Analysis of wayside energy storage devices for DC heavy rail transport

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Abstract. The proposed paper presents the possibility of using the wayside energy storage devices (WESD) for the DC Heavy Rail Transport treating the design, costs and payback time. Moreover a case study comparison for the use of wayside energy storage devices on the heavy transport at the supply voltage of 3.3kV DC is presented. A method of sizing the energy storage devices using vehicle characteristics, traction power supply and running timetable is presented. The paper also presents the cost analysis for the most commonly used energy storage devices and the payback time.

1 Introduction

Nowadays most of the traction vehicles have the ability of regenerative braking. The energy resulted from the braking process is used by other vehicle located in the vicinity of the braking vehicle. If the receiving vehicle is not able to receive the entire energy then it is lost on braking resistors to keep the line voltage under the limits. Different types of energy storage devices are proposed for storing the resulted braking energy like: batteries, supercapacitors, flywheels, superconducting energy storage systems or a combination of them [1, 2, and 3]. Beside the main scope of saving energy the energy storage devices can improve the train traction characteristic, the line voltage and can provide with longer distances between the traction substation supplies [4, 5].

The energy storage devices are widely used in the light transport and there are many research papers and studies detailing their design, control, effectiveness and payback time. The maximum power required for the light transport vehicles (metro, tram) is around 1.5MW compared with heavy rail trains that can be up to 6MW [6]. In theory the heavy rail trains could save more energy if we consider the power needed for powering them and the longer braking distances. If wayside energy storage devices are used, there is no restriction and constraints regarding the size and location allowing us to freely design those according with the power demanded.

2 Applications of wayside energy storage devices

The lead acid battery has been used for more than 150 years [7]. The first lead acid battery used for the electrified transport was called "battery post". They were used in Japan from 1912 to 1927 on Shin-etsu Line. The battery was installed at the Maruyama and Yagasaki traction substation. The space required for battery installation was 20% bigger than that for substation electrical equipment. The installed battery capacity was 1332 Ah and rated voltage 624V. The scope of battery use was to suppress the voltage drop [8].

A Ni-MH battery produced by Kawasaki Heavy Industry has been successfully used for wayside light rail application. The batteries Kawasaki Gigacell used for Osaka Subway improved the minimum line voltage from 703V to 718V and reduced the voltage spikes from 939V to 854V [9].

In table 1 is presented examples were the batteries Kawasaki Gigacell was used [10].

Table 1. Kawasaki Gigacell applications.

Location	Year of installation	Battery capacity	Installation scope
New York Subway	2010	367kWh	Verification tests
Osaka Subway	2011	205kWh	Power savings
Washington D.C. Subway (WMATA)	2012	385kWh	Verification tests
Tokyo Monorail, Shinagawa Substation	March 2013	203kWh	Power savings
Osaka Subway	2013	204kWh	Power savings
Sapporo Subway	2013	204kWh	Power savings
Tokyo Monorail, Tamagawa Substation	March 2014	203kWh	Power savings

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Lithium ion batteries produced by Hitachi was successfully tested on Myodani substation of the Seishin-Yamate Line of the Kobe city Subways in 2004 by Kobe Municipal Transportation Bureau. The rated power of the system was 1000 kW and the rated energy 37.4 kWh. The role of energy storage device was to absorb regenerative power. In parallel with the storage devices, the invertor equipment was used to check if they could operate together and no interference was noticed. It was noticed that the installation of the system can save more than 10% of the energy for power consumption [8].

In 2011, in South Korea on the Seoul Metro Line number 9 a stationary energy storage device was installed produced by Hitachi with lithium ion battery at three substation 903 (0.3MW inverter), 909 (1MW storage system) and 921 (1MW storage system). The estimation for the annual power savings on the substation 921 was 510MWh. During the operation in the first month the energy saved was 94 MWh which surpassed the initial expectations [11].

First stationary energy storage device on electrified railway using a flywheel was introduced in 1988 in Japan. The stationary storage device was installed at the Zushi substation by Keihin Electric Express Railway. The device was able to convert regenerative energy to mechanical energy using a generator motor and converter and back to electrical energy. The total power of the system was 2000kW and was able to store up to 25kWh energy. The energy saved by the storage devices was believed to be around 12% [8].

3 Simulation of a DC heavy rail transport

Figure 1 gives the assumed line profiles including the stations and substations.

