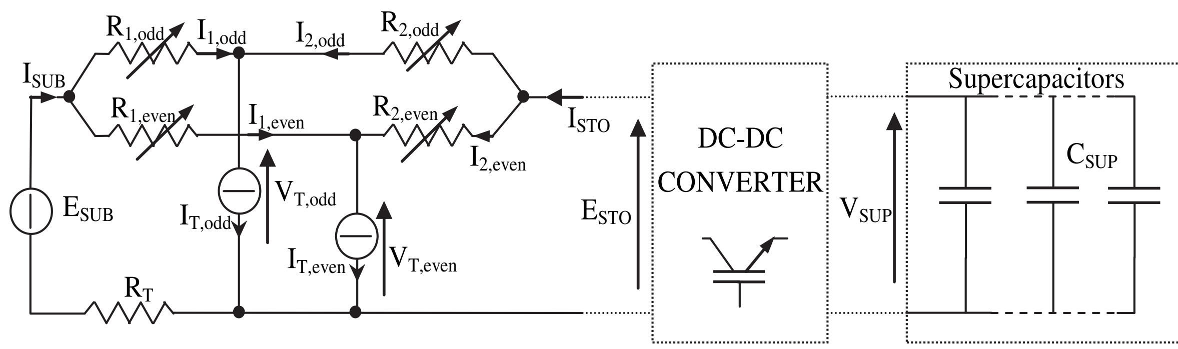


Fig. 5. Equivalent electrical circuit with wayside energy storage system.

In the model, the traction loads are modeled as current sources, $I_{Ti}$ , whose values depend on the powers required by the trains with reference to the track diagram and on the pantograph voltages through the relation at the at *k*-th time step:

$$I_{Ti}^{(k)} = \frac{P_{Ti}^{(k)}}{V_{Ti}^{(k)}} \qquad \text{k=1, 2,.......,K} \tag{1}$$

where *K* corresponds to the final state.
The discrete mathematical model is expressed in terms of non linear system where the power trains and the substation voltage, at generic instant (k), are known quantities. The un-known quantities are represented by the trains voltage, substation current and storage current and voltage.

$$\begin{bmatrix} I_{SUB}^{(k)} \\ I_{STO}^{(k)} \\ \frac{P_{T,odd}^{(k)}}{V_{T,odd}^{(k)}} \\ \frac{P_{T,even}^{(k)}}{V_{T,even}^{(k)}} \end{bmatrix} = \begin{bmatrix} \left(\frac{1}{R_{1,odd}^{(k)}} + \frac{1}{R_{1,even}^{(k)}}\right) & 0 & -\frac{1}{R_{1,odd}^{(k)}} & -\frac{1}{R_{1,even}^{(k)}} \\ 0 & \left(\frac{1}{R_{2,odd}^{(k)}} + \frac{1}{R_{2,even}^{(k)}}\right) & -\frac{1}{R_{2,odd}^{(k)}} & -\frac{1}{R_{2,even}^{(k)}} \\ -\frac{1}{R_{1,odd}^{(k)}} & -\frac{1}{R_{2,odd}^{(k)}} & \left(\frac{1}{R_{1,odd}^{(k)}} + \frac{1}{R_{2,odd}^{(k)}}\right) & 0 \\ -\frac{1}{R_{1,odd}^{(k)}} & -\frac{1}{R_{2,odd}^{(k)}} & 0 & \left(\frac{1}{R_{1,odd}^{(k)}} + \frac{1}{R_{2,odd}^{(k)}}\right) \end{bmatrix} \begin{bmatrix} E_{SUB}^{(k)} \\ E_{STO}^{(k)} \\ V_{T,odd}^{(k)} \\ V_{T,even}^{(k)} \end{bmatrix}, \tag{2}$$

k = 1, 2, ... , K.

### 4.3 Electrical network modeling with ESS on board

In 2nd case, the equivalent circuit of the traction system and the energy storage systems located on board are shown in Fig.6. The currents absorbed at trains pantograph is sum of the actual trains current and storage currents.

