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Review Paper

Energy Saving and Environmental Measures in Railway Technologies:

Example with Hybrid Electric Railway Vehicles

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The electric railway system is the highest class of energy efficient transportation means. This is due to two important points: (i) low running resistance (including low energy losses) and (ii) energy regeneration in braking.

Regenerative braking of railway electric vehicles is effective when the other powering ones, in other words electrical load, exist near the regenerating train on the same electrified line. So, early in the morning and at midnight, or in the low-density district lines, regeneration cancellation phenomenon often occurs and the regenerative brake force cannot be operated in accordance with the recommended value. Newly appeared high-performance energy storage devices press the issues of energy storage and reuse technologies on ground and on vehicles. Hybrid energy source is one effective solution. In this paper, as an example, we show our trolley and on-board battery hybrid controlled tramcar, developed to reduce regeneration cancellation. With the trolley line collective power as well as charge and discharge power of the on-board lithium ion rechargeable battery, the hybrid energy providing and regenerating technology is achieved. The running test results show a maximum regenerative ratio of 44%, which is top class value in an electric railway system. © 2008 Institute of Electrical Engineers of Japan. Published by John Wiley & Sons, Inc.

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1. Introduction

A railway system has better energy conservation features than other transportation systems. Its energy consumption to carry a person for a unit of distance, namely specific energy consumption, is 209 kJ/person-kilometer which is less than a tenth of that of a car, which is 2484 kJ/person-kilometer [1]. First of all, its features are smaller traveling resistance and less energy loss. For instance, it has been actually reported that a commuting train of ten cars with full passengers, whose mass is 400 tons, once having been accelerated to the speed of 100 km/h, can coast, if not applied with any braking, for a distance of 7.4 km during 370 s until its speed drops to 50 km/h. In addition, the 'power regeneration on braking' technology, which has been socially acknowledged recently owing to the popularization of hybrid cars, had been applied to commercially operated electric train system more than 30 years ago. The first application of braking regeneration on down-grade railway was carried out at the beginning of Showa Era.

The reason why the electric regeneration was utilized in earlier times is that an electric car can accommodate its power with other electric cars through an overhead wire. Electric power by its nature is difficult to store, and it is a very basic nature that generation and consumption should occur at the same time. Because it is not necessary to install its own power generator for its own motion, the car can be designed with light weight, and the car needs to obtain the necessary amount of power from the overhead wire only when needed. These are the most advantageous features of electric cars. In other words, the electric car is a moving flywheel system itself linked to the overhead wire.

However, this system has of course a regeneration loss on the collection of electric energy through regeneration braking. And, the present cars and power feeding system are not so designed as to be able to collect and reuse all the kinetic energy of running trains.

On the other hand, the energy storage technology through high-performance energy accumulating media has remarkably advanced these days, and electric vehicles (EV) are in the midst of booming technical development.

Under these circumstances, preventive technology against the invalidation of regeneration, as the first runner, and other technical developments are being well conducted also in the railway sector.

In this paper, the effective use of regenerating braking and the expected electricity storage technology in the future for further energy conservation in the electric railway field will be outlined. The outline and some examples of actual application of various electricity storage media viewed from a user's point will be introduced taking hybrid cars as an example; their advantages on environmental issues other than energy conservation will be also added.

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2. Various Energy Conservation Techniques in Railway and Environmental Activities

About 70% of the energy consumption, the largest portion, in railway operation is constituted by the energy consumed for running train cars. It is, therefore, effective to take the energy conservation measures at this point. There are mainly two measures for the purpose, namely reduction of loss and reuse of kinetic energy, on which the following activities have been conducted.

2.1. Measures to reduce energy consumption for running train cars

1. Weight reduction of cars: modification of steel structure and employment of aluminum
2. Reduction of running resistance: employment of optimum head shape and very smooth body sides
3. Reduction of electric equipment loss: reduction of eddy current loss by using thin magnetic steel sheets; reduction of excitation loss by using permanent-magnet-type synchronous motors; employment or development of air conditioners with higher coefficient of performance (COP); and so on
4. Measures at feeding side: reduction of equivalent resistance by employing parallel feeding circuits at inbound and outbound lines

2.2. Reuse of kinetic energy (electric regeneration at braking)

1. Employment of inverter: making regeneration braking easier and more secure
2. Control of vector: control of regeneration amount corresponding to regeneration load including standing-by for excitation, and optimization of regeneration-limiting current— voltage pattern
3. Measures at feeding side: increase of available power to and from overhead wire by employing parallel feeding circuits to give a greater existence probability of loadable cars on the rail line; installation of substation rectifiers that can supply regenerated power to power source lines owned by the electric power company

Some of the major activities for environmental issues are reduction of greenhouse gas emission by applying technology that rationalizes and upgrades energy use as stated above and technical development to introduce clean energy.

