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Energy-Efficient Emplacement of Reversible DC Traction Power Substations in Urban Rail Transport through Regenerative Energy Recovery

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ABSTRACT

Due to the high potential of urban rail transport systems as an effective solution to improve urban mobility services, these systems have faced an increasing demand in recent years. High capacity, reliability and absence of local emissions are some of the most promising advantages of these transportation systems. However, with the increase in capacity demands, energy costs and environmental concerns, and in a highly competitive context where other modes of urban transportation are improving technical and also economic aspects of their services along with their environmental performance, urban rail must be more energy-efficient while improving its quality of service.

In this paper, an energy-efficient method through different scenarios using regenerative braking and reversible substations has been proposed and tested on a typical metro line. This paper concludes that the energy consumption in simulated metropolitan subway line could be reduced up to nearly 33% through the use of regenerative energy recovery approach and implementation of reversible substations for different scenarios.

Keywords: Electrical railway simulator, AC/DC power flow, regenerative braking, reversible substation, traction energy

1. Introduction

"Urban rail transport" generally refers to railway systems utilized within cities as public transport services. Thus, short intervals between stations will be among their key characteristics. There are four categories in terms of typical types of urban rail transport: tramway, light rail transport, monorail, and metro. Metro systems are known to contribute the highest level of urban mass rapid transport among these categories.

High capacity, reliability, safety, and environmental friendliness are some major features of urban rail contributing to its reputation as an effective and sustainable method for decreasing metropolitan passenger traffic. However, given the competitive context where other modes of transportation are striving for higher energy efficiency and better environmental performance as well as the constant rise in energy costs, reduction in energy consumption seems crucial for the urban rail to keep its status as the most economical and sustainable means of transport.

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A few studies discussing different technologies and strategies using regenerative energy recovery through regenerative braking capability to increase energy-efficiency of urban rails, and decrease their impact on greenhouse gas (GHG) emissions at power plantshave been performed in recent years [1].

The energy harvested using regenerative braking is important because it can essentially convert a municipal train station to a microgrid. Likewise, taking advantage of regenerative energy recovery capability of trains due to its significant impact on reducing energy consumptionhas become an interesting and important manner these days. However, in direct current (DC) systems regenerative braking energy (RBE) could be utilized only when other trains are powered simultaneously and in the same electrical section [2]. Otherwise, this energy will be wasted in resistor banks on-board the train. More than 40% of energy consumption could be fed back to catenary or third rail [3-5]; though measurements have shown that share of returned energy is only 19% [6]. This should be noticed that the amount of recovered energy depends on many factors: frequency of service, train characteristics, power profiles, electric network configuration, rolling stock, line voltage, topology of track, length of feed sections, and train auxiliary power [7-9]. In order toimprove receptivity of feeding network, one of the known approaches is to implement controlled rectifiers in traction power substations (TPSs) which will enable DC regenerative energy feedback into the AC network [10-12].

The main objective of this paper is to optimally emplace the reversible substations taking into account the regenerative energy capability by rolling stocks. By performing power flow on DC and AC networks simultaneously, the quantity and quality of power flow through different sectors of electric railway system will be obtained and discussed.To achieve this objective, energy recoveredfrom regenerative braking of trains, and existence of TPSs equipped with controlled rectifiershave been considered for simulating a typical metro line. In order to scrutinize, different TPSs have been considered as candidates to be equipped by controlled rectifiers, and according to the results of simulating each scenario, the optimized number and location of TPS(s) equipped with controlled rectifiers will be achieved.

First, brief insight in the energy consumption of urban rail'sdifferent subsystems is provided. Next, a model for characterization of the network is obtained and then, brief overview of energy efficiency measures for urban rail is introduced. Afterwards, the electrical railway simulator program, and results of the work are presented. At the end, main conclusions of the paper are provided.

2. Energy consumption in urban rail systems

Energy use in urban rail systems is generally classified into two categories: traction and non-traction consumption. Traction consumption not only consists of the propulsion of the train itself, but also its auxiliary systems in service mode; in other words, the term “traction” refers to the power demanded by whole rolling stock running through the system. The term “non-traction” accounts for the power utilized at stations, depots, and other facilities in system such as tunnel ventilation fans, signaling system, groundwater pumps, etc.

2.1 Traction energy consumption

Unlike the diesel traction in which the required energy is generated within the train itself, electric traction requires an external electric power supply system. These supply systems may be in DC or AC form of electricity. Nevertheless, the most urban rail systems work with DC supply system, either at 600/750 V, 1500 V or 3000 V.

A typical traction energy flow for different urban rail systems within Europe [1], is shown in “Figure 1”. This diagram should be assumed as a typical energy flow, as there is significant variation between different systems.

In “Figure 1”, infrastructure losses are electric losses in substations and distribution network – the latter is significantly greater. In general, voltage level of rail system and its traffic are the two key factors in this part of losses – particularly in low voltage networks with high traffic loads. Additionally, in systems favoring RBE transfer through several electric sections of the line, resistive losses are also greater. Typical values for these losses can be as high as 22%, 18%, 10% and 6% respectively for 600 V, 750 V, 1500 V and 3000 V-DC networks [1].

