With an aim of reducing energy required to operate rolling stock, JR East has been deploying energy-saving type rolling stock equipped with regenerative brakes, which convert kinetic energy at braking into electric energy.

In order to accurately measure operation energy, we came up with an idea of simultaneously measuring the energy of cars and substations. We thus carried out simultaneous measurement on the Sagami Line with train cars and substations using watt-hour meters that have a GPS-based time correction function. The measurement results allowed analysis and assessment of the flow of operation energy. For example, we found results such as energy loss through overhead contact lines based on the fact that regenerated energy flows beyond a substation and the difference between substation output power and power consumed by the trains.

**Keywords:** Operation energy, Integrating power, Regenerative brake, Regenerative partial-cancellation control, Substation, Synchronization

### 1 Introduction

Aiming at reducing environmental load, the Environmental Engineering Research Laboratory installed watt-meters to the wayside and trains on the Sagami Line as a model line and carried out power measurement in detail. The objective in that was to find out issues in further reduction of operation energy consumption.

This article will cover the visualization of operation energy between the wayside and trains based on measurement data and the analysis results of power consumption and loss.

### 2 Measurement Details

#### 2.1 Overview of the Sagami Line

The Sagami Line is a single track line of a length of 33.3 km between Chigasaki and Hashimoto with 18 stations. The gradient between Ebina and Hashimoto is 12‰ at maximum, while the section between Chigasaki and Ebina is relatively flat.

#### 2.2 Substations and Contact Lines

The electric system of the Sagami line is DC 1,500V feeding. It has three substations: Chigasaki Substation (~2.9 km from Chigasaki Station), Ebina Substation (16.2 km), and Hashimoto Substation (32.6 km). The feeder lines are via a bus line connected to the Tokaido line at Chigasaki Substation and to the Yokohama line at Hashimoto Substation.

The feeder lines are two 325 mm$^2$ hard-drawn copper wires in a bundle between Chigasaki and Samukawa with prevention of salt damage in mind and two 510 mm$^2$ hard-drawn aluminum wires in a bundle between Samukawa and Hashimoto. The overhead contact line system is simple catenary suspension.

#### 2.3 Rolling Stock

All the rolling stock used on the Sagami line is series 205-500 EMUs equipped with electric command brakes combined with regenerative brakes using a field added excitation control system. Trainsets on the line consist of four cars, with a MT ratio of 2M2T. The M’ car is equipped with a 190 kVA motor generator.

#### 2.4 Number of Train Runs

The numbers of trains occupying the section between Chigasaki Substation and Ebina Substation and the section between Ebina Substation and Hashimoto Substation are four or five in peak hours and two or three in daytime hours.

#### 2.5 Operation Energy Measurement Method

For measurement, we installed a watt-meter to transformer Sagami 13H in Chigasaki Substation, transformers 11H and 13H in Ebina Substation and transformer Sagami 11H in Hashimoto Substation to measure the fed energy. At the same time, we replaced the existing disconnecting switch box on the cars with the disconnecting switch box with a watt-meter to measure running energy. For the time synchronization between the wayside and trains, we also installed GPS antennas that could correct time to substations and the end of car bodies.
the power regenerated by trains is not consumed in each substation control section on the line, and that power is often transferred to outside of those sections. We thus quantified the energy transferred to outside of the substation control sections. Fig. 5 to 8 show the average transferred power per substation line and the average transferred energy on a weekday in spring (May) and summer (July).

3. Data of Substations

3.1 Change of Voltage of Substation Bus

Fig. 3 and 4 show the change in average voltage on the busses of Chigasaki, Ebina and Hashimoto Substations on a weekday in spring (May) and summer (July).

3.1.2 Quantification of Energy Transferred to Outside of Substation Control Sections

As the Sagami Line is a single track line with few train services,
The figures indicate that more energy was transferred to outside of the substation control sections in spring than in summer. This is assumed to be because more regenerated power was used in the substation control sections on the Sagami Line in summer due to constant use of train air conditioners. At the same time, more energy was transferred from the section between Ebina and Hashimoto Substations (Ebina 13H and Hashimoto Sagami 11H transformers) than from the section between Chigasaki and Ebina Substations (Chigasaki Sagami 13H and Ebina 11H transformers). This is assumed to be because more power was regenerated at braking in the section between Ebina and Hashimoto Substations due to the larger gradient in that section.

By individual time slot, the power transferred from the Chigasaki Substation Sagami 11H transformer line connected to the Tokaido line and from the Hashimoto Substation Sagami 11H transformer line connected to the Yokohama line decreased in the time from around 17:00 to 19:00, the evening peak hours. This is assumed to be because the load within the Sagami line increased as the number of trains running on the line increased in that peak time.

