Trends in Recent Research on Main Circuits and Traction Systems for Railway Vehicles

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Progress in electrical railway vehicles traction systems has mainly been made in the field of main electric circuits, the system has been developed to AVAF (Adjustable Voltage Adjustable Frequency) inverter method from the resistor control method via the field added excitation control method. On the other hand, in the 2000s, the study of battery technology applied to railway vehicles as the energy saving technology has started. This report introduces examples of research and development relating to these fields and trends in main circuit and traction system development for railway vehicles.

Keywords: inverter, traction motor, inductive obstruction mitigation method, gear unit noise reduction, battery capacity deterioration estimation method

1. Introduction

Electric powercar traction systems have progressed mainly in the field of main circuits, evolving from rheostatic control, to chopper control, then to field added excitation control and combinations AVAF inverters and induction motors. Electrical semiconductor devices used in AVAF inverters have also been changing, from thyristors to GTO, to GTR, to IGBT, and more recently to SiC. As switching frequency increases, so have controllability and efficiency.

Then, in around the year 2000, more and more attention was attached to energy saving technologies. Studies into regenerative electric power gained momentum and as part of that, research on the application of battery technology started.

At the same time, traction motors went from being DC to AC, which then moved onto brushless squirrel-cage induction motor designs before evolving into the permanent magnet synchronous motors of today, which are highly efficient and do not require excitation currents. This paper describes some research and development activities that have been conducted in this field at RTRI over the past few years, and introduces a number of topics from other recent programs.

2. Past studies at RTRI on railway vehicle traction systems

Table 1 shows some of RTRI’s past studies on railway vehicle traction systems, listing the study subjects and their themes. The study subjects in the list consist of in-
2.1 Studies on inverters

Railway vehicles have low running resistance due to hard wheels running on hard rails, which helps save energy. Low frictional forces between the rails and wheels however, making it easy for wheels to slip during acceleration. Wheel slipping has been studied ever since the days of rheostatic control and DC motor driving systems. The more recent combination of AVAF inverters and induction motors offers finer control and therefore improved controllability. Details on this topic are presented in the paper entitled “Slip Suppressing Control Method Using Information from Traction Motor Current on EMUs Driven by Multiple Traction Motors Without Speed Sensors” in the Vol. 31, No. 6, June 2017 issue of ‘RTRI REPORT’.

Advances in inverter electrical semiconductor device technology has led to higher switching frequency and improved controllability. At the same time this has caused electromagnetic interference on signaling systems. Efforts to resolve the issue will be outlined in Capture 3.1.

In the days of rheostatic control, unit switches and cam shaft control mechanisms required regular maintenance. With the relatively recent introduction of maintenance-free chopper and inverter control systems, there has been a growing number of sudden system breakdowns, without any prior warning. Power semiconductor modules used in inverters are difficult to monitor for damage or wear even when using electrical parameters which can be used relatively easily to measure soundness. To overcome this obstacle, a deterioration monitoring method was developed and is presented in the paper "Deterioration of High-Voltage / High-Current Power Semiconductor Modules for Trains [1].”

2.2 Studies on traction motors

The 1980s saw the gradual introduction of AVAF inverters combined with induction motors. At around that time, only small-sized permanent magnet synchronous motors were being brought into service. In order to be used on railway vehicles, permanent magnet synchronous motors needed to be capable of withstanding high temperatures for many hours and have high magnetic flux density. Then in 1982, the invention of Nd-Fe-B (neodymium - iron - boron) magnets provided the impetus for mainstreaming synchronous motors, helping them achieve higher capacity. In 1991, RTRI started a study on running high-speed electric railcars at 250 km/h on narrow-gauge conventional lines and as part of the program, proposed using permanent magnet synchronous motors for a system in which independent wheels were mounted with direct drive traction motors. The compact, high efficiency concept can also be applied to the conventional gear driven system. Taking advantage of its low heat generation and reduced cooling requirement, a totally enclosed, low noise motor with no need for internal cleaning was developed [2]. Thanks to this step forward, permanent magnet synchronous motors were adopted for use on some new commuter electric railcars models. However, many railway operators still chose to have induction motors on their new vehicles, one reason being that every AVAF inverter requires a dedicated permanent magnet synchronous motor which bloats costs and secondly because powerful magnets require very careful maintenance. On induction motors, a “high efficiency induction motor [3]” featuring low-loss material, an optimum number of stator winding turns, a redesigned rotor, etc. was developed. Low-loss design should enable totally enclosed motors to be adopted in the future.

