Technologies for Efficient Energy Management in Electric Railway Operation using Energy Storage Devices

Warayut Kampeerawat

Department of Electrical Engineering and Information System, The University of Tokyo,
Bunkyo, Tokyo, 113-0022, Japan

warayut@koseki.t.u-tokyo.ac.jp

Abstract — **This paper presents a review of technologies for energy management in electric railway operation focusing on applications of Energy Storage Devices (ESDs). In modern electric railway systems, Energy Management System (EMS) is responsible for railway operation and control. A key factor of effective EMS is integration of ESDs in railway operation. In the viewpoint of energy management, the regenerative energy management and non-electrified track operation are the interesting issues.**

Keywords — **Energy Storage Devices, Energy Management, Electric railway systems**

I. Introduction

Basically, energy management involves consumption and optimization of energy usage at various stages in the system operation in the most efficient way. By integrating engineering technique, applications, devices, and the operation and maintenance of electric power systems, energy management system continuously monitors, critically examines, and control energy flows through systems so that energy is utilized with maximum efficiency. [1]

Reduction of energy consumptions and CO_2 emissions is a prominent trend in transportation system. Because of uncertainty in power and energy consumption in railway systems, energy management is a big challenge task. Energy Management System (EMS) provides the efficient railway system operation of traffic control under energy use plan. However, cooperation of many functions and components makes EMS a complicated system. [2]

To increase the degree of energy management capability, Energy Storage Devices (ESDs), e.g. Batteries, Flywheels, Supercapacitor etc., are integrated in railway system as onboard and trackside components. Owing to advancement of power electronic technology, ESDs are more flexible and reliable for various purposes. However, substantial cost of ESDs and addition control system are considered as a primary condition for practical implementation. [3]

This paper presents a review of technologies for energy management in railway operation focusing on application of ESDs. The contents are organized as follows. Section II presents energy management in electric railway system that is responsible for railway operation and control. A promising solution of effective EMS is integration of ESDs in railway operation. The briefly detail of ESDs for railway application is discussed in Section III. In the viewpoint of energy management, the regenerative energy management and non-electrified track operation are the interesting issues. Section IV presents the regenerative energy management with ESDs and some practical examples. Section V reviews non-electrified track operation using ESDs and some practical examples. Future trends for developing EMS in railway system with ESDs are discussed in Section VI. Finally, section VII concludes this paper.

II. Energy Management in Electric Railway System

In railway system, energy saving is always supposed to be an important issue in all relevant subsystems such as power supply, vehicle, traffic management, and vehicle operation departments. System operators try to find the efficient way to manage power and energy use in the systems but there are many conditions and factors to be considered. For this reason, the “railway energy management system” has been developed aiming at cooperating system operation and control with reasonable energy consumption.

The main tasks of the Railway EMS are to make an energy use plan and to control both the operation and power supply of trains corporately under the plan. Furthermore, it is realizing the effective utilization of regenerative energy and renewable energy sources.

Fig. 1 illustrates the railway EMS, there are two main functions, ground control function and vehicle control function. On the ground side, Ground control function is responsible for managing overall system with cooperation of Transport planning function, Power supply planning function and Train traffic control function. In general, train traffic control function obtains the planned values from planning functions and then controls operation of each train to a daily change of preset value and operation and everyday disturbance. On the vehicle side, vehicle control function operates the train and onboard systems based on information from train traffic control and substation. To realize the effective energy management of energy from utility grid, regenerative braking, and renewable energy sources, Energy Storage Devices are

