Development of Contact-wire/battery Hybrid LRV
Hybrid Technology with Lithium Ion Rechargeable Battery for LRV

Masamichi OGASA*, Yoshiaki TAGUCHI*
*Railway Technical Research Institute/vehicle control technology division
ogasa@rtri.or.jp

***Abstract*-Contact-wire/onboard battery hybrid railway electric vehicles run on a hybrid power source that enables energy to be fed from contact wires and /or onboard batteries. We developed a contact-wire/battery hybrid LRV (Light Rail Vehicle) and had it manufactured. This paper concerns the hybrid source technology for the contact-wire/battery hybrid system, and on the running results with onboard rechargeable lithium ion battery (600 V-system). The LRV ran on a commercial service on-street line on an actual operation diagram, and recorded a regeneration ratio of 41 % (the volume of regenerated energy divided by the energy consumed in powering), cutting the energy consumption by maximum 30 % over that of existing inverter vehicles, with the hybrid controlled running. The LRV also achieved the running distance by one spell of charge of 25 km over on a street line and 49 km on an existing railway main line.**

Keywords-energy storage; hybrid vehicle; regenerative brake; lithium ion rechargeable battery; power flow

I. INTRODUCTION

The ‘power regeneration on braking’ technology, which has recently been socially acknowledged owing to its popularization on hybrid cars, had been applied to commercially operate electric train system more than 40 years ago. The reason why electric regeneration was utilized in earlier times is that a rail electric vehicle (EV) can share its power with other EVs through an overhead contact wire. Because it is not necessary to install its own power generator for its own motion, the vehicle can be designed with light weight, and the vehicle needs to obtain the necessary amount of power from overhead wire only when needed. These are the most advantageous features of electric vehicles.

However, this system has of course a regeneration cancellation loss on the collection of electric energy through regeneration braking. When there exist no electric vehicles on the railway line that act as electrical loads for an electric-regenerating vehicle, the energy otherwise returned to the overhead wire cannot be consumed, and the ‘cancellation of regeneration’ (which invalids regeneration braking) occurs. The higher the rate of regenerative vehicles goes up, the more tends to go rise the rate of the regeneration being cancelled out, by the increased amount of regenerative power. It shows the importance of the steady regenerative load, even for the electric vehicles supplied from the trolley lines. And the present vehicles and power feeding system are not designed to enable collection and reuse all the kinetic energy of running trains.

On the other hand, the energy storage technology through high-performance energy accumulating devices has remarkably advanced these days, and auto EVs are in the midst of booming technical development. Under these circumstances, preventive technology against cancellation of regeneration, as well as energy storage technology on board, is also being intensively pursued in the railway sector [1], [2], [3], [4].

In this paper, the effectiveness use of regenerating braking and our developed preventive technology against cancellation of regeneration with electricity storage device on board are outlined. Also we described the test results of quick charge, hybrid running, battery running and the energy conservation.

II. EFFECTIVENESS OF EMPLOYING THE HYBRID SYSTEM

A. *Current status of energy regeneration and regeneration cancellation*

Today, the common braking method used for electric railway vehicles as standard is ‘regenerative brake’ in which the kinetic energy generated by a running electric train is converted into electric energy which then returns through the overhead wire. This is a non-contacting braking system without any mechanical friction, and therefore without any heat generation and without any resulting dust from brake shoes. As is discussed before, this is an energy-conserving and less maintenance braking system. The energy returned to the overhead wire can be used for driving other electric vehicles. This means electric vehicles connected to the overhead wire can provide or receive electric energy among them; this way the electric energy is not wasted but reused.

