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Energy Consumption Assessment in A DC Electric Railway System with Regenerative Braking: A Case Study of Isfahan Metro Line 1

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A B S T R A C T

Regeneration of electric energy during braking is an important issue in electric railway systems. Especially in older electric railway systems that have non-reversible DC traction substations, the goal is to modify the structure of the DC traction substations and replace them with reversible converters at the lowest cost. Accurate evaluation of the power flow and the energy distribution in an electric railway system needs a comprehensive study of the whole railway system with multiple moving trains. But, the modeling and simulation of an electric railway network are complicated due to its nonlinear, time-variant, and large-scale structure. This paper presents the electric energy distribution in the Isfahan Metro Line 1 with and without regenerative braking. For this purpose, a simulator is developed for the DC electric railway systems with multiple moving trains. Driving control strategies, including coasting control, have been applied. The understudy system consists of 7 DC traction substations and 10 trains traveling on the up track. Different scenarios have been simulated with various combinations of reversible and non-reversible DC traction substations. Results reveal that the electric energy consumption of the system with regenerating trains and reversible DC traction substations is 27.13% lower than the system without regenerative braking. To mitigate the energy consumption in the Isfahan Metro Line 1 using the regenerative braking system, it is not mandatory to upgrade the structure of all 7 DC traction substations. Results show that it is possible to reduce electric energy consumption by 26% through installing only 5 reversible traction substations.

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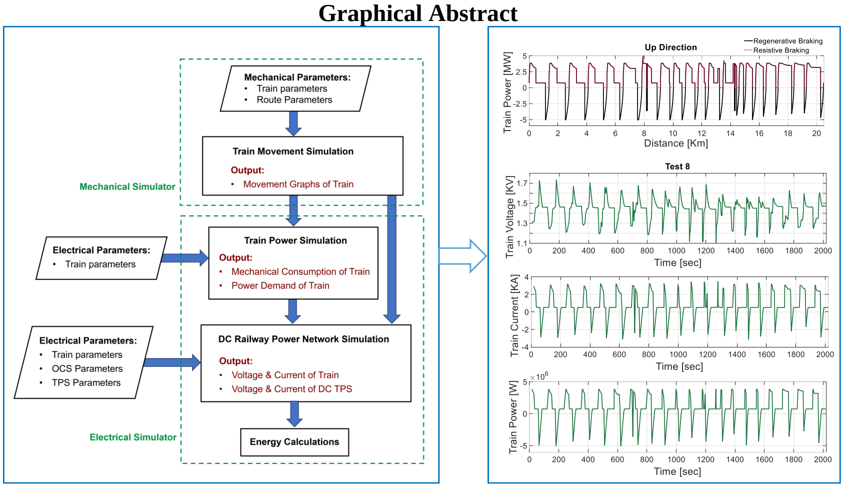
Graphical Abstract



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1. INTRODUCTION

Nowadays, research in the field of managing electric energy consumption, reducing greenhouse gas emissions, and decreasing environmental impacts has become more and more important (1-5).

With the growing demand for public transportation, electric railway transportation has become more popular. Electric railway systems are supplied with AC or DC traction substations. Table 1 shows the pros and cons of using DC electric railway systems compared to AC. Urban metro systems are commonly supplied with DC traction substations. 750 VDC and 1500 VDC are usually applied in metro systems. 750 VDC is typically used for the third rail system, while 1500 VDC is preferred for the overhead contact system (OCS) (6-9).

Energy consumption evaluation is an important issue in electric railway systems. In DC electric railway systems, this issue becomes more significant because the voltage levels that are commonly utilized are lower in comparison with the AC. However, accurate energy consumption evaluation requires appropriate modeling and simulation of the whole railway system with multiple moving trains (6-9). In addition, the modeling and simulation of an electric railway network is a complicated issue due to its nonlinear and time-variant nature. Simulating an electric railway system includes the mechanical simulation of the trains' movement and the electrical simulation of the traction substations, trains, overhead contact line (OCL), and current return circuit.

The train movement simulation was studied in the literature (10-13). Train movement modeling depends on the track and train parameters, including train weight, aerodynamic resistance force, quality of brakes, gradient profile and curve profile of the movement path, friction coefficient, speed limitations, and acceleration limitations. As a result, extracting the movement graphs needs complicated analytical methods (11). Chymera and Goodman discussed the principal equations for train movement modeling. The outputs of the mechanical simulation part are the movement graphs and speed profiles of trains. The movement graphs are the inputs of the electrical simulation part. In addition, extracting the movement graphs can help in evaluating the train performance, calculating the train travel time, planning the train movement, increasing the line capacity, and computing the energy consumption (11-13). The train speed profile was optimized to mitigate energy consumption (14-17). According to the results, travel time and energy consumption were reduced on different electric railway tracks.