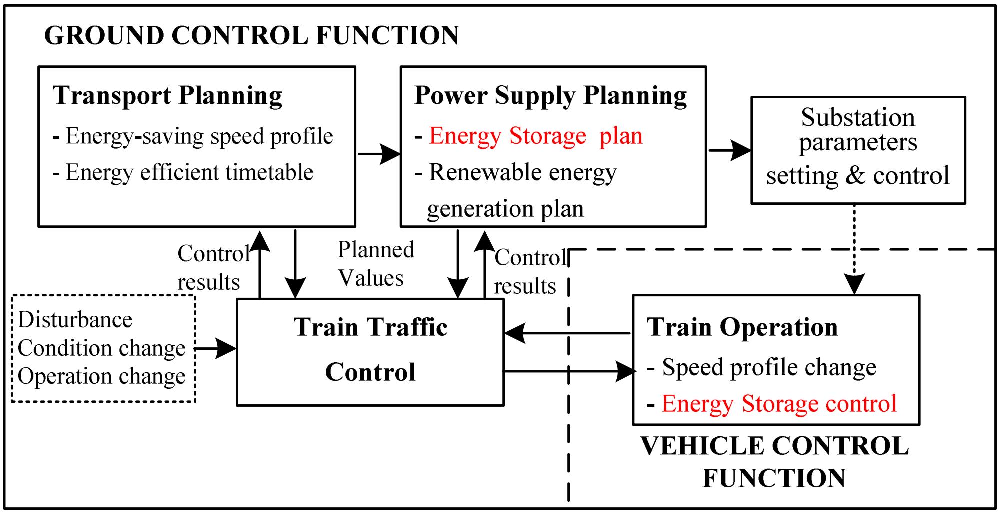

Fig. 1. Railway Energy Management System [4]

applied to the railway system by means of onboard or trackside installation. [4]

III. Energy Storage De vices for Railway Application

Energy Storage Devices (ESDs) have been commonly used for many purposes in electric power system. For railway applications, ESDs are effectively applied to enhance the operation with high efficiency. Generally, the purposes of using ESDs in railway operation are the following:

- To stabilize the network voltage.
- To shave power peaks during accelerations.
- To power a train as a temporary source.
- To power a train as the main source.

In the viewpoint of Energy Management in railway operation, ESDs are supposed to reduce of traction energy consumption by means of storing and recycling regenerative energy and powering in non-electrified track operation. [5]

A. Types of ESDs for railway application [6],[7]

(1) Batteries

Batteries are common energy storage devices based on chemical energy conversion. Basic characteristics of Batteries are very high energy densities but low power densities leading to very high charging times.

The common types of batteries for railway application are Lead-acid, Li-ion and Ni-MH. Due to advance technologies, high energy density batteries are widely used to enhance energy management in modern railway operation.

(2) Flywheels

Flywheels store energy in rotating masses based on electro-mechanical energy conversion. They have high power, high energy densities, and virtually infinite number of charge-discharge cycles. For this reason, they can effectively utilize for many purposes in railway operation. Owing to operating on moving parts, the maintenance cost is a considerable issue when compared to other kinds of ESDs.

(3) Electric Double Layer Capacitors (EDLCs)

ELDCs store energy in the electric field of an electrochemical double-layer and work in the same principle as traditional capacitor. However, they are designed based on the use of high surface-area electrodes resulting in an extremely large capacitance. Therefore, they are also classified as *Supercapactor* or *Ultra-capacitor*.

ELDCs have high power density and discharge time, and very long life cycle. Thus, they are widely used for regenerative operation in public transportation.

(4) Superconducting Magnetic Energy Storage (SMES)

SMES store energy in the magnetic field created by circulating direct current in a superconducting coil. It has the extremely low energy but very high power density and efficiency.

For railway application, SMES have been proposed to serve as the energy sources at the substation. Because of low energy density, it is not an attractive option for brake energy storage.

B. Types of Installation [3],[6]

(1) Onboard Installation

ESDs can be equipped as onboard equipment on a vehicle. Onboard ESD can utilize the train itself and also the other trains accelerating nearby. The independence of traffic control makes this scheme flexible to operate. However, space and weight are the considerable concerns for decision of installation.

TABLE I
SOME SPECIFICATIONS OF ENERGY STORAGE DEVICES

Type	Energy Efficiency (%)	Energy Density (Wh/kg)	Power Density (W/kg)	Cycle life (cycles)	Life time (years)	Discharge time	Suitable Storage Duration
Lead-Acid	70-80	20-35	25	200-2000	5-15	seconds-hours	minutes-days
Li-ion	70-85	100-200	360	500-2000	5-15	seconds-hours	minutes-days
Ni-MH	50-80	60-80	220	<3000	-	seconds-hours	minutes-days
Flywheel	95	>50	5000	>20000	15	millisec-15 min	seconds-minutes
EDLC	95	<50	4000	>50000	>20	millisec-60 min	seconds-hours
SMES	-	0.5-5	500-2000	>100000	>20	millisec-8 sec	minutes-hours

(2) Trackside Installation

ESDs can be installed along the trackside, commonly in substation. Trackside EDSs are used to serve any train in an operating section depending on the traffic condition. The space and weight of ESDs are not the serious problem for this installation scheme but energy losses in transmission line are considered as the condition of the acceptable operating range. Moreover, the optimum location of installation is important for consideration.

C. Consideration for integrating ESDs in railway operation

Integration of ESDs in railway system is not new issue but the optimum selection to suit the purpose of installation still be interested. There are many factors to be considered before decision such as, the type of ESD, capacity, installation scheme and investment cost. Table I shows some specification data of ESDs extracted from [6] and [8].

However, the most important factor is the cost of investment which should be estimated by means of economic assessment. For example, urban and suburban railway system which serves the large traffic demands are reasonable for justifying additional investment to wayside infrastructure e.g. trackside ESDs. On the other hand, for regional or intercity railways, it is too expensive for investment trackside ESDs.[9]

IV. REGENERATIVE ENERGY MANAGEMENT WITH ENERGY STORAGE DEVICES

In railway operations, energy saving operation can be achieved by many approaches, e.g. optimize design of vehicle, advanced technology of traction motor, energy management control system, integration of ESDs. One considerable achievement for efficient energy use is storing and recycling regenerative braking energy.

Nowadays, the regenerative braking system is commonly used for electric railway vehicles by a running electric. When the regenerative braking system is operated, a traction motor will temporary turn into a generator which generates amount of energy and then feeds back into the feeding system. The regenerative energy can be effectively managed by the following ways, [3]

- Powering accelerating vehicles nearby using Timetable optimization for interchanging energy among running trains.
- Storing and recycling using ESDs
- Feeding into utility grid by reversible substation or inverting substation.

Normally, the first priority method for utilizing the regenerative energy is powering nearby trains. When the amount of energy exceeds the capability of the system, an excess of energy will be turned into waste heat or the regenerative system will be cancelled. [5]

Due to the advancement of power electronics and energy storage technologies, integrating Energy Storage System, i.e. ESDs and additional power electronic control devices, into railway system become a very promising option to manage regenerated braking energy effectively. Regenerative energy can be managed efficiently by Trackside Energy Storage System or Onboard Energy Storage System.

A. Trackside Energy Storage System

With trackside energy storage system , ESDs collect the regenerative energy that cannot be instantaneously consumed in the system, and deliver it back to the line when the energy demand is needed, e.g. a vehicle is accelerating in its operating section. The stored energy in ESDs can contribute to shave power peaks during accelerations of train vehicles, and, it may be temporary supply for trains in case of power grid failure. Therefore, these kinds of systems cannot only provide the efficient management of energy consumption but also enhance the ability to stabilize the network. Moreover, their maintenance do not affect the service. [3]

In contrast, energy management with trackside ESDs depends mainly on the traffic control and energy losses in the transmission line will be considerably high when the distance from train to ESDs increases.

As shown in Table II, there are many kinds of ESDs practically applied to operate as trackside scheme. EDLC are the most commonly commercialized. Advanced electrochemical batteries with fewer weight and smaller size are also valid choices for railway operation. The safety concerns related to flywheels are less considered in trackside applications because they can be installed with heavy containers or even underground. [3],[7]

TABLE II
PRACTICAL EXAMPLES OF REGENERATIVE ENERGY MANAGEMENT WITH ESDS [3]

Project Detail	**Energy Storage Devices**				
	Type	**Installation**	**PC (kW)**	**SC (kWh)**	**Company**
Beijing metro, China (in service, 2007)	EDLC	Trackside	700	2.5	Siemens
Toronto rail transit, Canada (in service, 2011)	EDLC	Trackside	700	2.5	Siemens
Hannover & Rennes metro, Germany (pilot project, 2004 & 2010)	Flywheel	Trackside	1000	5	Piller Power Systems
Osaka City Subway (tested, 2007)	Ni-MH	Trackside	-	150-400	Kawasaki
Kobe transit system (in service,2007)	Li-ion	Trackside	500-2000	-	Hitachi
Philadelphia transit system, USA (pilot project, 2012)	Li-ion	Trackside	900-1500	400-600	Saft
Daejeon Metro Rapid Transit, South Korea (tested, 2010) [7]	EDLC	Trackside	1865.5	10.386	-
Seoul Metro9, South Korea (in service, 2011) [11]	Li-ion	Trackside	1000	-	Hitachi
Central Japan Railway (tested, 2005-2010) [5]	EDLC	Onboard	200	0.28	Toshiba
East Japan Railway (tested, 2009) [5]	Li-ion	Onboard	-	163	Mitsubishi

PC : Power Capacity, SC: Storage Capacity

The location where is suitable for the installation of trackside ESDs for regenerative energy should be the area where the system can utilize smaller amount of regenerative energy than other areas. [10]

B. Onboard Energy Storage System

Onboard ESDs can manage the regenerative energy by the same ways as those of trackside ESDs but they present higher efficiency due to the absence of line losses. Besides, energy management is simpler due to the independent of traffic conditions. However, required spaces on the vehicle and considerable increase of weight are the main issue for design and operation. [5],[12]

As shown in Table II, different types of ESDs are practical used for onboard system. Recently, EDLCs seems to be the suitable option of the onboard ESDs due to its fast charge and discharge response, high power density and relatively low costs. However, novel types of batteries such as Li-ion or Ni-MH may be considered as alternative options, especially if higher power densities, longer lifecycle and reduced costs are achieved as expected. Composite flywheels present satisfactory cycle life and power density, while offering fast responses. However, they are not suitable for operation of urban rail due to their potential risk of explosive. [3],[7]

V. NON-ELECTRIFIED TRACK OPERATION USING ENERGY STORAGE DEVICES

In some emergency situations such as upstream power supply failure, onboard or trackside ESDs can be operated as a temporary supply for trains to run for a short distance or to reach the nearest station.

By some technical problems or area restrictions, rail vehicle is designed for running without external power source for a short distance or considerable distances. For example, Light Rail Vehicles (LRV) which is operated in some city area where electrification may present problems, e.g. level crossings, heavily populated regions, conservation areas, limited clearances, etc. Non-electrified track or catenary-free operation is needed to satisfy the condition. The operation can be operated as follow: [1],[5],[7],[12]

- Partial non-electrified track system
- Complete non-electrified track system

A. Partial non-electrified track system

For this scheme, the rail vehicle is designed to be operated in a short distance of non-electrifies section by onboard ESDs which take energy from charging stations at terminals. When vehicle runs in electrified track sections, the vehicle will take energy from track or catenary. Therefore, small storage devices, e.g. super capacitor, can be used to provide power for short durations through non-electrified section.

B. Complete non-electrified track system

For this scheme, the system is designed to use ESDs as energy sources for operating train on non-electrified section with substantial distances, a few kilometers. The onboard ESDs are designed to take power from charging point midway stations and terminals without installing contact wires between stations.

C. ESDs for non-electrified track system

Basically, Batteries are reasonable option for powering the vehicle through non-electrified section. There are two main issues to consider cost and useful life. Advanced type of batteries providing better performance, longer life, smaller weight and volume can promise the better performance of operation but their cost is considerably higher than conventional lead-acid batteries. Moreover, energy management and control systems may be required

TABLE III

PRACTICAL EXAMPLES OF NON-ELECTRIFIED TRACK OPERATION WITH ESDS

Project Detail	Energy Storage Devices			
	Type	PC (kW)	SC (kWh)	Company
Railway Technical Research Institute (RTRI), Project name : Lithey-Tramy (tested, 2005&2007) [5]	Li-ion	300	33	-
Railway Technical Research Institute (RTRI), Project name : Hitram (tested, 2007-2008) [5]	Li-ion	600	72	-
Supporo Municipal Transport & Kawasaki Heavy Industry Project name : SWIMO LRV(tested, 2007-2008) [5]	Ni-MH	250	120	-
Mannheim LRV, Germany (in service, 2003-2007) [3]	EDLC	300	1	Bombardier
Paris Tramway, France (tested, 2009-2010) [3]	EDLC	-	0.8	Alstom
MTS light rail system in South Lisbon, Portugal (in service,2008) [3]	EDLC+Ni-MH	288+105	0.85+18	Siemens

PC : Power Capacity, SC: Storage Capacity

for more complex operation. Table III shows some practical uses of ESDs in non-electrified track operation.