In addition, also important measures are the environmental measures in the area along the railway lines such as reduction of noise and vibration, appropriate disposition of polluting substances and waste disposal technology.

Furthermore, the temperature control in the railway stations, etc. necessitated by passenger movement is one of the environmental measuring technologies in a broad sense.

3. Current Status of Energy Regeneration and Effectiveness of Employment of the Hybrid System

3.1. Principle of electricity regeneration by regeneration braking

Today, the common braking method used for electric railway cars as standard is 'regeneration braking' in which the kinetic energy generated by a running electric train is transformed into electric energy which then returns through the overhead wire. This is a noncontacting braking system without any mechanical friction, and therefore without any heat generation and without any resulting dust from brake shoes. As is discussed above, this is an energy-conserving and less-maintenance braking system.

The energy returned to the overhead wire can be used for driving other electric cars. This means electric cars connected to the overhead wire can provide or receive electric energy among themselves; this way the electric energy is not wasted but reused (Fig. 1).

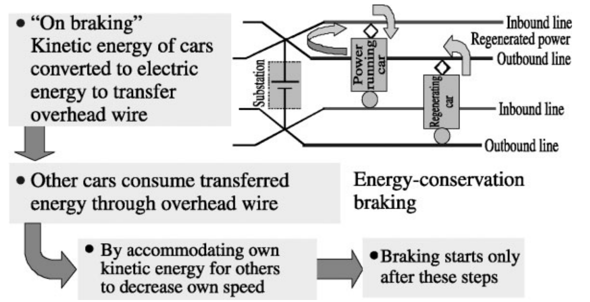

Fig. 1 The mechanism of how electricity is returned to overhead wire

3.2. Invalidation of regeneration and issues on designing cars and feeding circuits

When there exist no electric cars on the railway line that act as electrical loads for an electric-regenerating car, the energy otherwise returned to the overhead wire cannot be consumed, and the 'invalidation of regeneration' (which invalidates regeneration braking) occurs. If this happens, the subject electric car is forced to stop with its friction brake and therefore it cannot collect the intended energy, and worse still, wastage and deterioration of the relevant parts occur. On lines other than crowded lines and those operating in the early mornings and late nights, invalidation of regeneration occurs in which regeneration braking cannot function as directed, or 'limited regeneration (Fig. 2)' occurs, which is less significant than the invalidation, where only a part of the kinetic energy can be transferred to electric energy. This is called 'light load regeneration' because its origin is the electric load.

When the returnable power to the overhead wire is exceeded by the regenerated power through the inverter, the voltage at the pantograph rises sharply. To avoid this disadvantage, electric cars with inverters today control the voltage so as not to exceed a specified value by limiting the power (current) from the inverters to the overhead wire. Owing to this control, the regenerated braking power is limited. When all the regenerated power is completely invalidated, the status is called 'regeneration invalidation'.

Particularly in the direct current line, because the rectifiers in the substation are of a diode bridge type, the power cannot be returned to the power supply lines and therefore it is necessary to treat the regenerated energy at the direct current side.

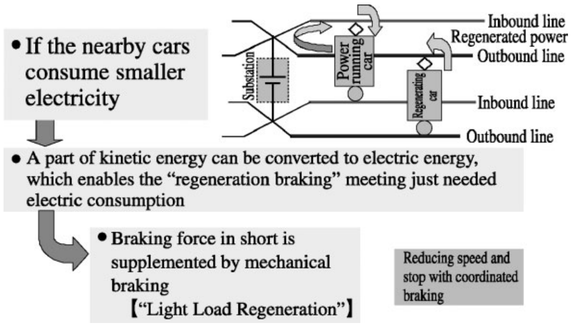

Fig. 2 Limited regeneration (light load regeneration) and regeneration invalidation

