Paper

Technologies for saving energy in railway operation —General discussion on energy issues concerning railway technology —

Takafumi Koseki*, Member

Abstract Early technical history of electric supply to electric railways is briefly reviewed as an introduction to the following seven papers included in the special issue on technologies for saving energy in railway operation. Continuous power supply played significant role in the early history of railway technologies. The VVVF power electronic technology gave also substantial impact to railway traction systems after 1980's. VVVF technology made it possible to have more efficient drives, downsizing of rolling stocks, and regenerative brakes. Because detailed discussions about each technical development are described in the following papers, the general descriptions of those technologies made in this introduction provide logical links to the ideas presented in the accompanying articles.

Keywords : electric railway, electric traction, electrification, rolling stock, electric energy storage, energy saving technology,

1. Introduction

Railway has been playing significant social role in significant ground mass-public transportation. In spite of the discussion regarding its social role in the era of motorization in the latter half of the 20th century, electric railway systems are of growing importance again in recent arguments on energy saving and environmentally friendly sustainable civilization.

A substantial advantage of electrical railway compared to other transportation is the usage of electric energy, which allows variety of primary energy sources. That is also the reason for recent intensive technical development of electric traction in automobile industries including hybrid and fuel-cell electric vehicle technologies. The enhancement of the ratio of electric traction to mechanical/petroleum traction is expected to contribute to the reduction of carbon dioxide emission due to transportation and consequent sustainable growth of mobility as shown in Fig. 1.

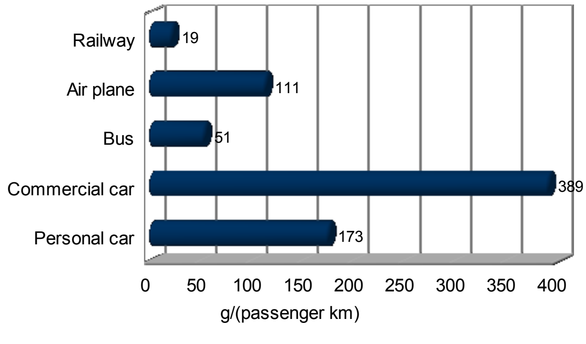

Fig. 1 CO_2-emission of different transport modes.

This paper reviews the historical growth of electric railway in the 20th century in comparison with automobiles. This history is necessary for explaining the advantageous aspects of early electric railways and significant contributions of power electronic technologies to recent further growth of useful, economical, and ecological railway systems.

2. Overview of history of electric railway

New pure electric and plug-in hybrid automobiles are currently being presented. They made an actual hot technical trend in the market of the automobile industry this year. For instance, Mitsubishi Electric Corp. starts commercial sales of the new pure electric personal car i-Miev, which has three different ways of electric energy charging in summer 2009(1). The technical breakthrough of that car is light Li-Ion batteries, which are economically acceptable. But even with the newest technical achievement, the weight of the battery is approximately twenty percent of a total car, and the battery cost still accounts for a half of the total price. In light of these facts, onboard energy storage is still the most significant and critical component in electric vehicles.

2.1 The birth of electric railway and electrification: Railway and the electric automobile(2) The history of electric vehicles started earlier than electric railway, in the mid-19th century, when the first electric train was demonstrated by Werner von Siemens in 1879 at an exhibition at Berlin in Germany. The electrical vehicle achieved good performance and held the vehicular land speed record before 1900.

After enjoying success at the beginning of the 20th century, the electric car lost its position in the automobile market. Improved road infrastructure was created between American cities by the 1920s. To make use of these roads, vehicles with greater range than that offered by electric cars were needed.

The discovery of large reserves of petroleum in Texas, Oklahoma, and California led to the wide availability of affordable gasoline, making gas-powered internal combustion engine (ICE-) cars cheaper to operate over long distances. Electric cars were limited to urban use by their slow speed, no more than 32 km/h, and short distance, 65 km. Cars driven by internal combustion engines were able to travel farther and faster. ICE-cars became ever easier to operate thanks to the invention of the electric starter by Charles Kettering in 1912, which eliminated the need of a hand

---

* Department of Electrical Engineering and Information Systems, The School of Engineering, The University of Tokyo, 7-3-1, Hongo, Bunkyo-Ku, Tokyo 113-8656, Japan

crank for starting a gasoline engine. The noise emitted by such cars became more acceptable thanks to the use of the muffler. Finally, the initiation of mass production of ICE-vehicles by Henry Ford brought the prices low in 1915.