The combination of high power batteries and EDLCs seems to be an efficient solution for non-electrified track operation. EDLCs can absorb the peaks of regenerated braking energy and deliver the power required for acceleration, whereas batteries can absorb the remaining braking energy and release it during coasting/rolling phases, which will increase their life and performance.[3]

VI. FUTURE TRENDS

There are many researches demonstrating the successful operation of railway system with ESDs. For future energy plan, energy conservation and energy consumption cost reduction will be more important issues.

Therefore, the trends for developing the energy management in railway operation with ESDs may be presented as follows:

- Development of Energy management Strategies for interoperation between grid and railway system by means of novel Energy management system [2]
- Utilization of Advanced ESDs or Combination of ESDs (Hybrid Energy Storage Device) [3],[6],[7]
- Development of Advance power electronic control for operating ESDs [6]

VII. CONCLUSION

Utilizing advanced technologies for energy management can achieve the reduction of energy consumptions and CO2 emissions in transportation system. Nowadays, there are many kinds of ESDs applied for various purposes in modern railway systems, e.g. Batteries, Flywheels, EDLCs, and SMES. Anyway, many conditions and factors will be taken into account for practical applications. In the viewpoint of energy management purpose, the advanced development of ESDs increases the possibility of efficient regenerative energy management and the capability of non-electrified track operation. Furthermore, the progresses of relevant technologies, e.g. power electronics, computer system and etc., will provide room for endless developments of railway systems.

REFERENCES

[1] P. Giridhar Kini and Ramesh C. Bansal. *Energy Efficiency in Industrial Utilities*. INTECH Open Access Publisher, 2011.

[2] S.Khayyam, H. Lakhdar, F. Ponci, and Monti, A., “Agent-based energy management in railways,” in Proc. International Conference on Electrical Systems for Aircraft, Railway, Ship Propulsion and Road Vehicles (ESARS), 3-5 March 2015, pp.1-6.

[3] A. Gonzalez-Gil, R. Palacin, P. Batty, and J. P. Powell, “Energy-efficient urban rail systems: strategies for an optimal management of regenerative braking energy”. In Proc. 5th Conference: Transport Solutions from Research to Deployment. In Transport Research Arena (TRA), April 2014.

[4] M. Miyoshi, T. Takeba and M. Miyatake, “Development of an Energy Efficient Train Traffic Control System for Saving Electricity,” *Computers in Railways (COMPRAIL 2012)*, Vol. XIII, pp.499-510, Sept 2012.

[5] O. Masamichi, “Onboard storage in Japanese electrified lines,” in Proc. 14th International Power Electronics and Motion Control Conference (EPE/PEMC), 6-8 Sept. 2010, pp.9-16.

[6] S.Vazquez, S. M. Lukic, E. Galvan, , L. G. Franquelo. J. M. and Carrasco, “Energy storage systems for transport and grid applications,” *IEEE Trans. on Industrial Electronics*, vol.57, no.12, pp. 3881-3895. 2010.

[7] T. Ratniyomchai, S. Hillmansen, and P.Tricoli, “Recent developments and applications of energy storage devices in electrified railways,” IET Electrical Systems in Transportation, vol.4, no.1, pp.9-20, March 2014.

[8] H. Chen, T. N. Cong, W. Yang, C. Tan, Y. Li, and Y. Ding, “Progress in electrical energy storage system: A critical review,” *Progress in Natural Science*, vol.19, no.3, pp. 291-312. 2009.

[9] T. Koseki, “Technologies for Saving Energy in Railway Operation: General Discussion on Energy Issues Concerning Railway Technology”. *IEEJ Trans. on*

Electrical and Electronic Engineering, vol.5, no.3, pp.285–290, 2010.

[10] T. Suzuki, H. Hayashiya, T. Yamanoi, and K. Kawahara, “Application examples of energy saving measures in Japanese DC feeding system”. In Proc. Power Electronics Conference (IPEC-Hiroshima 2014-ECCE-ASIA), May 2014, pp. 1062-1067.

[11] H. Takahashi, K. Aoki, A. Maoka, and Y. I. Kim, “Current and Future Applications for Regenerative Energy Storage System,” *Hitachi Review*, vol.61, no.7, pp.336-340. 2012.

[12] Rafat Kadhim, “Energy storage systems for railway applications: Phase 1 (T779 Report)”, Rail Safety and Standards Board (RSSB), 2009, Available from: http://www.rssb.co.uk/pages/research-catalogue/pb009843.aspx