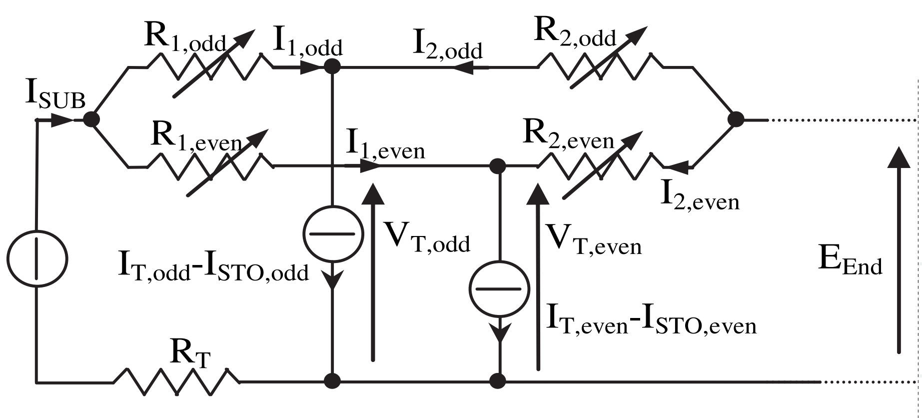


Fig. 6. Equivalent circuit with energy storage systems on board

The following mathematical model holds:

$$\begin{bmatrix} I_{SUB}^{(k)} \\ 0 \\ \dfrac{P_{T,odd}^{(k)}}{V_{T,odd}^{(k)}} - I_{sto,odd}^{(k)} \\ \dfrac{P_{T,even}^{(k)}}{V_{T,even}^{(k)}} - I_{sto,even}^{(k)} \end{bmatrix} = \begin{bmatrix} \left(\dfrac{1}{R_{1,odd}^{(k)}} + \dfrac{1}{R_{1,even}^{(k)}}\right) & 0 & -\dfrac{1}{R_{1,odd}^{(k)}} & -\dfrac{1}{R_{1,even}^{(k)}} \\ 0 & \left(\dfrac{1}{R_{2,odd}^{(k)}} + \dfrac{1}{R_{2,even}^{(k)}}\right) & -\dfrac{1}{R_{2,odd}^{(k)}} & -\dfrac{1}{R_{2,even}^{(k)}} \\ -\dfrac{1}{R_{1,odd}^{(k)}} & -\dfrac{1}{R_{2,odd}^{(k)}} & \left(\dfrac{1}{R_{1,odd}^{(k)}} + \dfrac{1}{R_{2,odd}^{(k)}}\right) & 0 \\ -\dfrac{1}{R_{1,odd}^{(k)}} & -\dfrac{1}{R_{2,odd}^{(k)}} & 0 & \left(\dfrac{1}{R_{1,odd}^{(k)}} + \dfrac{1}{R_{2,odd}^{(k)}}\right) \end{bmatrix} \cdot \begin{bmatrix} E_{SUB}^{(k)} \\ E_{End}^{(k)} \\ V_{T,odd}^{(k)} \\ V_{T,even}^{(k)} \end{bmatrix}, \quad for \quad k = 1, 2, \ldots, K. \tag{3}$$

where the power trains, the substation voltage, at generic instant (k), are known quantities. The unknown quantities are represented by the train voltages, storage currents and end line voltage.

Finally, both systems are completed taking into account the relation between converter and supercapacitors device. In fact, with respect to the boost converter laws, the quasi stationary modeling becomes:

$$\begin{cases} V_{\sup,j}^{(k+1)} - V_{\sup,j}^{(k)} + \dfrac{I_{\sup,j}^{(k)}}{C_{\sup,j}} \Delta t = 0 & k = 1,2,\ldots,K\text{-}1; \\ I_{\sup,j}^{(k)} = \dfrac{V_{\sup,j}^{(k)} - \sqrt{V_{\sup,j}^{(k)^2} - 4R_{C,j} E_{sto,j}^{(k)} I_{sto,j}^{(k)}}}{2R_{C,j}} & k = 1,2,\ldots,K; \end{cases} \tag{4}$$

with $j = \{odd, even\}$.