●☆ Advantages of car-installation:

- Possible to give and receive more regeneration power than the power limited by feeding resistance
- Prevention of regeneration invalidation (highly reliable electric control)
- Movable even when feeding stopped (prevention of passenger-containment)
- Possible to move through non-electrified range
- Saving traveling time by assisting power running
- Unnecessary to add facilities fixed on land

☆ Advantage of land-installation:

- Possible to store energy without additional weight on cars
- Prevention of regeneration invalidation (highly reliable electric control)

Fig. 3 Advantages of car-installed and land-installed energy storage

These days, the introduction of inverter cars is on the increase as the energy-conservation cars; however, the increase of regenerating cars may increase the regeneration amount, which may cause higher probability of regeneration invalidation. Even regarding the cars running under overhead lines, the importance of holding the regeneration load is growing for energy conservation.

Other than above matters, owing to the voltage decrease caused by the electric resistance of overhead wire and rails, the maximum power given to and received from the electric cars is limited in combination with the maximum overhead wire voltage capacity. If a large braking force, such as regular braking at the maximum speed, is applied, all the kinetic energy of the electric car cannot be collected instantaneously.

3.3. Effectiveness of hybrid power source by electric storage The residual regenerated power that has not been returned to the overhead wire may be stored. This brings improved reliability of regenerated braking by preventing regeneration invalidation, reuse at power running and power assisting. Depending on the capacity of the installed electric storage system, it may be possible to increase the regeneration braking force at the high-speed range and running in a range without the overhead wire.

In this case, it should be noticed that these measures may be accompanied by additional cost on the cars and cost increase in manufacturing. If the amount of energy reduction obtained from regeneration, absorption and reuse exceeds the amount of running energy increase due to additional car weight, it becomes possible to effect superior energy conservation to that currently.

In addition to that, there are some advantages in car-installed electric storage to energy conservation (Fig. 3). The electric driving in the range without overhead wire does not generate exhaust gas (zero emission), accommodates better scenery in an area where scenery is important, and so on, which are significantly advantageous in the entire environmental aspect.

4. Selection of Electric Storage Facilities and Application for Car Installation

4.1. Selection of electric storage media To store electric energy from regenerated braking power of electric cars in whole or in part is the same function as charging quickly electric storage media. There are only a limited number of media that can absorb the energy, considering the size and continuing time of the regenerated power by railway cars, and also with reasonable volume and mass.

Realistic electric storage media are flywheels, electric dual layer capacitors, quick rechargeable batteries of nickel-hydrogen and lithium ion, etc. Each of them has merits and demerits, and none is universally applicable.

After satisfactorily arranging the design performance, which depends on the hybrid ratio of power and energy, it is necessary to select the electric storage medium from the viewpoint of allowable mass, volume, life and cost. In other words, it depends on the design policy of the performance of the car as to what type of car is to be designed for which type of running.

4.2. Energy amount required for electric storage media The kinetic energy of a 40 ton car at the speed of 108 km/h is equal to 18 MJ calculated using a simplified formula, without including its rotary inertia, namely $K = 1/2\ MV^2$. The kinetic energy of a 20 ton Light Rail Vehicle (LRV) running at 72 km/h is 4 MJ. The energy necessary to run a tramcar, of which maximum legal speed is 40 km/h, for a distance about 250 m between two adjacent stops is obtained from experiment as 3 MJ. [2] Supposing an LTV running with its stored energy without overhead wire, considering recharging at every few stops, waiting at signals and congestion, it is necessary to install a set of media that satisfy the energy capacity of 10 MJ or more with its system mass about 1 ton.

5. Development Examples of Several Types of Hybrid Cars

5.1. Installation of electric storage system on railway cars A comparative list of domestic and foreign developments is shown in Table I together with the features of electric storage media. The cars are installed with a hybrid system in which the main energy is supplied from overhead wire, engines or fuel cells, and sub-energy is supplied from an electric storage system.

Here, the term hybrid system means a system that can simultaneously conduct coordinated performance, i.e. supposing that the necessary power for acceleration and deceleration is 100%, 60% of the power is given from a main energy source and rest 40% from a sub-energy source at a given instance.

