SCUOLA DI INGEGNERIA INDUSTRIALE
E DELL'INFORMAZIONE

EXECUTIVE SUMMARY OF THE THESIS

Hybrid energy storage system for recovering regenerative braking energy of railway systems taking advantage of EVs battery

TESI MAGISTRALE IN ENGINEERING – INGEGNERIA

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1. Introduction

According to the EU climate commitment objectives by 2050, moving towards a zero-carbon and environmentally friendly energy transition requires an evolution in the transportation section, especially in the electrification of transportation infrastructures based on sustainable and renewable energy sources (RES) [1, 2]. Supplying the required energy of widespread electric transportation means would overload the power grid and cause some additional problems. There are many kinds of research in the literature dedicated to the integration of RESs into the supplementary supply of EVCIs [3-5]. However, the integration of these sources in railway sectors has been investigated in very limited studies [6-8]. Given that ERSs possess a high potential to be integrated with RESs due to the existing distributed lines and inherently DC hubs, utilizing the available installations and equipment, can facilitate the energy transfer between them [9]. Despite the RESs, the inherently recovering energy feature during multiple braking of trains in stations makes it a susceptible solution to a supplementary supply of EVCIs. Despite that many publications exist explaining different types of RBE saving methods [10-12], a few papers have paid attention to charge EVs with it together with utilizing energy storage systems [13- 15]. In other words, the direct transferring of RBE to EVs batteries is still a challenge due to the megawatt range of power generated during the braking of trains and its short length. The integration procedure can be implemented in two scenarios based on the different architectures of smart ERSs [9, 16]. Interconnecting DC ERS with DC EVCI or integrating DC ERS with DC EVCI. The high-power ultra-fast charging stations can be a suitable option to be connected to ERSs to increase the power absorption potential of EV parking lot [17]. However, the establishment of multiple numbers of mode 4 DC fast charging systems in park-and-ride areas with the current high costs of power electronics equipment does not have any economic justification. Motivated by this issue, in this research, a novel strategy is presented to integrate mode 3 EVCIs into the DC metro railway system inside urban and park-and-ride areas.

The proposed weighting management method in EV aggregator unit is designed in such a way that each EVs battery based on its situation can contribute to the absorption of RBE or supplying train in accelerating mode. In other words, the bidirectional connection proposed by converters allows the aggregated EVs also to discharge providing traction energy for close accelerating trains in order to reduce peak demand stresses from the grid. The main challenge for the proposed strategy is the availability of EVs in sufficient numbers parked in parking lots. This research investigates the scale of the needed EV population in park-and-ride areas with a real distribution profile of EVs. The rest of the research is structured as follows. In section 2 the proposed system modeling including ERSs and EV station is presented. Then in section 3, the proposed power management system for aggregator is discussed. Section 4 is dedicated to the simulation results of different scenarios and analysis for the considered case study. Finally, section 5 concludes the research.

2. Principles of proposed system

2.1 Railway System Modeling

The overall model of the proposed system is shown in Fig.1. It is assumed that an EVCI supplied by the grid is located at a traction substation (TSS) in a park-and-ride area with the possibility of more than 300 vacant parking places for cars. As a real case study, San Donato station in Milan city is considered as shown in Fig.2. Due to the daily profile analysis of the park-and-ride area, the daily traffic of trains is considered in the station with both braking and acceleration events. Figure.3.a shows the one-hour power profile related to the TSS in semi-rush hours. The maximum power demand of 1.1 MW is typical for metro locomotives. Due to this power range and because of the internal loads of TSS, a contracted power known as grid connection limit is required to supply continuously the substation. As it is obvious from the figure, the expected profile for the substation is considered almost ideal with normal rail operation. (differences in train weight, passenger numbers, and same moments of train arrival and train departure are not considered). The daily 24-hour power profile model reveals 115 train departures/arrival. Based on the time of each event, in other words, about 4 hours (17% of the day hours) is dedicated to the traction power needs for acceleration and about 2 hours of the day (9%) is for regenerative braking power which can charge EV lots.

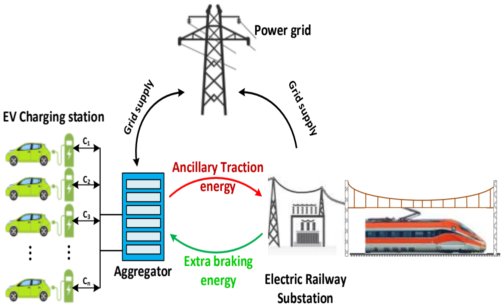


Figure 1: Proposed integration system in park & ride area.