TABLE 1. Advantages and disadvantages of the DC electric railway compared to the AC electric railway

Advantages	Disadvantages
• Easy control of DC traction motors • Low cable impedance • Low voltage drops in low-voltage railways • Fewer number of substations in low-voltage railways • More economical in low-voltage railways	• Higher cost for voltage step up and step down • Not economical for high-voltage railways • Higher cost of DC cables

Solving complex problems in various fields of power system engineering has been the challenge of many previous research works (18, 19). Mathematical modeling of an electric railway network, including the urban metro systems, is one of the complex problems that needs to be solved. However, the electric model of a DC electric railway system is nonlinear (due to the DC traction substations) and time-variant (due to the running trains). Therefore, the modeling becomes complicated. Different methods have been reported for modeling the DC electric railway systems (20-22). Gauss-Seidel, Newton-Raphson, and current injection are famous methods for solving DC railway power flow (23-25). Moreover, the point-Jacobi method, Zollenkopf's bifactorisation, and incomplete Cholesky conjugate gradient method have been proposed and investigated (26-30).

Kulworawanichpong (9) developed a simplified Newton-Raphson method for multi-train simulation of the electric railway system. A case study based on the Sukhumvit line of Bangkok was performed with 10 traction substations and 22 passenger stations. According to the results, the proposed method was 18 % faster than the traditional Newton-Raphson method. The maximum number of busbars in this work was limited to 24 (24), Alnuman et al. (24) proposed a multi-train simulator for DC electric railway systems with Matlab software. Braking resistors were utilized to avoid overvoltage in the OCS caused by the regenerative braking condition. A case study was performed on a one-way single track with 6 trains, 3 traction substations, and 7 passenger stations. However, in this work, the distances between the traction substations and between the passenger stations were supposed to be equal. Moreover, the costing mode was neglected. Also, a similar speed profile was applied for all moving trains.

Tian et al. (25) simulated a DC railway network for energy evaluation considering regenerative braking. A case study based on the Beijing Yizhuang subway line was performed with 12 DC traction substations and 14 passenger stations. The energy assessment was performed using different headways. By changing the headway value, the relative position of the motoring and braking train was changed. Consequently, the energy exchange between the running trains varied significantly, and the regenerative braking energy could not be effectively utilized. In this work, the concentration was on using regenerative braking energy inside the railway network. Therefore, only a small part of the energy flowed back to the national electricity network.

Tian et al. (30) investigated the modeling of the DC electric railway systems considering different operating styles. In addition, the effect of substation outages and short-circuit faults was studied. A case study based on the 750 VDC third rail metro line of Singapore was performed with 26 traction substations and 32 passenger stations. Only 10 substations were equipped with inverters. The main concentration of this work was to study the effect of substation faults on power supply system operation.

Recently, the application of electric trains with regenerative braking has been significantly expanded in the urban transport network and subways. Various studies have been reported on the evaluation and management of electric energy consumption in electric railway networks, including regenerative trains (31-34). However, consideration of the regenerative braking capability complicates the railway network modeling and the power flow solving.

According to the above-mentioned, considering the time-consuming and complicated process of the load-flow programming for electric railway line analysis, there is a scientific motivation to suggest a new modeling strategy that is simpler than the traditional methods and at the same time maintains accuracy and completeness in studying the entire railway system.

On the other hand, the operation of Isfahan Metro Line 1 has started in 2015. Since the installation of this line, very few research studies have been done on subject. Hamedani et al. (35) have been suggested to study the performance of this line as a single-train simulator. However, the evaluation of energy consumption and power distribution was not investigated in that work. In this regard, the necessity of a comprehensive study is clear. The present work tries to cover this research gap. The first step is to provide an accurate simulator according to the needs and challenges of this electric metro line. Consequently, this work aims to cover both mentioned gaps. This paper proposes a simplified simulation model for the DC electric railway network with multiple running trains, which is suitable for energy evaluation investigations. The train mechanical movement model and power supply system model are included. Regenerative braking and driving control modes with coasting control are applied in the simulation. Based on the route data of Isfahan Metro Line 1, the simulation results of the power network are presented for 10 running trains on the up track. Results manifest the correctness and simplicity of the suggested method, which facilitates the investigation of the DC electric railway networks. The main contributions of this paper are as follows:

- Including the main pillars of an electric railway network that contains mechanical motion simulation and electric power network simulation, i.e. DC traction substations, overhead contact lines, and trains, as well as various driving control strategies.
- Evaluating the system performance and electric energy distribution with and without regenerative braking
- Employing actual data from the Isfahan Metro Line 1 to perform the simulation
- Considering different scenarios with various combinations of reversible and non-reversible DC traction substations for the energy consumption and loss calculations

2. MODELING OF DC ELECTRIC RAILWAY

Figure 1 shows the flowchart of the DC electric railway network simulator. The overall simulator for the DC electric railway network consists of the mechanical and electrical simulator.