If a ‘cancellation of regeneration’ happens, the subject electric vehicle 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 early in the morning s and late nights, cancellation of regeneration occurs in which regenerative brake cannot be operated as directed, or ‘limited regeneration (Fig.1)’ occurs, which is less significant than the complete cancellation, where 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 current collector, pantograph, rises sharply. To avoid this disadvantage, electric vehicles with inverters today control the voltage so as not to exceed a specified value by

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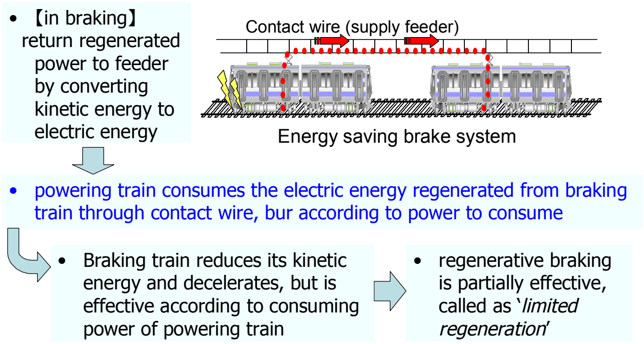


Fig. 1. Limited regeneration.

limiting the power (current) from the inverters to the overhead wire. Owing to this control, the regenerated power is cancelled; the status of complete cancellation is called 'regeneration cancellation' [5].

B. *Issues on designing vehicles and feeding circuits*

Particularly in the dc (direct current) electrified line, because the rectifiers in substations are almost of the diode bridge type, power cannot be returned to the supply grids and therefore it is necessary to treat the regenerated energy at the dc side. It is not realistic to replace all rectifiers in substations to bidirectional PWM rectifiers; because the suppression of high harmonic currents of reverse power flow to grids is severely restricted, and the cost of accompanied control filters often becomes a problem.

These days, the introduction of inverter fed vehicles is on the increase as the energy-conservation vehicles; however, the more numbers of regenerating vehicles may increase the regeneration amount which may cause higher probability of regeneration cancellation. Regarding the vehicles running under overhead lines, the importance of holding the regeneration load is growing for energy conservation.

And owing to the drop cause by the electric resistance of overhead wire and rails, the maximum power given to and received from the railway EVs is limited in combination with the maximum overhead wire voltage capacity. If a large braking force, such as maximum service braking at high speed, is applied, all the kinetic energy of the EVs cannot be collected in a present design.

C. *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 regenerative braking by preventing regeneration cancellation, 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 areas without the overhead wire.

In this case, it should be noticed that these measures may be accompanied by additional weight on the vehicles 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 vehicle weight, it becomes possible to effect superior energy conservation to that currently.

There are some advantages in vehicle-installed electricity storage as bellow:

- Ensure the effective utilization of energy (Fig. 2);
- Prevention of regeneration cancellation (highly reliable regenerative braking);
- Getting more power to vehicles than the power from/to supply wire limited by feeding resistance and voltage of current collector (larger regenerative braking force);
- Saving traveling time by assisting power especially in high speed range (larger electric traction force);
- Mobility even when the feeding is stopped (prevention of passenger containment);
- Running in no electrified track sections (Fig. 3)
- Avoiding the necessity to add facilities fixed on land;
- Through operation between electrified sections and no electrified sections;
- Low-maintenance hybrid system unified only by electric energy, compared to engine hybrid or fuel cell hybrid system.

Electric driving areas without the overhead wire does not generate exhaust gas (zero emission), accommodates better scenery in an area where landscape is important.

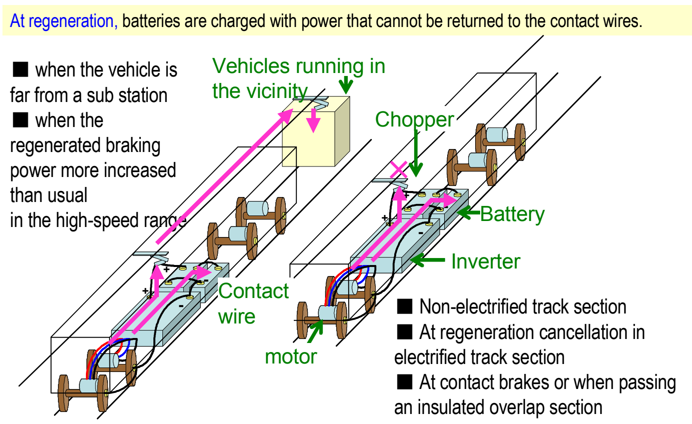


Fig. 2. Contact-wire/battery hybrid power flow.