2.2 EV Charging Parking Lot Modeling

As mentioned before, due to the mismatch between power ranges (the power of trains in the range of megawatts and the power of EVs in the range of several kilowatts), high-power DC EV chargers or large AC EVCIs with many low-power chargers are suitable choices for integration. In this context, a parking lot with more than 500 available spaces in which the portion of 200 are equipped with AC EV chargers' technology (mode 3) is considered to be integrated. The proposed EVCI is connected to the DC hub of the metro railway system by a DC/AC converter. Controlling of converters depends on the aggregator management system, the number of available EVs, the maximum charging/discharging power, and EVs SOC. To design the large parking lot together with the substation of the railway system, the real

Figure 2: Under study park & ride area in Milan city.

distribution profile which demonstrates the number of EVs during the day and arrival and departure times must be defined. Two power profiles regarding large parking lots in park-and-ride areas can be considered as Fig.3.b.

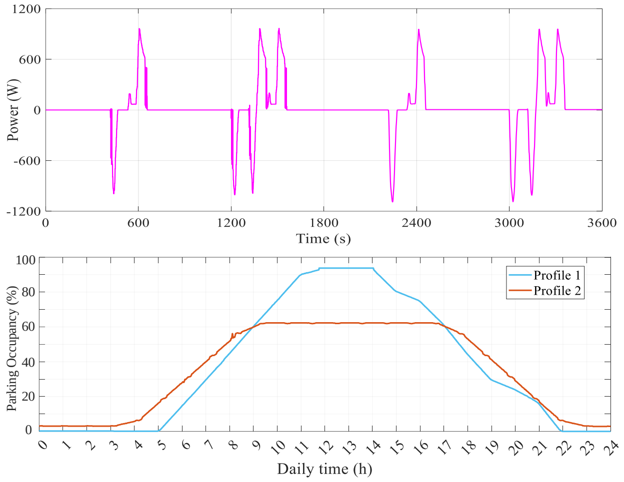


Figure 3: Distribution profile of Train substation and EV parking lot. a) Consumed and generated power of TSS during semi-rush hours. b) EV parking lot daily occupancy profile.

2.3 Battery and supercapacitor

When the train is in acceleration mode, the train has a power that is not zero, and when it is in regenerative braking mode, it can send power back to the power grid. When the power demand goes beyond a certain limit, the EVs in the park and ride location are used to either reduce the peak power demand or fill in the gaps in power demand [19]. However, whole during the day it cannot supply the total train power, so in the proposed method if the power demand is higher than the available power capacity of EVs, the HESS is in charge of supplying the remain load power and vice versa.

A HESS main idea is that heterogeneous energy-storage systems (ESSs) have complimentary qualities, specifically with regards to power density and energy density. Instead of adopting only one kind of ESS, hybridization combines the benefits of both to offer better performance. In railway settings, an HESS is usually a combination of at least two (ESS) devices, one for high-energy requirements and one for high-power demands. The high-power device can be utilized to provide power for brief periods of high power demand, while the high-energy device can be employed to meet prolonged energy needs. To address the energy needs of rail systems, batteries and supercapacitor are ESS components that can be combined into a HESS.

Also, [20] Using energy reserves during periods of low load, HESS helps to reduce the need for peak power. To do this, the charging threshold line PL1 and the discharging threshold line PL2 are used to build the power allocation criterion. A part of a power network's load power and demand curve is shown in Fig. 4.

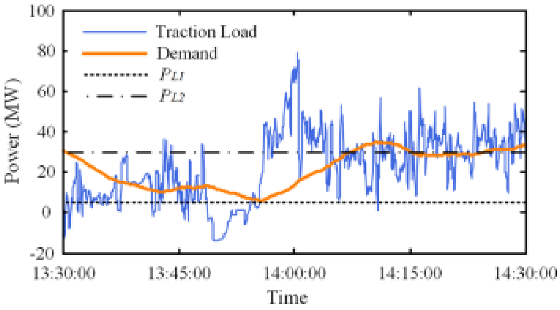


Figure 4: Feeder traction load power curve [20].

HESS is set up to discharge if the traction power is greater than PL2. If the traction power is less than PL1, HESS is charging. Sometimes, the HESS is in standby mode. The following formulas can be used to state it precisely:

$$P_{HESS}(t)=\begin{cases} P_{HESS}, P_{Load} > P_{L2} \\ 0, P_{L1} < P_{Load} \leq P_{L2} \\ P_{Load} - P_{L1}, P_{L1} - P_{HESS} < P_{Load} < P_{L1} \\ -P_{HESS}, P_{Load} \leq P_{L1} - P_{HESS} \end{cases}$$

where P_{HESS} is the rated power of HESS, and P_{HESS} > 0 indicates HESS is discharging state.