2.3 Studies on hybrid vehicles

There are several types of hybrid vehicles, including diesel hybrid vehicles, overhead contact line - battery hybrid vehicles, and fuel cell hybrid vehicles, that have been either placed into service on revenue lines or being investigated. All of these versions carry on-board energy storage devices. Secondary lithium-ion batteries are widely used for this purpose. More recently, secondary lithium-ion batteries are being made smaller, lighter in weight, lower in price and with longer life spans; they are therefore gradually being introduced onto railway vehicles. However, secondary lithium-ion batteries are known to be vulnerable to deterioration with use. Therefore, serviceable lifespan is critical in battery design. In the meantime, methods for predicting battery life are being developed, and appear to be one of the key factors behind the increased adoption of these batteries. As secondary lithium-ion batteries become more widely used, more accurate prediction methods for their deterioration are expected to become available. Related activities are presented in Section 3.2.

Research activities are also underway for the development of fuel cell railway vehicles using hydrogen energy with a view to building a sustainable energy society. To this end, RTRI has been conducting running tests for about ten years on an R291 electric test railcar mounted with hybrid 100 kW-class fuel cells and secondary lithium-ion batteries. A development program is also under way for a hybrid vehicle running simulator which to verify the energy-saving performance of hybrid vehicles. Further details about the development of hybrid vehicles can be found in the article entitled, “Trends and Recent Studies on Hybrid Railway Vehicles [4]” in the February 2017 issue of RTRI’s Quarterly Report.

2.4 Studies on other subjects

With the aim of developing a smaller, lighter and higher efficiency transformer for AC electric railcars, a superconducting main transformer (25 kV, 4 MVA) was developed for vehicles to adapt maglev-train superconducting technology to conventional railways. Minimization of AC loss is one of the challenges that have to be overcome to adapt this type of transformer for practical use. Once this goal achieved, new technologies are expected to be developed including the use of yttrium (Y) based superconducting wire materials instead of conventional bismuth based superconducting tape.

Reactors are now not only used in inverter-based main circuits, but increasingly applied to hybrid vehicles as they adopt DC-DC converters. For this purpose, reactors need to be smaller and lighter in weight and generate smaller...
losses. Work is therefore being carried out on reactors to clarify the mechanisms underlying losses and to reduce these losses by increasing the degree of inductive coupling [5].

As vehicle design improves to reduce the amount of noise they emit through total enclosure of traction motors and other means, gear box noise from under the floor is becoming more pronounced. To make gear boxes quieter, less costly and lighter in weight, studies are underway to clarify the sources of noise. This subject is covered in Section 3.3.

Regulatory developments aimed at reducing diesel engine emissions are also being watched carefully, and proposals are being made for running patterns that will allow evaluation of exhaust emissions. In addition, research is underway to develop a method for monitoring and detecting anomalies based on analyses of vibration octave bands [6].

3. Recent topics on railway vehicle traction systems

3.1 Electromagnetic interference

The impact of electrical noise emitted by railway vehicles on ground-based communication and signaling systems is called electromagnetic interference. The latest communication systems experience very little electromagnetic interference as they use optical fiber and other preventive means. As a result, discussions on electromagnetic interference today center mainly on the issues it raises for signaling systems.

As there are many types of railway vehicles and ground facilities, it is difficult to test them in all possible combinations. Adding to this complexity is the increasing number in recent years of through operations. Against this background, in 2008, seven JR companies (passenger and freight) and RTRI launched a joint meeting for their signaling and vehicle representatives to exchange information on electromagnetic interference. The joint meeting produced guidelines for signaling system development and procedures for electromagnetic interference testing (Fig. 1). Recent joint sessions discussed simplification of testing in general, and covered subjects such as ‘one-time measurement of direct noise from electronic train detectors’ and ‘reduction in maximum speeds in return current testing’ [7].

3.2 Estimation of long-term capacity deterioration rate for secondary lithium-ion batteries

Unlike other electric components, secondary lithium-ion batteries deteriorate with long-term use. This makes replacement frequency and lifespan important factors when considering whether or not to use this kind of battery, and to calculate these factors it is necessary to have a method capable of accurately estimating the rate of battery capacity deterioration. As such, RTRI conducted trials where secondary lithium-ion batteries were stored for over four years while varying the storage temperature, and estimated the batteries’ deterioration which was then compared with actual deterioration of the batteries.

The resulting estimation method is shown below. The aging deterioration factor $K_i$ is assumed to be an approximate straight line using Arrhenius plots, (1), and parameters $a$ and $b$ are identified from the results of experiment running over a period of about 11 months. In the comparison mentioned above, $K_f$ was used in (2) to estimate capacity deterioration rate $L_f$.

$$K_f = \exp\left(\frac{a - b}{273.15 + T_b}\right) \tag{1}$$

$$L_f = \sqrt{\int K_f^2 dt} \tag{2}$$

where $t$ is number of days in storage from the factory floor (i.e. from new) and $T_b$ = battery temperature [°C].

Figure 2 shows actual capacity deterioration over four years and three months and the corresponding estimation.

![Fig. 1 Return current test procedures (Contents)](QR of RTRI, Vol. 59, No. 1, Feb. 2018)
based on (2). The actual capacity deterioration rate from the testing was around 20% and the estimation was 1.3% off that rate. The primary cause for this error appears to have been the high storage temperatures above 50°C. The estimation method is considered to be valid for estimating the capacity deterioration rate over a long period of more than four years even with storage temperature fluctuation [8].