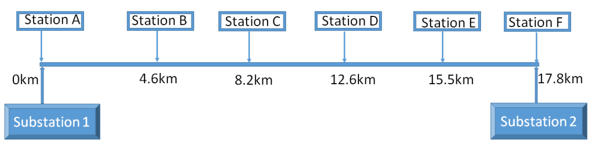

Fig. 1. Simulation line profile.

In table 2 the assumed specification is presented for the vehicle and the line.

Table 2. Simulation parameters.

Parameter	Unit	Quantity
Track length	km	17.8
Catenary and rail resistance	Ω/km	0.07
Substations internal resistance	Ω	0.21
System Voltage	kV DC	3.3
Number of stops	-	6
Number of trains	-	1
Train mass	t	120
Maximum train speed	km/h	120
Average train speed	km/h	80
Average train acceleration / deceleration rate	m/s²	0.8

If we consider a train running from Station A to Station F the train voltage, current and power simulation results are presented in figure 2. Train simulation was provided in the train simulation program prepared by Electric Traction Division of the Warsaw University of Technology [12, 13].

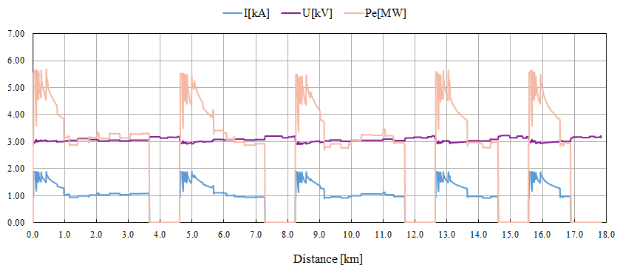

Fig. 2. Simulation results for the train running between Station A and Station F.

The results of the simulation for a train travelling from Station A to Station F are presented in table 3.

Table 3. Simulation results for the train running between Station A and Station F.

Stations	Track length [km]	Total Energy used [kWh]	Energy used per km [kWh/km]	Average power [MW]
A-B	4.6	132.2	28.73	2.86
B-C	3.6	106.3	29.52	2.79
C-D	4.4	121	27.5	2.77
D-E	2.9	83.7	28.86	2.65
E-F	2.3	68.1	29.6	2.6
Total	**17.8**	**511.3**	**28.72**	**2.73**

Figure 3 shows the train movement diagram used for operation calculations for a 5 minute headway and 1 minute stop at each station.

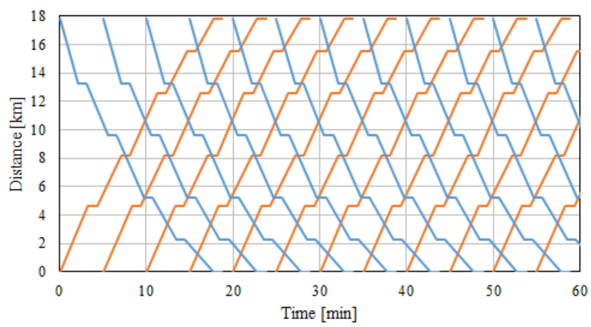

Fig. 3. Assumed train movement diagram for 5 minute headway.

From figure 3, the train operation was calculated for one year and presented in table 4.

The average train speed for the simulation was considered 80km/h with a train mass of 120t. From figure 4 we can conclude that the wayside energy storage system should be capable of absorbing minimum energy of 38.4 MJ (10.7kWh). The charging / discharging current for the WESD is considered 1kA. If we consider the WESD power 3MW and the absorbed energy of 40MJ the charging time for the WESD is 20s

(40MJ/3MW=13s). For 13s charging time and 2C current the depth of discharge (DOD) is 0.7% (13*2/3600=0.7%), for 3C current the DOD is 1.1% (13*3/3600=1.1%) and for 5C current the DOD is 1.8 % (13*5/3600=1.8%).

Table 4. Assumed train operation for a calendar year.

Time	Headway	Cycles per Day	Total cycles
Peak hours (6-9AM and 4-7PM)	5 minutes	144	52560
Off - peak hours and weekends	15 minutes	128	46720
Between 1AM and 3PM	No train services	-	-
Total			**99280**

4 Calculation of the energy that can be saved

The Polish transport company SKM provided test of braking with regeneration on 3.3kV DC trains manufactured by Polish company Newag S.A in April 2012 [14]. The measurements was taken in train with the energy meter LE3000 Elester. Table 5 presents the measurement results provided by SKM.

