Applied Energy 260 (2020) 114177

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Study of trackside photovoltaic power integration into the traction power system of suburban elevated urban rail transit line

Xiaojun Shen, Hongyang Wei, Li Wei*

Department of Electrical Engineering, Tongji University, Shanghai 200092, China

HIGHLIGHTS

- Trackside PV power integrated into the traction power system of urban rail transit (URT) is studied.
- Trackside PV installation in suburban elevated URT Line is economically feasible in Shanghai.
- A DC side PV integration scheme and energy management strategy has been suggested.
- Simulation models based on the characteristics of URT power system and moving trains are developed.
- Challenges and future directives for DC side PV integration in URT system are outlined.

ARTICLE INFO

Keywords:
Urban rail transit
DC traction power system
Trackside PV
DC side PV power integration
Energy storage

ABSTRACT

The trackside of suburban elevated urban rail transit (URT) line is a potential platform for placing Photovoltaic (PV) panels. This paper has made a comprehensive study of trackside PV power integration into the direct current (DC) traction power supply system of URT. With the elevated section of Metro Line 11 in suburban Shanghai as an example, the potential PV installation capacity has been evaluated. Based on the unique feature of the DC traction power supply system, a DC side PV integration scheme and control strategy has been proposed. The simulation models based on the electrical characteristics of URT power system and the moving train have been especially developed as an effective tool to perform the scenario analysis of different PV integration schemes, and an energy saving parameter "k" has been proposed to evaluate the energy saving effect. It concludes that DC side PV integration can help to compensate the traction voltage and reduce the catenary transmission loss in the traction stage of trains, thereby it has a higher energy saving rate. Even better performance can be achieved with both PV and energy storage system (ESS) integrated into the DC traction power system. The energy saving result can achieve the effect of "1 + 1 > 2", which means the total amount of energy savings is even larger than the sum of PV or ESS working alone. Moreover, the traction power quality and safety will also be improved.

1. Introduction

URT has become the preferred solution to solve traffic congestion in large and medium-sized cities in China because of being fast, safe, punctual, and having a large passenger capacity [1,2]. However, it is also a huge energy consumer. In Shanghai, the annual energy consumption of URT is more than 1.9 billion kWh. The energy conservation problem is becoming increasingly prominent [3].

As a kind of renewable energy, PV power generation has no pollution and no noise, and it is convenient and flexible to install [4], which has been widely used in many fields [5,6]. A number of studies have been carried out on PV plants [7], PV grid connection systems and control strategy [8,9]. It is very attractive to install PV panels in URT system. The future development of URT urgently needs the introduction of this green, sustainable and low-carbon technology. There have been already some demonstrative projects in URT. Singapore has installed 1 MW of PV system on the roof of metro depots, which can reduce carbon emissions by 500 tons per year. The Belgian Railway Company has built a 3KM long PV tunnel with a power capacity of 3 MW. Indian Railways installed PV modules on the roof of trains to provide ventilation, lighting, and air conditioning [10]. Japan's JR Railway Company installed a 453KW PV unit on the roof of the Tokyo platform, which is expected to generate 340MWh of electricity per year and reduce carbon emissions by 101 tons [11]. Shanghai Shentong Metro

* Corresponding author.
E-mail address: weili@tongji.edu.cn (L. Wei).

https://doi.org/10.1016/j.apenergy.2019.114177
Received 16 April 2019; Received in revised form 7 November 2019; Accepted 13 November 2019

Company also started construction of PV roof for 6.8 MW vehicle segment [12]. Those demonstrative cases show that PV access to rail transit can achieve direct energy consumption and utilization of the terminal, which not only reduces the operating cost, but also effectively reduces the power transmission loss, thereby achieving the goal of green low carbon development of URT. Therefore, it is of great value to study the application of PV power in URT system.

The integration mode of PV is determined by the characteristic of URT power supply system. There are two possible PV integration modes: AC (alternative current) side access and DC side access. The AC side access mode either inverts the PV power into the low voltage system, or feeds it back to the power grid. The DC side access mode converts PV power into DC traction power system and provides traction power to the train directly.

Currently, the AC side PV access mode, which is easier to implement, is adopted by most of the above demonstrative projects and attracts more attention of researchers. Jin et al. [13] expounded the feasibility and energy efficiency of PV power generation system in URT system, and proposed to use low voltage side access in elevated stations to provide a prospect for changing the energy supply mode of URT. According to the characteristics of URT and the advantages of PV system, Wang et al. [14] put forward the application scheme of PV integration in the elevated station, depot parking lot and elevated section. Pankovits et al. [15] propose a topology of PV integration into the URT system, while Meng et al. [16] proposed to combine ESS with PV power generation to achieve full use of PV energy. Şengör et al. [17] proposed a railway station energy management system model composed of PV and ESS, indicating the future development trend of URT. Beyhan et al. studied the feasibility of using PV power for the interior lighting of the urban rail vehicles [18].

Interestingly, the voltage generated by PV panels, generally around 600–800 V DC, matches coincidently with the DC traction voltage. It means that the PV power could be integrated directly into the DC traction power system with less power loss through a simple DC/DC power converter. Moreover, the DC side PV access mode can also work with ESS which will not only reduce energy transmission loss, but also help to stabilize the traction network voltage. Nevertheless, there are few studies on DC side access mode. Hayashiya et al. [19] studied the feasibility of using smart grid technology for rail transit power supply systems, and pointed out that DC side access mode can reduce energy consumption and transmission loss, but only through estimation. Ciccarelli et al. [20] explored the feasibility of connecting PV and supercapacitor ESS to DC traction systems, and analyzed the PV cost. Sayed et al. [21] proposed a DC/DC converter topology of the PV system connected to the DC side, but did not make an in-depth study on the PV power consumption strategy. In addition, Green et al. [22] and the mutation change charity 10:10 are working together on the topology and control mode of direct access to the traction power supply system using PV panel along both sides of the track. So far, there has not been any related report on DC side access demonstrative project.

