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Catenary overvoltage stabilization of DC railway electrical system by integrating EV charging stations

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***Abstract*—The DC railway electrification systems are widely used to supply the national, regional, and urban (metro and tramway) railway systems. However, the catenary line voltage is subject to high voltage variations due to the moving train loads. The catenary line voltage drops when the train accelerates, while the overvoltage occurs when the train brakes. The frequent overvoltages can increase system maintenance costs and reduce life cycles of the onboard devices. In a practical design, if the catenary voltage reaches its upper limit, the rheostat brake is performed to maintain the voltage stability. The braking energy is dissipated as heat by the onboard rheostat, such operation can reduce the global energy efficiency. Therefore, this work proposes to install Electrical Vehicle (EV) charging stations along the DC electric railway line in order to stabilize the catenary voltage. The braking energy is used by charging EV to achieve higher energy efficiency. A regional 850 V DC railway microgrid located in mountain area is considered in this work. Two cases without and with EV chargers are modeled, simulated, and compared by using Matlab/Simulink. The results highlight the performance of the EV charging solution in terms of voltage stabilization and braking energy savings, also economic aspects.**

***Index Terms*—DC railway electrical network, catenary voltage, overvoltage stabilization, EV charging, droop control, braking power, energy savings, global energy efficiency.**

NOMENCLATURE

E_{SST}	Rated voltage of substations [V]
I_{SST}	Current of substations [A]
U_{Train}	Trains voltage [V]
I_{Train}	Trains current [A]
P_{Train}	Trains tracking power [W]/[kW]
P_{Brake}	Trains braking power [W]/[kW]
V_{Train}	Trains speed [m/s]/[km/h]
X_{Train}	Trains position [m]/[km]
U_{EV}	EV chargers voltage[V]
I_{EV}	EV chargers current [A]
P_{EV}	EV chargers power [W]/[kW]

I. INTRODUCTION

The DC Railway Electrical System (DC-RESs) are widely used in the national, regional, and urban (metro and tramway) railway systems [1], [2]. In a typical DC-RES, the substation consists in a transformer and diode rectifiers, in which the power flow is unidirectionally transferred from the AC grid to the DC Traction Network (DCTN) [3]. The trains connect with the DCTN though a pantograph or a third rail [3]. Moreover, the trains continuously change their physical connection points with the DCTN. The DC catenary line voltage is subject to high voltage variations due to the moving train loads [4]. The catenary voltage drops when the train accelerates, while the overvoltage occurs when the train brakes. Moreover, the power electronics converters and the electrical devices equipped with trains are sensitive to the overvoltages. Frequent overvoltages lead to an increase of maintenance costs and reduce the life cycles of onboard devices. Consequently, a defined limit of catenary voltage is required to ensure efficient and safe operation of the trains. In particular, some railway lines are located in the mountain area. A large amount of braking power is regenerated when the trains decelerate or come down in a downhill area. As the energy transfer is unidirectional in a DC-RES, the braking power cannot be sent back to the AC grid. The braking energy could be used by other trains in traction state provided that their actual positions are very close. Otherwise, if the catenay voltage reaches its upper limit, the braking rheostat should be activated to maintain the voltage stability [3], [4]. As the braking energy is dissipated as heat by the onboard rheostat, obviously, such operation will reduce the global efficiency of energy system.

Many solutions have been investigated to deal with the catenary line overvoltage problems. Firstly, the overvoltage can be mitigated by optimizing the train timetables. However, this strategy must be adapted to the actual traffic conditions [5]. Besides, this method is sensitive to the transport delay. The situation can be improved by upgrading the distribution network such as renewing the transmission line or adding the parallel feeder lines [6]. It is also possible to install inverters in parallel to the diode rectifier to achieve the reversible energy transfer, thereby stabilizing the catenary voltage and saving braking energy to the AC grid [7]. However, large investments are required for these upgrading solutions. The overvoltage issue can be alleviated by building new substations [6]. However, this solution is not always industrially achievable and economically feasible due to a lack of space, or the challenge to reach a connection to the local utility network within rational budget. It is also possible to install on-board or wayside energy storage batteries to achieve a better voltage stabilization and energy savings [8], [9]. However, large costs are needed to purchase these storage devices.