As seen in “Figure 1”, a great part of total incoming energy to the rolling stock is consumed by auxiliary systems. Heating, ventilating and air conditioning (HVAC) equipment have the greatest share of this part of consumption, which drastically depends on the climate condition [1].

Motion resistance is another major share of traction energy which consists of aerodynamic opposition to the vehicle advance and mechanical friction between wheels and rails. As shown in “Equation 1” – motion resistance according to Davies formula – the aerodynamic drag is proportional to square of velocity, this part of motion resistance plays a significant role in high speed services. In contrast, mass of the rolling stock is more important in mechanical friction [1].

$$F_{mr}=A+Bv+Cv^2 \tag{1}$$

In “Equation 1”,v is train speed in km/h, and A, B, and C are constant coefficients which depend on train specifications[1].

Traction losses compriseinefficiencies in the converters, the electric motors and the transmission system. Speed and power range, and also duty cycle may have impact on the efficiency of these components. Recent reports show that the efficiency of traction converters (mainly GTO and IGBT), DC traction motors, induction traction motors, and also gear system are 98.5-99.5%, 90-94%, 93-95%, and 96-98%, respectively [1].

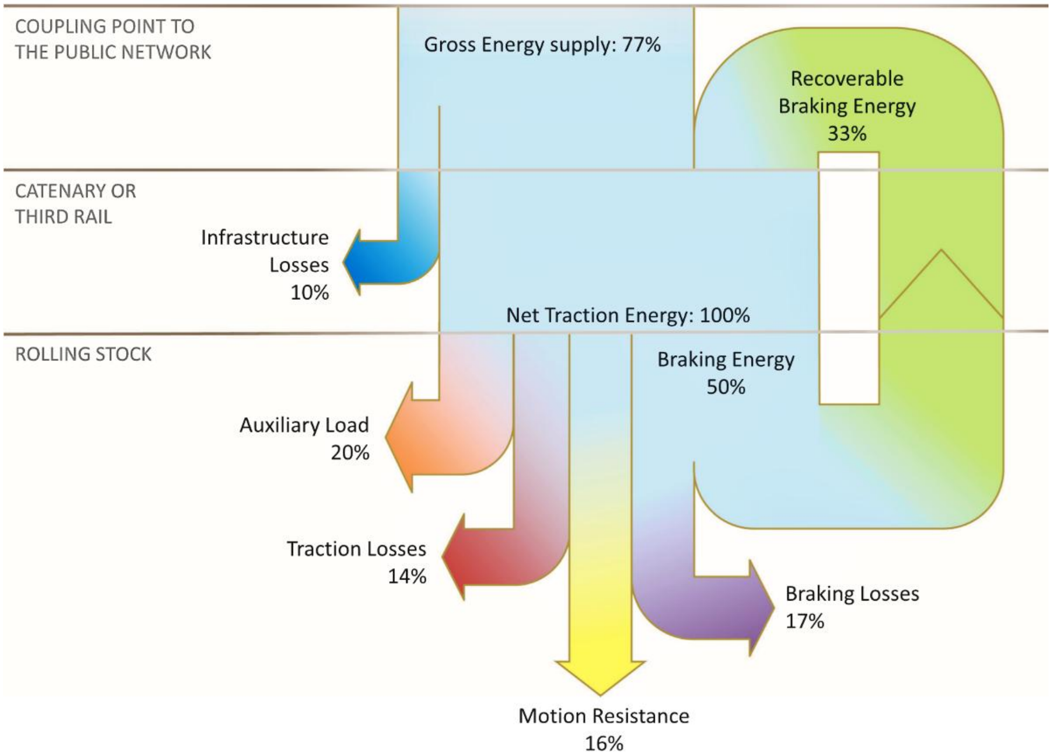

Figure 1. Typical traction energy flow in urban rail systems [1].

The greatest share of traction energy is wasted in braking processes, see “Figure 1”. Depending on the type of urban rail power supply system, the amount of wasted energy in braking process may vary close to half of the incoming energy to the rolling stock. If the electric motors can be act as a generator during the braking process, it is possible to recover and reutilize a considerable proportion of the braking energy. In contrast, approximately one third of the braking energy lostdue to the use of friction brakes and the losses in motors, converters and transmission system during dynamic braking and consequently is not recoverable.

2.1 Non-traction energy consumption

The term non-traction energy consumption stands for whole energy required by several services of urban rail system to ensure the proper system operation. These typical non-traction services comprise stations, depots and other infrastructure installations such as signaling systems, tunnel ventilation fans, groundwater pumps, and tunnel lighting.