3.3 Clarification of gear box noise phenomena

As Shinkansen running speeds increase, vibration and noise from the traction systems tends to increase, and there has been a growing need to abate this noise. Vibration and noise experiments were conducted on Shinkansen gear boxes under various running conditions. The results showed a high correlation between gear meshing vibration and nearby noise in the high speed range (above 300 km/h). More specifically, the noise (O.A) level increased as Shinkansen speed rose and the first order gear meshing vibration peaked at around 240 km/h. However, measurement of real Shinkansen vehicles found that a number of vibration and noise sources existed around the bogies and that the frequency range of around 1 kHz, which is close to the primary vibration mode of gear housings, was located near the frequency range that may easily cause rolling noise. All this suggests that it is difficult to measure accurately the noise produced by gear boxes alone. Given the above, stationary rotation tests were conducted on Shinkansen gear boxes. Using beamforming techniques, attempts were made to clarify the characteristics of vibration and noise from real gear boxes [9]. Beamforming techniques use an array of microphones (four used in the rotation test) to search for sound sources in specific directions based on arrival time intervals (phase differences) between incident waves. In the rotation tests, various subjects were evaluated including the vibration propagation characteristics of gears and gear housings. The correlation between gear meshing vibration and nearby noise and search for noise sources is outlined below.

Figure 3 shows the correlation (average of all points) between gear meshing vibration and nearby noise at a constant speed in a high speed (315 km/h) range. At a primary gear meshing frequency (•) near 2800 Hz, coherence is greater than 0.9, which is high. At a secondary gear meshing frequency (♦) near 5600 Hz, coherence is around 0.8, which is still high.

![Figure 3](image)

**Fig. 3** Correlation between gear meshing vibration and nearby noise (315 km/h)

The center of the sound source computed by beamforming techniques is shown in Fig. 4. It shows that, when powering the center of the sound source from the first order gear meshing vibration is near the gear bearings and that when coasting the center of the sound source spreads across a wider area including the gear housing near the pinion, and the sound level increases.

4. Conclusion

The promotion of energy saving measures in recent years is also aimed at railway vehicles. As a result, efforts are being made to make on-board components more efficient. For many years, non-electrified sections were served with diesel cars and electrified sections by electric motor cars. With the introduction of hybrid vehicles using on-board power storage technology and other means, this division in vehicle type used is beginning to shift. At the same time, technologies are being developed to reduce longitudinal vibration and noise to improve ride comfort. Further contributions will be made to make railway vehicles more environmentally friendly and more comfortable for passengers.

Work will also be carried out to further improve railway vehicle traction systems, which have already progressed greatly over the past few years. By continuing to improve the quality of railway vehicles for passengers, it is hoped that these efforts will contribute to maintaining rail-
way systems as a means of public transport for many years to come.

References

[1] Tenko Fukuda: “Degradation of High-Voltage/High-Current Power Semiconductor Modules for Train,” RTRI Report, Vol.27, No.12, pp.41-46, 2013 (in Japanese).

[2] Minoru Kondou: “Development Progress and Technical Outline of Permanent Magnet Synchronous motor,” Rolling Stock & Technology, No.117, pp.17-23, 2006 (in Japanese).

[3] Minoru Kondou: “Development of a High Efficiency Induction Motor and the Estimation of Energy Conservation Effect,” Quarterly Report of RTRI, Vol.55, No.3, pp.138-143, August 2014.

[4] Takamitsu Yamamoto: “Trends and Recent Studies on Hybrid Railway Vehicles,” Quarterly Report of RTRI, Vol.58, No.1, pp.1-5, February 2017.

[5] Takayuki Nakamura: “Clarification of No-load Loss in DC-DC Converter and Reduction in the Loss with Electromagnetic Coupling,” Paper of IEEJ (D), Vol.135, No.3, PP.258-267, 2015 (in Japanese).

[6] Minoru Kondou: “Traction Diesel Engine Anomaly Detection Using Vibration Analysis in Octave Bands,” Quarterly Report of RTRI, Vol.57, No.2, pp.105-111, February 2017.

[7] Satoru Hatsukade: “Activity of a Railway Electromagnetic Compatibility Council in Japan,” J-rail, S7-5-2, 2014 (in Japanese).

[8] Yoshiaki Taguchi: “Long-term Estimation of the Calendar Capacity Loss of the Lithium-ion Battery under the temperature varying circumstance,” The 56th Battery Symposium, 2M03 (p.28), 2015 (in Japanese).

[9] Minoru Sasakura: “Experimental Study on Vibration and Noise of the Railroad Gear Unit using ODS and Beamforming Method,” Dynamics and Design Conference 2016, OS3-2-5 (p.334), 2016 (in Japanese).

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