Table 5. Measurements results provided by SKM.

Train Type	EZT19 WE	EZT27 WE	EZT35 WE
Max power	3.5 MW	4MW	4MW
Train mass	190t	190.5t	197t
Maximum train speed	130km/h	160km/h	160km/h
Average train speed	42km/h	41km/h	36.8km/h
Track length	Approx. 35.5km	Approx. 23km	Approx. 29km
Stations	Pruszkow – Sulejowek Miłosna	Warszawa Zachodnia – Sulejówek	Warszawa Zachodnia (Platform 8) - Legionowo Piaski
Total energy used	362.2kWh	302.9kWh	329.7kWh
Total energy saved	129.9 kWh	59.4kWh	121.5kWh
Percent energy saved	35.31%	19.58%	37%
Average energy used per km	10.2kWh/km	13.17kWh/km	11.37kWh/km
Average energy saved per km	3.1kWh/km	2.58kWh/km	4.19kWh/km

The total energy that can be recovered by the WESD can be calculated with the formula:

$$E_{WESD} = E_{Breake} - E_{Aux} - E_L \tag{1}$$

where:
E_{WESD} - potential energy that can be recovered by the storage device [kWh],
E_{Breake} - total energy resulted from the braking vehicle depending on the mass, speed and brake force [kWh],
E_{Aux} - energy recovered by the braking vehicle and used for auxiliary supply (lighting, ventilation, heating etc.) [kWh],
E_L - energy line loses [kWh].

If we consider that the traction vehicle loses only mechanical energy and we have only kinetic energy ($E_{Breake} = E_k$) we can use the following formula to determine the energy resulted from braking:

$$E_k = m \times V^2 / 2 \tag{2}$$

where:
V - the vehicle velocity in [km/h],
m - the vehicle mass in [kg],
E_k - the kinetic energy in [kWh].

Figure 4 shows estimated braking energy for different vehicle mass and velocity calculated according with formula (2).

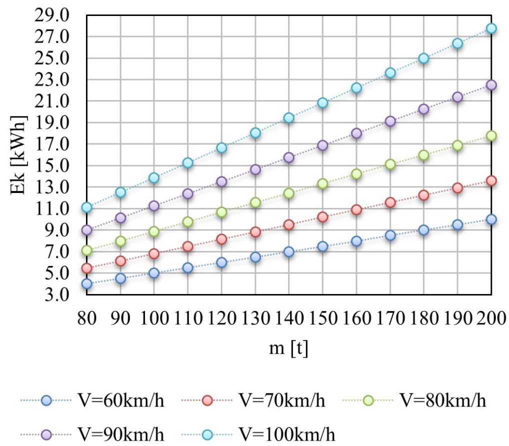

Fig. 4. Braking energy in kWh.

The power needed for the auxiliary train equipment can be around 40kW depending on the weather conditions (cold or hot), period of the day (day or night). We assume the energy recovered by the braking vehicle to be around 3kWh.

Depending of the location of the WESD and the braking current we can have different catenary losses.

$$\Delta E_L = R \cdot \int_0^t I^2 dt \tag{3}$$

where:
ΔE_L - energy losses in wires [W] function of time t [s],
R - resistance of the line [Ω],
I - the load current [A].

If we consider the energy loses in catenary around 10% of the braking energy 10.7 kWh according to figure 5 we have approximately 1.1kWh catenary loses for a maximum distance of 17.8km between the braking train and the WESD.

According to figure 4 and figure 5 the potential energy that can be recovered by the storage device is approximately 6.6kWh (10.7 kWh - 3 kWh - 1.1 kWh = 6.6kWh) considering that there is no other train to recover the braking energy which is around 60% from the braking energy that can be recovered.

The recovered braking energy can take values from 5% to 30% from the total consumed energy depending on the receptivity of the other trains to consume the energy. The energy for a train to travel from Station A to Station F is 511kWh. For the worst case scenario where the recovered energy is 5% we have 25kWh potential recovered energy divided between the catenary losses, auxiliary train equipment and the WESD.

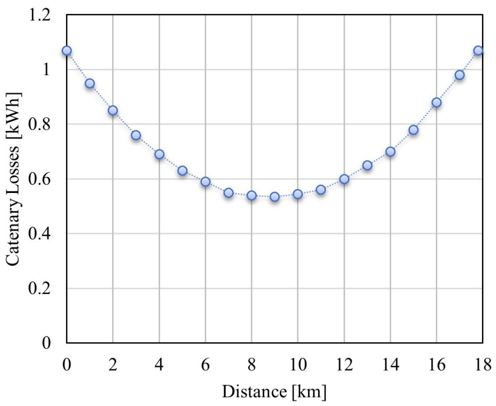

Fig. 5. Catenary loses for different location of the WESD in kWh.