In the 1st case (stationary), the storage system is the same for both tracks (*odd* and *even*); otherwise in the 2nd case the storage systems are different and the terminal voltage on dc side of power converters $E_{sto,j}$ are the same of terminal voltages at trains pantograph $V_{T,j}$.
The above relationship can be easily deduced by the converter power balance. Hence, by neglecting the fast transients, the electrical systems can be described as a sequence of stationary states whose input data are the substation voltages and the train powers for each current position.

## 4. Optimal design

Some preliminary concepts are briefly summarized in order to better understand the design optimization procedure based upon the formulation of an isoperimetric problem.
A rational way to face with this kind of problem is to make the recourse to classical calculus of variations. Substantially, the objective is to search the functions of extrema of a functional, subject to known side-conditions. In the following, the Euler-Lagrange formalism of the calculus of variations is adopted (Pierre 1986).
Let us consider the problem of identifying the real curve x*(t) which yields the minimum or maximum of the functional:

$$J = \int_{t_a}^{t_b} f(x, \dot{x}, t)\, dt,$$

where $t_a$, $t_b$, $x(t_a) = c_a$ and $x(t_b) = c_b$ are assigned. Provided that the real-valued function $f(x, \dot{x}, t)$ is of class $C_2$ with respect to all of its argument, in short, a necessary condition is the well-known Euler-Lagrange equation:

$$\frac{d}{dt}(f_{\dot{x}}) - f_x = 0,$$

If a constraint equation of the following kind is imposed:

$$h = \int_{t_a}^{t_b} g(x, \dot{x}, t)\, dt,$$

where $h$ is a constant and $g$ a known real-valued function, this equation is usually called isoperimetric condition. The solution $x^*(t)$ which yields the minimum or maximum of the functional, while satisfying the isoperimetric constraint, is the one obtained by assuming that $x^*(t)$ is a first-variational curve resulting in the minimum or maximum of the functional:

$$J_1 = \int_{t_a}^{t_b} f(x, \dot{x}, t) + \lambda\, g(x, \dot{x}, t)\, dt\,,$$

where $\lambda$ is the Lagrange multiplier.
On the other hand, it is quite impossible to obtain analytical closed solutions for very large and complex systems, especially if the side-conditions are posed in the form of inequalities. However, after a discretization procedure, the optimization problem can be formulated as a

nonlinear programming problem, as performed in (Battistelli et al. 2009) at the aim of determining the optimal size of supercapacitor storage systems for transportation systems. In mathematical terms, the constrained optimization problem can be summarized as:

$$\begin{aligned}&\min \phi[\mathbf{x},\mathbf{u},\mathbf{m}]\\&\theta(\mathbf{x},\mathbf{u},\mathbf{m})=\mathbf{0},\\&\psi(\mathbf{x},\mathbf{u},\mathbf{m})\le \mathbf{0}.\end{aligned}$$

where **x** is the state variables vector, u the control variables vector, **m** the parameters vector , $\phi$ is the objective function to minimize and $\theta$, $\psi$ refer to equality and inequality constraints respectively.

The optimal sizing of the energy storage device has to be effected guaranteeing contemporaneously the voltage profile regularization at both train pantographes, the substation current minimization and the supercapacitor size reduction. In the case of a single stationary storage device, this can be pursued by selecting the following objective function $\phi$ to be minimized:

$$\phi = \int_0^T \left[ w_1 \left( V_{T,even} - V_{ref} \right)^2 + w_2 \left( V_{T,odd} - V_{ref} \right)^2 + w_3 I_{SUB}^2 + w_4 I_{\sup}^2 \right] dt \tag{5}$$

where $w_1$, $w_2$, $w_3$ and $w_4$ are suitable coefficients which are able to weight the previously mentioned requirements, $V_{ref}$ being the rated line voltage. In an analogous way, the proper objective function for on board arrangement can be determined.