Table I. Features of electric storage media and application status of railway vehicle installation (as of February 2007)

Media	Flywheel	Secondary battery	Electric dual layer capacitor
Feature	• Even a small system can store large energy with high revolution speed.	• No moving parts • Large energy density • Small voltage fluctuation	• No moving parts • Large power density • Usable upto zero voltage
Development issues	• Development of bearings • To decrease loss (wind loss) • To sustain suppressed Coriolis force	• Increase of power density • Elongation of life • Balance control among cells	• Increase of energy density • Measures against voltage fluctuation • Balance control among cells
Durability	• Approx. 20 000 to 50 000 h (Mainly depending on maintenance of auxiliary parts)	• 1000 to 3000 cycles (at DOD = 100%) • Approx. 6 years (calendar-year life)	• 100,000 to 500 000 cycles = >5 to 15 years depending on applications and environmental conditions
Development trends	• Running test on the commercial line (German railway: diesel hybrid LIREX: since 2000)	• Li+: Durable running test on the commercial line (JR East: NE Train diesel hybrid: since 2003 (planned to start commercial run in 2007); Fuel cell hybrid: since 2006)	• Running test on the commercial line (Mannheim Public Transport Company, Overhead wire hybrid LRV: since 2003)
	• Running test on the commercial line (Europe ULEV-TAP (Ultra Low Emission Vehicle Transport using Advanced Propulsion): Diesel hybrid LRV: 1997 to 2001, ULEV-TAP II: 2002 to 2005)	• Li+: In-factory running test (Railway Technical Research Institute: A tram without overhead wire: since 2003, overhead wire hybrid tram: since 2005) • Li+: In-factory running test (Mitsubishi Heavy Industries: A new transport without overhead wire: since 2004) • Li+: Running test on the commercial line (Fukui Railway: A tram without overhead wire: since 2004, Echizen Railway: A commuting train without overhead wire: since 2006)	• Running test on the commercial line (JR Tokai: Overhead wire hybrid commuting train 313 series: since 2005)
	• Test production (USA: Gas-Turbine JET-Train: since 2000)	• Ni-MH: Running test on the commercial line (Nice, France: Overhead wire hybrid LRV: since 2005 (it will be employed as the commercial cars in 2007) • Ni-MH: In-factory running test (Kawasaki Heavy Industries: A tram without overhead wire since 2006)	

The Fig. 4 shows a hybrid test car using a diesel engine set and secondary lithium ion batteries introduced by the JR East Japan in April 2003. It clocked approximately 20% improvement of fuel consumption. [3] It completed test runs with fuel cells instead of a set of diesel engines in 2006.

The Fig. 5 shows an experimental battery tramcar with lithium ion secondary batteries without overhead wire presented by the Railway Technical Research Institute in August 2003, which was modified and again presented as a hybrid electric car with overhead wire and batteries in February 2005. In the range with overhead wire, it performs energy conservation run with increased regenerated energy through its regeneration-invalidation preventive function, whereas in the range without overhead wire in scenic areas it can run with battery power.

In foreign countries, hybrid-type cars mainly using a flywheel-type electric storage system have been developed for many years. In Canada, hybrid-type locomotives using a diesel engine and lead batteries have been commercially operated already since 2005. And at the city of Nice in France, an LRT line will be put into commercial operation in the summer of 2007, where the LRV is going to be powered by the hybrid system with overhead wire and nickel-hydrogen batteries.

Fig. 4 The ‘NE Train’ (Diesel Hybrid Car)

Fig. 5 The ‘Richy-Tramy’, a tram with hybrid overhead wire

6. Power Circuit, Control and its Effectiveness on Hybrid Railcars

Here, an overhead wire hybrid type railcar with electric storage system is outlined, taking the system developed by the Railway Technical Research Institute [4] as an example.

6.1. Main circuit of railcar installed with electric storage system This system distributes the electric energy received via a power collector to driving use and storage use (when not returned to the overhead wire, it is treated as regeneration storage) through the parallel connected circuit. By use of a power-source-reversible chopper, it is possible to convert the voltage on the overhead wire and electric storage media and to control current of the redundant power (Fig. 6). The difference from the common engine hybrid cars is that the regeneration point is not a single but multipower-source circuit having dual regeneration points.

