Peer-reviewed version available at *Energies* **2018**, *11*, 410; doi:10.3390/en11020410

Article

Integration of Photovoltaic Plants and Supercapacitors in Tramway Power Systems

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Abstract: The growing interest in the use of energy storage systems to improve the performance of tramways has prompted the development of control techniques and optimal storage devices, displacement, and sizing to obtain the maximum profit and reduce the total installation cost. Recently, the rapid diffusion of renewable energy generation from photovoltaic panels has also created a large interest in coupling renewable energy and storage units. This study analyzed the integration of a photovoltaic power plant, supercapacitor energy storage system, and railway power system. Random optimization was used to verify the feasibility of this integration in a real tramway electric system operating in the city of Naples, and the benefits and total cost of this integration were evaluated.

Keywords: Optimization; Photovoltaic; Supercapacitor; Tramway.

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1. Introduction

The substantial increase in the use of electrified collective transport systems, which has occurred in recent years in large urban centers, has made it necessary to increase the vehicle frequency rate and capacity of convoys in terms of transportable passengers. This has been reflected in the use of vehicles with more propulsion power, as well as lower time displacement, with consequent voltage variations, which are critical factors in the proper operation of the transport system. Maintaining the line voltage within certain limits is in fact dictated by the need to properly power the input bus of the electrical traction drive, which is currently the most popular propulsion system in metropolitan, tram, and tramway trains. Major voltage drops in the line occur mainly at the acceleration stages of the convoys and are therefore directly related to the number of vehicles simultaneously operating on the line and to the total power required. During the braking phases, however, the kinetic energy of a convoy is converted into electrical energy and, if possible, supplied to the other accelerating convoys.

In this context, the use of braking energy recovery storage systems located along the contact line or near the passenger stations could result in significant energy savings, compensating for the costs incurred for their installation. The stored energy could also help to support the contact line during consecutive congestion restarts, thus reducing voltage drops and energy dissipation. Among the different rail transport systems, a solution with energy storage systems can be particularly effective and beneficial if applied to metropolitan, suburban, and tramway systems. In fact, these are characterized by operating convoy sets that accelerate and brake in short time intervals. In such applications, the placement of the energy storage system in the station is optimal because of the availability of space and therefore may be preferable to on-board installation. This solution also enables recovery and re-use for other convoys passing near the same station.

Energy storage systems are essentially made up of components for energy storage and static energy converters that regulate the incoming and outgoing energy flows, ensuring high reliability and high efficiency. They are capable of allowing a controlled bi-directional flow of electrical energy by stepping up or down converting voltages between the feed lines and storage components.

Supercapacitors (SC) are a good alternative to electrochemical batteries in applications where it is necessary to quickly compensate for the discontinuous power absorption of electric loads. A proper storage capacity design allows the use of SCs in different practical applications.

Researchers are paying increasing attention to different utilizations of these technologies in urban and suburban railway traction systems [1,2] because they are capable of improving the efficiency by recovering the braking energy and contributing to the starting of engines or boosting the contact line voltages. Their presence also allows for the under dimensioning of the power feeding plant during the project or for the more intensive use of existing plants. Practical applications can be either stationary or movable [3,5]. In the first case, they can be devoted either to recovering energy and returning it or to smoothing electrical power peaks in the electrical supply network or supporting the line voltage. Therefore, they must be installed either near suburban train stations and streetcar stops (energy recovery) or at some critical points along contact lines. In movable applications, they are installed on-board and, hence, are used to improve the efficiency by recovering mechanical energy during braking [6,7]. The action is also useful for smoothing electrical power peaks during train start-up.

In the following sections of this paper we will pay attention to the boosting action of electrical storage systems, because this practical application can be useful in solving the feeding problems arising today in many large towns. In practice, in recent years, numerous trolley cars of a new design have gone into service on suburban and city lines, and their traction drives have a higher rated power than any previously used streetcar designs. However, the contact lines have rarely been changed or properly updated to consider the increased current drawn. As a consequence, contact lines sometimes become overloaded, which results in drops in their operating voltages, sometimes below their minimum allowed values. Other trolley cars travelling in the vicinity, in the same or in the opposite direction and fed by the same DC source, can sometimes enter a stand-by condition as a result of the protective action of their minimum voltage relays. The same problem arises in suburban traction systems when passenger carrying capacities during the day are improved by increasing the number of trains operating simultaneously on the same section of the traction line. To avoid this situation, a good and useful solution to improve line performance and avoid undesired voltage drops without substantially changing the structure of the existing contact lines is the use of SC stations allotted along contact line sections [8]. Such new configurations are only capable of improving the performances of old contact lines if SC sets are properly designed with reference to their size and capacitance, the number and locations of the stations, and the strategies used for the involved power electronics devices [9,10].