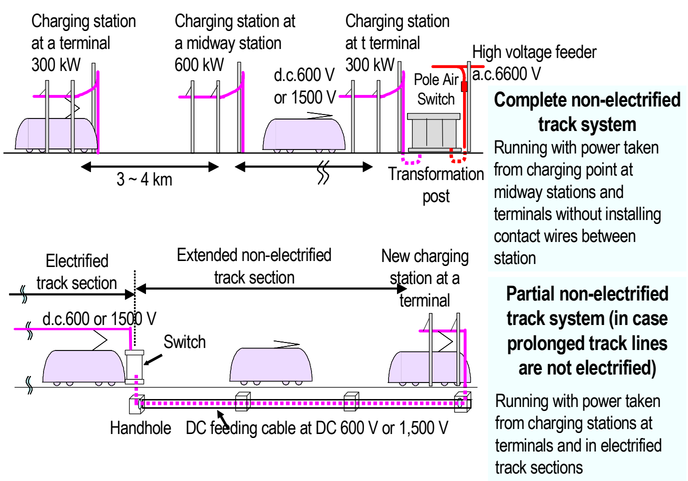


Fig. 3. Running in nonelectrified track sections.

III. DEVELOPMENT OF CONTACT-WIRE/BATTERY HYBRID LRV WITH LITHIUM ION RECHARGEABLE BATTERY

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. Our developed basic configuration of traction circuit with control strategy is outlined below [5].

A. *Basic configuration of the traction circuit*

The basic traction circuit system (Fig. 4) distributes the electric energy received via power collector to driving use and storage use (when not returned to the contact wire, it is treated as regeneration storage) through the parallel connected circuit. By use of a current reversible chopper in front of the storage battery, it is possible to convert the voltage on the contact-wire and electric storage devices and to control current of the redundant power. As the chopper control is independent from the traction inverter control, it is advantageous in that it can be mounted to the existing inverter-driven trains.

B. *Control strategy*

1. *Control for powering and regenerating*

On the condition of the light load regeneration, the redundant power, which otherwise would sharply raise the voltage at the current collector, is stored in the electric storage system installed in parallel instead of limiting operation on the normal inverter car.

In powering, on the contrary, the power is supplied from the electric storage system when the voltage at the current collector drops to a certain level. This is the basic scheme.

It is common 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.

2. *Control for coasting and in halting*

For coasting and in halting, the control strategy is to keep the amount of remaining stored energy within the upper and lower reference values. The reference is set at 40-60 % of the S.O.C. (State of Charge), while the charging and discharging current is set at 80-160 A per current collector. When discharging, the chopper works to return the redundant energy to the contact wire and to the auxiliary machine, and during charging operates to provide the required energy from the contact wire and to the battery. When the open voltage at the battery terminal or the S.O.C. goes beyond the reference range, an adjusting charge or discharge control is executed, enabling the battery to maintain the energy required to correspond to both powering and regenerating.

In running on no electrified track sections, the S.O.C. lower reference will be higher and the battery becomes almost the fully charged.

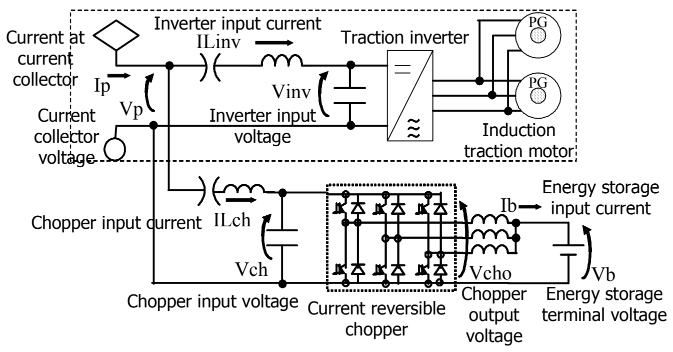


Fig. 4. Basic traction circuit of hybrid e.m.u.

C. *Vehicle development*

Table I shows the specification of the dual feeder voltage contact-wire/battery hybrid LRV "Hi-tram" (Fig. 5), manufactured in September 2007 after the durative running test by the basic hybrid system of the remodeled tramcar 'Lithey-Trammy' from April 2003 [4],[5],[6]. in the RTRI test lines. This new vehicle is applicable to commercial use.