3. Aggregator charging management system

The proposed EV parking lot is connected with a AC/DC converter with bidirectional power flow capability to ERS realizing energy transfer in both directions. The configuration of such a converter, its control method, and its performance is out of this research's goals. The main issue in the power management system is determining charging rates for each EVs based on its situation. In this regard, the base power capacity of batteries is assumed as 1 kWh and step changes of charging power are considered as 0.5 kW. For each EV charger, two main factors are defined to determine the instantaneous charging rates.

Charge Weighting Factor (CWF)

This factor demonstrates the EV's priority to absorb power (the higher amounts show the higher chance of EV being selected to charge). The equation of CWF can be calculated as follow.

$$CWF = (1-SOC) \times \frac{C_i}{C_b} \times \frac{P_i}{P_b} \qquad (1)$$

Where, C_i, C_b are EV_i battery capacity and base capacity and P_i, P_b are maximum charging rate and base power rating. In other words, CWF is 0 when SOC of the EV's battery is 100%

Discharge Weighting Factor (DCWF):
This factor demonstrates the EV's priority to discharge power for supplying traction power required by train (the higher amounts show the higher chance of EVs to be selected to discharge). - see equation (2). The equation of CWF can be calculated as follow.

$$DCWF = SOC \times \frac{C_i}{C_b} \times \frac{dP_i}{P_b} \tag{2}$$

Where, dP_i, is the maximum discharging rate. In other words, DCWF is 0 when SOC of the EV's battery is 0%.

Simulation Results

To demonstrate the effectiveness of the proposed integrated system, the influencing factors are selected as different scenarios. The three main parameters which affect the integration are the number of EVs, maximum charging rate, and grid limit connection power. Therefore, three scenarios are considered for the number of available EVs as 75, 100, and 150. Meanwhile, according to the mode 3 charging features, 11 kW is determined as the maximum charging rate. Figure. 4 shows the provided supplying power potential from the EV parking lot during the day in each of the three scenarios.

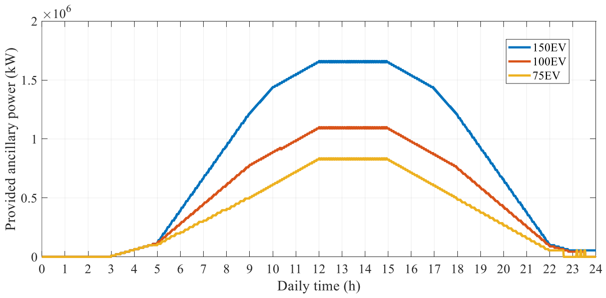
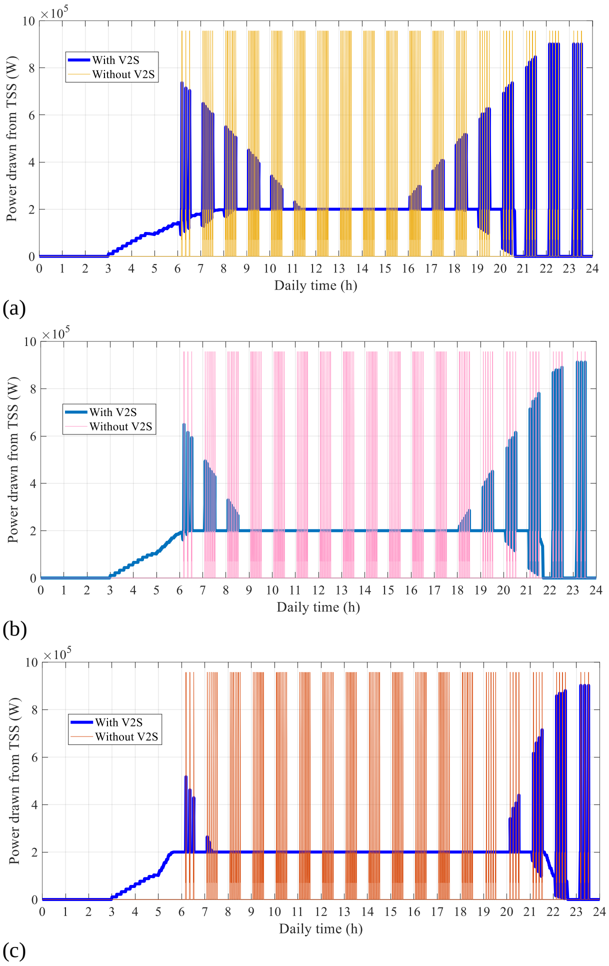


Fig. 4. Provided supplying power in EV parking lot for V2S technology.