The energy storage conservativeness on the whole time cycle can be described by the following isoperimetric condition:

$$\int_0^T V_{\sup} I_{\sup} dt = 0 \tag{6}$$

The isoperimetric problem is completed by the equality constraints which have been described in 4.3 which substantially take into account the electrical network relationships and the electrical modeling of components.

In (D. Iannuzzi et al., 2011) the authors have provided an analytical solution to this problem for a simple case study, on the assumption that the input of the design procedure are the currents rather than the traction powers, this permitting to obtain a closed form to the optimization problem. In this paper the discretized version of the optimization problem is arranged, providing in this way a numerical solution. The sequential quadratic programming method, which belongs to the class of iterative methods, is employed which solves at each step a quadratic programming problem.

## 5. Numerical application

In order to verify the validity of the proposed procedure a realistic case with respect to actual operation, a 1.5 km double track line, 750 V nominal voltage, is investigated. A 120 seconds operation has been foreseen with two regular stops. The trains, equipped with regenerative braking, depending on the load dynamic behavior, absorb or generate the corresponding electrical powers. The simulation data are reported in Table I.

The driving cycle used for simulation is based on the observations of the real route measurements. It follows the theoretical directives of accelerating up to 75 km/h with an acceleration of 1 $m/s^2$, whenever it is possible. The electrical power required by the vehicle has been deduced by measurement at the pantograph during the travel on a typical track. The data have been post-processed and interpolated. The speed and electrical power cycles are shown in Fig. 7. It is assumed that the two trains are timely shifted of 20 s. Substation no load voltage is assumed to be constant and equal to $V_0$ = 750 V. The storage system has been located at the end of the line in the first case and then they are located on board.

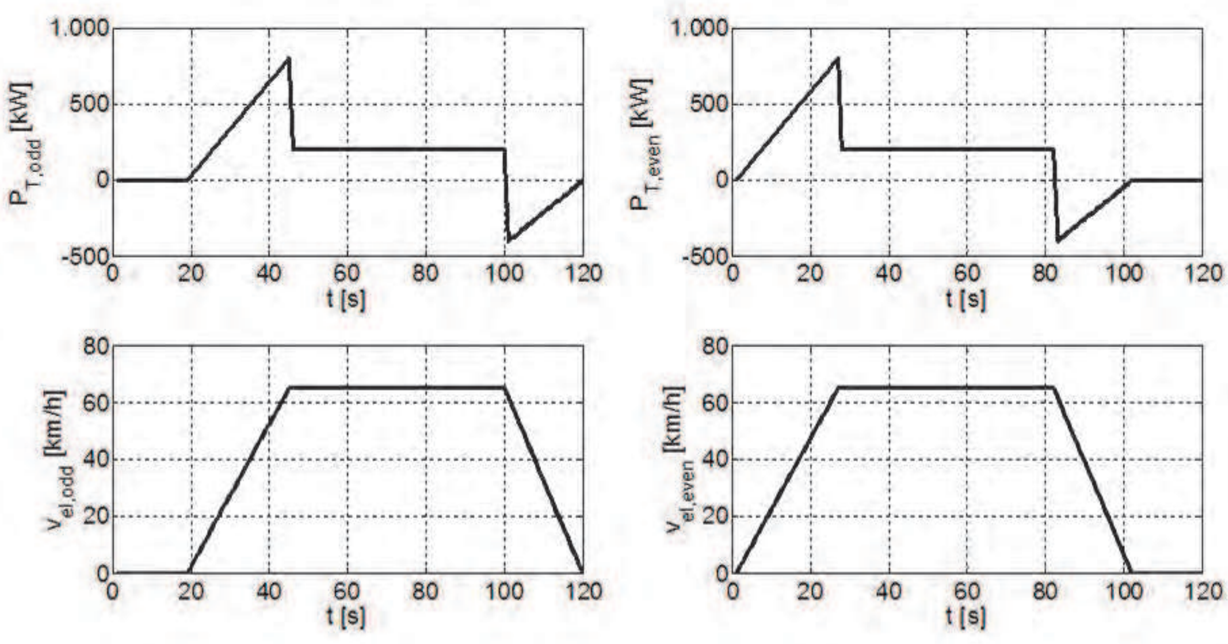


Fig. 7. Traction cycles of the two trains in terms of electrical power at pantograph and vehicles speed

At this purpose, it has to be highlighted that the traction powers has to be regarded as an input data in the optimization procedure, the most convenient vehicle displacement being not investigated.