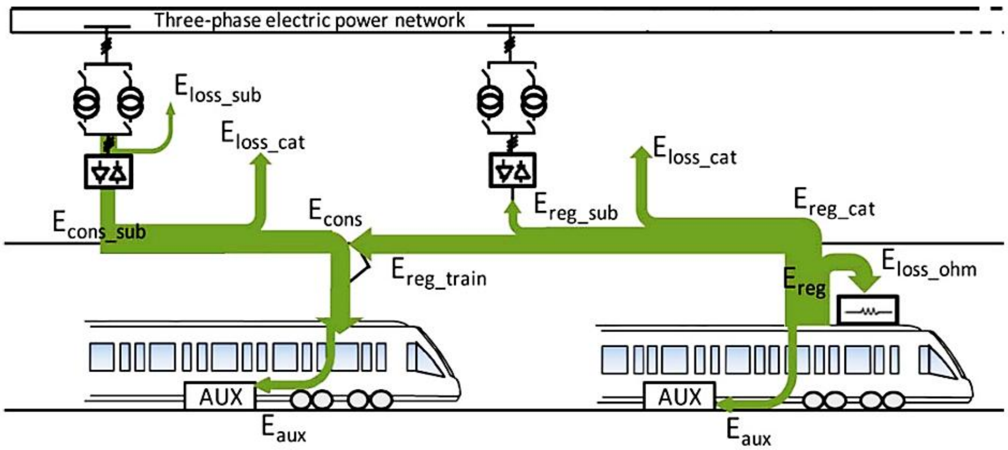

Figure 2. The electrical network configuration and energy flow exchange [14]

The major share of energy consumption in stations, and particularly in underground stations, generally is consumed by HVAC equipment especially in summer, when the amount of energy demand of air conditioning and ventilation may reach to two thirds of the total non-traction energy consumption [1].

Whether the system is underground or on the surface, and also how the climate condition is, this will affect the proportion of non-traction energy consumption. In [13], it has been claimed that the non-traction energy consumption in metro systems can be up to one third of the total energy use.

3. The electrical network model

In this section, traction power supply system model will be introduced to achieve energy consumption of every TPS and all the rolling stocks running the track in different scenarios. The electrical network configuration and energy flow transfer of running rolling stocks through the line are shown in “Figure 2”.

In “Figure 2”, the regenerated energy by the braking train which is not used by its on-board auxiliary systems (E_{aux}) is named available regenerative energy (E_{reg}). If there is any demanding train or any load in the TPS next to the braking train, the energy E_{reg}can be injected to the catenary (E_{reg_cat}) and if not, itwill be wasted on resistor banks on-board the train (E_{loss_ohm}). Ifregenerative energy exceeds the energy required by potentialloads (other accelerating trains and/or loads on the TPSs in that electrical section), the additional regenerative energy would increase thedistribution grid voltage at the station or that of filter capacitors located on trains. In such cases, regenerative brakingwould fail as a supply, so as to avoidexcessive voltage on the line (according to IEC60850 more than 20% of the nominal value), energy E_{reg} must be wasted on resistor banks on-board the train. The energy E_{reg_cat} can flow through the catenary to other accelerating trains (E_{reg_train}) and to reversible substations (E_{reg_sub}).

From the perspective of power supplying, it can be concluded from “Figure 2”, demanding energy of a train can be fed by the substation (E_{cons_sub}) and by RBE of other trains (E_{reg_train}). Therefore, due to the RBE of the trains the energy supplied by the traction substations has been decreased. It should be noticed that in all cases, because of losses and efficiencies in motors, traction converters and transmission systems, the initially regenerated energy is greater than final energy consumption by other trains and by traction substationloads. Accordingly, in this paper a constant coefficient to that matter has been proposed entitled “recovery coefficient”.

4. Energy efficiency measures for urban rail systems

In this section, the most effective approaches to obtain minimum energy consumption of urban rail systems have been introduced and scrutinized. These measures are classified into two categories: operational and technical measures [1]. Operational measures utilize both existing rolling stocks and infrastructures in an optimized manner with minor changes to available installations. In contrast, introduction and implementation of new technologies requiring more investment costs and radical modifications in existing facilities can be achieved through technical measures.

These operational and technical measures according to their level of application; that is, the rolling stock, the infrastructure or the whole system, are classified into five clusters of actions, namely: using regenerative braking, implementing eco-driving strategies, minimizing traction losses, reducing the energy demand of comfort functions, measuring and managing the energy flows efficiently [1]. In this paper, only regenerative braking recovery and equip substations with controlled rectifiers in the level of infrastructure have been used. Details of these approaches will be given below.

4.1 Regenerative braking

Dynamic (electric) braking and the more traditional friction braking are the two types of braking in rolling stocks. In dynamic braking, when the traction motor is switched to generator mode, the output current should be wasted in rheostatic banks on-board the trains or employed for regenerative braking. In rheostatic braking, by dissipating the generated current in resistor banks, the train slows down to low speeds. This type of braking is worth a lot on heavy-haul diesel-electric locomotives running through extreme downhill [15]. In regenerative braking mode, the current polarization is reversed in order to slow down the train.

In principle, braking can be all dynamic with the friction braking used only for emergency stops and for bringing the train to a halt. However, dynamic braking alone would often be insufficient to stop a locomotive, as its braking effect rapidly diminishes below about 16-19 km/h [15]. Therefore, it is always used along with the friction braking.