In order to achieve a satisfactory braking energy recovery, it is necessary to consider that the amount of energy that can actually be recovered during vehicle braking and reuse is only a part of the kinetic energy owned by the vehicle itself at the start of braking. This part is smaller than the power losses incurred in converting the kinetic energy into electric energy and transferring it to the storage components. In practice, the efficiency of the electrical traction motor during generator operation is very high. The leaks in static converters are very low, because of their high efficiency. Joule leakage losses in the conductors between the storage systems and contact lines increase considerably with the distance between the storage device and the point where the vehicle brakes, because braking is a short-term phenomenon and is generally constrained to deceleration values that are easily acceptable to passengers. Consequently, the power and current values involved are relevant. These losses can, therefore, also counteract the energy recovery benefits. Therefore, the use of energy recovery storage systems for tramcars can only be effective with the on-board installation of the systems themselves. Their arrangement along the contact lines may be useful when they are used to support contact line voltages. In our opinion, this last goal can be achieved, together with an optimal recovery of braking energy, by integrating the recharge of stationary SC energy storage sets with energy from local photovoltaic (PV) sources, appropriately installed along the rail path.

There have been few recent papers that dealt with the application of PV sources to urban railway networks. In [11], the authors investigated the performance of solar PV modules mounted

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on the roof of a rail coach to quantify the reduction in diesel consumption of the end-on generation system that powered the electrical load in the new generation coaches.

The roof coach installation of the panels was proposed in [12], which introduced a technical scheme for the auxiliary power supply system of a passenger train based on PV and battery energy storage. This auxiliary power has to be injected into the DC power supply system in order to obtain an annual output power payback, energy conservation, and emissions reduction [13,14]. Moreover, [15] presented the concept of an embarked power source using SCs that were charged by means of a combination of a roof-placed PV source and an aerogenerator, which supplied power to the DC link of the main traction drive. The design and energy management strategies were applied to a miniature train in the laboratory.

In [16,17], the potentials, peculiarities, and prospects of using solar power generation systems on the platform roofs of railway stations were analyzed for power injection into the main electrical grid. The prospects for realizing a solar generation system with lithium ion batteries for a local station called a "zero-emission station" were also shown to realize a more eco-friendly traction power supply system.

Ultimately, in [18,20], the feasibility and application modes of a fixed PV generation system with an auxiliary SC or battery storage equipment was studied for urban rail transit. The AC grid-connected mode and DC grid-connected mode were presented, and the grid-connected topology and energy management strategy were developed. The intrinsic capability of saving regenerative energy with a consequent increase in the energy savings of the systems and reduction in the voltage drop was highlighted.

This paper proposes a procedure for the optimal integration of PV power plants, SC storage systems, and railway power systems. The PV modules are installed on the available surfaces of shelters positioned along the track. In order to use a modular approach for the storage systems, each shelter is also provided with SC units. The modular distribution of storage systems makes it possible to improve the discharge phase, reduce the losses in the connection to the railway power system, and improve the control because it is possible to act in a different manner in the various nodes of the railway systems. The approach utilized for the optimal integration is based on the use of a random optimization procedure. This is based on a minimization cost function that takes into account the cost of the entire system and can solve the mathematical problems with integer variables. Some simulations were performed taking into account the case of a tramway of Naples (Italy) and using the software Matlab© and Simulink©.

2. The Photovoltaic Power Plant

The considered tramway track, which is shown in Fig. 1, is approximately 1.8 km long and has five stops placed 300 m apart. The total time needed to pass over this track is about 300 s. A yellow circle in Fig. 1 indicates the presence of one shelter, while the green circles correspond to two shelters. The green circles are also positioned at the initial and final stops of the track. At each shelter, it is possible to install five PV panels with the characteristics reported in Table 1.

The maximum power generated by a plant assembled on a single shelter is about 1 kW_P. Considering the total number of shelters, it is possible to install 12 kW_P of PV panels along the entire track. The electrical power generated by this power plant can be utilized by connecting the PV panels directly to the low-voltage power system through an inverter to exchange electrical energy with the power system, or by linking the panels to a storage system based on SCs and using the energy during the tramway operation.

