Measurement and Prediction Method for Low-frequency Magnetic Fields on Railway Vehicles

Yoshihito KATO
Electromagnetic Systems Laboratory,
Maglev Systems Technology Division

Hitoshi HASEGAWA
Cryogenic Systems Laboratory,
Maglev Systems Technology Division

In Japan, regulations on low-frequency magnetic fields came into force. Initial regulations in 2011 applied to power equipment in general, but the scope of regulatory control was expanded in 2012 to cover track-side railway power equipment. Although railway vehicles are not included in the scope of the regulation at the moment, it is thought that it is necessary to assess magnetic fields in railway vehicles. As such, a series of studies have been launched to develop a method to measure and predict low-frequency magnetic fields in railway vehicles.

**Keywords:** low-frequency magnetic fields, electromagnetic field analysis, magnetic shield, international standard

1. Introduction

In recent years, the movement toward the regulation and the standardization of low-frequency magnetic fields has accelerated. Initial regulations in 2011 applied to power equipment in general, but the scope of regulatory control was expanded in 2012 to cover track-side railway power equipment [1, 2]. Concurrently, methods are being developed both in Japan and other countries to measure low-frequency magnetic fields on railway vehicles.

In light of these international trends, this report describes a method of measuring low-frequency magnetic fields in accordance with standards, a magnetic field visualization device that was developed, and railway vehicle magnetic field analysis models that take into consideration factors such as the magnetic shields and vehicle structure.

2. Trends in low-frequency magnetic field standards

“Low-frequency magnetic fields” does not have a clearly defined range of frequencies. However, standards for measurement procedures of magnetic field levels in the railway environment, which will be described later, mention "DC ~ 20 kHz," this was taken as a guideline (Fig. 1).

In broad terms, the influence of a low frequency magnetic field exists in two forms: influence on an electrical appliance and influence on a living body. The standards described below relate primarily to magnetic fields which have an influence on the living body.

2.1 International guidelines

Currently, the ICNIRP (International Commission on Non-Ionizing Radiation Protection) guidelines [3] are deemed to be the international standard governing the in-

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**Fig. 1** Frequency image of the electromagnetic field

**Fig. 2** Conformity judgment relating to ICNIRP guidance for the protection of living bodies
fluence of electromagnetic fields on the living body. Biological protection guidelines stipulated by the ICNIRP focus on the short-term effects of electromagnetic fields which are scientifically supported. This protective guidance, involving magnetic fields below 100 kHz, is divided into "basic restrictions" expressed as electric field strength induced in the living body, and "reference levels" (expressed as values of the magnetic field in a particular place) as a simple method to determine whether a particular location meets basic requirements. In this case, the magnetic fields in a particular location which can be easily measured are gauged to determine whether or not they satisfy reference levels. If basic reference levels are not met, the case must be examined to see whether or not the following basic restrictions are met (Fig. 2).

ICNIRP guidelines were revised in 2010 for the frequency range 1 Hz ~ 100 kHz. Conventionally, basic restrictions should be evaluated on the basis of current density induced in the body, but this was revised to allow evaluation through field strength (Fig. 3).

2.2 Measurement standards on railway vehicles

Currently, there are no regulatory values for low-frequency magnetic fields on railway vehicles in Japan, but measurement method standards have been established or revised both in Japan and elsewhere. The basic standard for measuring low-frequency magnetic fields generated by electrical apparatus in the railway environment is EN 50500 [4, 5] and was formulated in 2008 in Europe. However, this standard did not become an international standard for a variety of reasons. Furthermore IEC/TS 62597 [6] was issued as a reference for technical specifications in 2011.

The IEC/TS 62597 describes the procedure for measuring magnetic fields in railway apparatus based on the EN 50500 and the magnetic field measurement method in Japan. The subject is divided into the ground facilities and vehicles. In the part covering vehicles, both the European standard and validated measurement procedures in Japan are described. Two measurement approaches are described, namely the "Surface method" and the "Volume method." The former method measures a maximum of one point on the floor or on the wall surface closest to the magnetic source. For example, when measuring the magnetic field from the vehicle equipment under the floor, it can be used to take measurements at one point on the floor directly above the vehicle equipment. If necessary, spatial distribution of the magnetic field is measured at heights of 0.5 m, 1 m and 1.5 m from the floor surface. On the other hand, by the latter method the magnetic field is measured at 3 heights of 0.3 m, 0.9 m, 1.5 m from the floor surface and the maximum values is used.

In addition, the Japanese standard JIS E4018 [7] describing the procedure for measuring on-board magnetic field on railway vehicles was revised in November, 2012 (Table 1). JIS E4018 is a standard that was originally formulated in 1995, but this was revised because of the spread of inverter vehicles, the development of measurement instruments and the issuance of IEC / TS 62597 mentioned above.