In general, by increasing the frequency of the train stops, the use of regenerative braking energy is expanded.Therefore, the technique is especially valuable for urban rail systems, which stop frequently. As explained before, regenerated energy primarily is consumed by auxiliary services and the surplus regenerated energy is fed back to the supply line in order to be consumed by other accelerating trains and/or loads in TPSs. However, due to the minor consumption of auxiliary services and low probability of trains’ accelerating and braking at the same time, significant amount of the regenerated energy will still be wasted in resistor banks. There are three options available to optimally take advantage of regenerated energy, namely: optimizing timetables in order to maximize concurrency of accelerating and braking of the trains, utilizing on-board or wayside energy storage systems (ESSs) and feeding back the regenerated energy to upstream AC network [16]. This paper uses reversible substations approach to fully take advantage of regenerative braking energy.

4.2 Reversible substations

In reversible substations instead of diode rectifiers used in conventional DC substations, controlled rectifiers have been installed to enable bidirectional power flow between DC and AC networks. In this case, the surplus regenerated energy can be sent back to upstream AC network and may be used in traction substations and passenger stations (lighting, ventilating, escalators, elevators, offices, etc.) or even sold back to electricity market.

In comparison to ESSs, reversible substations are capable of recovering all the regenerated braking energy, due to permanent receptivity of AC lines. Also, resistive losses through the line are smaller than systems using only ESSs as an energy efficient approach, although these losses mainly depend on the position of the TPSs. In contrast, their investment costs are relatively high. Also, they cannot be used to stabilize voltage and power peak cut out, and operation in intervals without power supply. A few researches demonstrate that 7-11% saving energy can be achieved by applying this technology to existing infrastructures [17-19].

5. Electrical railway simulator program

The objective of this program is to simulate an electrical railway system from both electrical and mechanical points of view, simultaneously. Configuration of the electric network and also track topology along with the timetables of the trains are the inputs of the electrical railway simulator program (ERSP). As an output, both electrical and mechanical dynamics of the rolling stocks will be provided. The most important issues about the proposed program are given below.

5.1 Simultaneous AC/DC power flow

In order to achieve more comprehensive results on the whole system, dynamics of AC traction power substations and also their impact on the DC network have been considered in finding solution of the power flow problem. Since there is a mutual connection between DC and AC networks, it is impossible to separately perform the power flow on the two subsystems. In other words, their power flow equations must be solved in relation to the other, so that the actual resultcould be achieved. For this purpose, the proposed method in [20] has been used. Where it wasclaimed that performing a standard AC power flow separated from the DC traction simulation is better solution rather thana unified AC/DC power flow, since in previous proposed methods for unified AC/DC power flow some details of the DC traction network hadnot been taken into account. In the present program AC power flow and DC traction power flow have been performed by means of Newton-Raphson method and Nodal Analysis, respectively. In this algorithm, the basis of the connection between AC and DC networks is the power exchange between them.

In order to get the final actual solution for the entire system and also to consider the details of the DC traction network, AC and DC power flow equations must be solved together. The proposed program in this paper, first solves the DC traction network, then adjusts the loads of AC traction buses with the converters power consumptions, and then solves the AC network. To complete the cycle, after solving the AC network, currents and voltages of AC buses will be used to calculate converters' output voltages and these will be fed back to the DC power flow in the first step. The loop continuesuntil a stable result is obtained.

Finally, an outer loop can be carried out in order to update the voltage magnitudes, so that the train performance can be recalculated. The integration process may be summarized in the algorithm shown in "Figure 3".

5.2 Simulating regenerative braking operation

The other important feature of the proposed ERSP program is including regenerative breaking in the simulation. In AC networks applying power consumption/generation to each bus can be done by only a simple algebraic operation, but in DC networks there is some challenge to inject power from rolling stocks to the supply line. The cause of this complexity is hidden under converters' operation; generally, traction converters transfer power only in one direction – from AC to DC – so that considering regenerated energy in a bidirectional manner could result in incorrect answers. In order to obviate this problem in DC network, proposed program has been modified, so that notwithstanding single directional power flow, it returns proper answers in the output. More accurately, after solving the DC network equations at each step, considering the capability of each single converter to transfer the power in both directions or not, the calculated result is analyzed; for each converter if the power transfer direction does not match its feature, the converter will be removed from the equations. After withdrawal of each converter power flow should be resumed.

In addition, the possible overvoltage situation during regenerative braking is undeniably a crucial issue that needs to be followed up.