The market share of Electric Vehicles (EVs) in the mobility sector has been steadily growing [10]. Thereby, the EV charging stations services are increasingly required as well. In [10], the authors analyze the potentialities to supply fast-charging stations with the local light DC-RES. The work of [11] discusses the advantages of supplying electrical bus charging stations to the DC-RES. In [12], the authors investigate the benefits by using the DC-RES to supply charging stations located near highways. These research have proved the potentialities to supply EV charging stations with the DC-RES. In this work, therefore, we propose to stabilize the catenary line overvoltage by consuming the braking energy to charge the wayside EVs near the train stations.

In this work, firstly, the DC Railway Electrical Microgrid (DC-REMG) is formulated to study the proposed strategy. The EV charging stations are integrated along the railway line in order to stabilize the catenary line voltage. The braking power is used to charge EVs to achieve a higher global efficiency of the whole energy system. The droop control strategy is applied into Energy Management System (EMS) with the following rules: the charging power will be reduced when the locally measured voltage drops; the charging power will be rapidly increased up to its maximum power when some significant overvoltages occur. The EV charging stations sites must be properly chosen to enable an efficient droop control. The charging power values are configured by considering both the potential capacity of braking power and the attractiveness for EV charging users. Finally, two cases without and with EV chargers are modeled, simulated, and compared by using Matlab/Simulink. The comparative results indicate that the proposed solution can reduce the overvoltage variations and reach a better global efficiency of the energy system.

The paper is organized as follows. Section II describes the DC railway electrical micro-grid system under study including the main subsystems and its essential modeling information. Section III presents the proposed voltage stabilization solution. The droop control design is detailed here, and the sites of EV charging stations are reasonably determined as well. Simulation results are provided and analyzed in Section IV. Finally, some conclusions are remarked in Section V.

II. DC RAILWAY ELECTRICAL MICROGRID UNDER STUDY

The DC Railway Electrical Microgrid (DC-REMG) under study is illustrated in Fig. 1. The railway line is located in a mountain area with a length of 20 km. There are two trains running in opposite direction each hour. There are six train stops (S1-S6) along the whole railway line. The DCTN is supplied by two substations that are respectively located at 0 km and 20 km. The substations are composed of transformers and diode rectifiers. The power flow is thus unidirectional from the AC grid to the DCTN. The rated voltage of the substations is 850 V, and the maximum power is limited to 1500 kW.

The EV charging stations are integrated along the railway line to stabilize the catenary line voltage. The voltages of the charging sites are measured and sent to the EMS. The proposed voltage stabilization solution will be detailed in Section III.

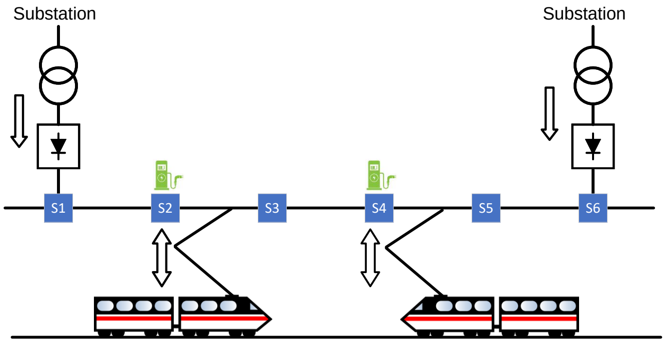

Fig. 1 Electrical DC railway microgrid under study

A. Modeling of the train traction system

The train traction model has been discussed in previous work [2]. Some essential modeling information will be briefly presented here. In each hour, there are two trains running along this railway line in opposite direction, whose speed and position profiles are shown in Fig. 2. Their speed profiles are formulated by considering the train timetable. Besides, the maximum speed is limited by the actual geographical conditions. As indicated in Fig. 2, the trains will stop for 2 minutes at each train station located at 4 km, 8 km, 12 km and 16 km. The two trains cross between stations S3 and S4.

