Application of energy storage systems for DC electric railways

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Abstract

Thanks to the recent development of electric vehicles (EVs), the application of electric energy storage techniques in electric railways is now widely believed to bring revolution to the energy supply system for railways. The author's research group uses RTSS, a multi-train power feeding network simulator, to evaluate the flow of energy in the network in their research into the development of DC electric railway systems with energy storage. In this paper, simulation results that will demonstrate the possibility of this approach are shown.
Keywords: energy storage, batteries, capacitors, EDLCs, multi-train simulation, pure electric brake.

1 Introduction

Thanks to the recent development of electric vehicles (EVs), recent years have seen very active developments in the electrical energy storage technology, mainly batteries and capacitors. The improvements include more energy density, more power density and longer battery life (especially cycle-life). The cost of the energy storage device is still unacceptably high, but in the near future it is expected to fall thanks to the start of the mass production of EVs. Because of this development, it is now widely believed that the application of electric energy storage techniques in electric railways will revolutionise the energy supply of the railways. Especially important is the fact that it is now feasible to think of energy storage on-board the trains as well as at any fixed installations along the railway tracks.

The author's research group at Kogakuin University has been conducting research on the use of energy storage systems in electric railways for some time. The group has maintained the object-oriented multi-train power feeding network

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simulator, named RTSS (Railway Total System Simulator), for more than fifteen years. In our current research, an energy storage subsystem model is being developed for the RTSS; the developed model is used to evaluate the energy-saving and other effects by the application of energy storage devices.
In this paper, the application of energy storage systems to DC electric railways is comprehensively discussed, and to demonstrate its effects the latest evaluation results obtained by our research is shown.

2 Energy-saving of DC electric railways using the energy storage systems

2.1 Introduction of wayside energy storage systems

2.1.1 Expectation, early experiences and new development

The idea of using energy storage systems in a DC railway is not new. Already back in the 1980s, Keihin Kyūkō Electric Railways in Japan has introduced a flywheel system into one of its substations. Even earlier, the JNR tested a lead-acid battery system in its rural Kabe Line back in the 1970s [1].

Introduced as fixed wayside installations, the energy storage systems are expected to reduce line voltage fluctuations. This will help reduce losses in the power feeding network, and will also help improve line receptivity where there are regenerative trains. However, these early attempts could not necessarily be called success; regular maintenance was required for the flywheel system, and very short battery life was observed for the lead-acid battery based system because of frequent charge-discharge cycles. Also, in both cases, charge-discharge efficiency (the ratio of the amount of energy that can be taken out of the energy storage system during discharge period to the amount of energy that has been put into the system during charging) was not high, and the introduction costs were such that wider application was anyway impossible.

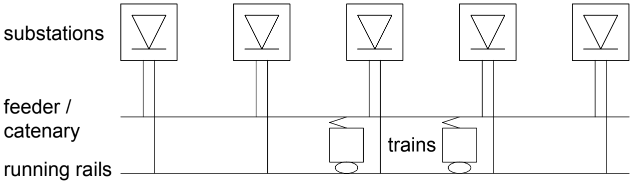
Thanks to the recent development in battery and capacitor technologies, it is expected that the problems observed in these early experiences will not be the issue anymore. Higher charge-discharge efficiency and longer cycle life will mean that these systems will save energy as expected, and will require no maintenance for years just like the existing power feeding substations using silicon rectifiers.

2.1.2 Comparison with other energy-saving techniques

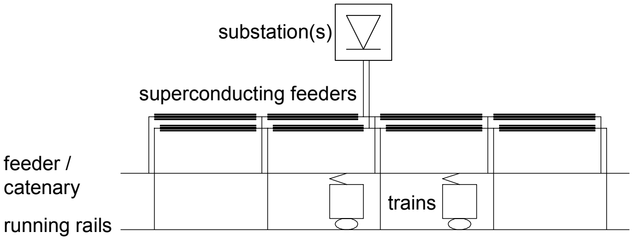
There are other techniques that will contribute to the energy-saving of DC electric railways. This section is concerned with the comparison of different technologies. Recent proposals include the use of PWM converters [2, 3] and superconducting cables [4, 5].

The use of PWM converters in the place of silicon (diode) rectifiers in DC feeding substations is a new idea. This has been used throughout the Tsukuba Express Line, a new commuter railway line that is inaugurated in 2005 and runs between central Tokyo and its north-eastern suburbs. PWM converters will enable bidirectional flow of electric power between the AC network and the DC power feeding network through the substations, which will maximise line receptivity. However, it is difficult to mix PWM converter-fed substations with conventional substations with diode or thyristor rectifiers on the same line, mainly because of incompatible V-I (voltage-current) characteristics (the Tsukuba Express Line exclusively uses PWM converters and the line is not connected to other railways). In addition, contract with the utility company is generally such that little or no monetary compensation is given by the utility company to the railway company when the power returns from DC (railway) to AC (utility company's) networks. Conventional idea of using thyristor inverters at substations is a similar option; however, inverters are too expensive to fit in all substations, which means the energy-saving effect will be limited.

The author's research group has proposed the use of superconducting cables for energy-saving. Using superconducting cables to replace some of the substations en route as shown in Figure 1, the following effects can be obtained: a) feeding losses will be moderately reduced (for current collection purposes, normal conducting cables cannot be eliminated, and therefore the reduction of feeding losses is typically around half of the original system), b) line receptivity will be improved because regenerated power can reach longer distance, and c) the capacity utilisation of substation converters will improve (the ratio of peak current to RMS current will decrease) because a substation will serve longer section. Although it is necessary to refrigerate the superconducting cables 24 hours a day, simulation results suggested that the overall energy-saving effect will exceed the refrigeration losses in a typical Japanese commuting railway model. However, currently this system is expected to be expensive, and although proposals have been made, no railway company has opted for this system to date.



(1) Conventional DC electric railway (for comparison)



(2) DC electric railway with superconducting feeder cables

Figure 1: Feeding network of DC railway with superconducting cables [4].

Compared with PWM converters, energy storage systems can simply be connected to the DC network, which means AC equipments are not necessary and issues related to contract between the railway operator and the utility company do not exist. Improvement of line receptivity using the superconducting cables has its limitations; using energy storage systems, the power feeding network can be designed so that the line is always fully receptive. However, to design a power feeding network with energy storage subsystems, the designer has to determine both the energy capacity and power capacity of the subsystems, which is a complex task.

2.1.3 Example simulation results

A simulation has been carried out using RTSS to demonstrate the energy-saving effects [6]. In the simulation, the track geometry data, train schedule data, etc. of an existing 26.5[km]-long commuting railway near Tokyo was used. The railway has 24 passenger stations, and every train stops at every station. Originally there are five substations; all of them are equipped with diode rectifiers and one substation has an inverter. It is assumed that four energy storage systems were to be added in between the substations. Each of these systems has the energy capacity of 1000[MJ], typical charge-discharge efficiency of 90[%], and the maximum charge / recharge power of 3[MW] and 5[MW], respectively.

As shown in Table 1, the introduction of energy storage systems gives better regeneration rate thanks to improved line receptivity. This will contribute to the reduction in the total energy consumption. Also to be noted is that, because of the addition of energy storage systems the average feeding distance also decreases, which means lower feeding losses; this also contributes to lower energy consumption.

Table 1: An example simulation result demonstrating the possibility of energy saving by the introduction of wayside energy storage systems (ESS).

Parameter	Without ESS	With ESS
Regeneration rate [%]	45	54
Overall energy consumption [MJ]	3480	2970
Feeder losses [MJ]	364	311

The author's research group is conducting further research on this system to find the proper design of the energy storage systems, i.e. what is the best combination of energy capacity, power capacity and the charge/discharge characteristics, which will typically be defined as the I-V characteristics shown in Figure 2. Here, the floating current will depend on the SOC (state of charge: the ratio of usable energy currently stored in the system to the maximum energy that can be stored in the system. SOC takes the value between 0 and 100[%]); also the discharging current will be zero if SOC is zero, and the charging current will be zero if SOC is 100[%]. This means that the current flowing in or out of the energy storage system is given as the function of line voltage and SOC.

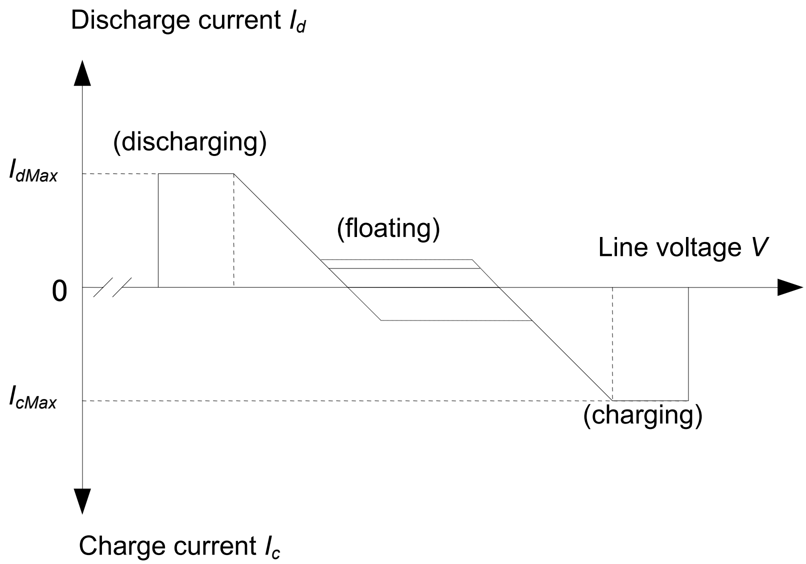


Figure 2: Typical charge-discharge characteristics of a wayside energy storage system [6].

2.2 Using the on-board energy storage systems

Recent energy storage device development has made it a realistic option to introduce railcars with on-board energy storage systems.

Because of the existence of current collectors (pantographs or collector shoes) that will limit the current, and the resistance of feeder cables and running rails as return conductors that will cause voltage drops, there are certain constraints on power exchangeable between railcars and wayside energy storage systems, which are similar to those between railcars and feeding or inverting substations. Using on-board energy storage in electric railcars, these constraints no longer exist. However, because of strict limitation on weight and space, the energy capacity of on-board storage will be limited. This means the charge/discharge control must effectively utilise the limited capacity to maximise the positive effects.

The author's research group has made a proposal of using "line receptivity estimation" to devise a "clever" charge/discharge control of on-board energy storage system [7, 8]. An on-board storage system is expected to absorb (charge) energy when the line is not receptive. However, if the SOC of the on-board storage system is too high when the line is not receptive, the system cannot be charged, and the regenerative brake may be ineffective. Similarly, if the power supply is insufficient during acceleration for various reasons, the on-board storage system is expected to discharge energy to assist the acceleration. However, if the SOC is too low then this cannot be done. To avoid this situation, the charge/discharge controller must “foresee” the need to charge or discharge, and prepare beforehand by controlling the value of SOC to a desirable level. It has been shown that, using the line receptivity prediction, train trajectory calculation and track gradient profile, the SOC can be controlled so that minimal energy capacity can be utilised.

3 Towards the re-designing of power supply systems for railways

3.1 The possibility of on-board energy storage beyond energy-saving

Although, as stated in Section 2.2, on-board energy storage is attractive from the point of view of energy saving, the author does not believe that energy saving alone would justify the idea, especially considering the fact that the on-board storage system is heavy and expensive, even after all the active developments in storage device technologies.

The author’s research group believes that on-board energy storage will be an integral part of the railcar design in which the capacity of regenerative brake is increased, so that it is not necessary to use friction brakes during service braking throughout the entire practical speed range [9]. This idea is called pure electric braking.

In order to realise pure electric braking, train performance must be enhanced so that the peak regenerative current becomes almost double the original. However, it is not economical to increase the ratings of traction motors and PWM inverters at the same time. To realise pure electric braking economically, the author’s research group has proposed the multiple-current divisional-voltage method [7], in which traction motors of 1/x times the rated voltage and x times the rated current compared to the original ratings are combined with the PWM inverters that have twice the current capacity as the original ones. Although the capacity of the inverters must be increased, the traction motor capacity remains the same. The maximum output voltage of the inverters is constant; therefore, the overvoltage capacity of the traction motor (x times the rated voltage) can be utilised. The comparison of original performance and the improved performance using the multiple-current divisional-voltage method is shown in Figure 3.

If such railcars were to be designed without energy storage and run under the existing feeding network, then the line receptivity would almost always be insufficient, making the ability of the railcars to regenerate large power meaningless. It would be possible to improve line receptivity by the modification of wayside equipments and the feeding network to a certain degree; however, the author believes that it would be difficult to allow peak regenerative current from a trainset twice as much as the original by such wayside modifications only.