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Figure 1. Map of possible installation of photovoltaic power plant in a part of Naples tramway.

Table 1. Electrical data of photovoltaic panels.

Quantity	Values
Maximum Power	212 W
Open circuit Voltage	36.2 V
Short circuit Current	7.93 A
Module efficiency	16.1 %

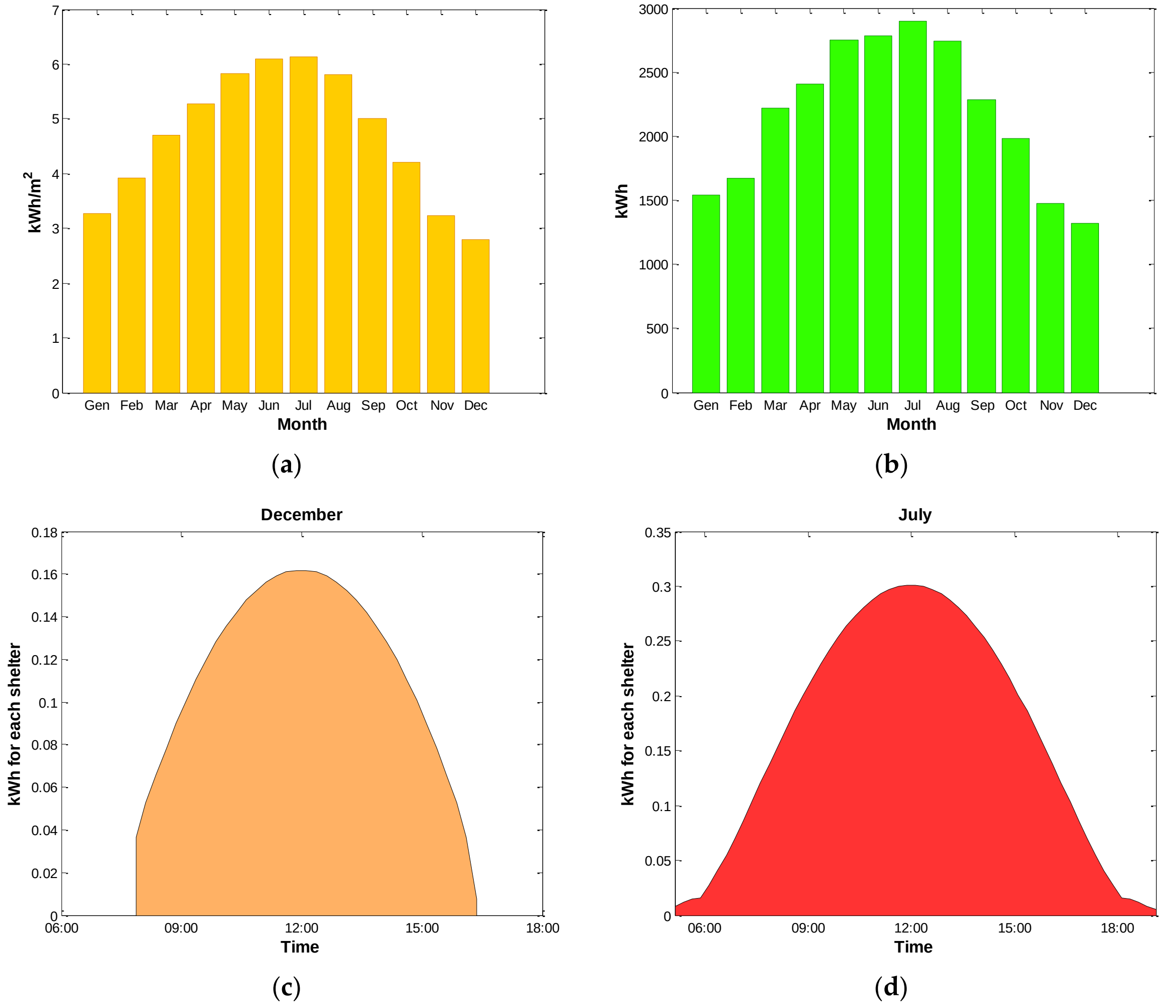
In recent years, because of the large development of distributed generation, the management of power systems, particularly low-voltage systems, has been affected by new problems related to the voltage drop along the line and the sorting of the locally generated energy. Therefore, the necessity of integrating storage systems in the power system continues to grow. Another important problem introduced by the integration of distributed generation in the power system is the random behavior of renewable energy sources. The feasibility of PV power plants is based on a study of the annual solar radiation that is typical for a geographical location. Figure 2a shows the mean value of daily global radiation in the case considered in this paper [21], in kWh/m^2.