TABLE I. SPECIFICATION OF CONTACT-WIRE/BATTERY HYBRID LOW FLOOR LRV (TYPE LH02) 'HI-TRAM'.

Item		Specification of 'Hi-tram'
train set		single car
type		LH02
passanger capacity		44 persons (seat: 20 persons including foldable seat)
weight (tare)		24.0 ton (2007-2008), 27.3 ton (after 2009)
size	length	12,900 mm
	width	2,230 mm
	height	3,800mm (current collector folded)
	floor height	350mm (low floor part) from rail surface
supply power		dc 1500 V / dc 600 V and on-board battery dc 600 V
vehcile performance		maximum operating speed 40 km/h (on-street line)
		maximum operating speed 80 km/h (railway main line)
		acceleration: over 0.97m/s^2 (3.5km/h/s)
		deceleration: service braking 1.3m/s^2 (4.6km/h/s)
		emergency braking 1.4m/s^2 (5.0km/h/s)
		preventive braking 1.4m/s^2 (5.0km/h/s)
main secondary battery		lithium ion rechargeable battery (lithium manganese oxided positive actual material) (rated voltage of dc 605 V, energy capacity of 120 Ah)
current controller		IGBT-VVVF inverter 1C2M (150kW max250kVA) × 2 units IGBT-current reversible chopper (600 kW) × 2 units
bogie (leverage ratio 5.14)		coil spring in-direct mounted bolster type
		・gauge 1,067mm
		・monoblock wheel (diameter of 660 mm)
		・1st axle : measuring wheelset for wheel/rail contact force
		・2nd,3rd,4th axles: with earthing brushes to axle boxes
		・1st, 4th axles: with jetting device (for adhesion improvement materials)
		length: 2,553 mm (including jetting device)
		width: 2,200 mm, height: 661 mm
braking system		electric command pneumatic brake with regenerative function for contact-wire/on-board storage
traction motor		three phase induction motor 60kW (atDC600V) × 4 units
auxiliary power supply		static inverter type: ・singl phase ac 100 V(3 kVA) ・three phase ac 200 V(28 kVA) ・dc 100 V(2 kW) ・dc 24 V(6 kW)
current collector		single arm current collector with spring rise and air descent
air compressor		610 l/min
supply select operation		mode selecting switch (1500 V mode <-> 600 V battery mode <-> 600 V mode)

Fig. 5. Contact-wire/battery hybrid LRV 'Hi-tram'.

1. Traction circuit

The traction circuit corresponds to the voltage of feeder lines of dc 600 V and 1500 V, to the voltage of onboard battery of dc 600 V (Fig. 6.). This configuration is a PWM (Pulse Width Modulation) chopper/inverter system.

The voltage of the intermediate dc link bus is controlled by 750 V, and all the equipments of load sides are for the low voltage (dc voltage is 750V or less) application. Two traction inverters drive two 60kW (at dc 600 V and redefine 75 kW at dc 750 V) AC traction motors respectively, and four all axes are driven.

Here note that the rated power of railway traction motors are usually expressed as r.m.s. (root mean square) values. Railway vehicles use coasting operation so often that the electric equipment would be thermally too much if they were set to correspond to the maximum power as the continuous vales. In general, the rated values of traction motors are almost the half of the maximum power for short time. This means that the traction motors with rated power of 60 kW use nearly the double of 120 kW or so for railway application.

2. Main battery

The battery module is 19kg in mass with eight-series lithium ion rechargeable cells. The positive actual materials of the cells are lithium manganese oxide.

The feature is that the cell permits the electrical charge/discharge current of 600 A, the 20 times to 30 A in ratings current. BMU (Battery Management System) for the overcharge prevention and the temperature watch of each cell is built into in the module, and an external signal output enables the current control and the interception control of an external circuit. Moreover, the automatic interception mechanism with the shutdown separator cope with an internal short are included, and the security function in which in case of emergency is assumed is prepared.

The units are consists of 972 cells, with an energy of capacity of 30 Ah each, 168 series and 4 parallel connected 3.6 V voltage cells, leads to the unit voltage of 605 V rated and 706 V maximum. The rated value of the maximum charging/discharging power, the installed energy, and the weight is 600 kW, 72.0 kWh, 2,000 kg, respectively.