Interestingly, using the multiple-current divisional-voltage method the accelerating performance can also be enhanced. This will result in the peak accelerating current to be nearly double the original, which will mean that voltage drop during acceleration reaches an unacceptable level. Again, on-board energy storage systems will be vital, in this case for assisting acceleration to reduce peak power input through pantographs or collector shoes.

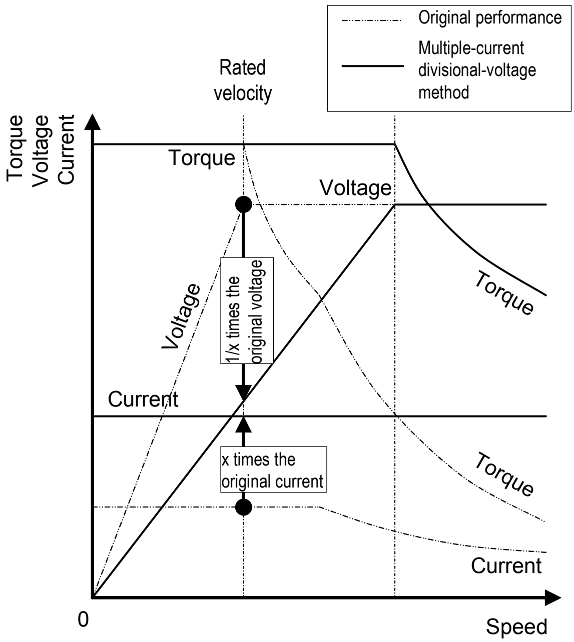


Figure 3: Performance of the original railcar and the railcar using the multiple-current divisional-voltage method. The graph is almost identical for both regeneration and acceleration.

Using on-board energy storage, it will be possible during regenerative braking to absorb high power at wheel rim while suppressing the current regenerated through pantographs (or collector shoes). The difference will go to the on-board storage system where the power is charged and reserved for future use. Also, it will be possible during acceleration to accelerate with high power at wheel rim while suppressing the current through pantographs. The difference will be "assisted" by the storage system, i.e. energy that has been charged beforehand is discharged.

Application of on-board energy storage also has various merits. For example, where track layout is complicated, like in a large station with many platforms or in a large maintenance depot, it may be possible to remove conducting contact wires to ease the maintenance of the catenary; trains may be able to run using stored energy. Also, to enhance safety on the railways, the braking distance may be shortened when the power supply fails, by using on-board energy storage systems to keep regenerative braking alive (generally, braking distance is shorter for electric braking including regenerative brake).

3.2 Combination of different techniques for the creation of revolutionary new power supply systems for railways

As shown and compared in Section 2, there are now a variety of methods to reduce energy consumption of DC electric railways. It is important to note that generally these techniques are not exclusive with each other, i.e. two or more techniques can be applied in combination. Although on-board energy storage is an attractive technology, it would generally be better not to rely entirely on it to realise improvements of the railway system as a whole, such as introduction of pure electric brake.

The multi-train power feeding network simulator will be a vital tool to find the optimum combination of different technologies. The author's research group will continue to use RTSS for such evaluation and optimisation.

4 State of health of the energy storage device

In spite of the recent development, it is expected that energy storage devices, namely batteries or capacitors, have shorter life than other components of either railcars or wayside feeding systems. The evaluation of state of health, therefore, is important.

The author's research group has conducted an attempt of creating a life-cycle cost model of EDLC (Electric Double Layer Capacitor)-based on-board energy storage systems, which incorporates the state-of-health model of the EDLC using the principle that the life of these capacitors will be half when the temperature increases by 10[K] [4, 10].

Unfortunately, currently virtually no data can be obtained to verify this new state-of-health model of EDLC, or in fact any kind of energy storage devices. Once the state-of-health model is established, the life-cycle cost and energy analysis must be performed to get a more precision evaluation of these techniques.

5 Conclusion

A variety of ideas of using energy storage systems in DC electric railways have been explained, together with the introduction of research being conducted very actively in the author's research group. The activity will help realise new railway systems, with improved maintainability and functionality.

Acknowledgement

Many of the works that are presented herein as those of the author's research group have actually been conducted as part of the students' project (both undergraduates' final year projects and MSc projects) of Kogakuin University. The author would like to express appreciation for the brilliant works that they have done. Unfortunately, because of space limitations, the name of each student cannot be listed; please see the references.

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