Considering the efficiency of the PV panels (Table 1), a power electronic converter global efficiency of 0.96, and the total surface of the shelters, it is possible to compute the mean value of energy (Fig. 2b) generated by the considered PV power plant.

The mean value of achievable energy in a year is approximately 26000 kWh. Considering the high power required in traction applications, the PV power plant cannot be directly coupled to the railway lines, but is necessary to use an appropriate storage system, i.e., one based on SCs, and to integrate it in the tramway electric power system. The integration of a PV power plant in the railway system requires an appropriate analysis of the distribution of solar radiation during a day, to avoid oversizing the storage system. Solar radiation is quite variable during the day. Thus, forecasting is difficult, and it is usually evaluated using statistical data. A correct knowledge of the radiation permits the optimal sizing of the storage systems. Figures 2c and 2d report the average values of solar radiation [22] in the summer and winter months for the case considered in this paper.

Figures 2c and 2d show the obvious and substantial difference between winter and summer, which must be taken into account for the correct sizing of the energy storage systems.

The choice of a storage system with a capacity equal to the maximum recovery energy in summer is oversized with respect to the energy available in winter. Thus, it is necessary to consider the possibility of storing only a part of energy obtainable by the PV power plant and exchanging the other part with the distribution power system. The energy storage depends on the behavior of the electrical load in the considered railway systems. The total duration of a single track is about 300 s, with five stops, and the total energy that can be stored in 300 s is very low. Thus, it is necessary to consider a longer interval (more tramway rides) to obtain a reasonable amount of energy, and increase the life of the storage system by reducing the number of charge and discharge cycles.



(**a**) (**b**)

(**c**) (**d**)

Figure 2. PV power plants solar radiation typical for the considered geographical location: (**a**) Mean value of daily global radiation [kWh/m^2]; (**b**) Mean value of generated energy per month [kWh]; (**c**) Daily distribution of energy in December [kWh]; (**d**) Daily distribution of energy in July [kWh].

3. The Photovoltaic Power Plant

The integration of the SCs in the railway power system is modular. The modularity of the storage systems involves the installation of multiple SCs near the shelters along the track, which increases the system reliability, prevents the complete exclusion of the storage systems during maintenance, introduces some optimal strategies for reducing losses, and minimizes the installation cost.

The electric scheme of the railway power system with the PV modules and SCs is shown in Fig. 3. The railway power system is fed by a transformer with a primary voltage of 20 kV. The secondary side includes a bridge rectifier that outputs a voltage of 750 V. During its performance, the voltage in the different nodes of the net can vary in the range of 600–900 V. The output of the bridge rectifier is linked to the catenary of the power system. Table 2 reports some data of the railway power system [23].

The PV modules are connected to the storage systems through a buck converter. In the same way, the storage systems are linked to the railway power system with a buck converter. A storage system can be installed at the end of the track to recover the energy generated by the train during braking. The electric layout of the system can be modeled as shown in Fig. 4.

Table 2. Parameters of the electrical railway system.

Quantity	Values
Substation Power	1150 kVA
Length	1.8 km
Catenary resistance	0.15 Ω/km
Nominal Voltage	750 V
Number of stations	5

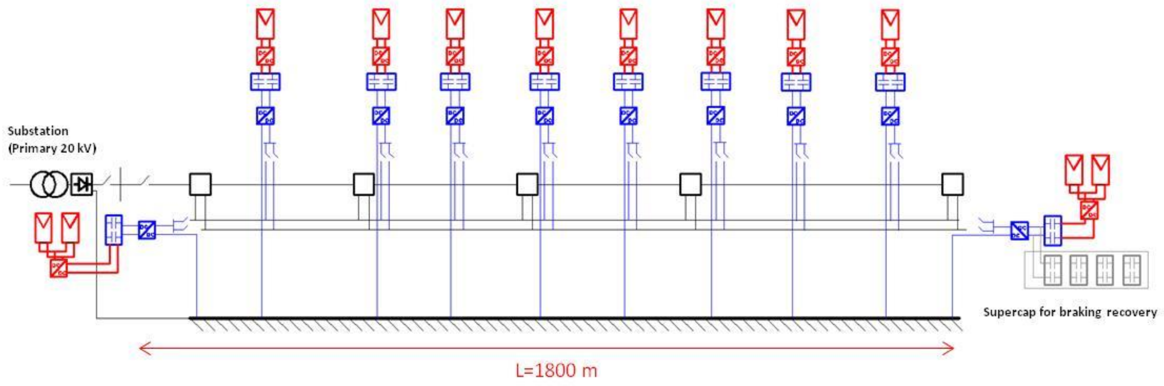


Figure 3. Electric layout of the railway power system for the considered track: integration of photovoltaic modules and of storage systems in the circuit.