Meanwhile, both in spring and in summer, much regenerative power was transferred to the Yokohama line via the Hashimoto Substation Sagami 11H transformer line. The reason is assumed to be that the potential difference from the voltage at the pantograph contact of trains at the time of regeneration was large because the voltage on the Hashimoto Substation bus was lower than that of the adjacent Ebina Substation bus, as described in 3.1.1. In this context, it is possible that more power regenerated by trains can be used by reducing the voltage on the substation bus. However, lower substation output voltage inevitably reduces the voltage at the pantograph contact, resulting in a tradeoff with lower running performance and more power loss through overhead contact lines due to current increase.

3.2 Data in Substation and on Train
3.2.1 Quantification of Loss Through Overhead Contact Lines
There is a difference between the energy sent out from the substations and the energy a train consumes alone. That difference is assumed to be power loss by resistance of overhead contact lines and rails. To quantify that loss, we measured the change of substation output power and train power consumption of a train running between Ebina and Hashimoto Substations in the time from 23:00 to 24:59. Fig. 9 shows the results.

The measurement showed the substation output energy was 113.7 kWh and the train energy consumption 110.0 kWh, so the loss was quantified as approx. 3.7 kWh. This is the measurement result with only one train in the substation control section. As the substation output power increases when more trains run, the energy loss through overhead contact lines increases too.

3.2.2 Flow of Regenerated Energy
Fig. 10 shows the quantification data of the regenerated current when braking at notch 6 from running speed 63 km/h from Ebina to Iriya. The data revealed that, of the 300A regenerated current, 20A was used by the auxiliary machines and 40A of the remaining 280A flowed in the direction to Ebina Substation and the remaining 240A flowed in the direction to Hashimoto Substation. We were thus able to confirm that regenerated energy can flow to a load more than 10 km ahead beyond the substation.

3.3 Data on Train
3.3.1 Relation Between Distance from Substation and Trolley Voltage
Fig. 11 shows the change of trolley voltage with only one train running between Ebina and Hashimoto Substations in the time from 23:00 to 24:59. In general, trolley voltage lowers the greater the distance is from a substation. Our onboard measurement data also shows the tendency that trolley voltage (at the pantograph contact) lowered as the train went away from Ebina or Hashimoto Substation to Shimomizo or Harataima Station between the substations. We also found that trolley voltage rose from 1,620V to around 1,700V by braking at each station.
3.3.2 Regenerated Current at Light Load

Regenerative power is consumed by the train on its own or by load such as another train. In some cases, however, such train load does not sufficiently exist. If regenerative power is not consumed, regenerative braking is canceled. Thus, with series 205 cars, energy regeneration is controlled to be partially canceled at trolley voltage of 1,830V. Fig. 12 shows a comparison between a case where a regenerative brake works to its maximum capacity and a case where regenerative partial-cancellation control is conducted, under the same conditions of braking start speed and brake notch (B6). The comparison clarifies that there was a regenerated current difference of 150 to 200A.

3.3.3 Power Consumption and Regenerative Factor for the Sagami Line

Fig. 13 illustrates train energy use and regenerative factor of each gradient section. When comparing data of trains in the commute hours in which relatively less regenerative partial-cancellation is performed, the energy consumption peaked in the section between Ebina and Hashimoto with an uphill gradient of 7‰, and that section's specific running energy consumption* was 1.95 kWh/km/car. On the other hand, the regenerative factor was 15 - 22% with an almost level average gradient of 1‰, reached its peak at approx. 40% with a downhill gradient of 7‰, and bottomed out at approx. 10% with an uphill gradient of 7‰. As specific powered running energy consumption is small and specific regeneration energy consumption is large with downhill gradients of around 7‰, the regenerative factor becomes large. The regenerative factor of the Sagami line as a whole measured in May and June was approx. 20%.

*Specific energy consumption: Energy consumption (kWh) for travel distance divided by the number of cars in the trainset

Fig. 14 shows the breakdown of the power consumption by the auxiliary machines per trainset (four cars). In winter heaters consume 42.5 kW, and in summer coolers consume 54 - 77 kW. Fluorescent lamp lighting consumes 5.5 kW at full lighting, however, that lighting power consumption decreased to 4 kW because the number of fluorescent lamps in cabins was reduced from 92 to 68 starting in spring of 2011 for energy saving.

4 Conclusion

In these measurements, we simultaneously measured total output power of the substations and total power consumption of rolling stock, enabling identification, analysis and assessment of operation energy flow. As the measurement was carried out on the single track line this time, we will conduct measurement on a double track line such as the Yamanote line for fact-finding of operation energy.

Reference: