Development of a Train Operation Power Simulator Using the Interaction between the Power Supply Network, Rolling Stock Characteristics and Driving Patterns, as Conditions

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In order to estimate train operation power consumption more precisely, a train operation power simulator has been developed which executes a coupled-analysis of the power supply network, rolling stock characteristics and driving patterns. First, the outline of the simulator is described. Secondly, the simultaneous measurement of substations and rolling stock within a limited feeder section is explained. Then, the degree of accuracy of this simulator was verified through comparison of calculation results with simultaneously measured results.

Keywords: DC feeding system, energy consumption, simulator, substation equipment, rolling stock characteristics, driving pattern, regenerative break

1. Introduction

In the past, one of the main purposes for estimating railway traction power was to obtain the maximum load power for designing ground equipment or vehicle devices. More recently however, there has been a growing need to reduce energy consumption in the railways, particularly in Japan. The revised Law on Rationalization of Energy Use was brought into force in 2005. After the 2011 Tohoku earthquake there were not only power shortages but also an increase in electric rates. This forced railway companies to introduce energy-saving policies, such as power storage facilities, energy-saving vehicles and energy-saving driving patterns. This situation also gave rise to the need for a method to estimate the energy-saving effect of each policy, accurately. As such, a simulation was developed to estimate the power needed for train operation, centered on interaction between the power supply network, rolling stock characteristics and driving regimes. A number of in-service railway lines and trains were used for the purposes of this study.

This report explains the calculation method used in the simulation and the simultaneous measurement of substations and rolling stock within a limited feeder section [1]. The accuracy of the simulation method was then verified by comparing calculated results with simultaneously measured results.

2. Related studies on train operation power simulation systems

Various train operation power simulation systems have already been put into practical use [2-5]. However, those systems focus only on isolated factors, such as power supply, rolling stock design or train operation. Although the calculation models and conditions for each element were implemented in detail, their treatment of ancillary factors was sometimes inadequate. As a result, calculated results often differed from measured results. Therefore, in order to obtain more accurate estimations of energy used during train operation, it was necessary to include other factors in the simulation, such as calculating the current and voltage of a number of trains, calculating the speed profiles of the trains reflecting their voltage, and reproducing different driving patterns. Furthermore, these functions needed to be included in the form of a coupled-analysis following a suitable procedure.

The effect of energy-saving policies is measured in percent of reduced energy use. Therefore, when estimating the energy-saving effect through simulation, the accuracy of calculated results for energy used during train operation needs to remain within a margin of error of ±10%. In order to verify the accuracy of the simulation, it is very important to compare calculated results with the simultaneously measured results from substations and rolling stock. Precise verification requires simultaneously measured experiment results from all substations and trains, provided that only the trains within the feeding section are measured. Synchronized data from substations and trains also need to be compared with the simulated results.

3. Calculation method of the train operation power simulator

In order to accurately estimate the amount of energy...
consumed by a train during operation a simulation system was developed which integrates the methods for calculating energy consumed by rolling stock, depending on driving patterns, train control and power supply. These methods were drawn from other studies conducted using expertise from other relevant sections within RTRI. The rolling stock component and the speed profile component are based on the calculation logic “Hybrid-Speedy” [4] which calculates speed profiles and rolling stock energy consumption. The feeding circuit component for the simulation method was devised by using and improving excerpts from the sub-module calculation of a DC feeding circuit voltage depression from a “power diagram,” [5] which is one of the conventional simulation methods for finding energy use during train operation. The train operation component controls the trains and manages the simulation time, was based on a “train operation and passenger flow simulator”.

3.1 Calculation components of the train operating power simulator

Figure 1 shows the input and output data, the functions and the components of the train operating power simulator. Figure 2 shows the display image of calculation results. The main functions of each component are as indicated below.

Train operation control component:
- Controls simulation time.
- Generates trains according to the train schedule and the vehicle schedule.
- Assigns a type of rolling stock to the generated train.
- Controls railway tracks and calculates the position of each train.
- Sets the data for train position, current, voltage and speed to the feeding circuit calculation component and the rolling stock calculation component and conducts a convergence calculation to solve circuit equations iteratively.
- Calls the speed profile calculation component according to the train schedule order and runs each train between stations.

Feeding circuit calculation component
- It is assumed that the current and voltage of each train are constant during each time unit $\Delta t$ [s].
- To calculate the voltage and current values of all trains until the relationships between them become appropriate at each $\Delta t$.
- Conducts a convergence calculation which requires solving circuit equations iteratively.

Rolling stock calculation component
- Simulates rolling stock characteristics in detail and calculates the current needed for the feeding circuit calculation.
- Calculates the tractive force needed for the speed profile calculation using the voltage of each train.

Speed profile calculation component
- Takes each predefined change point such as point where notch, gradient and curve are changed, as a cal-

![Diagram of train operation power simulator](image)

**Fig. 1** Input and output data, functions, components of the train operation power simulator
calculation point. Also adds a calculation point per maximum calculation unit distance $\Delta s$ [m].

- Calculates the speed profile of a specific section in accordance with speed limits, line conditions, rolling stock characteristics, driving regime specifications and tractive force, obtained from calculated results from the rolling stock calculation component.
- Produces the fastest speed profile unless driving regime specifications prescribe otherwise.

3.2 Method for coupling the components

Out of a need for discrete calculation, although train operation power is changing continuously, calculations are conducted per time unit $\Delta t$ [s] in the feeding circuit calculation component, while in the speed profile calculation component, calculations are conducted at calculation point intervals of distances less than the unit $\Delta s$ [m]. This asynchronous alternately coupled algorithm has an affinity with the speed profile calculation component because $\Delta t$ and $\Delta s$ can be selected independently. The calculation models of the speed profile, the rolling stock and the feeding circuit calculation components can be constructed independently, especially in the case of this algorithm. The images of current, voltage and the speed profile of calculation units are shown in Fig. 3. The actual method for coupling the components is indicated below.

(1) Using the simulation system, current and voltage for each train are calculated for the time period $t_i$ to $t_{i+1}$ (the feeding circuit calculation component and the rolling stock calculation component).

(2) Using the simulation system, speed profiles per $\Delta s$ [m] are calculated for the time period $t_i$ to $t_{i+1}$ based on the results of (1) (the speed profile calculation component).

(3) The simulation system put forward the time unit $\Delta t$ (the train operation control component).

4. Verification of the accuracy of the train operation power simulator

In order to establish whether estimations of energy used by trains during operation are realistic or not, it was necessary to verify if the calculation logic of the train operation power simulator was correct or not. Measured results from a real line were therefore compared with results obtained from a simulation conducted under the same conditions as those applied during measurement. It was difficult to correlate the measured results from substations with those of the target trains in operation because feeding sections are not divided.
per substation. In addition, it was also difficult to obtain the train operation data for all target trains. Initially therefore, night-time test runs were used to measure the current and voltage of all substations and the notch, speed, current and voltage of all target trains, provided that no other trains than the target trains were present in the feeding section in question. Next, we set the data of the target trains and substations as possible as correctly described below in section 4.3. Then, the train operation power simulator was then applied, and accuracy was validated by comparing measured results to the calculation results in order to confirm the calculation logic of the train operation power simulator.

Firstly, nocturnal test runs were held in an underground section of the JR-Tozai Line using one or two train sets in November of 2013 [1]. Measured results were compared with simulated results obtained under the same conditions, which confirmed that there was a large difference in regenerative power between the two cases. This is because in the simulation, the speed profile is calculated on the assumption that the brake notch, remains the same during braking, while in the test runs, drivers finely tuned the brake notch, which generated differences in current and voltage.

Therefore, the next test runs were held in an underground section of the JR-Tozai Line and an open section of the Osaka-higashi Line using one train set in November of 2014 with the condition that drivers used the same brake notch. Measured results and simulation results were then compared to verify the accuracy of the simulator.

The section below explains: the outline of the simultaneous measurement tests (4.1), efforts to indicate the most suitable driving pattern (4.2), entering input data into the simulator (4.3), calculation results from the simulator (4.4) and verification of accuracy based on comparisons with measured results obtained from the tests (4.5).

4.1 Outline of the simultaneous measurement tests

Two sections were selected for tests: one underground on the JR-Tozai Line from Kyobashi Station to Amagasaki Station, which had an inverter for regenerative electric power; and one above ground on the Osaka-higashi Line, from Hanaten Station to Kyuhoji Station.

The rolling stock was equipped with digital transmission equipment to collect information at ten to several hundred meter intervals, to calculate power consumption. The test train timetable was composed of three round trips per day for one train set and two train sets making a journey from one end to the other of both test sections. The train diagram for the two train sets is shown in Fig. 4. Water tanks were placed on the first train set in order to reproduce an occupancy rate of about 50% while the second train ran empty.

In the substations, measurements were made of voltage and current in each feeder circuit DC bus line and in the inverter for regenerative electric power. Off-the-shelf GPS module signals were used as recorder sampling clocks in order to synchronize time between the two subsections [8]. Figure 5 gives the example of measurements taken on the JR-Tozai Line subsection. The Kyobashi and Amagasaki substation DC circuit-breakers located at the edge of the test section were opened, to ensure that only power from the Shin-fukushima and Mitejima substations was supplied, and in order to cut off power interchanges between the target section and the other sections. Similarly, for the Osaka-higashi Line test section, electric power was supplied only from the Hanaten and Kami substations.

4.2 Efforts made to indicate the most suitable driving pattern

In order to reproduce simulation conditions as closely
as possible, the same brake notch was used during the test runs in November 2014. First, the running time between stations was set using historical running time data obtained from train data collection devices [9]. Next, speed profiles were calculated using these running times and applying the function for producing speed profiles used for estimating energy consumption [10], “Hybrid-Speedy”. Then, the speed profile data was then used to indicate a driving pattern, while taking into practical application of such driving patterns into account. This process was applied, while attempting to stop the test train as near the stop line as possible, using same brake notch, and with a running time which was as close as possible to the actual running time.

4.3 Entering of rolling stock data into the train operation power simulator

It is important to set input data correctly in order to obtain accurate calculations. As such the common running resistance equation was replaced with a method for estimating running resistance characteristics using train data collection devices [11]. The values of running resistance which were used in the calculation are shown in Fig. 6. As a result, this made it possible, using the simulator, to accurately calculate speed during coasting in high-speed areas.

The power characteristics and the auxiliary power of the rolling stock, etc., were modeled using design values and revised in the light of measured results from substations. The characteristics of the rectifier and inverter for regenerative electric power were set on the basis of static characteristics reflecting actual conditions.

![Fig. 6 Running resistance used in the calculation](image)

4.4 Calculation results

The simulation was conducted using the test run train schedule. Using the simulator function for specifying the driving pattern, the kilometer distance between periods when the train was coasting or powering after coasting, and the notch to be selected based on the test run to reproduce actual train operating conditions, were selected.

The measured results for the two train sets on the JR-Tozai Line in November 2013, the train set on the JR-Tozai Line in November 2014 and the train set on the Osaka-higashi Line in November 2014; and the calculated results obtained with the train operation power simulator, are shown in Figs. 7 to 9 respectively. The power of the rolling stock indicates traction circuit power without auxiliary machine power. “SS” is the abbreviation for a substation. Solid lines represent measured results, while the dashed lines represent the calculated results. The speed curve colors indicate the driving patterns and notch; blue dose powering, green dose coasting and red dose braking.

The speeds calculated were well accorded with the ones measured, confirming reproducibility of actual train operation by reproducing actual train operating patterns.

4.5 Verification of accuracy

This section verifies the accuracy of the train operation power simulator by comparing electrical energy use and regeneration. Concretely, energy supply and regenerative energy were calculated by dividing electric power into positive and negative groups and integrating them. The energy consumed is the energy supplied minus regenerative energy.

Given that in the November 2013 running tests, where trains were brought to a halt before the specified stopping line through drivers carefully adjusting the brake notches during braking, differed from the simulation where single-notch braking is applied for reproducibility, accuracy was verified using the November 2014 running tests. In the November 2014 running tests single-notch braking was applied, causing trains to overshoot the designated stopping point. In these cases, energy values were calculated without the small amount of traction energy required to bring the train back to the designated position in the station. On the JR-Tozai Line section, the regenerated energy from one train set was absorbed by the inverter at the Shin-fukushima SS and used for the other test-run train set. On the Osaka-higashi Line however, the test run was conducted using only one train set, which means that regenerative energy could not be reused except for the auxiliary equipment energy bringing final regenerative energy close to 0. Therefore, in order to verify accuracy of the method, in the case of the JR-Tozai Line consumed, supplied and regenerated energy were taken into account, whereas on the Osaka-higashi Line only consumed energy was counted.

Substation measurements were corrected offset values, and offered higher levels of resolution rolling stock measurements [12]. This suggested that the estimation accuracy using substation results was higher than when using rolling stock measurements, therefore, accuracy was verified using energy measurements from substations.

A comparison between obtained energy values is given in Figs. 10 and 11. The error between measured and calculated results was 3.6% on the JR-Tozai Line and 1.5% on the Osaka-higashi Line for the November 2014 test runs. The error in measurements for a single SS exceeded the error found after the summation of measurements from two SS. This showed that while there was high accuracy in total energy value calculations there was still a problem in calculating the load distribution between SS. The main reason for this was that the simulation had not taken into account occasional variations in voltage during the ten-minute test period, due to demand from external users and the electricity company as a result of normal grid operation.

This confirmed that if measurement data and all input data relating to rolling stock, electrical energy, driving patterns, etc, were provided in accordance with the specified
test conditions, then accuracy of the simulation would be high enough to achieve good agreement between measured and calculated results.

Fig. 7 Comparison between measured and calculated results (2013, JR-Tozai Line, test run with 2 train sets)

Fig. 8 Comparison between measured and calculated results (2014, JR-Tozai Line, test run with one train set)

Fig. 9 Comparison between measured and calculated results (2014, Osaka-higashi Line)

Fig. 10 Comparison between consumed, supplied and regenerated energy (2014, JR-Tozai Line, test run with one train set)

Fig. 11 Comparison between consumed, supplied and regenerated energy (2014, Osaka-higashi Line)

5. Conclusion

This report describes the calculation method used for a train operation power simulator which can be used when ground facilities, rolling stock and driver pattern are specified, and relates how the calculation was verified. This effort was aimed at improving a simulation system to repro-
duce real train operations more realistically. This included speed profile generation to estimate energy applied to calculate speed profiles with a specified running time [10] which was incorporated into the simulator. Other improvements were made to the simulator to be able to make calculations using commercial train timetables on a wide range of lines. In addition, a method was examined to input required data using train data collection devices [9][11][13]. There is also a need to be able to simulate brake notch operation more realistically. These paths for research will continue to be investigated in order to estimate the effects of energy-saving policies.

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References

[1] Minobe, S., Imamura, Y. et al., "The examination which measures power consumption simultaneously in the train and substation of a railway in a direct-current electrified section (Environment and Energy)," Proceedings of International Symposium on Seed-up and Service Technology for Railway and Maglev Systems: STECH 2015, 1E14, Chiba, Japan, November 10-12, 2015.

[2] Takagi, R. and Sone, S., "Precisely Fixed Start-to-Stop Time Simulation of DC Railway Power Feeding Systems," IEEJ Transactions on Electronics, Information and Systems, I.E.E. Japan, Vol. 115, No. 8, 1995 (in Japanese).

[3] Takeuchi, Y., Sakaguchi, T. et al., "A Train Operation Simulation System Based on a Detailed Model of Train Running," RTRI Report, Vol. 28, No. 4, pp. 41-46, 2014 (in Japanese).

[4] Ogawa, T., Kondo, M. et al., "Development of a Multi-purpose Energy Simulator for a Running Train," Joint Technical Meeting on “Linear Drives” and "Transportation and Electric Railway", I.E.E. Japan, LD-14-067/TER-14-030, 2014 (in Japanese).

[5] Hase, S. and Ito, T., "Power Simulation by Inputting Train Diagram for DC Feeding Circuit," J-RAIL2001, pp. 733-734, 2015 (in Japanese).

[6] 武内陽子, 小川知行, 森本大観: 複数分野の協調による列車運行電力シミュレータの開発, 運転協会誌, 2016年1月号, 2016 (in Japanese).

[7] Takeuchi, Y., Ogawa, T. et al., "Basic Development of Coupled-Analysis Traction Power Simulation System and Verification by Energy Consumption Measurement Examination, Technical Meeting on "Transportation and Electric Railway", I.E.E. Japan, TER-14-049, 2014 (in Japanese).

[8] Imamura, H. and Morimoto, H., "The time synchronization measurement technique between the substation by the general-purpose GPS receiver module, 2015 Annual Meeting Record I.E.E. Japan, I.E.E. Japan, 5-144, 2015 (in Japanese).

[9] Ogawa, T., Takeuchi, Y. et al., "Development of an Analysis System for Large-scale Data by a Train Data Collection Device," J-RAIL2015, SS3-1, 1705, 2015 (in Japanese).

[10] Ogawa, T., Sato, K. et al., "Speed Profile Generator for Energy Estimation of a Train Running Simulator," IEEJ Transactions on Industry Applications, I.E.E. Japan, Vol. 135, No. 5, 2015 (in Japanese).

[11] Ogawa, T., Manabe, S. et al., "Method of Calculating Running Resistance by the Use of the Train Data Collection Device," Quarterly Report of RTRI, Vol.58, No.1, 2017.

[12] Takeuchi, Y., Ogawa, T. et al., "Additional Verification for Coupled-Analysis Traction Power Simulation System by Energy Consumption Measurement Examination, Technical Meeting on "Transportation and Electric Railway" and "Linear Drives", I.E.E. Japan, TER-15-028/LD-15-019, 2015 (in Japanese).

[13] Kanno, H., Ogawa, T. et al., "Effect of seasonal factor and train congestion on the auxiliary power," J-RAIL2014, SS3-3-3, 2014 (in Japanese).

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