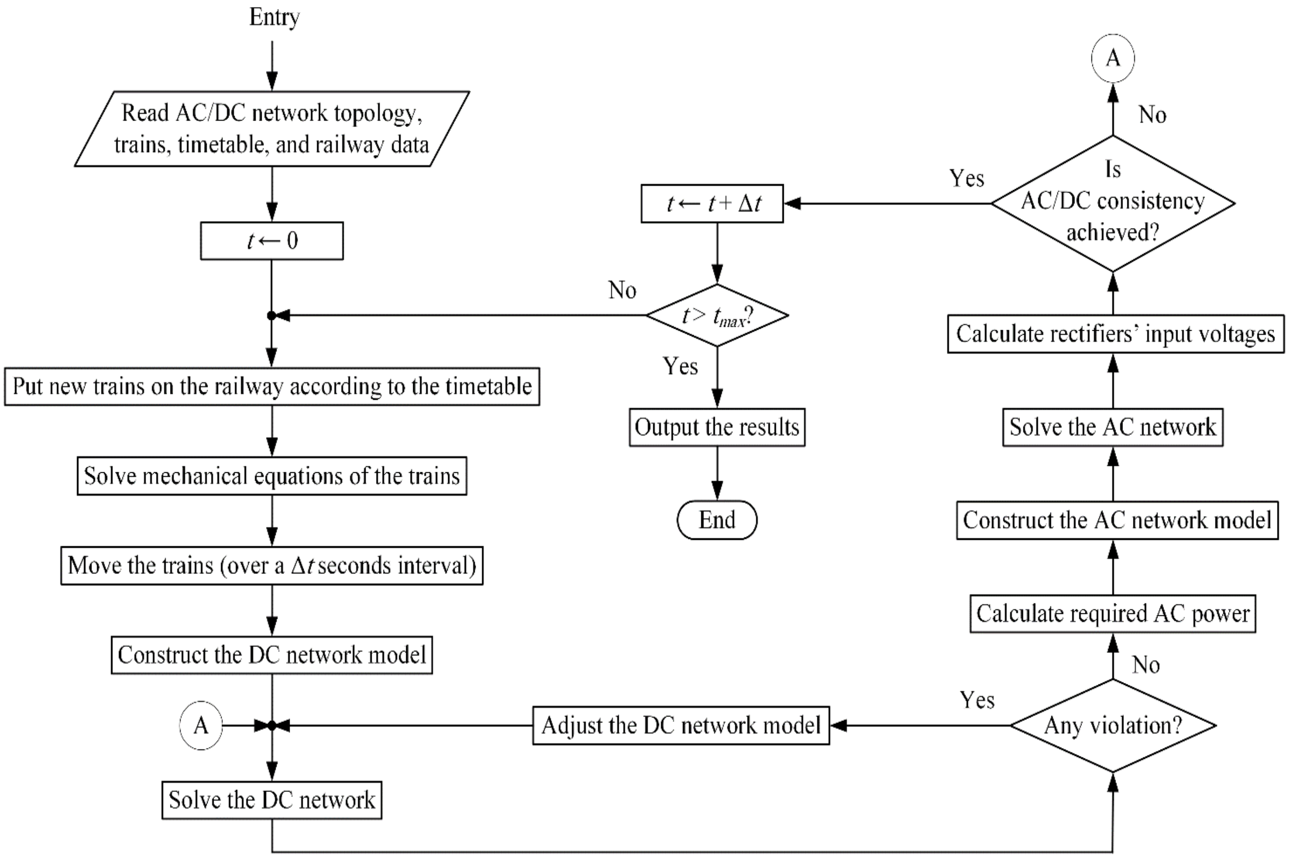

Figure 3. Flowchart of AC/DC power flow

Sometimes, due to unbalance between power generation and consumption, power injection from rolling stocks to the supply line can cause overvoltage in DC network. Therefore, another feature considered in the proposed program is the detection of overvoltage conditions and subsequently cutting off the regenerative trains from the network. Actually, cutting off a train from the distribution network means the surplus regenerated energy – after it is consumed in auxiliary systems – is wasted in on-board resistor banks.

5.3 Simulating mechanical system

Role of the mechanical portion in simulations is to address the interactions between all proportional, braking and resistance efforts along with geographical characteristics of the route. The traction and braking efforts parameters, and also other input mechanical parameters of the rolling stocks such as: effective mass, maximum traction and braking acceleration, maximum velocity and Davies formula coefficients has been presented in “Table 1”.

Table 1. Input mechanical parameters of the rolling stocks

Parameters	Value
Effective mass	335 [t]
Maximum traction effort	98 [KN]
Maximum braking effort	98 [KN]
Maximum traction acceleration	1 [m/s^2]
Maximum braking acceleration	0.7[m/s^2]
Maximum velocity	100 [Km/h]
Rotating mass factor	0.1
Davies formula coefficients	a = 3402
	b = 238.1
	c = 8.9

6. Results and discussion

In order to scrutinize quantity and quality of energy flow under different scenarios, typical subway network introduced in [21] has been used. The structure of this network has been shown in “Figure 4”.

As it can be seen in “Figure 4”, there are two 20 KV AC substationsin level of distribution network. Also there are three 3.5 MVA DC TPSsequipped with sixpulse converters at 2, 7 and 11 km far from beginning of the track.