2. 1. Train Mechanical Simulator The machanical equations of a train can be obtained from Newton's second law of motion (30). The main equation of movement is described in literature (35). In general, four different operating modes can be considered for a train, which include traction, cruising, coasting, and braking modes. As explained by Hamedani et al. (35), in each operating mode, by solving the train movement equation, the position, speed, and acceleration of train can be derived. Accordingly, the train movement graph and train timetable of Isfahan Metro Line 1 can be extracted as described by Hamedani et al. (35).

2. 2. Train Electrical Simulator The train electrical simulator consists of the train power simulation, DC railway power network simulation, and energy calculations. The train movement graph and train timetable are used as necessary inputs for the train electrical simulator program.

The power network includes trains, traction substations, overhead contact lines (OCLs), and rails as return current circuits (RCRs).

The trains are modelled as voltage-dependent current sources (35). To calculate the current, the total power demand of the train is devided by the pantograph voltage. The equations related to the calculation of the total train power demand are given in literature (35, 36).

In Isfahan Metro substations, twelve-pulse rectifiers are used. The Thevenin's model can be utilized for the traction substation (25). The Thevenin's equivalent voltage and the equivalent resistance of the traction substations are calculated in literature (35).

To model the DC railway power network, the OCL and RCR are modelled with resistance. The OCL and RCR resistance between the train and the passenger station are calculated dependening on the length (35).

The electrical energy of all the trains running on the track over time can be calculated as follows (36):

$$E_t = \int_0^T \sum_{n=1}^{N_t} (V_{train_n}(t) \times I_{train_n}(t))dt \quad (1)$$

N_t represents the number of trains on the line. T is the total traveling time of the train. V_{train} and I_{train} are the instantaneous voltage and current of the train, respectively.

The electrical energy of the DC traction substations can be calculated as follows (36):

$$E_s = \int_0^T \sum_{n=1}^{N_s} (V_{sub_n}(t) \times I_{sub_n}(t))dt \quad (2)$$

N_s represents the number of DC traction substations. V_{sub} and I_{sub} are the instantaneous voltage and current of the substation busbar, respectively.

3. RESULTS AND DISCUSSION

3. 1. Multi-Train Movement Simulation

Based on the modeling strategy of the DC electric railway described in previous sections, a train movement simulator has been developed in this work. In this section, a case study based on the Isfahan Metro Line 1 is presented. The train and line parameters required for the mechanical simulation of the rail system are taken from literature (35). Line 1 of the Isfahan Metro is about 20.464 km long. The gradient profile of Isfahan Metro Line 1 for the up track is taken from literature (35). The initial design of this line had 21 passenger stations and 7 DC traction substations. In this work, the initial design of Line 1 is studied. The location of the passenger stations and traction substations of Isfahan Metro Line 1 is given in literature (35). The up track corresponds to the running direction from the GHO station to the DEMO station. The down track corresponds to the running direction from the DEMO station to the GHO station. The DC traction substations consist of 12-pulse rectifiers. Trains are fed using the OCL system. The rated voltage of the DC OCL is 1500 V.