The weight of the battery units contained the cooler fans and the protection systems as breakers, and occupiers 7.3% of the mass of the vehicle.

The maximum electrical charge/discharge current in the vehicle design assumes 1,000A that includes enough margin (it is 8.3 times of current high rate to the rating), as the maximum current of the quick charge while stopping at stations. This current supplies the enough energy to the

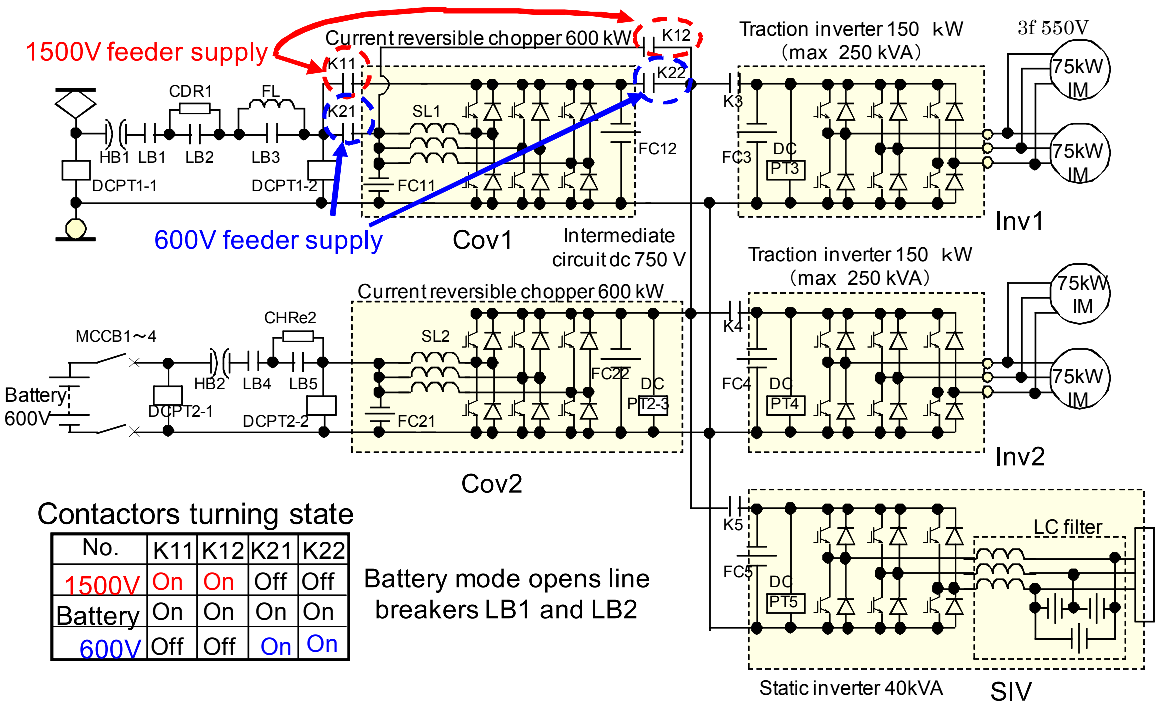


Fig. 6. Traction circuit of contact-wire/on-board battery hybrid LRV 'Hi-tram'.

batteries of the vehicle to run several kilometers only with the shot time as several ten seconds of quick charging when passengers get on and off at the station. Running distance of 7.5 km is possible with the 20% of the battery energy rating (approximately 15 kWh).

3. Charger/discharger (Hybrid control chopper)

The converter box consists of the feeder side chopper and the battery side chopper. Both of choppers are dc/dc current reversible type. Direct current with which harmonic current ripple is decreased by making both three phase three multiples chopper circuit, and shifting the PWM (Pulse Width Modulation) carrier phase by 120° is generated. The chopper circuit is possible to work as traction inverter for a usual train that doesn't need the accumulation of electricity, by shifting the modulation wave phase by 120° instead of the chopping operation and generating the three-phase alternating current. This configuration also enables the use of rechargeable batteries as well as EDLCs (Electric Double Layer Capacitor) as dc storage device, and also enables the use of flywheel motors for three phase ac storage device.