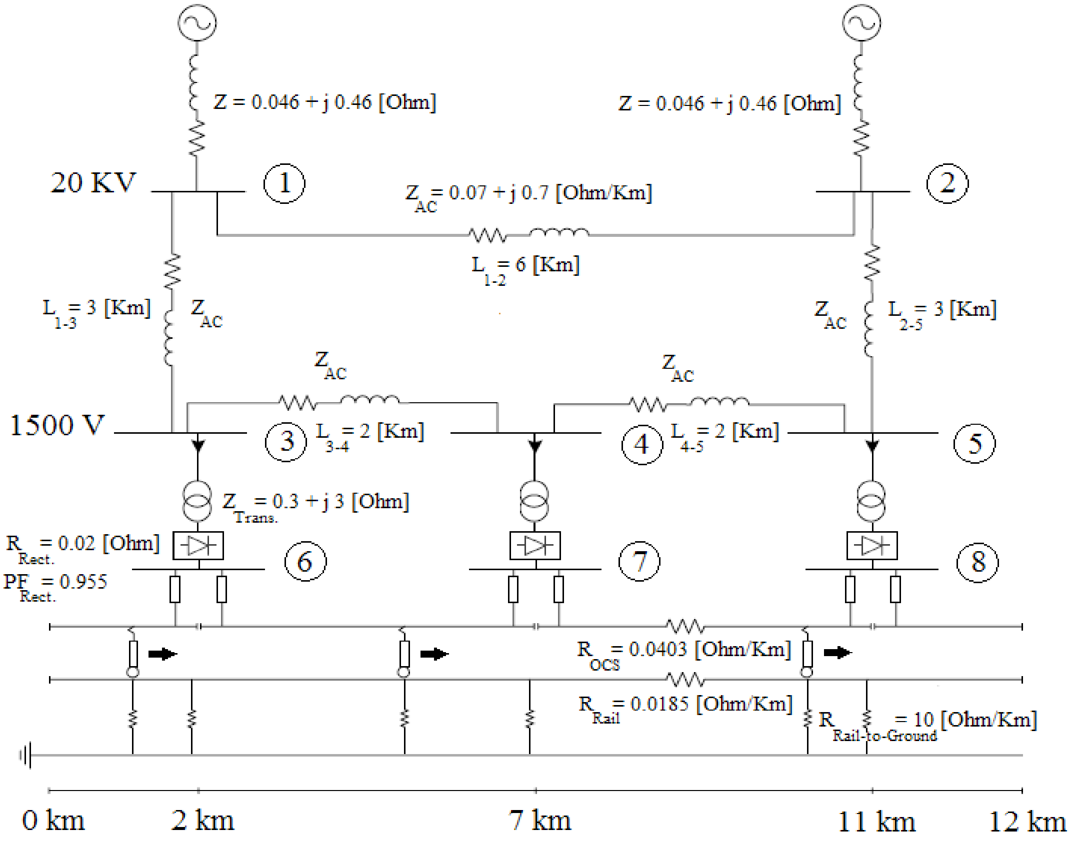

Figure 4. The network structure used in simulations [21]

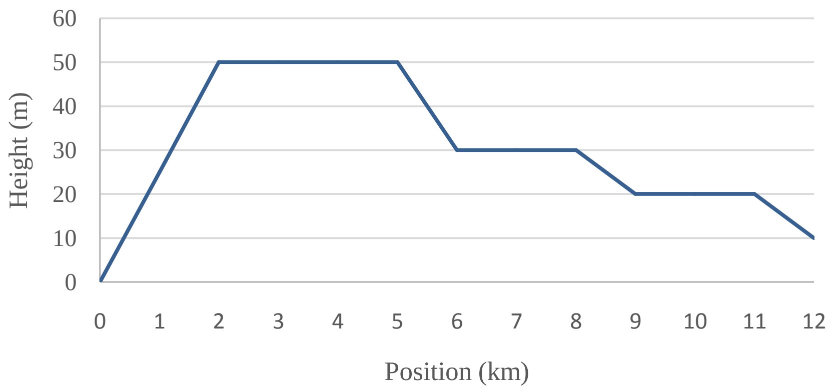

Figure 5. Profile of the simulated track.

Nominal voltage of the DC supply system is 1500V and lowest and highest permanent voltages have been assumed 1000 V and 1800 V, respectively.

Length of the track is 12 km and there are four stations one at the beginning, two at 4 and 9 km from the beginning and one at the end of the track. Ten trains on one track with 210 seconds operational headway time and 40 seconds dwell time have been used on the track. In “Figure 5”, track profile has been shown.

First scenario has been defined for electrical railway network without regenerative braking and reversible substations. In second one, it is assumed that all the

Table 2. Simulation results on typical metropolitan subway under several scenarios

Scenario No.	Total energy injected by converters at traction buses (MWh)		Energy of all trains (MWh)		Energy losses (KWh)	Wasted regenerated energy of all trains (KWh)	**Energy efficiency improvement percentage (in respect to the first scenario)**
	Bus No.	Energy	Type	Energy			
One	6	1.02965	Cons.	1.76359	55.97	0.00	**0%**
	7	0.27209	Gen.	0.00000			
	8	0.51782	Net	1.76359			
	∑	**1.81956**					
Two	6	0.96035	Cons.	1.76346	62.86	307.23	**16.03%**
	7	0.16819	Gen.	0.29849			
	8	0.39929	Net	1.46497			
	∑	**1.52783**					
Three	6	0.91513	Cons.	1.76343	65.06	255.92	**18.73%**
	7	0.16816	Gen.	0.34977			
	8	0.39542	Net	1.41365			
	∑	**1.47872**					
Four	6	0.97855	Cons.	1.76363	69.87	96.66	**27.22%**
	7	-0.09614	Gen.	0.50923			
	8	0.44185	Net	1.25439			
	∑	**1.32427**					
Five	6	0.90267	Cons.	1.76349	68.41	20.21	**31.50%**
	7	0.19012	Gen.	0.58554			
	8	0.15356	Net	1.17795			
	∑	**1.24635**					
Six	6	0.95992	Cons.	1.76374	66.31	0.70	**32.77%**
	7	-0.03023	Gen.	0.60671			
	8	0.29366	Net	1.15704			
	∑	**1.22335**					