As the discharging limit of chargers is larger than the maximum charging rate, the supplying potential power of the proposed EV parking lot is capable of completely supplying a train during acceleration mode whenever the provided supplying power potential exceeds the threshold of 1100 kW (in Fig. 3.a). It is clear from Fig. 4 that, for scenarios 2 and 3 with 100 and 150 EVs, the proposed system reach this threshold from 11:00 to 15:00 and 08:00 to 18:00.



(a)

(b)

(c)

Fig. 5. Power absorbed from TSS. a) With 75 EVs. b) With 100 EVs. c) With 150 EVs.

This period includes a significant share of the total traffic of trains. Even in scenario 3 with 75 EVs, it is possible to supply part of the required power of the trains in an auxiliary way.

Fig 5.a to Fig.5.c shows how EV parking lot provided supplying power can do peak shaving and reduce demanded power by TSS from the grid. The power demands of TSS with/without the auxiliary supply of EV parking lot known as vehicle-to-substation technology (V2S) are mentioned as legends in these figures. Based on the assumption in the railway system, as shown in the figure, the TSS includes a total of 115 power peaks of 1100 kW for each train departure. However, with V2S concept implementation for each scenario, power demand peaks (as shown in blue colors) are reduced. It is obvious that for scenario 3 with 150 EVs, excluding a short peak from 6:00 to 6:30, (due to the lack of EVs), power demand peaks for other time of the day is mostly mitigated. However, from 20:30 to midnight, the V2S concept cannot completely support TSS and eliminate peaks.

Fig. 6 illustrates the proposed system's potential for absorbing regenerative braking (RB) power over time. It is determined based on the aggregation of all EVs maximum charging rate at each working point with 11 kW threshold. In order to ensure about full accommodating RBE in EV parking lot, the total power absorption potential has to be more than the threshold of

1200 kW (the peak power during train braking). As can be seen in Fig. 6, this threshold is not reached at any point in scenarios 1 and 2 with up to 75 and 100 EVs. However, in scenario 3 with 150 EVs the proposed system is capable of completely absorbing RB power from 10:00 to 17:00, covering 65 of the 115 train breaking. The results reveal that, within scenario 3, the proposed system is capable of fully absorbing RBE (S2V) and also capable of fully supplying TSS (V2S).

Fig. 7 demonstrates the changes in SOC during the day for the three scenarios.

In reality, the initial SOC of each EV is random but, in this research to analyze the performance of SOC in a simple way, we assumed two scenarios with initial SOC of 40% and 60%. Comparing the three scenarios in figure 7, it is obvious that, for all of EVs SOC has been increased into an acceptable range. Considering the grid connection limit as 200 kW in these scenarios, the SOC increment per EV is higher in a scenario with a low number EVs (75 EVs). However, it should be noted that, with the low number of EVs, there is extra RBE which must be accommodated by implementing extra energy storage systems or sent back to the grid.

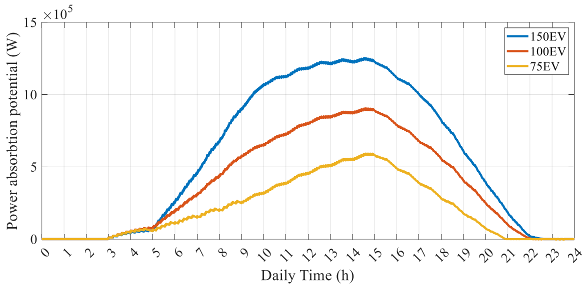
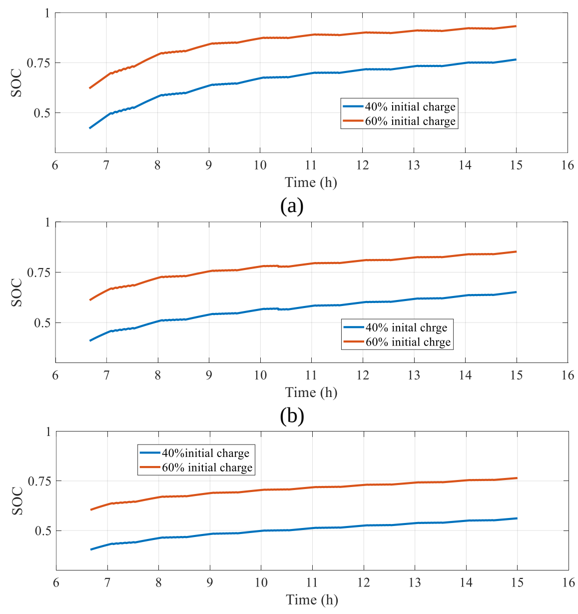


Fig. 6. RB power absorption potential for the proposed system with different numbers of EVs.