Consequently, the high cost and short distance to be covered by batteries of electric vehicles compared to ICE-cars caused a worldwide decline of their use in the 20th century. Beginning at the end of the 20th century, interest in electrical vehicles increased in light of growing concern over the negative aspects of ICE-vehicles, including the damage to the environment caused by their emissions and the sustainability of the current hydrocarbon-based transportation infrastructure.

On the other hand, the growth of the electric railway after the first demonstration by W. von Siemens was rapid and drastic. In 1885, the first German commercial operation of an electric railway between Meckenbeuren and Tettnang on standard gauge started. The first European full size locomotive was supplied by BBC (Brown Boveri & Cie) for use on the Swiss track by Burgdorf and Thun. The technical development for the first trial of fast train operation started in 1899 by a German consortium including Siemens and Halske, AEG, two major banks and Prussian administration and other research institutes and companies. A 33km-long test track was prepared on the section between Marienfelde-Zossen on the military railway Marienfelde-Zossen-Jueterbog near Berlin with three-phase AC-electric power supply. A test train with AC-locomotive supplied by AEG successfully demonstrated a test run with maximal speed of 210km/h in 1903. In spite of this success, the generic use of pantographs for the three-phase triple overhead lines was too complicated. Technical development for realistic electric power supply was switched to a singe-phase system. The first commercial operation with the single-phase AC electrification of 15kV 16+2/3Hz, which is still used today as a system of 15kV 16.7Hz, was started on the track between Ressau-Bitterfeld in 1911.

The key of the rapid growth of electric railway in its early history was the success in the development of efficient and continuous electric power supply, which solved the problem of the bulky and heavy lunch-box of vehicles, *i.e.* on-board energy source.

2.2 Changes in electrification After the early history of the electrification, various forms of electrification have been developed and applied for regional and intercity high speed electric railways as summarized in Table 1. Generally speaking, single-phase high voltage AC-electrifications are often preferred for high-speed long-distance intercity lines and compact low voltage DC-electrifications are common in frequent railway service for urban/regional transit and subways. A detailed technical discussion regarding recent trends shall be explained in the second paper of this special issuewritten by Prof. R. Takagi.

Table 1: Various electrification systems

Nominal voltage	Frequency	Applications
600, 750 V	DC	Many urban transports with a third rail for power supply
1.5kV	DC	Many urban transports with overhead catenary, intercity rail in southern France
3kV	DC	Intercity rail in Italy, Spain and Belgium
15kV	16.7Hz	Intercity rails in Germany, Austria, Switzerland, Sweden, Norway
20kV	50Hz	Intercity rails in eastern Japan
20kV	60Hz	Intercity rails in western Japan
25kV	50Hz	Shinkansens in eastern Japan, Intercity rails in France, UK *etc*
25kV	60Hz	Shinkansens in western Japan

3. Impact of power electronics

The second key technology of the 20th century is of course, power electronics, especially the variable frequency and variable voltage power conversion using self-commutated semiconductor power switching devices developed and applied in the 1980s. This technology had a substantial impact on both way-side electric energy supplying systems and on-board traction systems of rolling stocks as described in the next section. Also the regeneration and effective usage of braking power became possible by the use of power electronic technology.

3.1 AC drives with variable frequency VVVF-power conversion technology facilitates the use of on-board AC drives. Drives for electric trains need substantially variable speed controls. When power electronic variable frequency drives were not easy to implement, commutator motors including DC-motors were unique solution for wide-range variable speed control. The commutator was a weak point requiring periodic maintenance work and bottle-neck in the reduction of volume and weight of traction motors

AC-drives, mainly with induction motors, reduced the volume and weight of traction motors, the number of mechanical and electric/electronic components for onboard traction systems, and reduced drastically the maintenance work. For instance, the Shinkansen 0-series, born in 1964, had DC-motors of 185kW 485kg, and all 16 cars had motors. The Shinkansen 300 series, introduced in 1992 as the first AC-Shinkansen train, had just 12 motor cars and the weight of an induction motor had been reduced to 390kg, whereas the nominal power had been enhanced to 300kW.