From the above results the WESD can recover around 15kWh (60% from 25kWh) for a train travel between Station A and Station F. For 99280 cycles per year in both directions, theoretically we can save up to 1490MWh/year.

The kWh in Poland costs around 0.09 US $ for industry [15] which results on a potential saving of 134 000 US $ per year. For a 10 years calendar life of WESD system we can calculate the money saved as 1.34 million US $ (0.134million US $ * 10years = 1.34 million US $).

5 Designing of the energy storage devices

To directly connect the energy storage devices we need to design them to the voltage line to avoid electrical separation.

5.1 Lead acid batteries

The Hitachi LL1500-WS battery [16] has 2V and 1500Ah per cell with a recommended maximum discharging current of 900A, a maximum of charging current of 450A and energy capacity of 3kWh (1500Ah * 2V / 1000 = 3kWh). To connect the WESD to the 3.3kV we need 1650 batteries (2V * 1650batteries = 3.3kV) in series. The energy capacity of the unit is 5MWh (3kWh * 1650batteries = 5MWh). Because the maximum discharge current is 900A the power rating for the unit is limited to 3MW (3300V * 900A / 1000 = 3MW).

The number of cycles given by Hitachi for a 70% DOD is 4500 cycles. For 0.7% DOD number of cycles is 450 000 cycles and for 1.1% DOD number of cycles is 286 000 cycles. If we consider the calendar life of the battery to be 10 years, the number of cycles should be sufficient because on peak hours the braking energy is transferred between trains and the DOD is much smaller than calculated. For a DOD of 1.1% the maximum energy that can be saved by the WESD is 55kWh.

The price given by Hitachi Chemical for the battery is approximately 300 US $ per kWh [17]. If we consider the battery management system to cost 0.5 million US $ the WESD cost is around 2.5 million US $ (for 1650 batteries).

5.2 Nickel-metal hydride (Ni-MH) batteries

The Kawasaki Gigacell battery [10] has 36V (30cells * 1.2V = 36V) and 150Ah per battery with a charging/discharging recommended maximum current of 750A (5C) and energy capacity of 5.4kWh (150Ah * 36V / 1000 = 5.4kWh). To connect the WESD to the 3.3kV we need 91 batteries (36V * 91 batteries = 32730V) in series. The energy capacity of the unit is 491,4kWh (5.4kWh * 91batteries = 491,4kWh). The power rating for the unit at a 5C maximum charge/discharge rate is 2.46MW (3276V *750A / 1000 = 2.46MW).

If we want to capture all the braking energy we need to design the WESD capable of absorbing 40MJ. For 2 units connected in parallel we have 1.5kA maximum current at a 5C maximum charge/discharge rate per unit. The energy capacity of the system is 983kWh (491.4kWh * 2 = 983kWh).The power rating for the system at a 5C maximum charge/discharge rate is 4.9MW (3276V * 750A * 2 / 1000 = 4.9MW).

The number of cycles given by Kawasaki for a 0.33% DOD is 2 million. For 0.7% DOD number of cycles is 943000 cycles and for 1.8% DOD number of cycles is 367000 cycles. If we consider the calendar life of a battery as 10 years for our system the number of cycles should be sufficient because on peak hours the braking energy is transferred between trains and the DOD is much smaller than calculated. For a DOD of 1.8% the maximum energy that can be saved by the WESD is 17.7kWh.

For a battery price of 25000US $ and 0.5 million US $ cost assumed for the battery management system the cost of the WESD is around 5.1 million US $ (for 182batteries).

5.3 Lithium Ion (Li-ion) batteries

The Hitachi CH-75-6 battery [18] has 22.2V (3.7Vcell * 6cells = 22.2V) and 75Ah per pack with a charging/discharging recommended maximum current of 3C (225A) and energy capacity of 5kWh (225Ah * 22.2V / 1000 = 5kWh). To connect the WESD to the 3.3kV we need 148 batteries (22.2V * 148batteries =

3.3kV) in series. The energy capacity of the unit is 4.95MWh (5kWh * 148batteries = 740kWh). The power rating for the system at a 3C maximum charge/discharge rate is 4.9MW (3286V * 225A / 1000 = 739kW).