There are several installation alternatives of PV panel in URT which can be the train roof, parking lot, depot roof, sound barrier, the elevated platform roof and the two sides of elevated line. In this paper, with elevated Metro Line 11 in suburban Shanghai as an example, we focus on the feasibility of PV installation along the trackside of suburban elevated line as the probability of this area being shaded by tall buildings is less than that in downtown area. Based on the characteristics of URT power supply system, a comprehensive study is made of PV integration into the DC traction power system in terms of potential PV installation capacity, possible PV access points, energy saving rate and power quality improvement. The novelty of this paper is summarized as follows:

(i) Feasibility and installation potential of trackside PV installation in suburban elevated line has been evaluated with Shanghai Metro Line 11 as an example.
(ii) Based on the unique electrical characteristics of URT power supply system, simulation models of URT power system and the moving train have been especially developed as an effective tool to perform the scenario analysis of different PV integration schemes.
(iii) A DC side PV integration scheme and energy management strategy has been proposed. Scenario analysis has been performed to assess the energy saving characteristics of DC side PV integration. An energy saving rate parameter 'k' has been proposed to evaluate the energy saving effect.
(iv) Comparative analysis has been made on AC and DC side PV integration in terms of energy saving effect, power supply quality and safety, and we conclude that DC side PV integration has more advantage in terms of energy saving rate and power quality improvement.

The paper is structured as follows: Section 2 is mainly about the technical and economic analysis of the feasibility of trackside PV integration based on the data of Shanghai URT Line 11. Section 3 discusses the unique characteristics of URT power system, and a brief DC side PV integration scheme and energy management strategy has been proposed accordingly. In Section 4, the energy saving effect analysis of DC side PV integration has been performed based on simulation. Section 5 is a comparative analysis of AC and DC side PV integration in terms of energy saving effect, power supply quality and safety. Then in Section 6, the challenges and future opportunities are summarized and finally Section 7 summarizes this research.

2. Feasibility of trackside PV installation in suburban elevated URT line

2.1. Potential capacity of trackside PV installation

In the past two decades, URT has developed rapidly in China. As of April 2019, 38 cities have opened subways. Among them, Shanghai Metro has a mileage of 705 km, ranking the first in the world. It is noteworthy that the URT lines usually have long, elevated sections in the suburbs of China's big cities. The track side along the elevated sections, which is free of the shading of tall buildings, can be used for PV installation.

In what follows, we use Shanghai Metro Line 11 as an example and analyse the potential of the trackside PV capacity, and it is a quite representative metro line in China's big cities, which is featured by the long elevated suburban section. Shanghai Metro Line 11 has an operating mileage of about 82 km, starting at the Disney Station in southeast Shanghai, crossing the city centre, and ending at Huaqiao Station in northwest Shanghai. The city centre section runs underground, and the suburban section is elevated. There are 14 elevated stations in all, with a length of approximately 22.5 km. The possible trackside PV installation space can be the area between the track and the side barrier, as shown in Fig. 1.

Shanghai is located at the forefront of the Yangtze River Delta in China, with the coordinates of 31°14′ north latitude and 121°29′ east longitude. It has an annual sunshine of 1665.3 h and an annual average daily radiation of 12317.8 kJ/m^2 [23,24]. According to the study of Zang et al. [25], the yearly optimum tilt angle of solar panel in Shanghai is $\alpha = 24.\ 2^{\circ}$.The space which can be used for placing the PV panel for Line 11 is 1.60 m wide, and thus the installable area is approximately 39,500 m^2 for a single line. Since URT has uplink and downlink lines, the total available area is about 79,000 m^2. Suppose the effective possible area is 80% and the efficiency of PV modules is 15%, the PV capacity could be around 9.48MWp, and the annual power generation is about 11,840,000 kWh.

Table 1 shows the data of the elevated suburban sections of URT in Shanghai and Beijing by December 2018. Most of the lines have long suburban elevated sections, which are suitable for PV installation. It can be seen that suburban URT lines provide a new platform for distributed

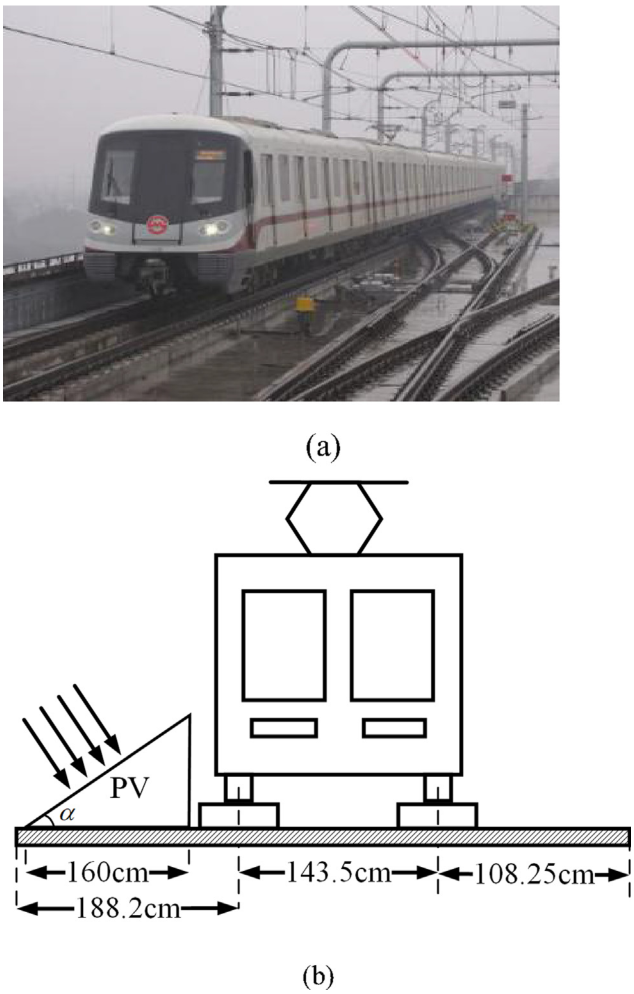

Fig. 1. PV Installation diagram on one track side of elevated URT line (a) The track of elevated line (b) Possible PV installation location on the track side.

Table 1
Data of some elevated suburban lines in Shanghai and Beijing.

City	Line No.	Length	Number of elevated stations
Shanghai	Line 5	30 km	18
	Line 8	12Km	4
	Line 9	12 km	4
	Line 16	50 km	10
	Line 17	17 km	6
Beijing	Line 5	9 km	7
	Line 13	40 km	15

PV power generation system and has great application potentials.

2.2. Return of investment (ROI) of trackside PV installation

ROI is another key issue to consider in the feasibility study of trackside PV installation in URT system. The on-grid price of PV power generation set by the National Development and Reform Commission of China is 1 yuan/kWh in Shanghai, and the yearly revenue generated by the PV system is 11,840,000 yuan accordingly. With the current cost of roof PV in China being about 10,000 yuan/kW, the one-time investment of trackside PV system in the suburban section of Line 11 will be 94,800,000 yuan and the ROI will be about 8 years. With the PV cost getting down and the power generation efficiency enhanced [26], the time cost for the ROI will be even less. According to Jinyue Yan et al, the subsidy-free PV electricity price can be even achieved in China with the development of PV technology [27]. The trackside PV installation which takes full advantage of the idle space on either side of the elevated track is very promising. It will bring huge economic and social benefits for a city like Shanghai.