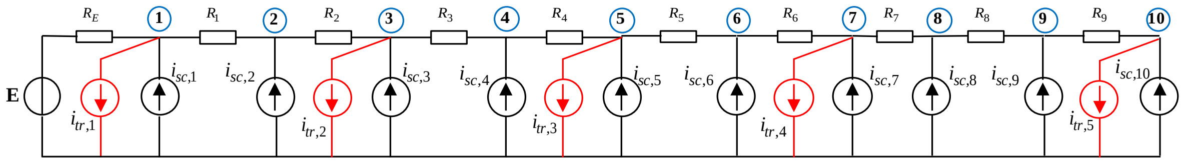


Figure 4. Model of the electric scheme shown in figure 6.

The output of the transformer is considered constant, and both the train and storage system units are considered to be current generators. R_E is the resistance between the substation and the first node of the net, and R_j (j=1,…,9) are the line resistances between the different nodes. The stops are positioned along the track at nodes 1, 3, 5, 7, and 10. The mathematical model can be used for the following systems:

$$\begin{cases} V_e(t) - R_E I_E - V_1(t) = 0 \\ V_h(t) - R_h I_h - V_{h+1}(t) = 0 \quad h = 1,\ldots,8 \\ V_9(t) - R_9\, I_9 - V_{10}(t) = 0 \end{cases} \tag{1}$$

$$\begin{cases} I_{sc,1}(t)\dfrac{V_{sc,1}(t)}{V_1(t)} + I_E(t) - \left[I_{tr,1}(t)S_1(t) + I_1(t)\right] = 0 \\ I_{sc,h}(t)\dfrac{V_{sc,h}(t)}{V_h(t)} + I_{h-1}(t) - I_h(t) = 0 \qquad h = 2,4,6,8,9 \\ I_{sc,h}(t)\dfrac{V_{sc,h}(t)}{V_h(t)} + I_{h-1}(t) - \left[I_{tr,h}(t)S_h(t) + I_h(t)\right] = 0 \quad h = 3,5,7,10 \end{cases} \tag{2}$$

Function $S_h(t)$ is a function that has values of 0 when the train does not start from node h and 1 when the train starts from the considered node. The model obtained with relations (1) and (2) is valid considering a quasi-stationary performance of the system [24]. In fact, the regulation transient

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of the chopper is considered to be very fast, and choosing an adequate stepping time for the simulation makes it possible to neglect the dynamic of the chopper and consider the output voltage to be constant.

4. Random Searching Optimization Problem

The optimal integration of PV plant and SC energy storage systems in the railway power systems is carried out by means of an optimization procedure based on a random searching algorithm. This procedure is suitable for performing the minimization of an objective function, usually depending on integer variables, starting from a set of possible solutions of unknown variables and using an iteration procedure that calculates the new value of cost functions using a random uniform distribution of unknown variables. After a certain number of iterations, the minimum (or maximum) obtained value of the objective function determines the optimal solutions. In the case considered in this paper, the optimization variables are the number of series (n_{sh}) and parallel (n_{ph}) SCs used on each shelter (it is supposed that the numbers of SCs are equal in the intermediate shelters and different at the first and last stops), the number of complete track performed by the train (n_t) during which the energy obtained by the PV cells is stored in the SCs. The last random variable utilized is the discharge power P_d of the SCs in the discharge process (divided into P_{d1} and P_{d3} for the final and initial shelters, respectively, and P_{d2} for the intermediate shelters).