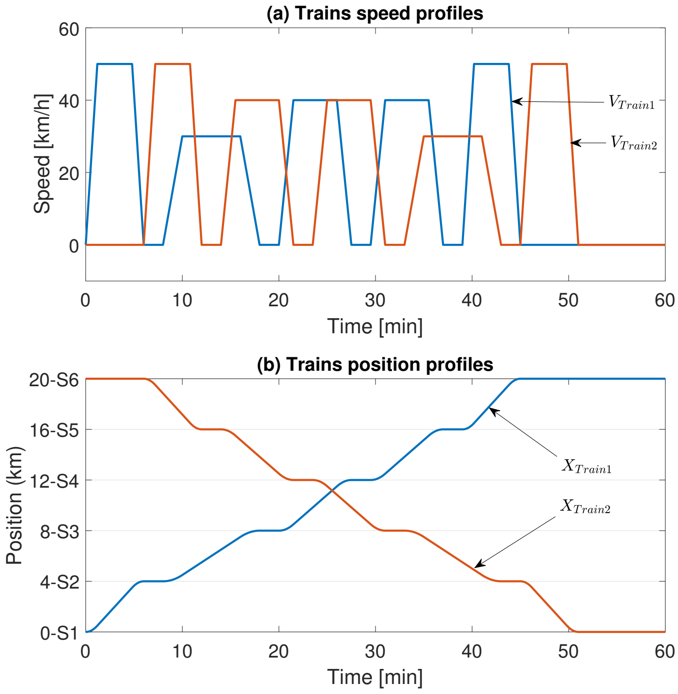

Fig. 2 Speed and position profiles of two trains per hour

As the trains pass through the mountain area, the force due to the steep ramp is a critical factor for the train traction system. The slope and the altitude information are provided in Fig. 3. It can be observed that the maximum slope reaches around 50 m/km between 4 km and 8 km. Consequently, a large amount of braking power will be regenerated when the train comes down. In this situation, the catenary voltage will increase significantly near this area.

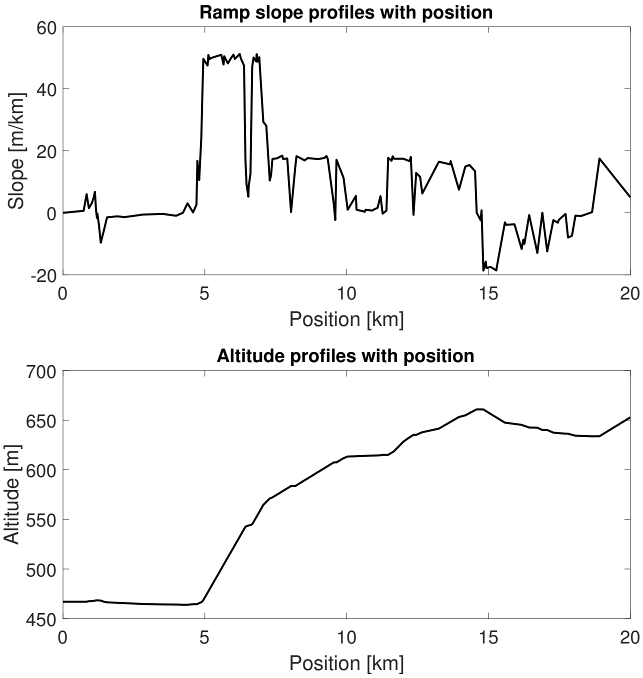

Fig. 3 Ramp slope and altitude profiles

B. Modeling of the DC traction network

The DCTN is modeled by using the method of Modified Nodal Analysis (MNA), which is fully described in [3]. The MNA can solve complex DC networks composed of several current or voltage sources. The MNA model can be mathematically represented by