In order to compare the effectiveness of the storage devices, the reference case, characterized by the absence of storage device, has been simulated. In Fig.8 the total feeding substation current, the odd and even pantograph voltages are depicted. In particular during the acceleration the substation current reaches a peak value of 1.5 kA, the line drop voltage on both tracks can be observed. The odd voltage at pantograph reaches a minimum value of 600 V with a decreasing of 20% of rated value (750V). On contrary, during the breaking time the train electrical powers became negative with consequence inversion of the substation current and increasing of line voltage. In particular the substation current reaches a negative peak of 500 A and an increasing of line voltage referred to even track equal to 7% of rated value.

Successively, two cases are examined for which the proposed optimization procedure is applied. The first one refers to the on-board solution.

The following constraints are imposed:

$$\begin{cases} I_{SUB}^{(k)} \geq 0[A], \\ 600\,[V] \leq V_{T,odd}^{(k)} \leq 850\,[V], \\ 600\,[V] \leq V_{T,even}^{(k)} \leq 850\,[V], \qquad k=1,2,.....,K. \\ 550\,[V] \leq E_{SUB}^{(k)} \leq 900\,[V], \\ 300\,[V] \leq V_{\sup}^{(k)} \leq 500\,[V], \end{cases}$$

The optimization procedure is performed, by choosing the following weight coefficients: $w_1$, $w_2$. The supercapacitor value has been evaluated by imposing a constraint in terms of weight. More specifically the weight of the storage device has been constrained to be less than *2%* of the train one.
By following this choice the supercapacitor equivalent capacitance has been resulted equal to *57 [F]* for each train. In the Fig.9 the total feeding substation current, the odd and even pantograph voltages.

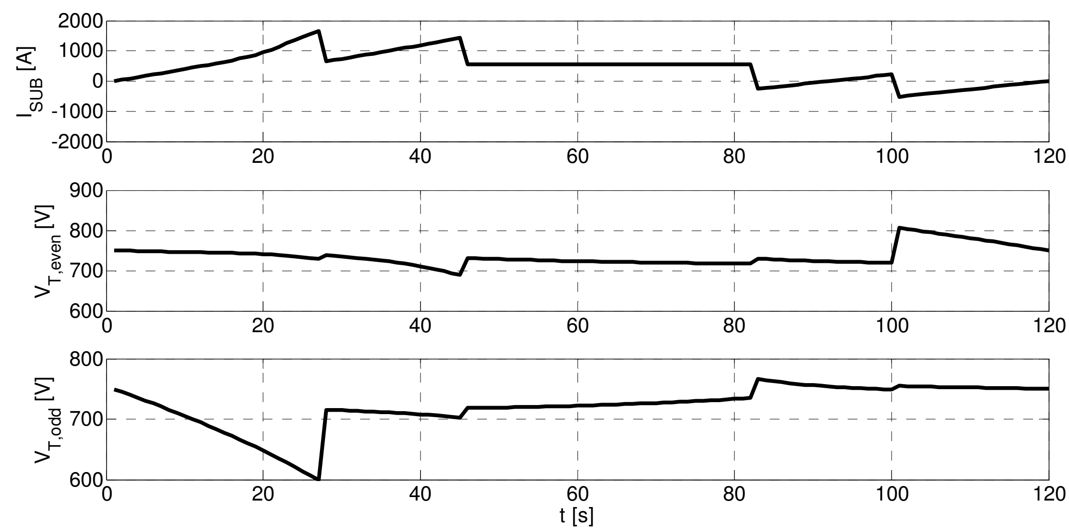


Fig. 8. Substation current and terminal voltages at trains pantograph in the case of absence of energy storage devices.