If we want to capture all the braking energy we need to design the WESD capable of absorbing 40MJ. For 4 units connected in parallel we have 900A maximum current at a 3C maximum charge/discharge rate for unit. The energy capacity of the system is 3MWh (740kWh * 4 = 3MWh). The power rating for the system at a 3C maximum charge/discharge rate is 3MW (3286V * 225A * 6/1000 = 3MW).

The number of cycles given by Hitachi for a 75% DOD is 4000 cycles. For 0.7% DOD number of cycles is 428000 cycles and for 1.1% DOD number of cycles is 273000 cycles. The calendar life of the battery given by Hitachi is 10 years the number of cycles should be sufficient because on peak hours the braking energy is transferred between trains and the DOD is much smaller than calculated. For a DOD of 1.1% the maximum energy that can be saved by the WESD is 33kWh.

The price given by Hitachi Chemical for the battery is approximately 900 US $ per kWh [17] (4500 US $ per module) excluding the battery management system that can be assumed to cost 0.5 million US $. If we consider a cost of 7000 US $ per module the WESD cost is around 4.8million US $ (for 592batteries).

5.4 Supercapacitors (SC)

The Maxwell BMOD0063 P125 B08 supercapacitors [19] has 125V (48cells), 140A continuous current and with a charging/discharging recommended maximum current of 1900A and energy capacity of 144Wh (3Wh * 48cells = 144Wh). Because the ESR can increase up to 100% during 10 years of service we have to reduce the continuous current to 100A. To connect the WESD to the 3.3kV we need 27 supercapacitors (125V * 27supercapacitors = 3.3kV) in series. The energy capacity of the unit is 3.9kWh (144Wh * 27supercapactiors = 3.9kWh). The power rating for the system at a 100A charge/discharge current is 0.38MW (3375V * 100A / 1000 = 0.38MW).

If we want to capture all the braking energy we need to design the WESD capable of absorbing 40MJ. For 10 units connected in parallel we have 1kA continuous current and a maximum charge/discharge current of 19kA. The energy capacity of the system is 39kWh (3.9kWh * 10 =3 9kWh).The system power rating for 1kA continuous current is 4.9MW (3276V * 1000A * 10 / 1000 = 3.3MW).

The number of cycles for charge/discharge given by Maxwell is 1 million times at 25° C with a live period of 10 years. The maximum energy that can be saved by the WESD is 39kWh.

The price for the BMOD0063 P125 B08 is approximately 5000 US $ not including the converter and the voltage equalizing circuit which can be estimated to cost around 0.5 million US $ the WESD cost is around 1.9million US $ (for 270 supercapacitors).

5.5 Flywheel

The Vycon VDC flywheel [20] has input voltage regulated between 400V to 600V, 500kW output power and can store up to 7.5MJ.

To connect the WESD to the 3.3kV we need 6 modules (600V * 6modules = 3.3kV) in series.

If we want to capture all the braking energy we need to design the WESD capable of absorbing 40MJ. For 6 units connected in parallel we have 45MJ (6units * 7.5MJ = 45MJ) and 3MW power.

The Vycon VDC flywheel has 20 year operational live with low maintenance (equipped with magnetic bearing).

The price for the flywheel is assumed 1 million US $ / MW and 0.5million US $ for the control circuit which give a total cost of the WESD 3.5 million US $.

6 Conclusion

In the article an example was presented on how to calculate the train braking energy. Simulation was provided with scope of calculation the energy needed for a train to run on an example line. The main cost for the WESD is the energy storage medium. The design and cost estimation was made for a period of 10 years calendar life given by the manufacturers for the batteries.

For a 10 years period the energy that can be saved for the example provided is 15 GWh which is 1.34 million US $. For 10 years life time the cost for the WESD with battery is 2.5 million US $ for lead acid, 5.1 million US $ for Ni-MH, 4.8 million US $ for Li-ion, 1.9 million US $ for WESD with SC and 3.5 million US $ for WESD with flywheel. When calculating the total cost of the WESD the installation, building premises, cooling and heating or maintenance were not taken into account; these factors will considerably increase the total costs.

The revised WESD from the example provided does not save enough energy to justify the installation by the customer. The most probable WESD that will be used on electrified heavy rail transport in the future will be with SC because it is the most cost effective.

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