$$\begin{bmatrix} U \\ I \end{bmatrix} = \begin{bmatrix} G & -B \\ B^t & -R \end{bmatrix} \begin{bmatrix} J \\ E \end{bmatrix} \tag{1}$$

where the vectors J and E are the variables of the known initial currents and voltages. The element of matrix B is 1 if the voltage source corresponds to the subsystem at the corresponding node, and 0 elsewhere. The matrix R is the internal resistance of voltage source, which is quite small for an infinite power system. The output vectors U and I are the unknown voltages and currents to be calculated at each node.

Another key question is how to integrate the moving train loads into the DCTN. This work introduces the modeling method discussed in [6]. Firstly, the contact lines are split into small elements. Then, according to their position, the trains are connected to the most suitable node. If a train is connected to a certain node, the load value of this node is set to the train power; otherwise, it is set to zero.

A switched model is introduced to describe the non-linear behavior of the diode rectifier using an ON-state model and OFF-state model, which has been described in [3]. The state is determined by the catenary voltage value U_{SST} corresponding to the node of substations calculated in previous step and the normal voltage of substations E_{SST}. The ON-state ($U_{SST} < E_{SST}$) current is calculated according to the DC current exchanged with the DCTN. The OFF-state model ($U_{SST} > E_{SST}$) imposes zero currents on the DC side.

It must be highlighted that the conventional MNA is unable to deal with the case where all the substations are disconnected, beacuse there is no voltage reference to solve the MNA equation. When all substations are disconnected, the train on braking mode will turn to a voltage source with a drop control [3]. The drop control is formulated by considering the voltage protection rules and the behavior of the rheostatic brake. Details can be found in [3].

III. OVERVOLTAGE STABILIZATION BY INTEGRATING EV CHARGING STATIONS

The catenary line voltage is variable due to the moving train loads. In this work, we propose to install wayside EV chargers along the railway to stabilize the catenary voltage. Moreover, a minimum and a maximum catenary voltage are defined with the values of 600 V and 1100 V in order to ensure efficient and safe operation of the trains. It must be highlighted if there are no EVs connecting with the wayside EV chargers to accept the braking power, the onboard rheostat should be activated when the overvoltage reaches its critical limitation.

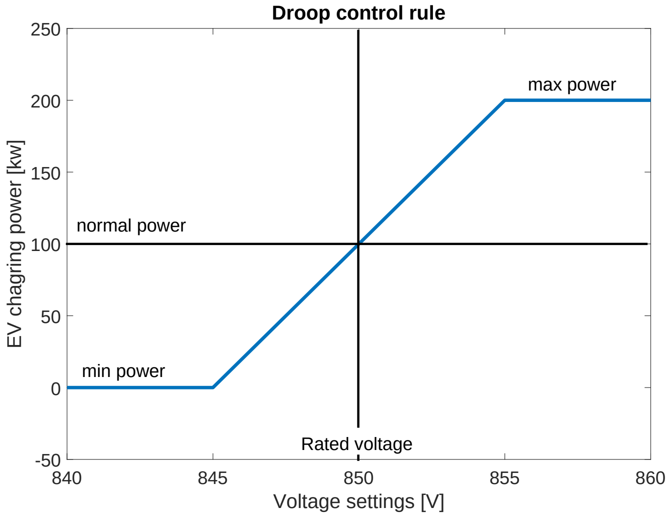

Fig. 4 Droop control rule applied to EV charging system

A. Droop control rule

When the overvoltage phenomenon happens, there is at least one train operating under the braking mode. The idea of this work is thus to stabilize the catenary voltage by recuperating the extra braking power to charge EVs. The Energy Management System (EMS) is achieved by applying the droop control strategy as shown in Fig. 4. The input information of droop control is the catenary voltage locally measured at each EV charging station; the output is the suggested charging power. The charging power values in a droop control are configured by considering two aspects: the potential capacity of braking power and the attractiveness of EV charging users. The droop control regulates the EV charging process with the following rules: the EV charger will reduce its charging power when the measured voltage drops; the EV charging power will be rapidly increased up to its maximum power when some large overvoltages occur at local sites.