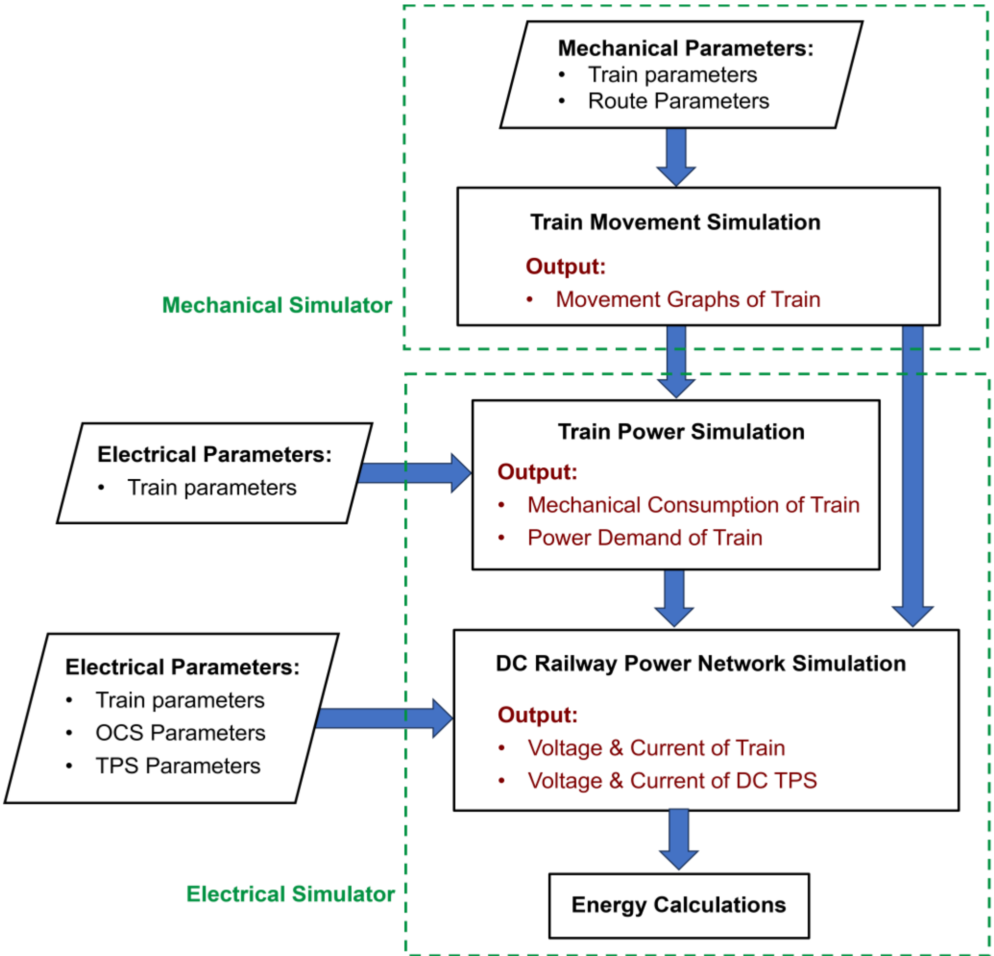

Figure 1. Flowchart of the DC electric railway network simulator

The required speed-distance profile of the first train of Isfahan Metro Line 1 for the up direction, the speed limit of the train on the route, and the distance-time profile of the first train of Isfahan Metro Line 1 for the up direction are taken from literature (35). The dwell time is considered 30 seconds. The travel time of a one-way moving train from the GHO station to the DEMO station is about 33 minutes and 40 seconds. Using the train movement graphs, the electric power graphs of the trains are extracted in the up track railway line. Figure 2 shows the power demand-distance profile of the first train of Isfahan Metro Line 1 for the up direction in case of regenerative braking (given in literature (35)) and resistive braking.

For power flow analysis, the simulation time step has been considered to be 1 second. The simulation results of the Isfahan Metro line 1, including 10 running trains on the up track, are presented. For the sake of simplicity, the length of the passenger stations and trains is neglected in this work. The required parameters in the simulation of this line are taken from literature (35). The goal is to study the reduction of energy consumption in the case of returning the regenerative power of the trains to the AC power network. Therefore, it is assumed that all trains are dispatched from the respective station simultaneously. In this way, the effect of absorbing and injecting electrical energy inside the railway network and by the trains themselves has been reduced. Thus, the obtained results are mostly affected by the scenarios related to the arrangement of traction substations. The extracted distance-time and electrical power-time curves are applied as inputs to the electrical simulator program. In each time step of the simulation, the train position and the electric power demand are extracted. Based on that, the power flow program is executed. The voltage, current, and power of the trains and substations are updated at each time step. This process is repeated during the trains' movement from the GHO station to the DEMO station.

The electrical multi-train simulator program of the Isfahan Metro Line 1 is obtained using Matlab software.

Figure 3(a) shows the voltage, current, and power of train 1 during the movement of 10 trains from the GHO station to the DEMO station, considering the resistive braking for all the trains. In this condition, all the energy obtained from the braking of the trains is wasted in the form of heat in the braking resistances of the trains. Figure 3(b) presents the voltage, current, and power of train 1 during the movement of 10 trains from the GHO station to the DEMO station, considering the regenerative braking. It is assumed that all traction stations can return the braking energy to the AC power network. In other words, in braking conditions, the braking energy of the train is used to provide the power of the auxiliary equipment, and the excess energy is returned to the power electricity network.

The current waveform is consistent with the electric power demand of the trains, which shows the correctness of the power flow program. Also, the pantograph voltage waveform has an opposite relationship with the electric power demand. Therefore, at the time of maximum power absorption from the power network, due to the increase in the OCL current, the pantograph voltage drops and is at its minimum value. Also, in the braking time, the excess power of the train is injected into the power network. Therefore, overvoltage occurs in the OCL and the substation busbar. At the maximum braking power of the train, the pantograph voltage reaches its maximum. The obtained results show the correctness of the electric power flow program.

In Figure 4(a), the voltage waveforms of the traction substations are shown during the movement of 10 trains from the GHO station to the DEMO station, considering the resistive braking. As it is clear, with the movement of the trains on the railway line, the voltage of the busbar connected to the traction substation fluctuates. The highest fluctuations are related to the substations in the middle of the track. The first and last traction substations have lower voltage fluctuations.