The feeder side chopper Cov1 steps down the feeder voltage of 1,500 V to the intermediate dc link bus voltage of 750 V as standard, and the Cov1 also steps up the feeder voltage of 600 V to 750 V as standard. The Cov1 operates by reversing the contactors of the input and output terminals of the circuit according to the mode of the voltage of the feeder.

The voltage fluctuation of the intermediate dc link is allowed, in order to transfer the current sum from/to each input terminals of the SIV (Static InVerter as auxiliary converter for lighting, air conditioning, controllers, etc.), the traction inverters, and the battery side chopper Cov2 as an active load. The maximum current of the both of choppers is 1,200 A, and the choppers control the feeder current from/to vehicle as given set values up to 1,000 A.

The battery side converter Cov2 steps up the battery voltage of 600 V to 750 V, and have functions and capacity of quick charge with a power of 600 kW (600 V-1,000 A). The Cov2 operates as basic control strategy described in the *B* passages.

When the battery mode is selected, the Cov1 stops operating, and the power supply from/to the load is achieved automatically by the voltage control of the Cov2.

As the S.O.C. of the battery reaches the upper or the lower bound value, the charging/discharging current instruction is commanded automatically. The charging/discharging current is 40-50 A per a contact strip of a current collector.

Moreover, when a train crew handles the quick charge button, the charging current up to 1,000 A flows to the battery as the vehicle is stopping at charging stations.

IV. RUNNING TEST RESULTS

A. Quick Charge

The vehicle charged its battery through the on-roof current collector while stopping under the short span of rigid overhead contact wire of 3 m in the length (Fig. 7). The charged energy over a period of 60 seconds at a charging current 1,000A was correspond to the running energy of the distance of 4 km over with the maximum auxiliary load of ac air-conditioning (Table II). This condition is assumed to be at a charging station on the way of the route. In the conditions assumed to be at turning terminals, a distance of 6 km over was charged in 3 minutes at a charging current 500A. This result shows that the energy necessary to the vehicle to run to the next charging station is supplied at time that does not influence the operation diagram. There was no melting at the contact point of contact strip of the current collector and the rigid contact wire. The increase of the temperature in the batteries is also restricted only to 3 degrees centigrade.

Fig. 7. Quick charging from rigid contact wires.

B. Hybrid running and effect of energy conservation

On the 600-V electrified commercial service line of Sapporo Municipal Transport, the “Hi-tram” vehicle was in operation since November 2007 to March 2008.

Paying attention to multi-source regenerative circuit topology and to measure power flow at the input terminals of equipment, the energy consumed amounts were calculated.

Compared result of consumed energy with the new

TABLE II. ENERGY OBTAINED BY QUICK CHARGING.

Battery charging current and duration	Charged energy at a battery terminals	Running distance after a one short time of quick charging (without air conditioning)	Running distance after a one short time of quick charging (at the maximum air conditioning load)
1000A × 61sec.	35.6MJ (13.7% of the capacity)	Equivalent to 7.9km	4.0 km or over
500A × 3min and 16sec	56.9MJ (21.9% of the capacity)	Equivalent to 12.7 km	6.4 km or over

developed contact-wire/battery hybrid LRV and an existed inverter-fed regenerative tramcar is shown in Fig.8. The powering energy is nearly the same value, and the difference is found especially in regenerated energy. This is caused by prevention of regeneration cancellation with the mounted energy storage devices. The former LRV utilizes the regenerated energy to the maximum extent and achieved the performance of 40.0 % of regenerative effective ratio to the powering energy at the inverter input terminals, while the latter tramcar showed 3.0 %. Over 30 % of energy saving was attained.

C. Running with batteries after a spell of charging

On a street tram line in Sapporo, the vehicle ran 25.8 km on an actual operation diagram while heating the passenger room without power from external sources, and recorded a regeneration ratio of 41% (the volume of regenerated energy divided by the energy consumed in running) (Fig. 9).