These advantages resulted in speed-up and energy savings for electric trains. Also the regenerative brake contributed to energy saving, easy cooling and reduction of the vehicle weight. The concrete impact of power electronics to onboard traction systems will be discussed in detail in the third and forth papers in this

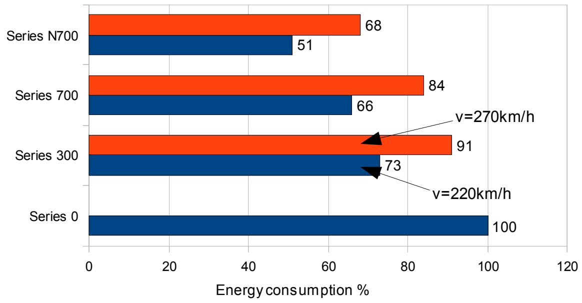

Fig. 2 Comparison of the energy consumption of the different series of Tokaido-Shinkansens.

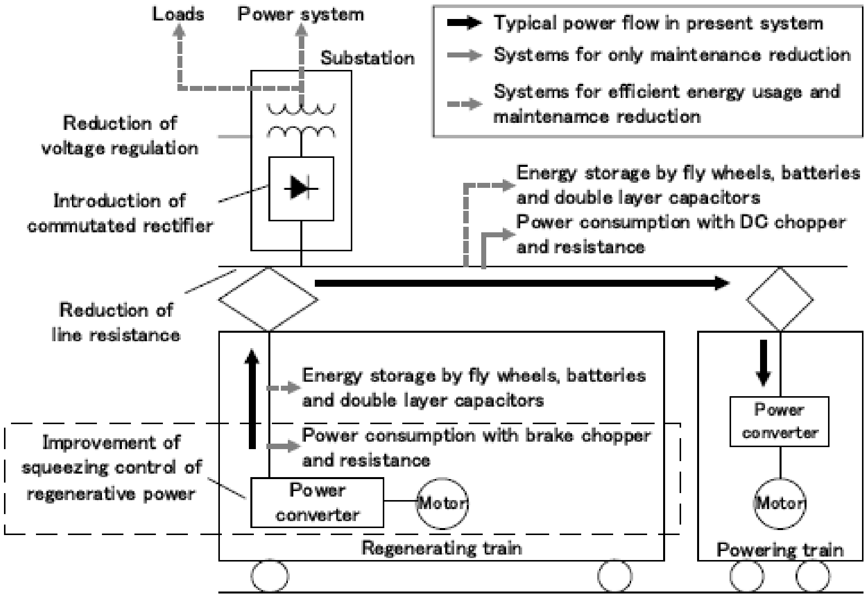

Fig. 3 Typical energy flow during regenerative brake at DC-electrification.

special issue written by Prof. Kondo and Mr. Matsuoka, respectively.

3.2 The regenerative brake and management of electric energy

Fig. 2 shows the gains made by energy saving technology in the Tokaido-Shinkansen trains. The newest series N700 accomplished a considerable reduction in energy consumption, thanks to downsizing and trimming weight, and a reduction of running resistance. The N700 also effectively utilize regenerating brakes and eliminates frequent acceleration/deceleration for passing curved track enabled by its body inclination control. This is a typical example of successful technical development contributing to both better performance and reduction of noise and energy consumption.

Our group proposed the concept of pure electric brakes(3) and studied its installation in a DC-electrified urban railway over a continuous period of time, as shown in Fig. 3. It important to note that the DC-substations cannot send back regenerated power from the DC-railway side to the AC-power utility side if there are no regenerative inverters at the substation; the regenerating electric brakes can work only when another train is accelerating simultaneously near the braking train. Because the control for protecting the on-board converter controls depend on the catenary voltage at pantographs, the functionality of the regenerating brake under such conditions can not be guaranteed. When the regenerating braking force falls to insufficient levels, the mechanical air brake starts its operation for compensating braking force as shown in Fig. 4. The energy absorbed by the mechanical brake is lost as heat and the abrasion of braking disk requests periodic maintenance of the rolling stock. The concept of pure electric brake creates a strategy for maximizing the effective usage of regenerative electric brakes for ordinary braking operation.

Railway traction has the following two problems for full usage of regenerating electric brakes:

(1) Speed detection at low speed is difficult, and consequently the electric braking is given up and substituted by mechanical brake at very low speed period:

(2) Sufficient braking force cannot be produced at a high speed range according to field-weakening as shown in Fig. 5.