Figure 4(b) shows the simulation results of line 1 from the GHO station to the DEMO station, considering the regenerative braking. All traction substations are equipped with eversible rectifiers. Therefore, the traction substations can return power to the power network. As it is clear from the comparison of Figure 4(a) with Figure 4(b), the voltage fluctuations are lower in the case of resistive braking. The reason is the lack of braking power

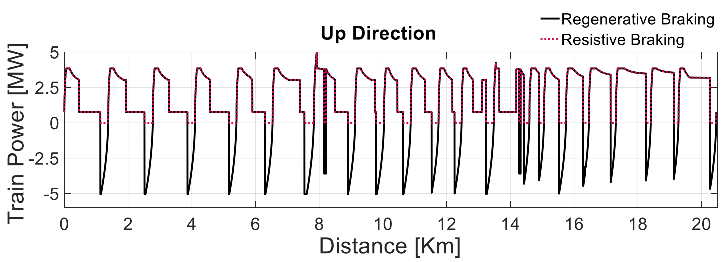

Figure 2. The power demand-distance profile of Isfahan Metro Line 1 for the up direction with the regenerative braking (35) and resistive braking

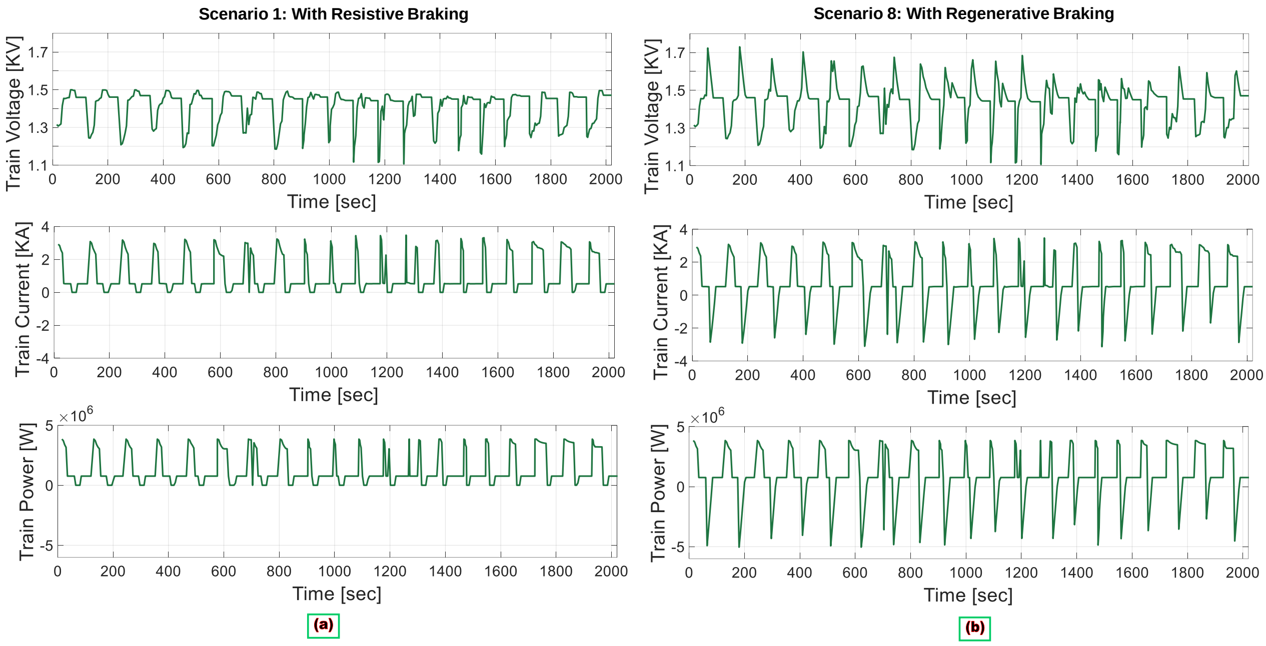

Figure 3. The voltage, current, and power demand of the first train during trains' movement on the up track with: (a) resistive braking; (b) regenerative braking