And on a railway main line in Shikoku, “Yosan Line”, the vehicle ran up to 80 km/h in November 2009. The running distance of contact-wire-less operation of stopping every station without external charging was up to 49.1 km, with 60 minutes running time (Fig. 10). The amount of consumed energy was 208 MJ, with the regenerative ratio of 23.9 %.

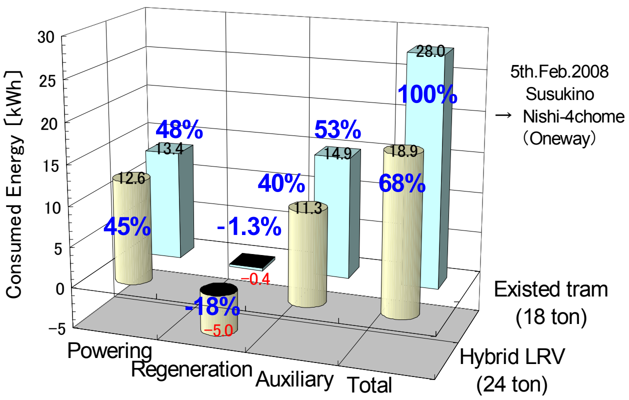


Fig. 8. Comparison of energy consumption with existed tram and contact-wire/battery hybrid LRV.

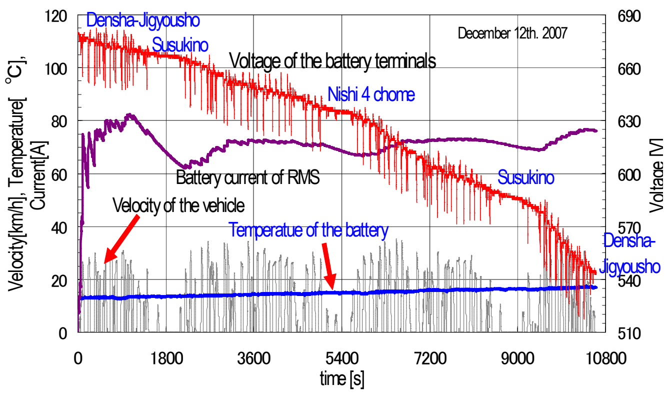
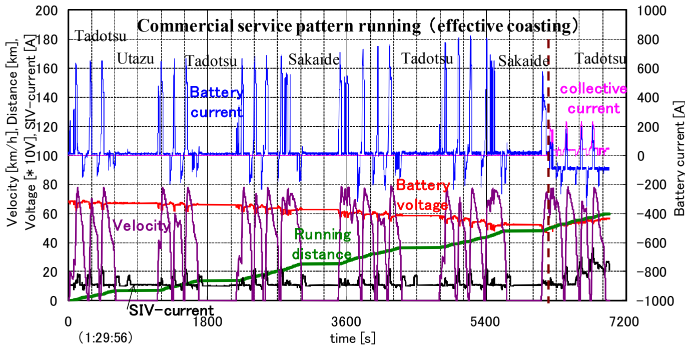


Fig. 9. Running with batteries after a spell of charging. (Battery one time full charge- running distance 25.8 km.)



“Hi-tram” battery running: distance of 49.1 km, time of 1h50min.(running 60min.), battery terminal voltage 683 V to 508 V (SOC 89.5% to 3.6%)

Fig. 10. Running by power of Lithium-ion battery (17th.Nov.2009).

V. CONCLUSION

The conclusion in this paper is as follows;

1) The purpose to mounting energy storage system for electric railway vehicles supplied from contact wire is clarified: i.e. effective utilization of regenerative braking and reuse of absorbed energy, and additionally partial contact-wire-less operation.
2) A traction circuit and control strategy, a contact-wire/battery hybrid LRV ‘Hi-tram’, with two-tons of lithium-ion rechargeable battery system including frames and safety equipment was presented.
3) From the on-commercial-line trial operation, the LRV achieved an energy saving over 30 % compared to an inverter-fed regenerative tram, the distance of contact-wire-less operation of 25.8 km and a maximum speed up to 40 km/h; the quick charge of 60-s duration by a battery charging current of 1000 A ensures over 4 km running with continuous maximum auxiliary power. Running on a main line in JR, the distance of contact-wire-less operation of 49.1 km and up to 80 km/h was also achieved

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