In this case the substation current diagram is quite flat and it is unidirectional reaching the peak value at 600 A, in fact it can be observed a drop voltages at pantograph about the 6-7% of rated value. This is due to effect of the presence of two supercapacitors devices located on board. The supercapacitors voltages and the storage currents are reported in Fig.10.
The supercapacitors devices, located on trains *odd* and *even,* supply the train during the acceleration giving a peak currents of about 750 A and 900 A respectively. In fact the supercapacitors voltages at its terminal decrease up to 300 V during the acceleration. On the contrary, the electrical energy recovery can be observed during the braking time when the supercapacitors voltages increase up to their rated values (500 V). So it is quite immediate to capture the actions of the two storage systems. The energy saving with respect to the base case is equal to *15,4%*.
As far as the second case is concerned, the storage subsystem is placed at the end of a single-side supplied line.

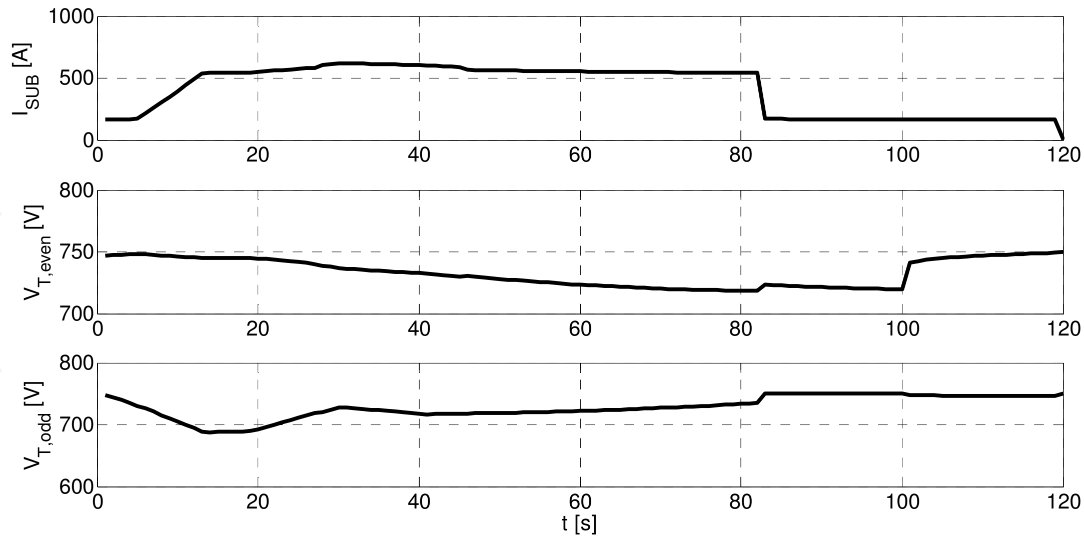


Fig. 9. Substation current and terminal voltages at trains pantograph with the energy storage devices on board.