For problem (1), we proposed speed detection using a dual-rate sampling digital observer(4)(5) in order to stabilize low

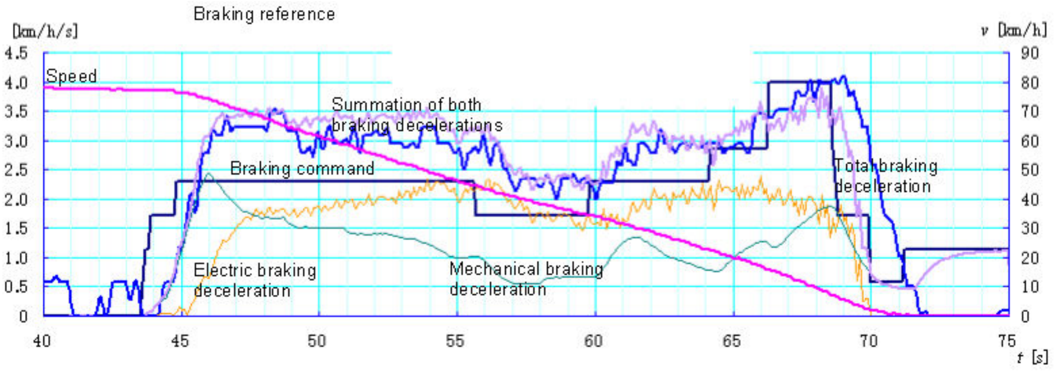

Fig. 4 Cooperation between mechanical and regenerative brakes.

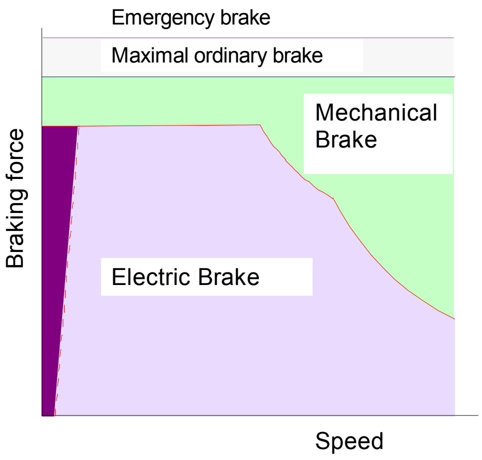

Fig. 5 Speed-dependent braking forces.

speed traction control. A speed-sensor-less drive(6) technique can also contribute to solving the problem. For solving problem (2), there must be change to the running pattern: one should apply just asmall braking force at high speeds at all yimes also for a better exchange of electric energy with other trains. Although the theoretical run-curve optimization(7) as shown in Fig. 6 will be discussed in the fifth paper of this special issue by Prof. Miyatake, the key-point regarding train operation for better usage of electric brakes is to start braking operation early with smaller braking force and stop the train at maximal force in low speed as show in Fig. 7. The style of the run-curve in Fig. 7 was named as, "constant power braking pattern". This braking pattern is difficult in manual operation by human drivers. The TASC: train automatic stopping control or ATO: automatic train operation is, hence, well-suited for such a braking pattern.

A mitigated on-board voltage protection(8)(9) and introduction of a seamless zero-regeneration mode to on-board inverters is useful to increase regenerated energy effectively in conventional DC-electrification.

The introduction of regenerative DC-substations is one way to guarantee regenerative braking action(10). The Tsukuba-eXpress (TX) has introduced modern and well-designed DC substations. For maximizing the advantage of such a system, the fundamental concept of train formation had to be reviewed(11). It was discovered that distributed electric multiple unit is well-suited for such modern energy management.

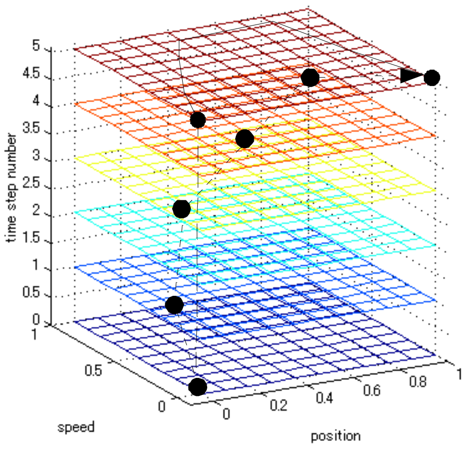

Fig. 6 Optimization of running profile base on dynamic programming.

3.3 Electromagnetic compatibility in railway electrification Since railway electric energy supply is a significant civil infrastructure around populated areas, electromagnetic interference must be appropriately suppressed. Also, the electronic appliances of the railway itself are safety-critical in many cases, and therefore they must be sufficiently immune to electromagnetic emission from components for traction and power supply. Systematic design of electromagnetically compatible power electronic components has been especially siginificant. Thus, railway specific standards are discussed at the International Electrotechnical Commission: IEC. An IEC-page(12) explains their activities on EMC-issues as follows.

The IEC prepares EMC documents that fall into one of two categories.

The first category, comprising what are known as the Basic EMC publications, is intended as a comprehensive set of background reference standards and technical reports that cover all general aspects of the problem. They deal with matters such as description of the EM environment, measurement methods, testing techniques and the like. Technical Committee 77: Electromagnetic compatibility, and CISPR, the International Special Committee on Radio Interference, is also part of the IEC, and takes the mission of horizontal documentation on EMC.

The second category comprises standards that apply to products. These may be either generic EMC standards or specific EMC product standards, which as a rule apply the appropriate publications from the Basic series.

Development of specific EMC product standards is almost exclusively allocated to the numerous IEC technical committees dealing with individual products or families of products, usually referred to as product committees. The following EMC-concerning documents on railway systems have already been published from the TC9 on electrical equipment and systems for railways(13).

Railway applications - Electromagnetic compatibility - Part 1: General outlines of the structure and the content of the whole IEC 62236 series.

The IEC 62236 series of standards provides both a framework for managing the EMC for railways and also specifies the limits for the electromagnetic (EM) emission of the railway as a whole to the outside world and for the EM emission and immunity for equipment operating within the railway. The main changes with respect to the previous edition are rewording of the introduction; and suppression of Annex B.

- *Part 1: General IEC 62236-1*
- *Part 2: Emission of the whole railway system to the outside world: IEC 62236-2*
- *Part 3-1: Rolling stock - Train and complete vehicle: IEC 62236-3-1*
- *Part 3-2: Rolling stock - Apparatus: IEC 62236-3-2*
- *Part 4: Emission and immunity of the signalling and*

telecommunications apparatus: IEC 62236-4

- *Part 5: Emission and immunity of fixed power supply installations and apparatus: IEC 62236-5*

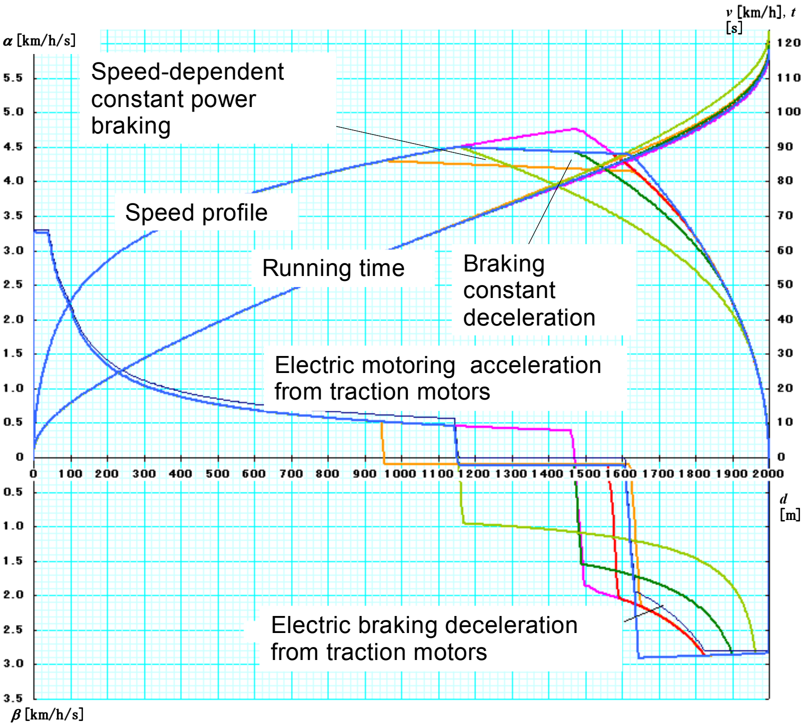

Fig. 7 Running profile between two stations with several different braking patterns including conventional constant deceleration and speed-dependent pure electric brakes.

