

urban area. But regenerative braking force does not reach designed values of performance, as regenerative current is squeezed at railway routes where train density is not high. If regenerative substations are set up, regeneration canceled and squeezing regenerative current is expected to be prevented. Then regenerative brakes would show better performance. The advantages are being able to reduce wear of brake shoe and time and money for maintenance.

The authors propose operation method which occurs full regenerative braking force in the range of torque characteristic of electric motor and generator assuming such advanced electrification equipments with regenerative functionality. The authors estimate the effects on run-curve and energy balance.

3. NUMERICAL METHOD AND ASSUMPTION IN CASE STUDIES

3.1 Condition of Case Studies

Condition setting for quantitative validation of using the full regenerative brakes at high speed is shown in Table 1.

Table 1 Conditions of the investigated line

The length of railway route	37.4 km
The number of stations	15
The number of substations	9
Sending voltage in substations	1600 V
Feeding	DC-electrification

In addition, regenerative substations can regenerate energies to commercial power system. Two cases in calculation are examined. One is conventional method which use both regenerative brakes and mechanical brakes to set to values of the force which reaches a constant acceleration. The other is proposal method which use only regenerative brakes as braking force.

Furthermore, the authors examine the case of sending voltage in substations which rises up to 1600V to use pure electric brakes more effectively. When sending voltage rises, characteristics of an electric train driven by induction motor improve in quality. Even if it is pure electric brakes, an electric train is able to get high deceleration at high speed. And it improves energy saving [3].

3.2 Numerical Method for Train Motion

Block diagram of rolling stock system is shown in Figure 2. Input values of this calculation are running speed and notch. Acceleration, speed and running distance as outputs are derived from total weight of a train set, running resistance and so on. Discretization with bilinear

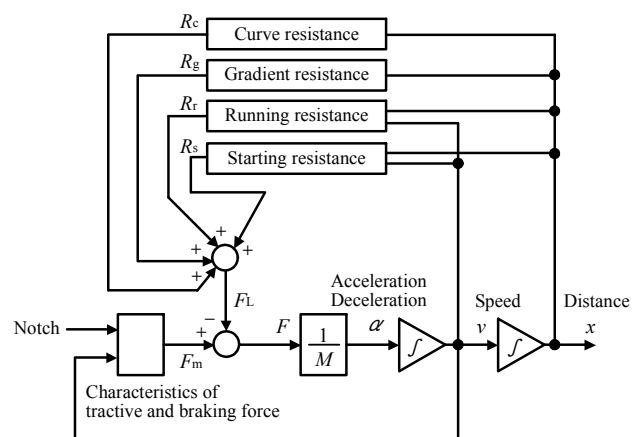


Fig.2 Block diagram of rolling stock system

transform based on linear approximation (Tustin transform) is used for derivation of recurrence equation. The values of resistances including running and gradient resistance are functions of train speed and position.

3.3 Electric Power Interchange between Multiple Train Sets

An electric train use regenerative brakes effectively when there are powering trains as its electric load near the braking one. Regenerated energy is primary used by other powering trains as shown by Figure 3. Then it contributes to energy saving. For validating the effectiveness of regenerative braking quantitatively, consideration of electric power interchange between multiple train sets is needed.

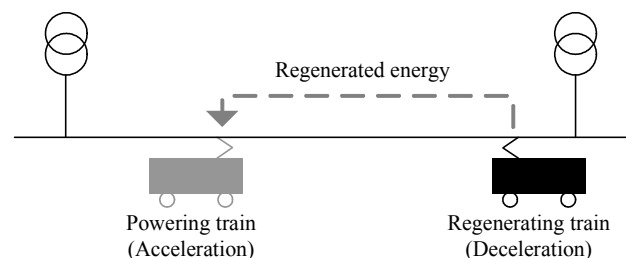


Fig.3 Electric power interchange of regenerated energy

4. EFFECTS OF USING THE FULL REGENERATIVE BRAKES AT HIGH SPEED

4.1 Effects on Change of Run-Curve

Run-curve is changed significantly when mechanical brakes is not used like proposal method. An example of run-curve at a station interval is shown in Figure 4. When conventional method is changed to proposal method, braking force is not enough at high speed range. Accordingly, braking distance increases by 150 m. The maximum increment of braking distance is about 400 m. Proposed method have a characteristic that deceleration decreases at middle and high speed ranges. For this reason, implementation of pure electric brakes is difficult

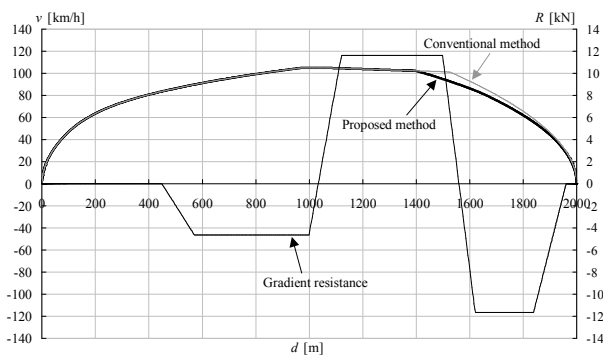


Fig.4 Comparison of run-curve at a station interval

on several counts like in practice, for instance, from the viewpoint of manual operability by manual operation. If a driver is called on to manipulate notch in line with regenerative braking torque, he needs to be given some supporting information to [4]. However, if a train equips Automatic Train Operation (ATO) and Train Automatic Stopping Control (TASC) which are being applied recently, pure electric brakes are realizable.

Change of a run-curve leads to a problem of increasing running time. Total running time is shown in Figure 5. This is the time of a local train from station A to station O. When proposed method is compared to conventional method, total running time increases by 22.0 sec. However the increase from regular running time is mere 0.3 sec. Enhancement of substation-output voltage curbs the increase of running time. Increment of running time is not negligible. But train scheduling has margin time. Therefore, this increment is able to be included in the margin time.

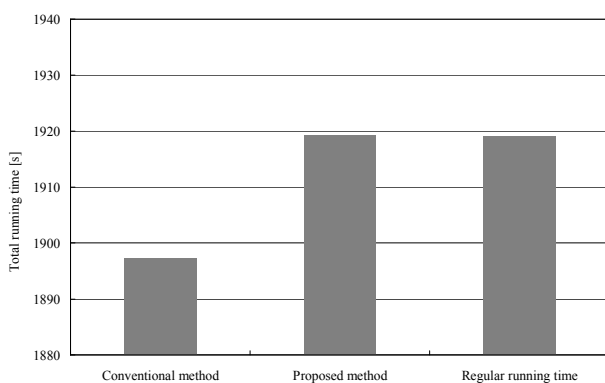


Fig.5 Comparison of total running time

4.2 Effects on Diagram

When a run-curve is changed, it imposes change of diagram. Diagram of conventional method is shown in Figure 6. Diagram of proposed method is shown in Figure 7. Trains for the case studies run in 30 minute periods. There is about a 20 sec disparity between conventional method and proposed method of a local

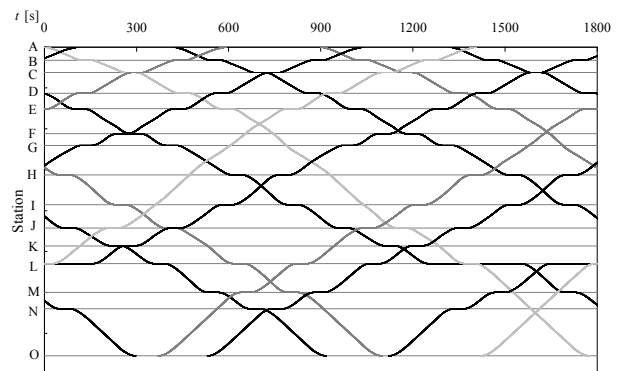


Fig.6 Diagram for the case study of conventional method

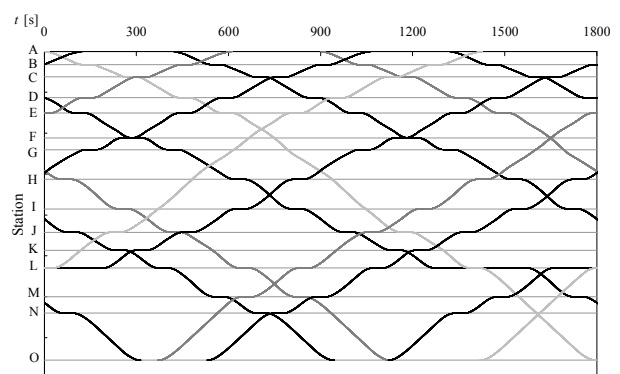


Fig.7 Diagram for the case study of proposed method

train. So it is apparent that diagram is different slightly. But the change is small from a viewpoint of whole diagram. It has a relatively small effect on train operation. Therefore even if braking system of an electric train turns from conventional method to proposed method, railway operators do not need to make a significant change to train schedule.

4.3 Effects on Energy Balance

Total regenerated energy is shown in Figure 8. Loss on feeding resistance is shown in Figure 9. Total consumed energy is shown in Figure 10. When the conventional method is changed to the proposed method, total regenerated energy increases by 627 kWh/h. It is increase of 22 percent by ratio. This is because all energy expended by mechanical brakes is recovered as regenerative energy. When current flowing along feeder increases, loss at feeding resistance also increases. The loss increases by 32 kWh/h. It is increase of 7 percent by ratio. But percentage of consumed energy is low. These difference has a great effect on energy saving.

As seen in Figure 10, proposed method has a profound effect on energy saving. When conventional method is changed to proposed method, total consumed energy decreases by 684 kWh/h. It is decrease of 13 percent by ratio. In particular, it has a higher proportion of loss of

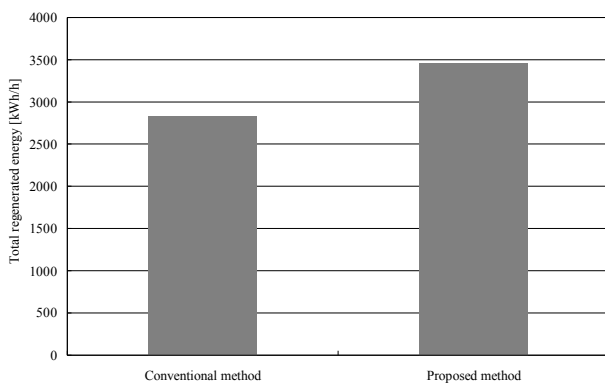


Fig.8 Comparison of total regenerated energy

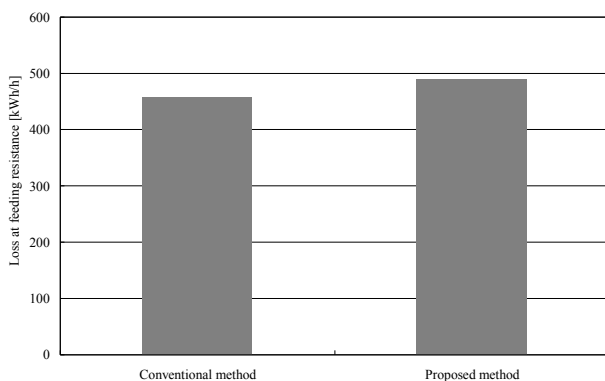


Fig.9 Comparison of loss at feeding resistance

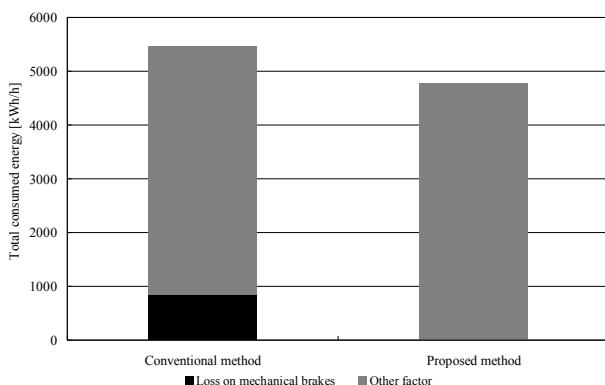


Fig.10 Comparison of total consumed energy

mechanical brakes in decreased consumption energy. Loss of mechanical brakes vanishes in proposed method. It is found that regenerative brake is used more effectively. Proposed method has a good performance of energy conservation.

4.4 Economic Effects

Total purchased energy from electric power company is shown in Figure 11. Decrease of purchased energy seems not much. It is decrease of mere 1 percent. This amount is dependent on running timing of trains. However, in any way, change to the proposed method contributes to energy saving. Electric power rate that electric power

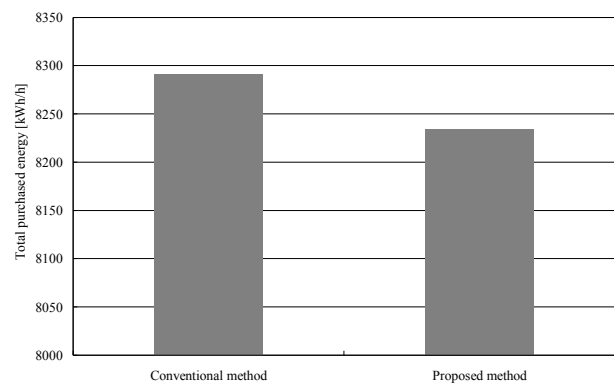


Fig.11 Comparison of total purchased energy

company pay is billions of yen. Therefore, 1 percent energy saving has a great effect.

In addition, train operators can use surplus regenerated energy not to use by powering trains. Ancillary facilities as Stations and substations always need power. If the energy is used at ancillary facilities, it can improve energy saving.

5. CONCLUSION

This paper describes an idea of pure electric brakes for an electric train at high speed and design of a run-curve for energy saving operation in a DC-electrification. As a result, it shows effectiveness of perfect regenerative braking. When proposed method is applied to an electric train, train operators can save 13 percent energy. And they can also reduce purchased energy from electric power company.

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