6.2. Control of cars installed with electric storage system On the condition of the light load regeneration, the redundant power, which otherwise would sharply raise the voltage at the pantograph, is stored in the electric storage system installed in parallel instead of limiting operation on the normal inverter car. On power running, on the contrary, the

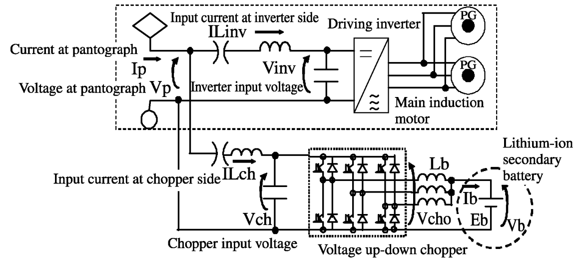

Fig. 6 Parallel-connection-type overhead wire hybrid electric storage circuit

Fig. 7 Pantograph forced to lower during supply of electricity

power is supplied from the electric storage system when the voltage at the pantograph drops to a certain level. This is the basic scheme.

It is a common way to optimize the energy solution through addition of ‘energy management control’ in which, on the basis of core control, the timing and amount of giving and receiving power are controlled depending on the running lines and running patterns.

6.3. Effective energy conservation examples depending on experimental running

1. Overhead hybrid running
   An experimental run was conducted up to the speed of 50 km/h with 750 V overhead wire using a test tram car installed with lithium ion secondary batteries as the electric storage media, the battery specification of which was as follows: nominal voltage 605 V; maximum rated discharge and charge current $\pm$500 A; nominal capacity 33 kWh; system mass 1160 kg.
   Even when the pantograph was forced to rise or lower during supply of electricity (Fig. 7), the electric energy that could not be received from or supplied to the overhead wire was received from or supplied to the installed batteries, and the car was smoothly accelerated, decelerated or stopped switching the power sharing well. In this test, the brake power recollection percentage from the speed of 50 km/h (the rate of recollected electric power at the pantograph and battery terminals over the kinetic energy of the car including rotation inertia at the start of braking) was 70%.
2. Running without overhead wire (with battery)
   Regarding the continuous running test without the overhead wire, a test was carried out under a pattern in which the car stopped at approximately every 250 meters with acceleration

up to 40 km/h and deceleration to stop repeatedly simulating the commercial tram operation. [2] Consuming about two-thirds of the battery capacity, the car completed 62 cycles, in which the total running distance was 17.4 km in 75 min.

This time the brake energy re-collection percentage was 72%, and the regeneration percentage, which is the percentage of re-collected regeneration energy over the energy consumed for power running, of which the best record was 42% performed by Yamanote Line, was 44%.

According to this test result, though depending on the types of lines, it can be estimated that the energy conservation effect of using the hybrid technology accounts for 5 to 15%.

7. Features and New Applications of Hybrid Electric Cars

7.1. Charging technology during coasting operation By gradual discharge through the overhead wire during coasting operation, it is possible to adjust the residual energy in the electric storage system. On the through running on the line with and without overhead wire, when running on the line with overhead wire, just before the connecting point the car charges the electric storage capacity to almost full, and after passing the line without the overhead wire connecting the pantograph to the overhead wire, it is possible to charge the electric storage system during coasting operation when running on an overhead wire line.

It is expected to select an appropriate mode in which running with the battery system is performed in a the scenery-emphasized area in the center of a city, with very little vertical space such as in crossings with an overpass or underpass, on a partially elongated line without overhead wire which may accommodate construction cost reduction, and running in other areas is performed accompanying charge and discharge of batteries with collected electric power from the overhead wire.

7.2. Technology of charging during parking By conducting quick charging through rigid overhead wire when parking at a station after running without overhead wire, it is possible to continue the running without overhead wire. Installing the optimum capacity of an electric storage system, it is possible to plan charging at every few stations or at the turn-around stations.

This technology is directly applicable to the idling stop function on an engine-hybrid car parking at a station, the modified configuration of which may be used as a charging system for buses and trucks at the same time.

8. Conclusion

Here we discussed a technology of the overhead wire hybrid tram car by use of an electric storage system installed on the car that uses electric regeneration effectively and accommodating scenery-emphasized area in the city by applying partial running without the overhead wire. This is an example of technologies that can contribute to enhancement of energy conservation and environment in the railway business.

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