Recently, discussions on assessing the biological consequence of electromagnetic emission and immunity to intentional electromagnetic interference have taken into consideration the growing importance at further technical developments for the future.

4. Technical trends

4.1 Technical trends in urban and regional transports

The technology of electric traction for automobiles is being intensively developed, and automobile manufacturers are presenting plans for new commercial products for electric vehicles. In response to this trend, railway operators cannot justify railway service just by ecological aspects. However, efficient, safe and precise scheduled operation of electric railways plays a substantial role in urban areas as mass public transportation. Railway and automobile industries should be able to exchange and share their achievements in electro-technical research and development more effectively. On the other hand, regional railway must be made more attractive by appropriate cooperation with personal transports, *e.g.*, "park and ride". The electric automobiles shall play a complementary role as personal transports for convenient door to station access.

Way-side electric energy storage is useful for guaranteeing regenerative braking functions by absorbing regenerated energy effectively, especially. It is useful for suppressing the usage of mechanical energy at hilly sections without significant increase in the weight of on-board equipment. Such systems can be applied

Fig. 8 Translohr on a road guided by a single rail.

Fig. 9 Dual Mode Vehicle as a combination of rail-guided public transport and a bus developed by JR-Hokkaido.

only to urban/suburban transports, the traffic demands of which are large enough for justifying additional investment to way-side infrastructure for storing the electric energy. This technology will be described in the 6th paper by Mr. Konishi in this special issue.

Some technical developments are targeted at high quality economical transportation service, *e.g.* catenary-less, single rail or rail-less, dual mode systems as shown in Figs. 8 and 9, and maintenance-light and standardization of maintenance projects. There are innovative developments for vehicle power sources. For partial catenary-free solution, Li-H or Li-ion batteries are used for new tram systems, *e.g.* in SUIMO developed by Kawasaki Heavy Industry and PRIMOVE with Mitrac presented by Bombardier(14) Transportation. Quickly chargeable double layer capacitor is gaining importance in urban trams. Also contactless wireless energy transmission is being studied intensively. Technologies for the application of onboard power storage to electrified section will be explained in the 7th paper by Mr. Ogasa in this special issue.

For regional transport with a small transport demand where the electrification and way-side energy storage are too expensive, hybrid series diesel and an onboard battery can also be a useful solution for efficient, ecological, and attractive railway service as shown in Fig. 10 at Koumi Line by East Japan Rail Corp. This technology is introduced in the 7th paper by Mr. Furuta in this special issue.

4.2 Technical trend in intercity high speed ground transportation Power supplies of most intercity fast electric trains are AC-electrifications. Since the commercial utility and electric railway power network are connected by transformers, bi-directional power flow is naturally realized, and effective and reliable use of regenerative brakes is inherently easier than DC-electrification. Actual R & D efforts for intercity rail are dedicated to speed-up, efficient operation of power electronic devices, stabilization of voltage control and internal power flow management in railway electric system, *i.e.* the efforts are for enhancing the performance of transportation rather than increasing energy savings. Since intercity train service already has substantial advantages in energy-saving and environmental friendliness compared with automobiles and air planes, the impact of further energy saving is marginal. The efforts to enlarge a global market share of electric rails by realizing more attractive train services are more important than such marginal efforts to further energy saving technologies.

Fig. 10 Diesel hybrid train Kiha-E200 developed by JR-East and applied to Koumi-Line.

5. Concluding remarks

In this paper, the early technical history of electric supply to electric railways has been reviewed as an introduction to the following seven papers in the special issue . Continuous power supply played a significant role in the early rapid growth of railway technologies. The VVVF power electronic technology also substantially impacted to railway traction systems after the 1980's. The technology made it possible to have more efficient drive, downsizing of rolling stocks, and regenerative brakes. Currently, the following researches are significant:

- light and small electric power storage and its application,
- detailed life-time assessment of the storage devices under various using conditions,
- effective power exchange with commercial power utility network, and
- total energy flow control system.