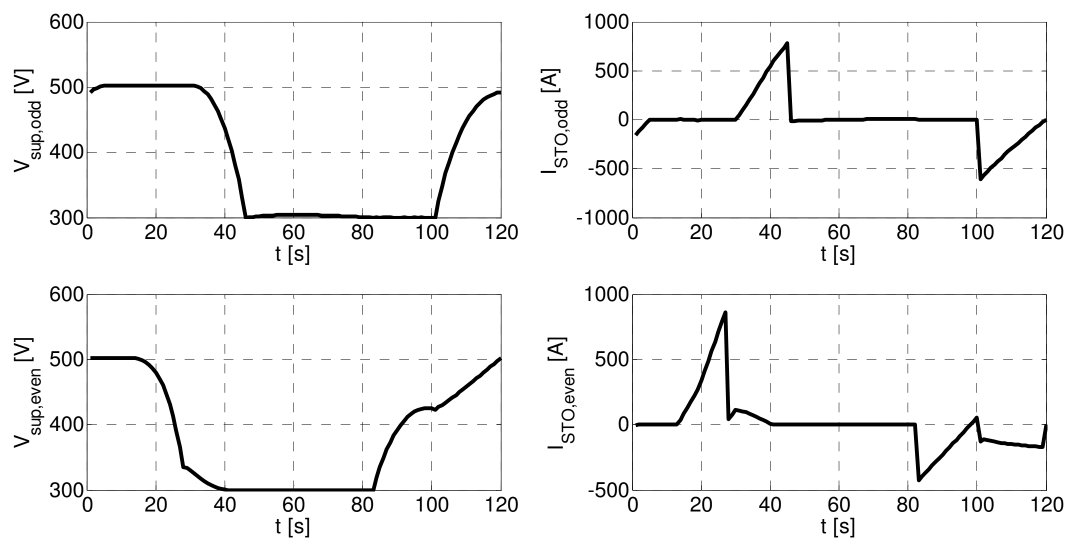


Fig. 10. Supercapacitors voltages and storage currents for each train

The case corresponding to the weight choice $w_1 = w_2 = w_3 = 1$ is reported. This choice was motivated for emphasizing the systemic role played by the storage device which modulates continuously the electric power, in order to contribute both at voltage profile regularization and substation current minimization. Also in this case, it can be observed the quite flat profile of the substation current and the reduced value of the pantographs voltage drop. By following this choice the supercapacitor equivalent capacitance has been resulted equal to *188 [F]*. In the Fig.11 the total feeding substation current, the odd and even pantograph voltages.

The supercapacitors voltage and the storage current are reported in Fig.12. It can be observed that in the case of storage device located at the end of line the supercapacitors current profile is very similar to substation current shown in the fig.8. This shows the compensation action of supercapacitors during the different operation conditions of the electrical line.

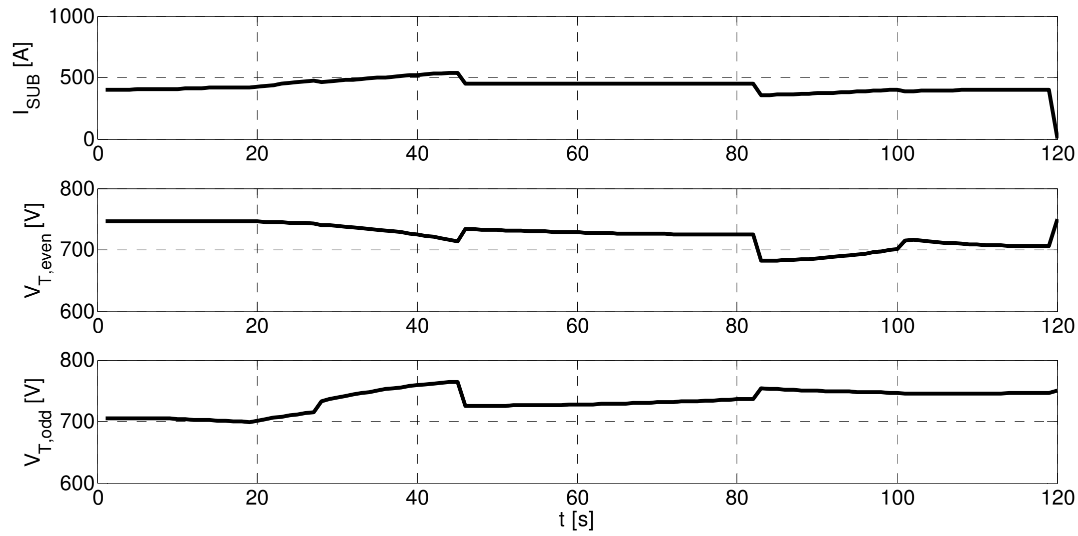


Fig. 11. Substation current and terminal voltages at trains pantograph in the case of energy storage devices located at end of line.