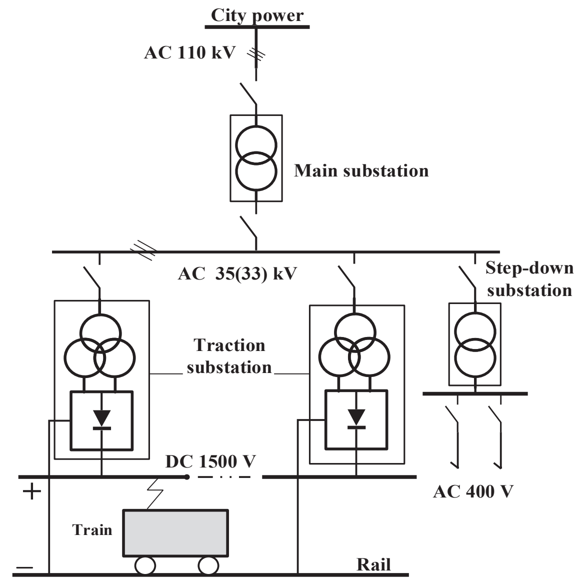

Fig. 2. The diagram of URT power supply structure.

3. PV power integration into the DC traction power system

3.1. Possible PV access points in URT power system

In China, the input of the URT power supply system is AC power grid, and the output is DC traction power system (750 V or 1500 V) and AC low voltage system (400 V). The DC traction power system provides traction power to the train by converting 35 kV AC input into 750 V or 1500 V DC output; the AC low voltage system provides lighting, ventilation and air conditioning power to stations by transforming 35 kV AC input into 400 V AC output.

Fig. 2 illustrates one of the typical structures of URT power supply system. The input is a 35 kV AC voltage source transformed from the 110 kV AC city power grid. The output of URT power supply system is the 400 V AC system transformed through the step-down substation and 1500 V DC traction power system converted by the traction substation.

According to the feature of URT power supply system, the possible grid connection points for PV power access is shown in Fig. 3. The AC side access point can be 35 kV or 400 V AC bus and DC side access point is the 1500 V DC bus.

The AC side PV access mode can be realized through a grid-connected inverter to ensure that the output power meets the voltage and frequency requirements of the AC bus [28,29]. The energy management strategy of AC side access is relatively simple and can refer to the existing research findings in related fields [30,31]. The disadvantage of AC side access is that it always needs an inverter to ensure the proper

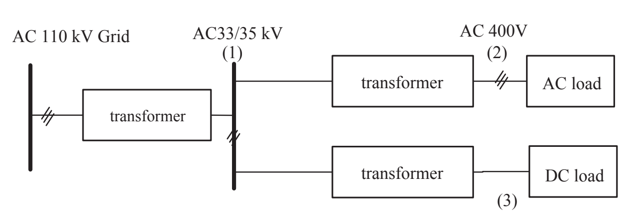

Fig. 3. The possible grid connection points for PV power access.

integration of PV power into the AC bus, which will introduce harmonic pollution to the original system and increase the operation cost. Moreover, if PV power is integrated into the 35 kV AC bus and sent back to the urban grid, the bidirectional power flow between the grid and the URT power system will cause voltage fluctuation and increase the risk of short-circuit, which will not only affect the normal deployment of the power sector, but also poses a safety hazard to the operation of rail vehicles [32].

As mentioned in Section 1, the DC side PV access mode can feed the PV power directly into the DC traction power system through a simple DC/DC converter, which is more efficient compared with AC side access. Since the PV power will not be sent back to the upper level AC system but absorbed by the trains, the power quality and harmonic pollution issues are not so dominant [33]. Another unique advantage is that the DC side access mode can help to stabilize the voltage fluctuation of traction power system caused by the frequently switching operation mode of the train. In the following part, based on the characteristics of DC traction power system, the DC side PV access scheme and energy management strategy are fully discussed.

3.2. Characteristics of DC traction power system

The DC traction power system of URT is a time-varying interactive system. The unique feature is characterized by its load — the moving train. The power delivered to the train is mainly supplied by the two nearby traction power stations. When the train is moving, the impedance between the traction power substation and the train is also changing, and the voltage drop in the catenary cannot be neglected. Meanwhile, the train frequently switches the working mode from accelerating, coasting to braking, which will cause serious voltage fluctuation.

Fig. 4 is a schematic diagram the typical speed profile of the metro train between two stations and the corresponding catenary voltage fluctuation under different working modes of the train. The speed profile of the metro train is predefined by the metro train timetable. 'U_0' is the rated catenary voltage without moving train, which is usually around 1500 V. For a DC 1500 V URT traction power system, the working voltage fluctuation ranges from 1000 V to 1800 V.

There are three typical operation stages for the train running between two stations: stage '1' is the acceleration stage, stage '2' is the coasting stage, and stage '3' is the braking stage. In stage '1', the train is accelerating, and the power demand is increasing. The maximum power of a single train can reach up to 4 MW or even higher, and the current transmitted through the catenary can reach 3000A or even higher, which will cause significant catenary voltage drop at the pantograph. In stage '2', the train is coasting, and the power demand is much less compared with stage '1'. In this stage, the power is mainly consumed by the constant low power load such as air condition and ventilation system. Therefore, the current transmitted through the catenary will be much smaller and the voltage fluctuation is much less accordingly. In stage '3', the train is braking. It will first regenerate the braking energy to the nearby accelerating trains through the DC catenary resulting in the catenary voltage rise. If the regenerative voltage exceeds the threshold, generally set as 1780 V, the on-board resistor will be triggered to consume the extra braking energy.

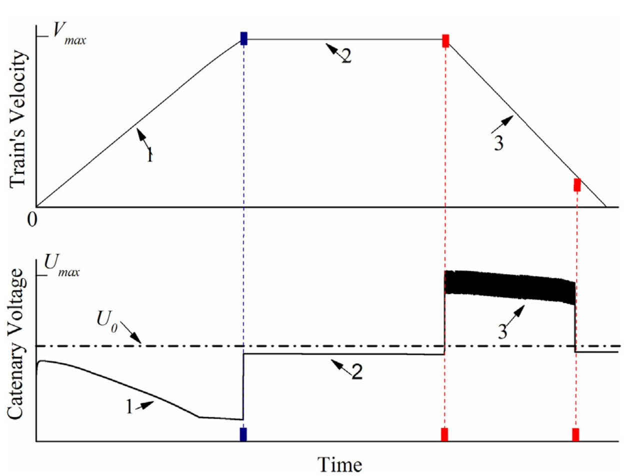

Fig.4. Typical speed profile of train and the corresponding catenary voltage fluctuation.