All of the variables are strictly related to the electrical optimization of the net, because they determine the improvement of the total power dissipated in the railway system. The optimization problem is resumed in the following system:

$$
\begin{aligned}
&\min \quad (c_1 - c_3)\Delta E \cdot \left(n_{s1}n_{p1} + n_{s2}n_{p2} + n_{s2}n_{p2}\right) + \ldots \\
&\qquad\ \ \ldots + c_2 E_{loss} - c_3 E_{pv,p} \\
&\text{subject to} \\
&V_{\min} \le V_h(t) \le V_{\max} \\
&Isc,_h(t) \le I_{\max}
\end{aligned}
\tag{3}
$$

In (3), c_1, c_2, and c_3 are weight parameters expressed in Euro/kWh related to the cost of the SCs (ΔE is the energy stored in a single SC unit), cost of the energy losses (E_{loss}), and the cost of the energy generated by the PV cells ($E_{pv,p}$). The optimization procedure takes into account the solution of a complete track section for the train with all the stops, along with the calculation and evaluation of the cost functions for each combination obtained by the procedure (Fig. 5).

The time dependence of variables V_h and $I_{sc,h}$ is directly considered because the optimization procedure simulates the complete railway track. The minimum and maximum voltage limits for the considered electric system are 600 V and 900 V, respectively, while the maximum discharge current depends on the type of SC adopted.

5. Optimization Results

The optimization procedure is applied to the considered railway track, and the mechanical power and speed profile of a train traveling on the railway are respectively represented in Figs. 6a and 6b. As can be noted, the profiles are typical of light railway power and speed profiles, with numerous accelerations and stops; this also shows that the current absorption presents numerous peaks, which can influence the behavior of the power electronic converter installed in the power system.

The power stored in the SCs is supplied during the acceleration phases in order to reduce the total power absorbed by the substation.

The optimization procedure was implemented considering SCs with the features reported in Table 3.

The random optimization procedure was carried out with 17 iterations, fixing $c_1 = 30000$, $c_2 = 0.2$, and $c_3 = 0.1$. Figures 7a and 7b show the parallel and series SCs that must be installed at the initial and terminal stops (blue) and in the intermediate shelters, while Fig. 8 shows the normalized cost

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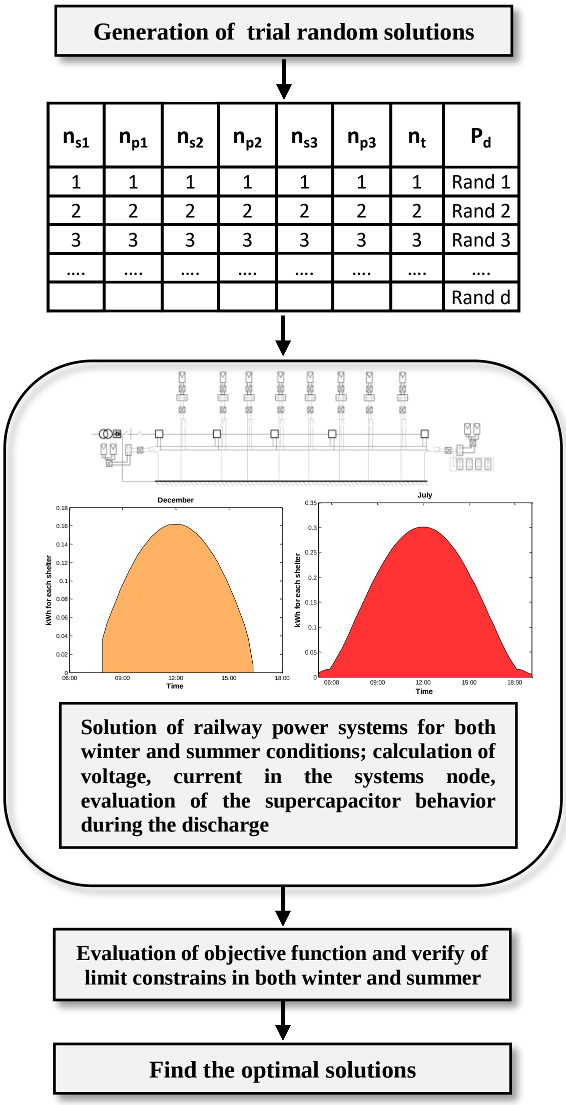
function with various interval recharge times for the SCs, and Fig. 9 shows the distribution of the cost function values as a function of the discharge power.