For ecological and sustainable growth of ground transportation, engineering efforts shall be furthermore dedicated to the research and development of a total control system for traction power and energy, complementary cooperation with other personal transport modes, exchange of technological achievements in R & D efforts, and sustainable growth of market share of ecological electric railway by faster, more comfortable and more convenient passenger train service. The role of electric railway engineers is becoming more significant in the rapid growth of the railway network in eastern Asia including China and India. The electric railway has a substantial advantage in realizing integrated energy controls for the rational use of way-side/ on-board energy storage, efficient use of regenerated energy, and the application of new power sources like fuel cells. These advantages are possible because the railway is a carefully designed, closed, and infrastructure-based mass-transportation. On the other hand, the number of commercial products for railway is much smaller than in the automobile industry, and hence it is substantially more difficult to obtain scale-merits. There will be many technical seeds which railway engineers can learn from the automobile industries.

(Manuscript received Aug. 31, 2009, revised Jan. 19,, 2010)

References

(1) Information on i-Miev: http://www.ev-life.com/

(2) Roman Rossenberg: "Deutsche Eisenbahnfahrzeuge von 1838 bis heute", VDi-Verlag (1988)

(3) S. Sone: "Power Electronic technologies for Low Cost and Energy Conservation on World Railways Vehicles", IPEC-Tokyo 2000. VOL. 1, PP. 452-458 (2000)

(4) L. Kovudhikulrungsri and T. Koseki: "Precise and Torque Control for AC Traction Pure Electric Braking System in Low Speed Range", Trans. IEE of Japan, Vol. 122-D , No. 11, pp. 1027-1033, Nov. 2002

(5) L. Kovudhikulrungsri and T. Koseki: Improvement of Performance and Stability of a Drive System with Low-Resolution Position Sensor by Multirate Sampling Observer", IIIJ Trans. IA, Vol. 124, No. 9, pp. 886-891, 2004

(6) Keiichiro Kondo: “Application of Speed-sensor-less Induction Motor Control for Traction Motor Control System”. Quarterly Report of RTRI, Vol. 44, No. 1 pp.22-27 (2003)

(7) H. Ko, T. Koseki and M. Miyatake: "Numerical Study on Dynamic Programming Applied to optimization of Running Profile of a Train", IIIJ Trans IA, Vol. 125, No. 12 (2005)

(8) Y. Okada, T.Koseki and K.Hisatomi: "Power management control in DC-electrified railways for the regenerative braking systems of electric trains" COMPRAIL IX, pp.919-929, May-04, Germany (2004)

(9) N. Kani etal: "Grasp the Actual Conditions of Regenerative Brake and Optimize the Partial Cancellation Pattern of Regenerative Control", paper-ID 360432, International Symposium on Speed-up, Safety and Service Technology for Railway and Maglev Systems 2009 (STECH’09) 2009.6.16-19 Niigata JAPAN (2009)

(10) T. Koseki, Y. Okada, Y. Yonehata, S.Sone: “Innovative Power Supply System for Regenerative Trains”,COMPRAIL 2004 pp.931-939, May-04, Germany (2004)

(11) T. Noda *etal*: "Design of a Run-Curve for Energy Saving Operation in a Modern DC-Electrification -Efficiency Assuming Perfect Regenerative Braking-", paper-ID 360659, International Symposium on Speed-up, Safety and Service Technology for Railway and Maglev Systems 2009 (STECH’09) 2009.6.16-19, Niigata JAPAN (2009)

(12) http://www.iec.ch/zone/emc/iechelps.htm

(13) http://webstore.iec.ch/webstore/webstore.nsf/ArtNum_PK/42423!openDocument

(14) Bombardier GmbH PRIMOVE, http://www.bombardier.com/en/transportation/sustainability/technology/primove-catenary-free-operation

(15) On-line encyclopaedias, *e.g.* Wikpedia are detailed good information source regarding historical and current situations of railway technologies: http://en.wikipedia.org/wiki/Main_Page A part of historical description in this article is based on the open information.

Takafumi Koseki (Member) Graduated from the Department of Electrical Engineering at the University of Tokyo in March 1986, nd was awarded the degree of Doctor of Engineering from the University of Tokyo in 1992. His present research interest is the application of control and electrical engineering to rail-guided transportation and human-based motion controls. He is a member of IEEJ, JSME, JSPE, JAEM, Japan Railway Electrical Engineering Association, IEEE, and Verein Deutscher Ingenieure.