Regarding the modeling, the EV chargers are integrated to the DCTN in the form of loads node, which are fixed to the closest node according to their installed position. The EV charging power is distributed into the corresponding node.

B. Choice of the charging site

A critical issue is how to choose a proper site of EV charging station to allow an efficient droop control. Firstly, the train stations are the first choice due to their attractiveness for EV charging users. Secondly, as the droop control regulates the charging power by observing the voltage variations, the sites with large voltage variations are mainly concerned to apply the proposed droop control strategy.

The voltage curves of main train stops (S1-S6) along the railway line during one hour are shown in Fig. 5 for the case of absence of chargers. Firstly, when the chosen sites are far from the main substations or near the large ramp area, their voltages changes are more sensitive to the varying train loads. Secondly, if the sites are closer to steep ramp or deceleration areas, the EV chargers can recuperate the braking power more easily. The droop control applied to such sites can hence perform more efficiently. Eventually, note that the braking energy can be consumed directly by the trains themselves when two trains are very close. Therefore, it is better to place the EV charging sites far from the crossing point of trains. Following the above remarks, two train stops located at 4 km (S2) and 12 km (S4) are finally chosen to install the EV chargers.

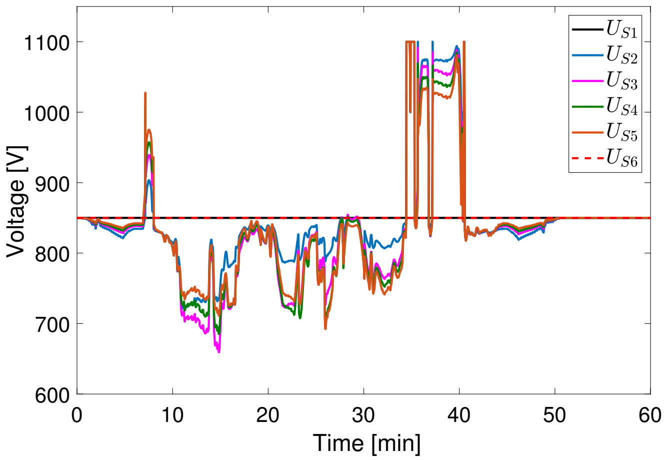

Fig. 5 Voltage profiles of main stops (S1-S6)

IV. SIMULATION RESULTS AND ANALYSIS

The complete simulation model of the DC-REMG system described in Section II are built under Matlab/Simulink environment as shown in Fig. 6. The subsystems of two trains and EV charging stations are integrated into the DCTN.

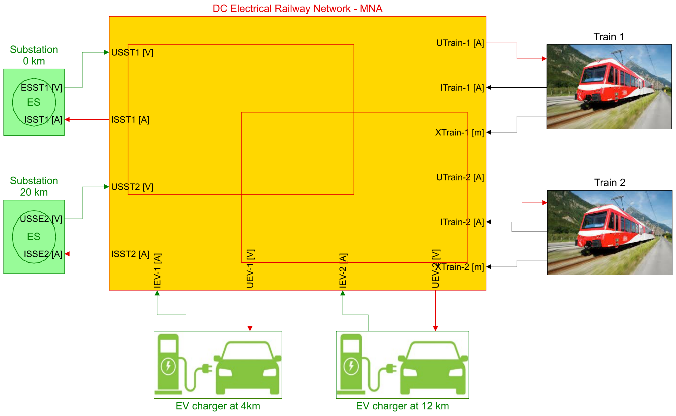

Fig. 6 DC-REMG simulation model with Matlab/Simulink

Two cases as follow are simulated and compared:

Case 1: No EV chargers are integrated along the railway line. When the train catenary voltage reaches its maximum limitation, the generated braking power has to be wasted by the onboard rheostat.