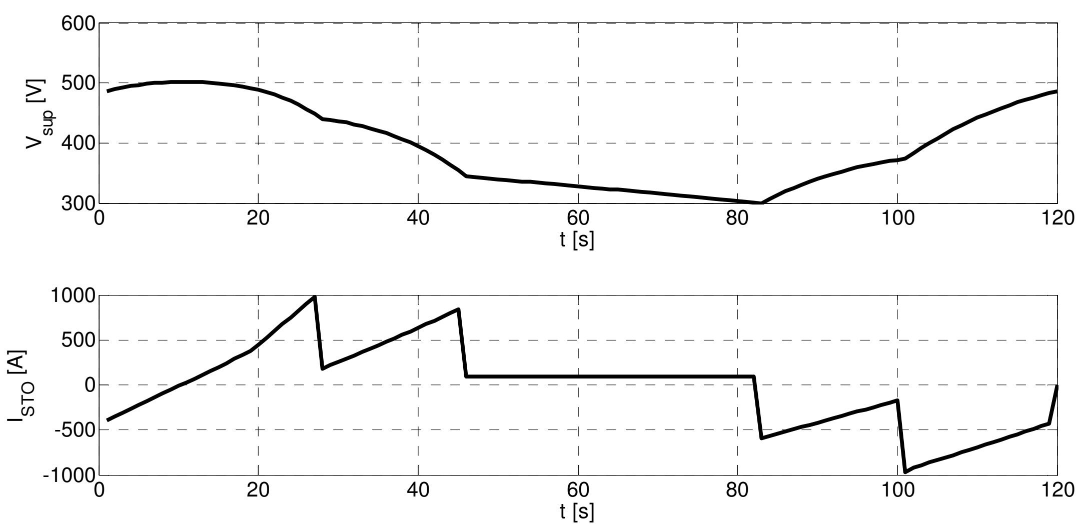


Fig. 12. Supercapacitor voltage and storage current

The energy saving with respect to the base case is equal to *11,6%*.

## 6. Conclusion

In the paper a new Supercapacitor Design Methodology for Light Transportation Systems Saving has been described. The supercapacitor design has been directed towards the energy efficiency improvement, voltage regulation and high reduction of peak powers requested to feeding substations during the acceleration and braking phases.

More specifically, the supercapacitor design problem for light transportation systems energy saving has been handled in terms of isoperimetric problem. Starting from this point, the problem has been tailored as a constrained multiobjective optimization problem which without restrictions has been proven able to face with all the interest cases. The optimization procedure has been tested both for both stationary supercapacitors and for on-board arrangement. The procedure output are the supercapacitor storage size and the supercapacitor reference voltage which can be employed as reference time trajectory to track during operating conditions. A numerical application has been performed for a case study with two trains along double track dc electrified subway networks, both for stationary and on-board configurations. The obtained numerical results allow to confirm the feasibility and the goodness of the proposed optimal design technique.

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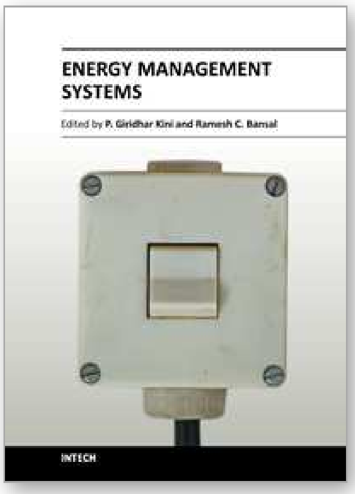


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This book comprises of 13 chapters and is written by experts from industries, and academics from countries such as USA, Canada, Germany, India, Australia, Spain, Italy, Japan, Slovenia, Malaysia, Mexico, etc. This book covers many important aspects of energy management, forecasting, optimization methods and their applications in selected industrial, residential, generation system. This book also captures important aspects of smart grid and photovoltaic system. Some of the key features of books are as follows: Energy management methodology in industrial plant with a case study; Online energy system optimization modelling; Energy optimization case study; Energy demand analysis and forecast; Energy management in intelligent buildings; PV array energy yield case study of Slovenia;Optimal design of cooling water systems; Supercapacitor design methodology for transportation; Locomotive tractive energy resources management; Smart grid and dynamic power management.



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