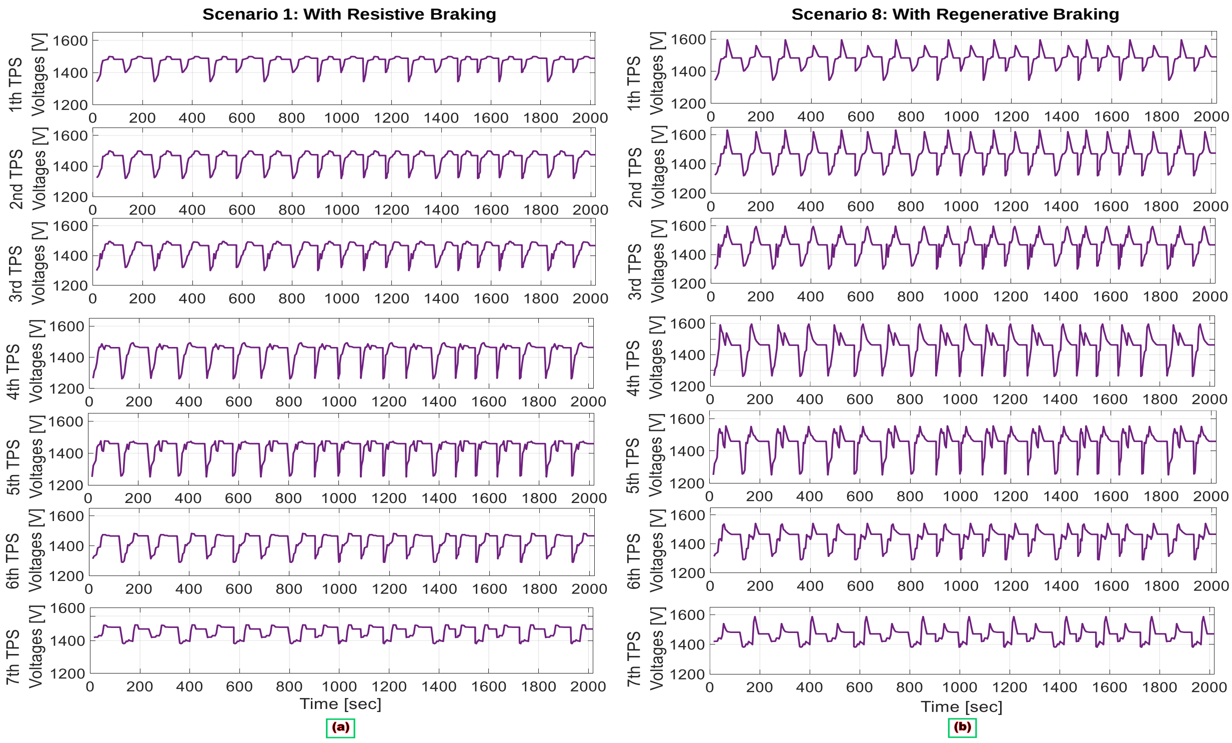

Figure 4. The substations' voltages during trains' movement on the up track with: (a) resistive braking; (b) regenerative braking

injection to the overhead network. If the traction substations are equipped with reversible rectifiers, the braking energy will return to the AC power network. Therefore, the energy injected from the traction substations will be mitigated.

3. 2. Energy Evaluation in DC Electric Railway Network In this section, different scenarios are defined for modeling the electric railway network, including reversible or non-reversible DC traction substations. For each scenario, a specific structure is considered, and a new simulation program is written.

Selection of the structures depends on the distance between the non-reversible DC traction substations. The effectiveness of regenerative braking relies on the distance between the traction substation and the braking train. When the distance between the traction substation and the braking train is long, the transmission loss in the OCS increases.

In Table 2, the defined scenarios are introduced. The simulation results of Isfahan Metro line 1 are presented considering 10 trains in the up track. This railway line has 7 DC traction substations. By running the electrical simulator programs, the current, voltage, and power waveforms in the trains and also the current, voltage, and power waveforms in the traction substations are extracted. Consequently, the consumed and regenerated energy of the trains is calculated. In addition, the injected and absorbed energy in the traction substations is computed.

Attempts have been made to examine various possible combinations of reversible and non-reversible DC traction substations. It should be mentioned that all the trains depart simultaneously from the stations. Therefore, the time range when the energy consumption of the trains reaches the maximum and also the time range when the trains are in braking conditions are close to each other in all the trains. Consequently, the energy exchanged between the trains and inside the railway network is relatively low. Thus, the obtained results are affected by the power returned to the AC power network through the DC traction substations.

TABLE 2. Different scenarios of the traction substations in understudy electric railway network

Scenario Number	Trains with Regenerative Braking		Substation Number with Reversible Rectifiers						
	None	All	1	2	3	4	5	6	7
1	√								
2		√	√	√	√		√	√	√
3		√	√	√		√	√	√	
4		√	√		√	√		√	√
5		√	√		√	√	√		√
6		√	√	√		√			√
7		√	√	√			√	√	√
8		√	√	√	√	√	√	√	√

In addition, due to the coordinated schedule of the trains, the peak energy consumption and peak energy regeneration of the trains are significant. Therefore, if most substations cannot return electric power to the network, the voltage fluctuations in the substations' busbar exceed the permissible limit, and the results are not acceptable. For this purpose, in this work, the maximum number of non-reversible DC traction substations has been limited to two numbers.