Case 2: EV chargers are integrated at train stop S2 and S4. The catenary voltage is stabilized by using the extra braking power to charge the wayside EVs.

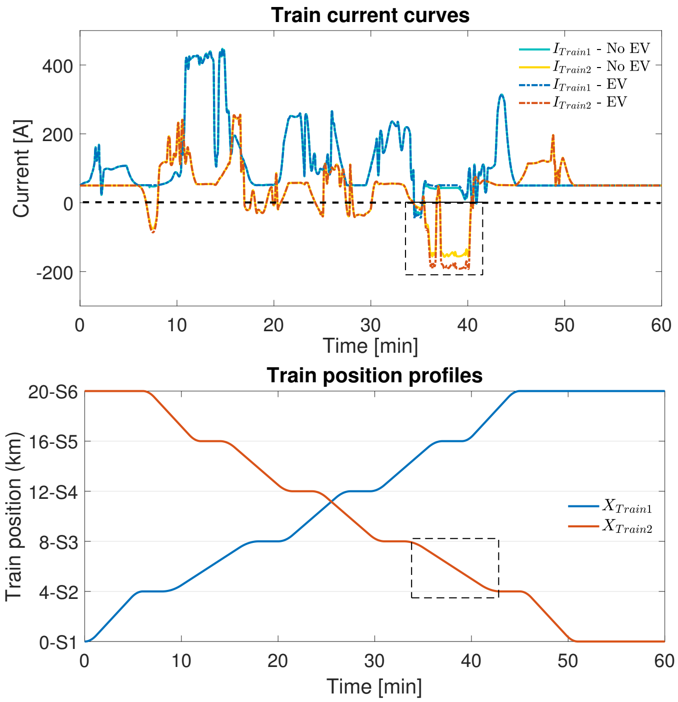

Fig. 7 Currents and position profiles of two trains

The current profiles of two trains are analyzed as shown in Fig. 7. Note that the currents are positive when the trains are operating in traction mode and negative under braking mode. The braking power is regenerated when the trains decelerate or come down in a downhill area. In particular, large braking power is regenerated when the train comes down between 4 km and 8 km. The currents profiles of the two cases perform similarly in traction mode. The integration of EV chargers will not effect the performance of the trains.

The critical simulation results of two trains during one hour for both cases under study are presented in Fig. 8. For both cases, the catenary voltages are maintained in the safe operation range ($600V < U_{Train} < 1100V$) as shown in Fig. 8 (a)-(b). The overvoltage variations of case 2 are much smaller compared to that of case 1. For case 1, the overvoltage protection is achieved by activating its onboard rheostat brake. For case 2, the droop control regulates the EV charging power according to the overvoltage variations measured at the charging sites. The EV charging power will be rapidly increased up to its maximum when large overvoltages occur as shown in Fig. 8 (c). The results indicate that the proposed solution can efficiently reduce catenary voltage rises.