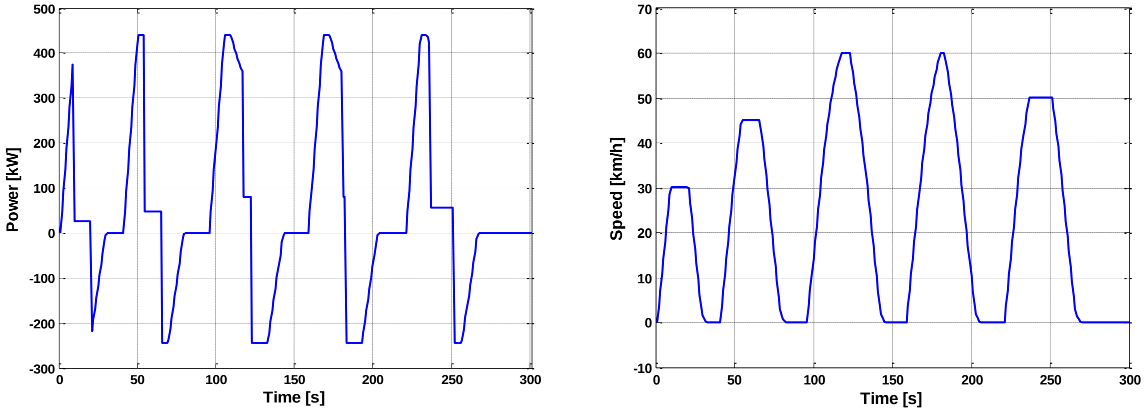
The results obtained through the optimization procedures are reported in Table 4. The optimal value of the cost objective function is approximately 199 kEuro, which was practically determined by the high cost of the storage unit systems and could be reduced by the improvement and production of new SCs. The positive role of the SC is also inherent to the reduction of the peak power required for the distribution power systems. Figure 10 shows the new trend for the power required by the train.

In the proposed procedure, the SCs are controlled to keep the power used during the discharge process and train acceleration phases constant, but it is also possible to completely discharge the SCs in a limited time, which corresponds to the maximum value of power required.



n_{s1}	n_{p1}	n_{s2}	n_{p2}	n_{s3}	n_{p3}	n_t	P_d
1	1	1	1	1	1	1	Rand 1
2	2	2	2	2	2	2	Rand 2
3	3	3	3	3	3	3	Rand 3
....	....	....	....	....	....	....	....
							Rand d

Figure 5. Flow chart of the optimization procedure.

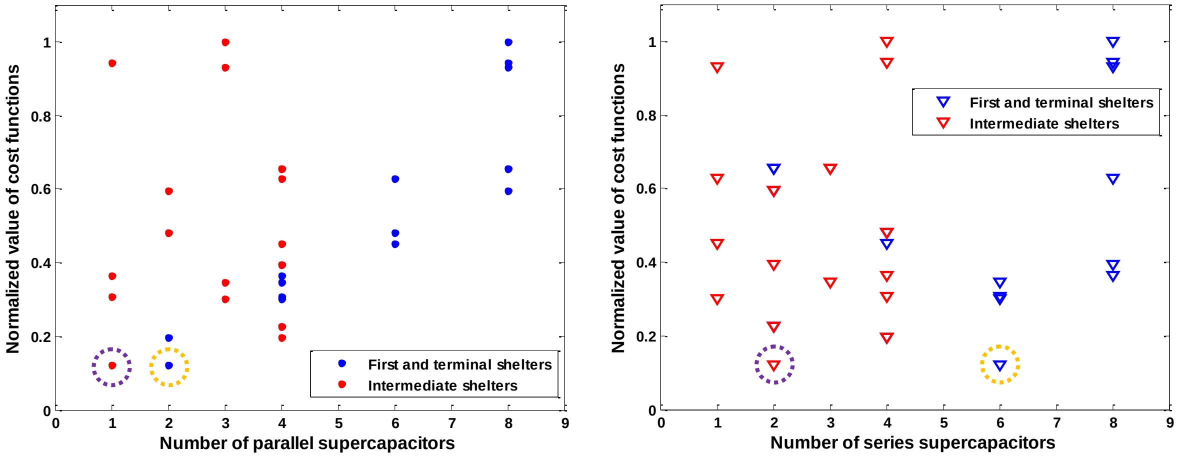


(**a**) (**b**)

Figure 6. Mechanical power and speed profile of a train traveling on the railway: (**a**) Mechanical power necessary by the train; (**b**) Train speed along the track.

Table 3. Datasheet of Maxwell BMOD0063 P125 B08.