In the first scenario, none of the DC traction substations are reversible, and all trains use only resistive braking. In this scenario, all the braking energy of the trains is wasted in the form of heat in the braking resistance .In other scenarios, all trains have regenerative braking, and the excess electrical energy resulting from train braking is returned to the AC power network through the reversible DC traction substations. In the second scenario, all traction substations, except the fourth substation, are reversible. In the last scenario, all traction substations are reversible and can return power to the AC power network. In the rest of the scenarios, all traction substations, except two substations, are reversible. In these scenarios, different combinations have been considered. In Table 3, simulation results of the electric energy consumed/regenerated by the trains and also the electric energy injected/absorbed by the traction substations in different scenarios are presented. The simulation time step is assumed to be 1 second. The total simulation time for implementing the power flow program and energy calculations is considered equal to 2024 seconds.

As it is clear, in the first scenario, the braking energy of trains is dissipated in the braking resistances, and it is impossible to recover the braking energy. Therefore, this scenario has the highest net injected energy from the DC traction substations to the OCL. In addition, as it is clear from the results, the eighth scenario has 27.13 % lower net injected energy compared to the first scenario. The reason is that all DC traction substations are reversible and can return the braking energy of the trains to the AC power network. Therefore, in the eighth scenario, the net injection energy from the traction substations to the OCL is minimal. Moreover, the first scenario has the lowest energy transmission loss in the overhead network. After the first scenario, the eighth and second scenarios have the lowest loss of the OCL network, respectively.

3. 3. Validation of The Proposed Multi-Train Simulator To verify the correctness of the proposed multi-train simulator for DC electric railway networks, the suggested methodology has been applied on a railway network with the parameters given in literature (36). The parameters required for the validation test of the electrical simulator are given in Table A1 in the Appendix. Table 4 shows the train data that is required validation test. The line is 8 km long and has three DC traction substations and a paralleling substation. Four trains are moving on the railway line. Two trains are moving on the up track in the motoring condition and two trains are moving on the down track in the braking condition. The power and location of the trains are the inputs of the simulator. The currents, voltages, and power of trains and traction substations are the outputs of the electric railway simulator.

Table 5 presents the obtained results from the proposed electric railway simulator and the results given in literature (36).

In both methods, the current and voltage of trains and substations are the same. The power results from the proposed simulator are very close to the results given in literature (36). By comparing Tables 4 and 5, it is clear that the proposed method is more accurate.

TABLE 3. Simulation results of energy consumption and loss in the system

Scenario	Total Energy Injected from The Substations [MWh]		Total Energy of Trains [MWh]		OCS Energy Loss [MWh]	Reduction of The Net Injected Energy from The Substations Compared to The First Scenario [%]
	Type	Energy	Type	Energy		
	Injected	8.466	Consumed	7.794		
1	Absorbed	0	Regenerated	0	0.672	**0**
	Net Injected Energy	**8.466**	**Net Consumed**	**7.794**		
	Injected	7.353	Consumed	7.794		
2	Absorbed	1.153	Regenerated	2.348	0.754	**26.76**
	Net Injected Energy	**6.200**	**Net Consumed**	**5.446**		
	Injected	7.379	Consumed	7.794		
3	Absorbed	1.153	Regenerated	2.348	0.780	**26.46**
	Net Injected Energy	**6.226**	**Net Consumed**	**5.446**		
	Injected	7.372	Consumed	7.794		
4	Absorbed	1.147	Regenerated	2.348	0.779	**26.47**
	Net Injected Energy	**6.225**	**Net Consumed**	**5.446**		
	Injected	7.402	Consumed	7.794		
5	Absorbed	1.184	Regenerated	2.348	0.772	**26.55**
	Net Injected Energy	**6.218**	**Net Consumed**	**5.446**		
	Injected	7.351	Consumed	7.794		
6	Absorbed	1.129	Regenerated	2.348	0.776	**25.50**
	Net Injected Energy	**6.222**	Net Consumed	5.446		
	Injected	7.296	Consumed	7.794		
7	Absorbed	1.038	Regenerated	2.348	0.812	**26.08**
	Net Injected Energy	**6.258**	Net Consumed	5.446		
	Injected	7.444	Consumed	7.794		
8	Absorbed	1.275	Regenerated	2.349	0.724	**27.13**
	Net Injected Energy	**6.169**	Net Consumed	5.445		

TABLE 4. Train data inputs for validation test (36)

	Power [kW]	Location [m]
Train_up1	8000	1000
Train_up2	8000	7000
Train_down1	-3000	3000
Train_down2	-3000	6000

TABLE 5. Comparison of the results from the proposed simulator and reference (36)