Usually, the baking energy of the train is about 40% of the tractive energy. However, in the actual working scenario of URT, the braking energy cannot be fully utilized through regenerative braking because the nearby trains may not work in acceleration mode or have enough capacity to absorb the braking energy.

3.3. PV access scheme and energy management strategy in DC traction power system

With the purpose of efficient use of braking energy and smoothing the voltage fluctuation of DC traction power system, a DC side PV access scheme with ESS is proposed, as shown in Fig. 5. The PV is connected to the DC bus and the ESS via a single input, dual-output DC/DC converter. The ESS is connected to the DC bus through a bidirectional DC/DC converter which enables double direction power flow.

Based on the above PV access scheme, a brief DC side energy absorption and utilization concept is developed, as shown in Fig. 6.

In the morning and evening peak hours, the irradiation intensity is weak. There are more trains in operation with a larger passenger flow volume. The train is in a heavy load state, and there is a great demand for power in the traction stage, which will cause a large drop in the catenary voltage. The PV power generation during this period, however, is inadequate. On the one hand, the small PV power generation has little voltage compensation effect in this period of time, and on the other hand, there exists power loss in the transmission process. Therefore, during the peak hours of operation, the PV power generation system does not supply power to the catenary directly, but stores energy in the storage system to charge the energy storage device. The device provides stable power to the grid through the stored energy in the storage system, which compensates the catenary voltage in a timely manner and thus ensures the security of the traction network. The energy management strategy in morning and evening peak hours is shown in Fig. 6(a).

In the off-peak hours during the day, the irradiation intensity is usually strong. When the traction network voltage is relatively low (corresponding to the equivalent traction of the vehicle), the PV modules transmit power to the grid directly through the DC/DC converter. As it does not pass through the energy storage device, the energy loss is reduced. When the traction network voltage is relatively high (corresponding to the equivalent regenerative braking of the vehicle), the PV system charges the energy storage device, which then releases the energy when the traction network voltage drops to a certain value to

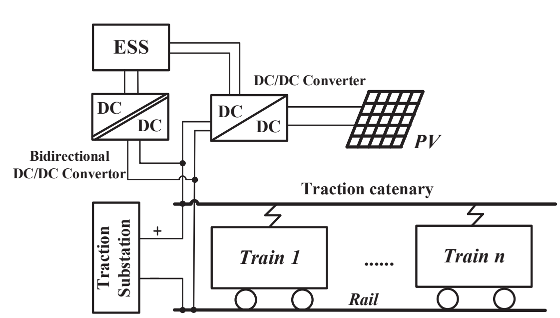

Fig. 5. A DC side PV access scheme with ESS.

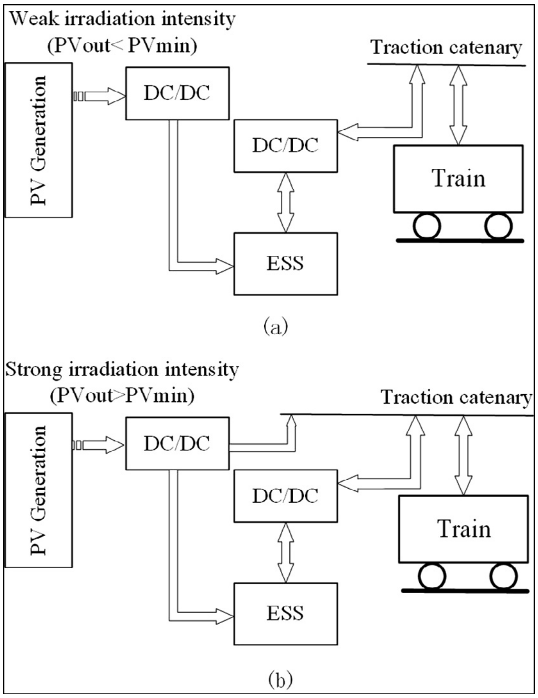

Fig. 6. Schematic diagram of DC side energy management strategy. (a) Power flow when PV*out* < PV*min* (b) Power flow when PV*out* > PV*min*.

achieve better energy efficiency. In any of the above stages or at night, the ESS in also involved in braking energy recovery. The energy management strategy in the off-peak hours is shown in Fig. 6(b).

The energy absorption and utilization strategy can be summarized as follows: when the output PV power is lower than the minimum set threshold PV*min*, it will be used for charging ESS; when the output PV power is higher than the minimum set threshold PV*min*, and if the catenary voltage U*net* < U*min* (the set minimum catenary voltage threshold), both PV and ESS will supply power to the catenary to fill the voltage valley caused by the traction of the train. If U*net* > U*max* (the set maximum catenary voltage threshold), ESS will absorb the power generated by PV and regenerative braking of the train to shave the voltage peak. If U*min* < U*net* < U*max*, the PV power will be delivered directly to the catenary which will help to reduce the energy consumption from traction power station.

4. Discussion on energy saving effect of PV power integration into DC traction power system

4.1. Energy saving rate parameter ‘k’

In order to evaluate the energy saving effect under different energy management strategies, here we introduce a parameter ‘*k*’ to represent energy saving rate. It can be calculated by the following expression:

$$k = \frac{W_0 - W_1}{W_{pv}} \tag{1}$$

where W_0 denotes the original energy consumption of the traction power system of URT without PV integration, W_1 denotes that with *PV* integration, and W_{pv} is the energy generated by the PV system. The energy consumption of the traction power system of URT is calculated based on the power flow of the traction power station. By introducing this parameter, we can have a clear judgement of the energy saving effect under different PV energy management strategies. Apparently, the larger the value of k, the better the energy saving effect achieved.

In what follows, the energy saving effect with PV integration under different energy management strategies will be studied through theoretical analysis and simulation, and we use parameter ‘*k*’ as an indicator to evaluate the energy saving effect.

Table 2
The parameters used in simulation.

Traction substation spacing	3 km
Traction distance (From I to II)	1.4 km
Unit impedance of catenary	34.36e − 6 Ω/m
Unit impedance of rail	39.5e − 6 Ω/m
System no-load voltage	1500 V
Rated capacity of traction station	8.8 MVA
Equivalent internal resistance of traction substation	0.05 Ω
Rated power of train	4 MVA
Maximum traction speed	80 km/h
Traction acceleration	0.9 m/s^2
Braking deceleration	−1.0 m/s^2

4.2. Energy saving analysis under different scenarios

Based on the topology of Fig. 5, simulation models consisting of the URT traction power system, the moving train, PV system, ESS and DC/DC converters are developed in PSCAD/EMTDC. Those models can reflect the dynamic behaviour of the interactive and time-varying URT power system, and can be used as an effective tool to perform the scenario analysis [34].

We simulated the typical operation process of the train moving from one station to another, including the working mode of accelerating, coasting, braking, and stopping. The parameters of traction power system, given in Table 2, are from Shanghai metro company. For the purpose of simplification, the available PV power during the operation of the train is 180 kW.

The main idea of the energy management strategy is that: when the catenary voltage is lower than 1500 V, the power generated by PV system will be fed to the DC bus so as to alleviate the catenary voltage fluctuation caused by the acceleration of train. Meanwhile, ESS will also supply power to the DC bus to help smooth the catenary voltage in a timely manner. When the catenary voltage is higher than 1500 V, the PV and the regenerated power will be absorbed by ESS.

4.2.1. Scenario I: Energy saving analysis of PV system working alone

This scenario is designed to test the energy saving effect of URT system with PV integration.

The catenary voltage fluctuation a with and without PV integration is recorded, respectively, and the simulation results are shown in Fig. 7. The voltage profiles of the train in acceleration, coasting and braking stages are shown in Fig. 7(a), and the acceleration stage are specially illustrated in Fig. 7(b). The PV system contributes to raising the catenary voltage in the acceleration stage in the first 24 s. In this stage, the voltage drops up to about 140 V, and with the 180 kW PV integration, the catenary voltage can be increased by about 26 V. As the power profile of the train is predefined, the catenary current delivered to the train will be lower and the catenary transmission loss will be reduced accordingly.

Table 3 shows the energy consumption of the DC traction power system with and without PV integration. Interestingly, the energy consumption in acceleration stage is reduced by 5.74 kWh with PV integration, which is even larger than the power generated by the PV system. The energy saving rate ‘*k*’ is 1.2. It can be explained as follows: the PV system helps to increase the catenary voltage and reduce the catenary energy loss, and therefore the total energy consumed by the traction system become less.

4.2.2. Scenario II: Energy saving analysis of ESS working alone

This scenario is designed to test the energy saving effect of URT system with ESS absorbing the regenerative braking energy. In the

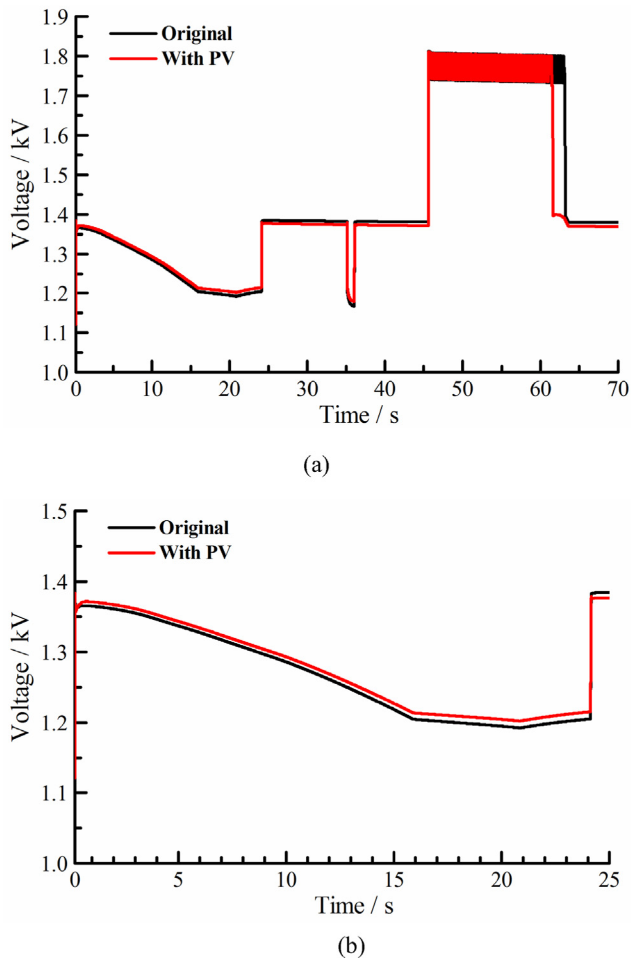

Fig. 7. Comparison of catenary voltage fluctuation with and without PV integration. (a) The simulated voltage profiles of train in acceleration, coasting and braking stages. (b) The voltage profiles in the acceleration stage.

Table 3
Energy consumption of the traction power system with and without PV integration.

	W_o	W_{pv}	$\triangle W$
Energy consumption without PV	55.80 kWh	/	/
Energy consumption with PV	50.06 kWh	4.79 kWh	5.74 kWh

Table 4
Energy consumption of the traction power system with and without ESS.

	W_o	W_{pv}	$\triangle W$
Energy consumption without ESS	55.80 kWh	/	/
Energy consumption with ESS	52.20 kWh	0 kWh	3.60 kWh

simulation, ESS will absorb the regenerative braking energy generated by the train when the pantograph voltage is higher than 1780 V, and release the stored energy to the DC traction network when the voltage is lower than 1500 V. The simulation results are summarized in Table 4. We can see that 3.6 kWh of the braking energy can be recovered by ESS.

4.2.3. Scenario III: Energy saving analysis of PV system and ESS working together

This scenario is designed to test the energy saving effect of URT system with PV and ESS working together. When the train is accelerating and the network voltage is lower than 1500 V, the ESS and the PV system will jointly supply power to the DC traction network. When the train is braking and the traction network voltage is too high, ESS will absorb the excess energy.

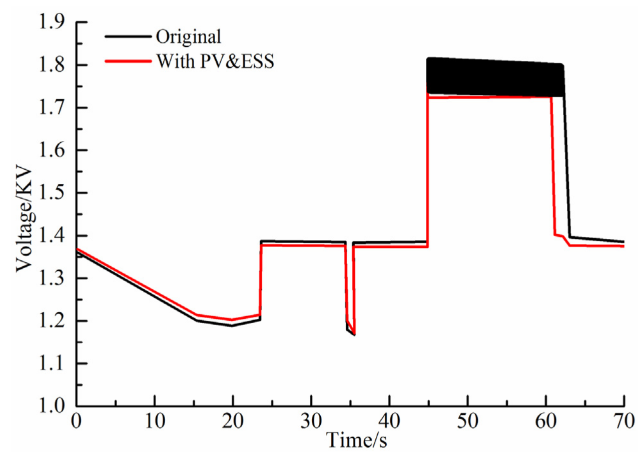

Fig. 8. Comparison of catenary voltage fluctuation with and without PV & ESS integration.

The simulation results are shown in Fig. 8. In the acceleration stage, the catenary voltage with 180 kW PV system is compensated by about 10 V. In the braking stage, the ESS absorbs the regenerative braking energy, and helps to shave the peak voltage by about 70–80 V. Apparently, the combined PV and ESS system effectively compensates the traction network voltage, and helps to suppress the voltage fluctuation caused by acceleration or braking of the train.

Table 5 summarizes the energy consumption of the DC traction power system with PV and ESS. We can see that the total energy consumption is saved by 9.7 kWh, and the energy saving rate 'k' is about 2.0, which is even higher than PV system working alone.

4.3. Discussion of energy saving effect

Through further comparison of the data in Tables 3–5, another interesting result can be found that the total amount of energy saving (9.70 kWh) when PV and ESS work together is even larger than the sum of PV or ESS working alone (9.34 kWh).

It can be explained as follows: in URT system, the train operates with a predefined speed profile, which means that the power profile of the train is also predefined. Since the integration of PV system will increase the catenary voltage, the current demanded by the train will decrease. Comparative simulation results of the train's current and catenary voltage with and without PV integration in the acceleration stage (0–24 s) are presented in Fig. 9. With PV integration, the catenary voltage can be raised by about 26 V and the current is reduced by about 18A. Therefore, the catenary transmission loss caused by the catenary resistance can be reduced. Consequently, the total energy consumption of the whole URT system will go down.

From the above discussion, it can be concluded that reducing the catenary transmission loss is one of the key issues for improving the energy saving effect. Effective energy saving can be achieved through PV integration, as it will not only supply traction power to the train but also help to reduce the catenary transmission loss. Through the combination of PV and ESS, even better energy saving result and catenary

Table 5
Energy consumption of the traction power system with PV and ESS.

	W_o	W_{pv}	$\triangle W$
Original system	55.80 kWh	/	/
PV system with ESS	46.10 kWh	4.79 kWh	9.70 kWh

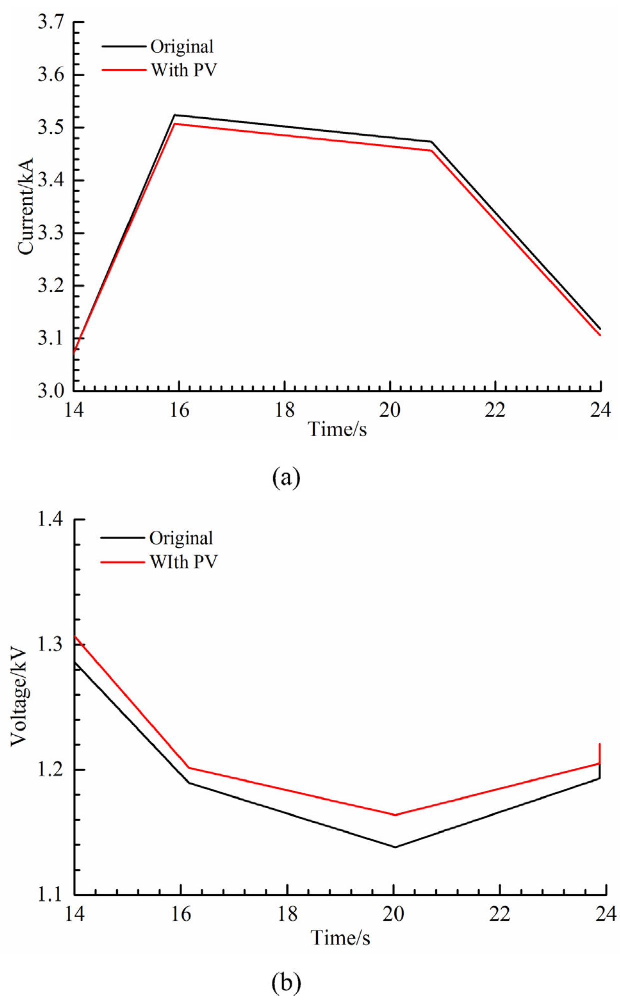

Fig. 9. Comparisons of the train's current and voltage in the acceleration stage. (a) The current absorbed by the train with and without PV integration (b) The catenary voltage with and without PV integration.

voltage compensation can be realized, which shows the effect of "1 + 1 > 2". The comprehensive benefit of PV and ESS combination will be further improved through optimized control strategy and system design.

5. Comparison of DC and AC side PV integration in URT system

In this section, a comparative analysis will be made of AC and DC side PV integration in terms of energy saving effect, power supply quality and safety.

5.1. Benefit assessment of AC side PV integration

Currently, the URT distributed PV power generation system for engineering applications mainly adopts AC side grid connection, as the installation and connection technology is relatively mature. Considering the system cost and grid security, special inverters for grid connection are required in the system to ensure that the output power meets the voltage and frequency requirements of URT power system. The use of inverters will definitely increase the operational cost and result in more harmonic pollution to the original power system.

In terms of energy saving rate and power supply quality, as AC side PV integration is connected to the AC power system of URT, it cannot provide voltage compensation to the DC traction power supply system or reduce the catenary loss. Thus, the energy saving rate is '1'. If the traction voltage decreases, it cannot fulfill the role of 'valley filling'. In some cases, the PV power may even be sent to the urban power grid, causing the oscillation of the original power system and affecting its normal operation. Thereby, the effect of energy saving and power quality improvement of AC side PV access is not satisfactory.

5.2. Benefit assessment of DC side PV integration

According to the previous analysis, the advantages of DC side PV access can be summarized as follows:

(i) DC side PV access can not only provide a backup power for train traction but also compensate the network voltage (valley filling) when the vehicle is in the traction stage. By doing this, the fluctuation of the network voltage during traction is not too large and the safety of the power supply network is improved.
(ii) The combination of PV and ESS can fulfill the role of 'valley filling and peak shaving', which will suppress the traction voltage fluctuation and benefit the operation safety of traction power system. As the catenary loss will be reduced, the energy saving result can achieve the effect of "1 + 1 > 2". The technology of ESS for URT braking energy recovery has been commercialized. The super-capacitor-based braking energy recovery system developed by Siemens has been successfully operated in Madrid and on Line 5 of Metro Beijing. All in all, the comprehensive energy utilization will be further improved with DC side access, which is conducive to shortening the static investment recovery cycle.
(iii) Harmonic and power quality issues are not prominent. For DC side PV access, the PV power can be integrated into the DC traction system through a simple DC/DC converter. There is no prominent problem with the power quality and harmonic pollution problems compared with AC side PV access.

In summary, the DC side PV access is superior to B in improving traction power supply safety and increasing comprehensive energy utilization. It is more conducive to energy saving and emission reduction of URT.

6. An outlook on outstanding challenges and future research opportunities for DC side PV integration in URT system

The issue of DC side PV integration into URT traction power system can be classified into the field of DC micro-grid [35]. However, the existing DC micro-grid is quite different from the URT DC traction power system in both voltage level and working conditions. The existing technologies of integrating PV system into DC micro-grid are still faced with great challenges when applied to the traction power system of URT. Some challenges and future opportunities are as follows:

(i) Topological structure of the PV & ESS system

The topological structure of PV & ESS that satisfies the characteristics and functional requirements of the long and narrow URT line is the basis to realize DC side integration and efficient power generation of the PV system.

(ii) Control strategy and the configuration of ESS

The system control strategy and grid-connection control algorithm need to consider the operational characteristics of the PV system and the URT traction network at the same time, so as to fully realize the PV power generation function and achieve more efficient energy-saving operations and energy flow control. The introduction of energy storage devices can not only maximize the comprehensive benefits of the PV power generation system, but also serve as an effective way to control the URT vehicle-network energy flow [36]. How to optimize the configuration of the PV power generation system and vehicle-network energy flow control will be crucial, which directly affects the function and economy of the system [37].

(iii) DC traction catenary state identification

The accurate and rapid identification of the equivalent traction, equivalent braking, and short-circuit faults of the traction network is a prerequisite for the PV & ESS to function safely. Although the DC traction catenary state is very complex and the identification is difficult, it is a key issue that must be solved.

(iv) The influence of power electronic equipment on system stability

PV & ESS are integrated into the DC traction power system through DC/DC power converters. Due to the negative impedance characteristics of power electronic devices, the system might be oscillated, posing a risk to the stability of the traction system. Therefore, the research on system stability should be conducted including the characteristics of traction substation, PV converters, power converters of train and the DC catenary impedance, which is drawing more and more attention in recent research [38,39].

7. Conclusions

The trackside of elevated URT lines is an interesting but still unexplored platform for PV integration. Based on the unique characteristics of the URT power supply system and the data of URT Line 11 in Shanghai, the paper has made a comprehensive study of PV integration into the DC traction power system including potential PV installation capacity, possible PV access points, energy saving rate and power quality improvement. On the basis of the analysis, we can reach the following conclusions:

(i) The trackside of elevated suburban URT lines of Shanghai provides broad space for PV panel installation. The PV installation capacity can reach 9.8 MWp for Line 11 in Shanghai. The ROI of PV system is 8.27 years with an expected life of 20 years, which is worth investing.
(ii) There are two types of PV integration into the traction power system — AC side access and DC side access. The DC side access, which integrates the PV power into DC traction power system directly, is superior to AC side access in terms of energy saving rate, traction power quality and safety improvement.
(iii) In order to evaluate the energy saving result, a parameter '*k*' has been introduced to represent the energy saving rate in the paper. Through numerical simulation, it is found that the key issue for improving the energy saving rate of URT system is to reduce the catenary transmission loss. The DC side PV integration can help to compensate the traction voltage and reduce the catenary loss in the traction stage of train, and thus it has a higher energy saving rate compared with AC side access.
(iv) Even better energy utilization can be achieved with both PV and ESS integrated into the DC traction power system. As the ESS can be used to recover the braking energy, the catenary voltage rise caused by regenerative braking can be suppressed. The result of 'valley filling and peak shaving' can be thereby fulfilled with PV and ESS working together, which will improve the traction power quality and safety. Moreover, the energy saving result can achieve the effect of "1 + 1 > 2", which means when PV and ESS work together, the total amount of energy saving is even larger than the sum of PV and ESS working alone.
(v) In spite of numerous advantages of PV integration into the DC traction power system, there are still challenges for practical applications. Scientific and reasonable control strategies can help increase the energy saving rate and improve the energy efficiency, but it needs to consider the URT traction network load and its operational characteristics. The control technology is complex and needs to be further studied.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This paper was supported by the National Natural Science Foundation of China (No. 51677135) & (No. E51777141); the Fundamental Research Funds for the Central Universities (inter-disciplinary program) under contract No. KX0080020173427 and the China Scholarship Council (the International Clean Energy Talent Program, 2017).

References

[1] Herrera Victor, Milo Aitor, Gaztañaga Haizea, Etxeberria-Otadui Ion, Villarreal Igor, Camblong Haritza. Adaptive energy management strategy and optimal sizing applied on a battery-supercapacitor based tramway. Appl Energy 2016;69:831–45.
[2] Lin F, Liu S, Yang Z, Zhao Y, Yang Z, Sun H. Multi-train energy saving for maximum usage of regenerative energy by dwell time optimization in urban rail transit using genetic algorithm. Energies 2016;9(3):208.
[3] Meng Fanxin, Liu Gengyuan, Yang Zhifeng, et al. Energy efficiency of urban transportation system in Xiamen, China. An integrated approach. , Appl Energy 2017;86:234–48.
[4] Orioli Aldo, Di Gangi Alessandra. Review of the energy and economic parameters involved in the effectiveness of grid-connected Photovolatic systems installed in multi-storey buildings. Appl Energy 2014;113:955–69.
[5] Roberts MB, Bruce A, MacGill I. Opportunities and barriers for Photovolatics on multi-unit residential buildings: reviewing the Australian experience[J]. Renew Sustain Energy Rev 2019;104.
[6] Arcos-Aviles Diego, Pascual Julio, Guinjoan Francesc, Marroyo Luis, Sanchis Pablo, Marietta Martin P. Low complexity energy management strategy for grid profile smoothing of a residential grid-connected microgrid using generation and demand forecasting. Appl Energy 2017;205:69–84.
[7] Yilmaz S, Dincer F. Impact of inverter capacity on the performance in large-scale photovolatic power plants – a case study for Gainesville, Florida[J]. Renew Sustain Energy Rev 2017;79:15–23.
[8] Purohit Ishan, Purohit Pallav. Performance assessment of grid-interactive solar photovolatic projects under India's national solar mission. Appl Energy 2018;222:25–41.
[9] Ahmadipour Masoud, Hizam Hashim, Othman MohammadLutfi, Radzi Mohd Amran Mohd, Murthy Avinash Srikanta. Islanding detection technique using Slantlet Transform and Ridgelet Probabilistic Neural Network in grid-connected Photovolatic system. Appl Energy 2018;231:645–59.
[10] Photovolatic In Railway Technology Reduces CO2, < https://www.gaiadiscovery.com/planet/railway-pv-technology-co2-reduction > .
[11] Hayashiya H, Furukawa T, Itagaki H. Potentials, peculiarities and prospects of solar power generation on the railway premises[C]. Renewable Energy Research and Applications (ICRERA), 2012 International Conference on. IEEE, 2012.
[12] https://www.nengapp.com/news/detail/2250436.
[13] He Jin, Huang Huang X. Application research of photovolatic power generation in urban rail transit[J]. Electr Appl 2018;37(10):31–5.
[14] Wang L, Jinfeng N. Application of photovolatic power generation in urban rail transit. Electrified Railway 2014;5: 44-46 + 50.
[15] Pankovits P, Ployard M, Pouget J. Design and operation optimization of a hybrid railway power substation [C]. European Conference on Power Electronics and Applications. IEEE; 2013. p. 1–8.
[16] Ming Meng, Shichao Chen, Lina Zhang. Coordinated control strategy for power supply system of urban comprehensive transportation[J]. High Voltage Eng 2017;43(6):2069–79.
[17] Şengör İ, Kılıçkıran HC, Akdemir H, Kekezo B, Erdinç O, Catalão JPS. Energy management of a smart railway station considering regenerative braking and stochastic behaviour of ESS and photovolatic generation. IEEE Trans Sustain Energy 2018;9(3):1041–1050.
[18] Kilic Beyhan, Dursun Erkan. Integration of innovative photovoltaic technology to the railway trains: a case study for Istanbul airport-M1 light metro line. In: IEEE EUROCON 17th International Conference on Smart Technologies, Ohrid, Macedonia, 6–8 July 2017.
[19] Hayashiya Hitoshi, Yoshizumi Hiroshi, Suzuki Takashi, Furukawa Takayuki, Kondoh Takatoshi, Kitano Masayuki et al. Necessity and possibility of smart grid technology application on railway power supply system; 2011.
[20] Ciccarelli F, Di Noia LP, Rizzo R. Integration of photovolatic plants and supercapacitors in tramway power systems[J]. Energies 2018;11(2):410.

[21] Sayed K, Kwon S, Nishida K, Nakaoka M. New DC rail side soft-switching PWM DC-DC converter with voltage doubler rectifier for Photovolatic generation interface, In: 2014 International Power Electronics Conference (IPEC-Hiroshima 2014 - ECCE ASIA), Hiroshima; 2014.p. 2359–2365.
[22] https://www.pv-magazine.com/2019/02/04/solar-rail-and-roads-in-the-uk-to-get-financial-shot-in-the-arm/.
[23] He F, Xu J. Studies on precipitation resource change in Shanghai since the 1990's. J Nat Resour 2006;21(4):559–66.
[24] Bempah Kwabena Opoku, Kwon Kyoungjun, Kim Katherine A. Experimental study of photovolatic panel mounting configurations for tube-shaped structures. Appl Energy 2019;240:754–65.
[25] Zang Haixiang, Guo Mian, Wei Zhinong, Sun Guoqiang. Determination of the optimal tilt angle of Solar collectors for different climates of China. Sustainability 2016;8(7). 654-654.
[26] Bhang BG, Lee W, Kim GG, Choi JH, Park SY, Ahn H. Power performance of bifacial c-Si PV modules with different shading ratios. IEEE J Photovoltaics 2019;9(5):1413–20.
[27] Yan Jinyue, Yang Ying, Campana Pietro Elia, He Jijiang. City-level analysis of subsidy-free solar photovoltaic price, profits and grid parity in China. Nat Energy 2019;4:709–17.
[28] Guerrero M Josep, Hu Jiefeng, Xu Yinliang, Cheng Ka Wai. A model predictive control strategy of photovolatic-battery microgrid under variable power generations and load conditions. Appl Energy 2018;221:195–203.
[29] Leung Philip CM, Lee Eric WM. Estimation of electrical power consumption in subway station design by intelligent approach. Appl Energy 2013;101:634–43.
[30] Rasol Jannesar Mohammad, Sedighi Alireza, Savaghebi Mehdi, Guerrero Josep M. Optimal placement, sizing, and daily charge/discharge of battery energy storage in low voltage distribution network with high photovolatic penetration. Appl Energy 2018;226:957–66.
[31] Emmanuel M, Rayudu R. Evolution of dispatchable photovolatic system integration with the electric power network for smart grid applications: a review[J]. Renew Sustain Energy Rev 2017;67:207–24.
[32] Masa-Bote D, Castillo-Cagigal M, Matallanas E, Caamaño-Martín E, Gutiérrez A, Monasterio-Huelín F, et al. Improving photovolatics grid integration through short time forecasting and self-consumption. Appl Energy 2014;125:103–13.
[33] Ye T, Dai N, Lao KW, Lam C, Wong M. Low DC voltage PV generation system with power factor correction and harmonic suppression capability in a distribution network. IET Gener Transm Distrib 2019;13(7):1049–56.
[34] Xiaojun S, Hao F, Li W. PSCAD/EMTDC-based modeling and simulation of urban rail transit train electrical characteristics[J]. J Tongji Univ (Nat Sci) 2011;39(7):1050–5.
[35] Shen Xiaojun, Yu Chuanbao, Zhao Shimin. Concept of URT traction DC microgrid and its application feasibility study[J]. Adv Mater Res 2015:1361–5.
[36] Liu Y, Hou X, Wang X, Lin C, Guerrero JM. A coordinated control for photovolatic generators and energy storages in low-voltage AC/DC hybrid microgrids under islanded mode. Energies 2016;9(8):651.
[37] Ko Rakkyung, Jo Hyung-Chul, Joo Sung-Kwan. Energy storage system capacity sizing method for peak-demand reduction in urban railway system with photovoltaic generation. J Electr Eng Technol 2019;14(4):1771–5.
[38] Zhu Xiaojuan, Hu Haitao, Tao Haidong, He Zhengyou. Stability analysis of PV plant-tied MVdc railway electrification system. IEEE Trans Transp Electrif 2019;5(1):311–23.
[39] Perez Filipe, Iovine Alessio, Damm Gilney, Galai-Dol Lilia, Ribeiro Paulo F. Stability analysis of a DC microgrid for a smart railway station integrating renewable sources. IEEE Trans Control Syst Technol 2019. https://doi.org/10.1109/TCST.2019.2924615. (early access).