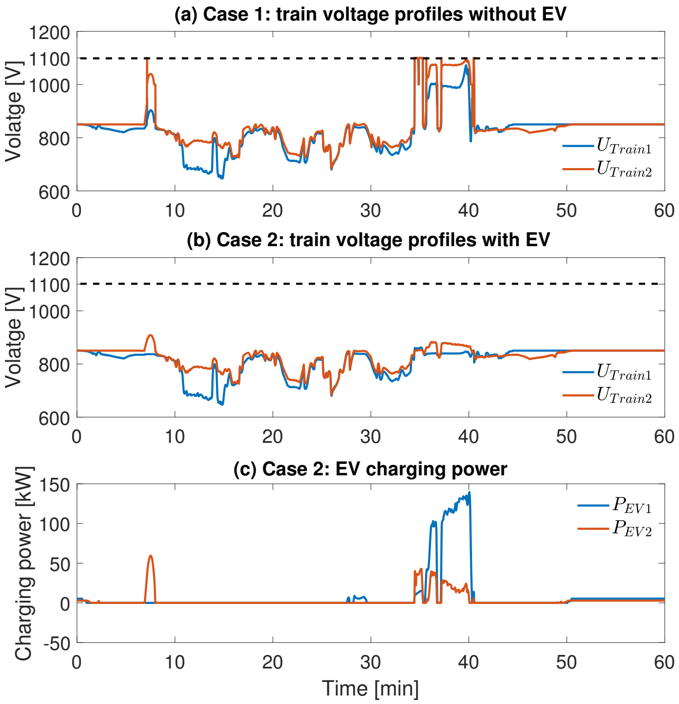

Fig. 8 Comparative results between case 1 and case 2

The braking power of trains and the EV charging power are compared and shown in Fig. 9. It is noted that the train in braking mode is considered as a voltage source for comparisons convenience. Thus, the braking power turns to be positive from the perspective of the EV charger. The results indicate that the braking power of two trains are efficiently recuperated by the wayside EV chargers by applying the droop control. Compared to case 1 whose braking energy is dissipated as heat by the onboard rheostat, the global energy efficiency of case 2 is obviously increased.

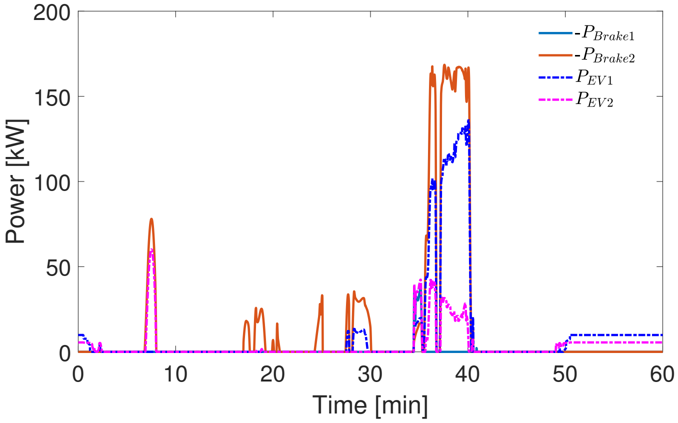

Fig. 9 Comparison of EV charging power and braking power

It is worth highlighting that when two trains are running near the crossing point between stations S3 and S4, as their positions are very close, the braking power is directly consumed by the train in traction mode. That is the reason why quite small amount of braking power is recuperated by the EV batteries for the period $t = 20 \sim 30$ min.

V. CONCLUSIONS

This work analyzes a regional 850 V DC railway microgrid located in mountain area. The EV chargers are integrated along the railway line to stabilize the catenary line voltage. The extra braking energy are consumed by charging the wayside EVs. The droop control strategy is designed to regulate the EV charging process. The EV charging stations sites are properly chosen that can ensure an efficient droop control. Two cases without and with EV chargers are modeled, simulated and compared. The results indicate that the proposed solution can significantly reduce catenary voltage rises, meanwhile, achieve better global energy efficiency. Moreover, the stable catenary voltages can reduce system maintenance costs and extend the life cycle of onboard devices, benefiting economic aspects.

It must be highlighted if there are no EVs connecting with the wayside EV chargers to accept the braking power, the onboard rheostat should be activated when the overvoltage reaches its critical limitation.

Note that the proposed solution can efficiently stabilize the overvoltage, however, it cannot deal with the voltage drops. Because the energy transfer is unidirectional from the DCTN to the EV batteries. The Vehicle-to-Grid (V2G) concept has been popular, which would be a potential research direction to address such issues in the near future.

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