	Results from the present work			Results from reference [36]		
	Voltage [V]	Current [A]	Power [kW]	Voltage [V]	Current [A]	Power [kW]
Train_up1	1654	4838	8000	1654	4838	8002
Train_up2	1661	4816	8000	1661	4816	7999
Train_down1	1794	-1672	-3000	1794	-1672	-3000
Train_down2	1813	-1655	-3000	1813	-1655	-3001
Substation No. 1	1770	3025	5353	1770	3025	5354
Substation No. 2	1791	859	1539	1791	859	1538
Substation No. 3	1776	2449	4339	1776	2449	4349

4. CONCLUSION

This paper presents a multi-train movement simulator for DC electric railway systems using Matlab software. The proposed model is accurate and easy to use. Moreover, there is no need to use conventional iterative methods to solve the nonlinear time-variant equations of the railway system model. Results are presented for a case study based on the practical parameters of Isfahan Metro Line 1. The suggested simulator includes the mechanical motion simulation, electric power network simulation, and energy consumption evaluation. Regenerative braking and driving control modes with coasting control are applied in the simulation. The effect of regenerative braking on the energy consumption and transmission loss of the railway system is evaluated. For this purpose, different scenarios are simulated with various combinations of reversible and non-reversible DC traction substations. Results reveal the effectiveness of the proposed method in the DC electric railway investigations. In addition, the results present that the energy consumption of the system with regenerating trains and reversible DC traction substations is 27.13% lower than the system without regenerating braking.

On the other hand, the DC traction substations in Line 1 of Isfahan Metro are currently non-reversible. In conclusion, attention was drawn to the regenerative braking energy of the trains that cannot be transferred back to the AC power network and is wasted through the braking resistors. According to the results, to mitigate the energy consumption in the Isfahan Metro Line 1 using the regenerative braking system, it is not mandatory to upgrade the structure of all 7 DC traction substations. Results show that it is possible to reduce energy consumption by 26% by installing 5 reversible traction substations at the first step.

5. ACKNOWLEDGMENTS

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7. APPENDIX

TABLE A1. Simulation parameters for validation test (36)

Parameters	Value
Line length	8000 [m]
Traction substation No. 1 position	0 [m]
Traction substation No. 2 position	5000 [m]
Traction substation No. 3 position	8000 [m]
Paralleling substation position	2500 [m]
Traction system nominal voltage	1500 [V]
Substation no-load voltage	1800 [V]
Substation source resistance	0.01 [Ω]
Contact line system resistance	29 [Ω]
Return rail system resistance	20 [Ω]

Persian Abstract

چکیده

بازیافت انرژی الکتریکی حاصل از ترمز یک چالش مهم در سیستم‌های راه آهن برقی است. به خصوص در سیستم های راه آهن برقی قدیمی که دارای پست‌های کششی DC غیرقابل برگشت هستند، هدف، اصلاح ساختار پست‌های کششی DC و جایگزینی آنها با مبدل‌های برگشت‌پذیر با کمترین هزینه است. ارزیابی دقیق پخش توان و توزیع انرژی الکتریکی در یک سیستم راه‌آهن برقی نیازمند مطالعه جامع سیستم راه‌آهن با قطارهای متحرک متعدد است. اما، مدل‌سازی و شبیه‌سازی شبکه راه‌آهن برقی به دلیل ساختار غیرخطی، متغیر با زمان و مقیاس بزرگ آن، پیچیده است. این مقاله به بررسی توزیع انرژی الکتریکی در خط ۱ مترو اصفهان با و بدون ترمز بازیافتی (احیا کننده) می‌پردازد. برای این منظور، یک شبیه‌ساز برای تحلیل سیستم‌های راه‌آهن الکتریکی DC با قطارهای متحرک متعدد ارائه شده است. استراتژی‌های کنترل حرکت قطار نظیر کنترل حرکت خلاص، در شبیه‌سازی اعمال شده است. سیستم مورد مطالعه شامل ۷ پست کشش DC و ۱۰ قطار است که در مسیر رفت، حرکت می‌کنند. سناریوهای متفاوت با ترکیب‌های مختلفی از پست‌های کشش DC با قابلیت برگشت‌پذیری توان و بدون قابلیت برگشت‌پذیری توان، مورد مطالعه قرار گرفته است. نتایج نشان می‌دهد که مصرف انرژی الکتریکی در سیستم ریلی شامل قطارهای برقی با ترمز بازیافتی و پست‌های کشش DC با قابلیت برگشت‌پذیری توان، ۲۷/۱۳ درصد کمتر از سیستم بدون ترمز بازیافتی می‌باشد. همچنین جهت کاهش مصرف انرژی الکتریکی در خط ۱ مترو اصفهان با استفاده از ترمز بازیافتی، ارتقای ساختار هر ۷ پست کشش DC الزامی نیست. نتایج نشان می‌دهد که تنها با نصب ۵ پست کشش DC با قابلیت برگشت‌پذیری توان، می‌توان مصرف انرژی الکتریکی را تا ۲۶ درصد کاهش داد.