Quantity	Values
Rated capacitance	63 F
Rated voltage	125 V
Stored Energy	140 Wh
Nominal Voltage	750 V
Number of passenger stations	5
Maximum series voltage	1500 V
Absolute maximum current	1900 A



(**a**) (**b**)

Figure 7. Supercapacitors that must be installed at the initial and terminal stops: (**a**) Number of parallel supercapacitor for the first and terminal shelters (blue) and the intermediate shelters (red); (**b**) Number of series supercapacitor for the first and terminal shelters (blue) and the intermediate shelters (red).

Table 4. Results of the optimization procedure

Quantity	Values
n_{p1}, n_{s1}	(2 , 6)
n_{p2}, n_{s2}	(1 , 2)
n_{p3}, n_{s3}	(2 , 6)
n_t	8
P_{d1}	460 W
P_{d2}	970 W
P_{d3}	460 W
Value of objective function	199 kEuro

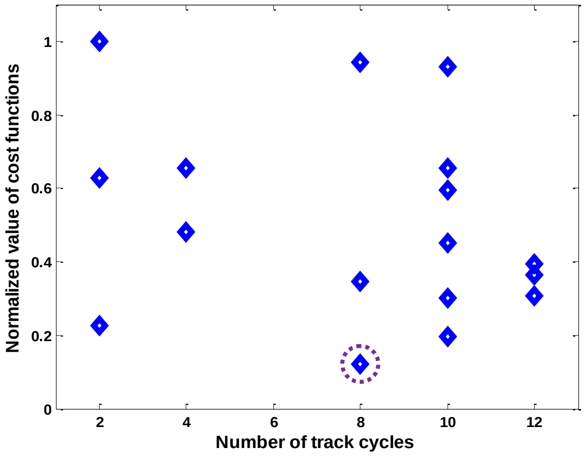


Figure 8. Number of time interval of 15 minutes utilized for the recharge of supercapacitors.

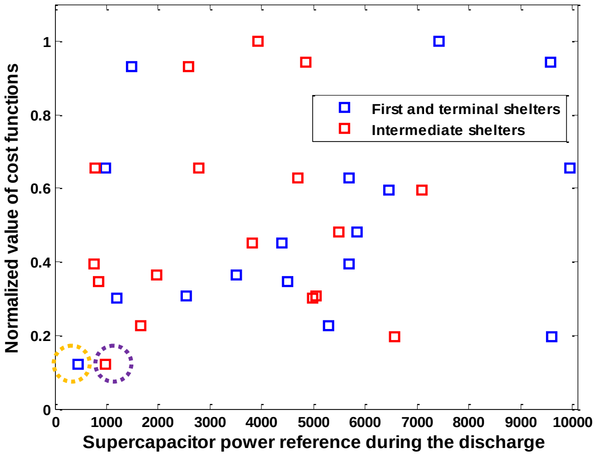


Figure 9. Power available for the control of supercap in the discharge process.

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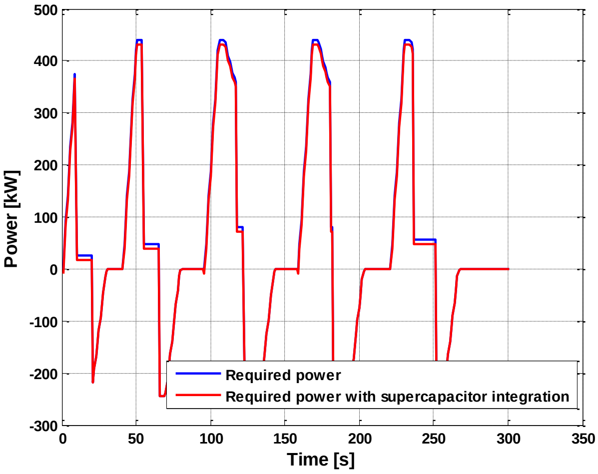

Figure 10. New power profile with integration of supercapacitor charged with photovoltaic modules.

6. Conclusion

The integration of PV panels, SC energy storage systems, and railway power systems was analyzed in this paper.

This study considered a real tramway track and simulated a real train operating on that track. Starting from the analysis of the available shelters and available surface, the PV energy was calculated, and the utilization of this energy in the railway power system was determined by means of an innovative random optimization procedure.

An appropriate random optimization procedure was proposed and implemented using the data available for the production of electrical energy in the worst and best cases during the year, in order to find the optimal size of the energy storage system, the time needed to charge the SCs with the PV panels, and the reduction of the total losses in the net.

The procedure found the optimal value of the cost functions and demonstrated the technical feasibility of integrating the PV power plant in order to supply a railway system.

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