(a)

(b)

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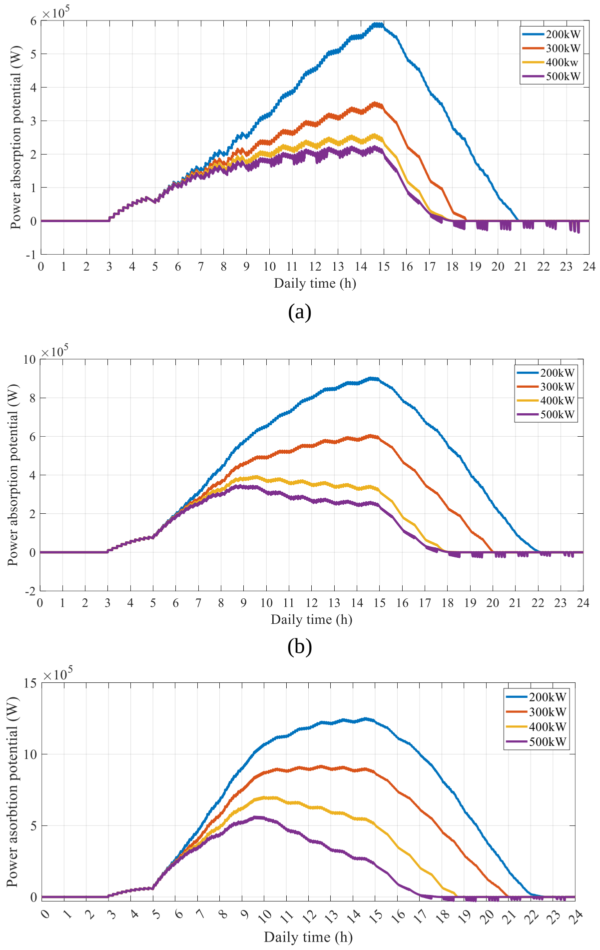
Fig. 7. SOC changes in EV. a) 75 EVs. b) 100 EVs. c) 150 EVs.

The other factor that impact the proposed system performance is the grid connection power which is available to both TSS and EVs in a joint DC hub. To show its performance, the 24-hour operation is simulated by changing the grid connection limit in the range of 200-500 kW. For this scenario, EV numbers also are variable from 75 to 150 with the maximum charging rate as 11 kW. The results shown in Fig. 8, reveal that enhancing the grid connection power remarkably prevents the capability of the EV parking lot to absorb RB power. Meanwhile, it is strongly in the afternoon than in the morning. The results also reveal that even with 150 EVs, if the grid connection power threshold is more than 250 kW, the proposed EV parking lots would no longer be capable of fully responsible for S2V and V2S technologies.



(a)

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Fig. 8. RB power absorption potential for the proposed system under different grid connection limits.. a) With 75 EVs. b) With 100 EVs. c) With 150 EVs.

5. Conclusions

In this research, an integrated sustainable transportation power supplying system for ERS and EVs is proposed objecting to increase energy efficiency in charging stations and decrease the cost. In this context, a coordinated charging/discharging-based power management system is designed for the aggregator to determine the momently power charging rate for each EVs and charge their batteries by regenerative braking energy of trains and taking advantage of batteries energy to auxiliary supply the trains during acceleration mode towards peak shaving purposes. A park-and-ride area in Milan San Donato metro substation is considered as a real case study. The 24 hours simulation results based on real data of train traffics and EV parking lot profile, with different global charging/discharging rate and grid connection limits, are carried out. According to the results, the proposed integration system performs well with the higher number of EVs. The low number of EVs in the morning and late evening remarkably prevents system performance. Meanwhile, the impact of EV numbers with lower SOC is higher than the increasing EV charging rates threshold. According to the obtained results, with the exact design of EV charging infrastructures in park-and-ride areas and implementing an accurate aggregator control system, significant peak shaving can happen for highly demanded TSS. The high number of EVs participating in the proposed system is the main challenge that can be facilitated by utilizing also other energy storage systems implemented in TSS.

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