trains have regenerative braking capability and still substations can’t feed back regenerated energy to upstream AC network. In third scenario, in addition to considering regenerative braking capability for all trains, only DC TPS at the beginning of the track (number 6 in “Figure 4”) has reversible feature. The only difference between fourth and fifth scenarios with the third one is the position of candidate TPS to have reversible feature; such that, in fourth and fifth scenarios, middle (number 7 in “Figure 4”) and the end TPS (number 8 in “Figure 4”) can return the regenerated energy to AC network, respectively. Finally, sixth scenario has been assumed to be equipped with all the measures available in this paper, i.e. all trains can regenerate braking energy and also all the TPSs have reversible feature. Simulation results are shown in “Table 2”.

As it can be seen in “Table 2”, total energy injected through rectifiers under scenario number one is the maximum. In this situation, the traction bus at the beginning of the track (bus number 6) supplies more than half of the demanded energy by the trains. This is because of the acute gradient at the first half of the track, so the net energy consumed by trains in this scenario is the maximum as well. In this scenario, total energy consumed in DC network (all the trains’ consumption and total energy losses) is approximately 1.82 MWh.

Utilizing regenerative braking capability leads to saving energy. As the results of the scenario number two indicate, by using this capability approximately 0.30 MWh of total incoming energy to trains is fed back to DC transmission network. The total energy consumption in this scenario is approximately 1.53 MWh, so that in comparison to first scenario approximately 16% saving energy is achieved, but there is more potential to recover energy. With respects to “Table 2”, approximately the same amount of the energy regenerated, there is wasted regenerated energy

(0.31 MWh) which is blocked due to the non-receptivity of the DC network.

It is still feasible to recover more energy through utilizing reversible substations. According to the results for scenario number three, by equipping the first TPS with controlled rectifiers which enable the bidirectional power flow between two AC and DC networks the blocked regenerated energy by the trains will be reduced (to 0.26 MWh).Compared to the first scenario, about 19% saving energy is achieved.Although, as mentioned before in “energy efficiency measures section”, the typical saving energy percentage presented in previous works through this technology, is far less than the savings evaluated in this paper. This could be due to the one-way operation of the track, so that more regenerated energy is available to being sent back through reversible TPSs to upstream AC network.

Taking advantage of reversible substations in order to recover regenerated energy depends on their proper emplacement on the route. As it was mentioned before, although equipping the TPS at the beginning of the track with controlled rectifiers improved the energy efficiency, it did not make a considerable improvement. This is because of the track topology, as shown in “Figure 5”. Due to the steep uphill at the beginning of the route the trains in this section consume powerinstead of regenerating and sending it back to the DC supply line, so utilizing reversible substations at the beginning of the route (first TPS, bus number 6) is not justifiable. But after the trains pass this steep uphill at the beginning of the route due to the successive downhill, not only in order to stop at the stations, but also not to exceed the speed limit they send back energy to DC network. For this reason, the fourth and fifth scenarios defined so as to equip the middle and the last TPSs with controlled rectifiers, respectively, have considerable impact (around 30% overall) on energy saving. In comparison to the scenario number four, the fifth scenario is associated with a greater reduction in energy consumption.

Finally, it was expected that in case all the TPSs are equipped with controlled rectifiers, the best energy saving mode can be achieved. The sixth scenario simulation results confirm this. In this situation, total energy consumption is about 1.22 MWh. Although, equipping the TPS at the end of the track (bus number 8) alone, can lead to approximately the same reduction in energy consumption. Actually, these results indicate the justifiability of equipping candidate TPS(s) with controlled rectifiers.

The other notable point here is increased level of energy losses through scenario number two to six compared to the first scenario. To explain this event, constant level of energy consumptions of trains (not the net ones) under different scenarios should be considered. As it can be seen in “Table 2”, energy consumption of trains is a constant amount of 1.76 MWh for all scenarios. Normally, there are always energy losses due to the energy transfer in any electrical networks. In the first scenario, due to the one directional operation of rectifiers (from DC network to trains) energy losses take place only at energy consumption intervals by the trains. But in scenarios number two to six, where a portion of incoming energy to trains is sent back to network there are also some other energy losses, so it is rational to have more energy losses for these scenarios with respect to base one. However, there is no specific analysis on energy losses’ variations under these scenarios.

Speed and acceleration profiles of train number five are shown in “Figure 6”. As seen in speed profile, the train has not exceeded velocity upper limit (80 km/h) at any time.

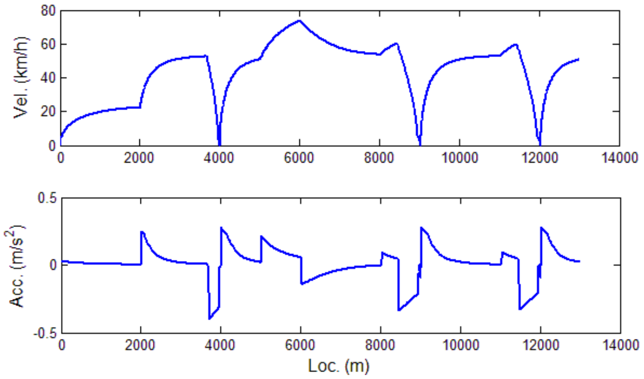

Figure 6. Speed and acceleration profiles of train number 5

Electrical and mechanical characteristics of the train number five have been shown in “Figure 7” and “Figure 8”, respectively. Electrical characteristics as seen in “Figure 7”, consist of voltage, current and power of train number five. The noteworthy point here is when the train is in regenerative braking mode, power (and also current) injected to it will be positive and the peak of it is nearly twice the consumption. The other important point as can be seen in voltage graph is the fact that the magnitude of instant voltage never exceeds the upper limit.

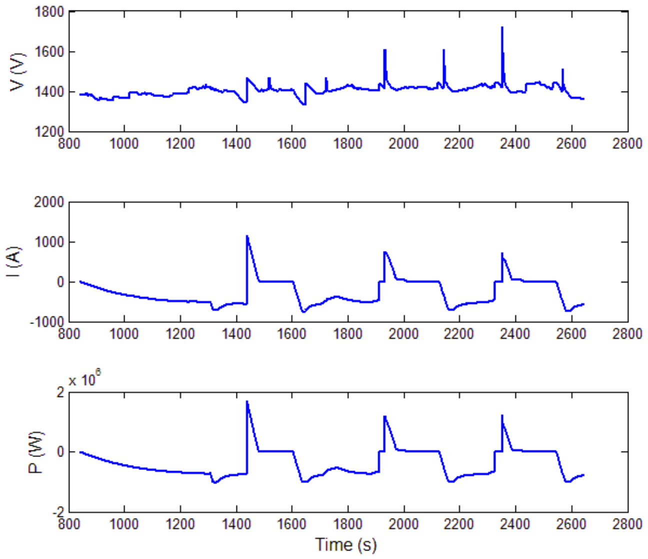

Figure 7. Electrical characteristics of train number 5

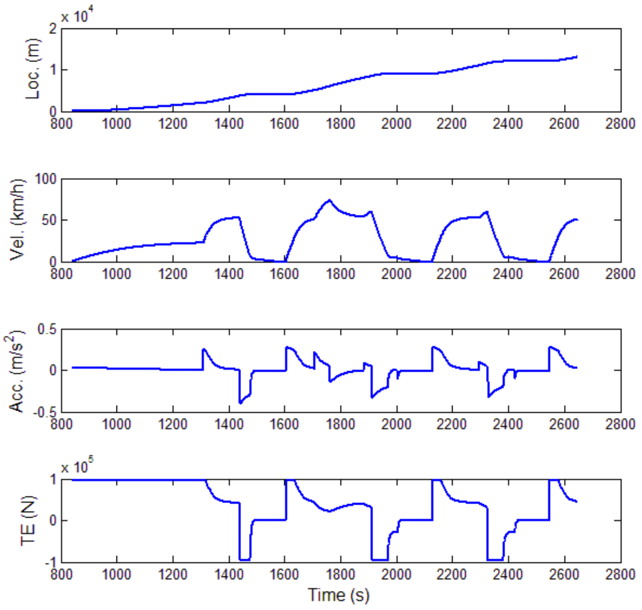

Figure 8. Mechanical characteristics of train number 5

In “Figure 8”, position, velocity, acceleration and tractive effort characteristics are shown. The notable point here is, applying maximum tractive effort from the beginning of the train’s departure (840 seconds) till 1310 seconds and still minor decrease in train’s acceleration due to the extreme gradient of the route, which can be seen in “Figure 5”. After that, train has accelerated until reaching the next station’s admissible breaking distance.

7. Conclusions

In this paper, energy flow (consisting of: consumed energy, regenerated energy and net energy) of the single trains evaluated at TPSs instead of trains’ pantograph through the proposed electrical model of network. Hence, the regenerative braking energy of the trains through this systematic point of view to the electrical supply network could be fully monitored and considered in power flow calculations. In addition, an energy-efficient approach was proposed to deal with the saving energy problem in urban rail systems. Through this approach, different scenarios in order to find the best technical and economical solution,along equip the existing infrastructures by controlled converters in an optimized manner were introduced.

In short, utilizing the rolling stocks’ regenerative braking capability has shown significant amount of energy saving (more than 16% with respect to scenario number one). Utilizing this feature along with the installation of controlled rectifiers at the simulated typical subway line’s TPSs in this paper, also demonstrated desirable operation (up to nearly 33% saving energy in the whole system) under several scenarios (scenarios number three to number six).Finally, the best solution for the simulated typical subway line in this paper from both saving energy and economical points of view, is to equip the TPS at the end of the track with controlled rectifiers. This energy-efficient solution, leads to 31.5% saving energy in the whole system with respect to scenario number one.

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