The JIS E4018 was fully revised and incorporated measurement methods from the IEC/TS 62597. Conventionally, only DC magnetic fields were measured, however, this was extended to DC and frequency bands up to 20 kHz. This upper frequency band limit was determined on the basis of the switching frequency of an inverter. The revised Japanese standard recommends types of the instrument, as in the IEC/TS 62597, and gives the “Surface method” and “Volume method” as the measurement methods to be employed.

3. Measuring equipment for magnetic fields

3.1 Magnetic field probes

The probes for measuring low frequency magnetic fields are various in kind. Measurable frequency bands and strengths differ from probe to probe, and must therefore

| Table 1 Standards for methods of magnetic field measurement on railway vehicles |
|-------------------------------|-----------------|---------------------------------|
| Class                         | Project number  | Issuance | Content                                              |
| European Norm                 | EN 50500        | 2008     | Standard of measurement procedures of magnetic field levels by railway apparatus |
| International Technical Specification | IEC/TS 62597 | 2011     | Technical Specification of measurement procedures of magnetic field levels by railway apparatus |
| Japanese standard            | JIS E4018       | 2012 : revision (1995 : issuance) | Standard of measurement procedures of magnetic field levels by railway vehicles |
Magnetic fields generated by railway vehicles, unlike other magnetic fields generated from general power equipment, are deemed to possess various frequency components. Therefore, it is necessary to measure using the appropriate magnetic field probes. The above-described JIS E4018 includes a new recommendation for the type of measurement probe used, whose features, described in JIS E4018, are listed in Table 2.

Since railway vehicles are generally considered to have a wide magnetic field frequency range, it has traditionally been difficult to cover such a large range with one type of probe alone. For example, the DC magnetic field generated from filter reactors would be measured by a Hall effect sensor, AC magnetic fields generated from inverters would be measured by a search-coil sensor. This generally meant that measurements were taken using several instruments. Technological progress over the years has produced a fluxgate type instrument which can cover the frequency ranges required, standalone (Fig. 4) [8]. This type of instrument was therefore adopted, while improvements were made to the actual measuring environment in order to speed up the measuring process.

### 3.2 Magnetic field visualization device

The above-mentioned measuring device will be employed to make precise magnetic field measurements on a railway vehicle. However, if a magnetic field with a complicated distribution in large space has to be measured, such as the inside of a railway vehicle, it is deemed that the process can be simplified by first estimating a rough magnetic field distribution for the space in question.

A small light-weight tool to make such preliminary measurements was therefore designed and developed by the Railway Technical Research Institute (RTRI) to obtain a preliminary visualization of the magnetic field [9]. A large number of sensors are arranged to picture the shape of the magnetic field distribution. Polarity of the S pole and N pole are shown in different colors (red and green) for each point, and the intensity of the magnetic field is indicated by their brightness (Fig. 5). For example, when the N pole of a permanent magnet is brought close to the device, the red lights become gradually brighter, and when it is moved away, the lights dim. In consideration of its use in the field, an added feature is that it is battery powered and does not require a mains AC supply. Furthermore, despite the small hand-held size of the device, magnetic flux density can be measured across a relatively wide range of ± 0.01 T. The main specifications of the device are shown in Table 3.

| Table 2 Types of magnetic field probe |
|--------------------------------------|
| **Type** | **Feature** |
| Fluxgate sensor | Possible to measure DC magnetic fields, and AC magnetic field as well |
| Hall effect sensor | Possible to measure the high level of DC magnetic fields |
| Search-coil sensor | Possible to measure precisely AC magnetic fields |

![Fig. 4 Fluxgate type measurement equipment (HANO MANUFACTURING CO.,LTD)](image1)

![Fig. 5 Visualization device of the magnetic field, developed by RTRI](image2)

| Table 3 Main specifications of a visualization device of the magnetic field |
|--------------------------|
| **Probe** | Hall effect sensor |
| **Range of measurement** | ± 0.01 T |
| **Ambient air temperature** | 0 ~ 40 °C |
| **Power supply** | Eight AA batteries or equivalent rechargeable batteries |
| **Overall size** | 320 mm × 250 mm × 20 mm |
| **Weight** | 1.2 kg (including batteries) |
| **Resolution** | N pole side : red 256 gradation, S pole side : green 256 gradation |
Using brightness and reversal of polarities (boundary point between red and green), the magnetic field distribution around the measuring points can be detected. This offers a rough idea of the flow of the magnetic field. Use of this kind of tool, it will make measuring magnetic fields on railway vehicles more efficient.

4. Simulation analysis

4.1 Magnetic field analysis

As described above, in order to accurately measure the magnetic field on railway vehicles, it is desirable to use the type of precision instrument recommended in the standard. Furthermore, since it is difficult to measure the magnetic field everywhere in a vehicle, it is necessary to perform a preliminary survey of the measuring point, rendering magnetic field measurement time and effort consuming. A technique has therefore been studied to perform a desktop estimate of the magnetic field distribution in a railway vehicle. To calculate the magnetic field distribution on railway vehicles where various magnetic and conductors are existent, it is not possible to use a simple formula, magnetic field analysis is required.

In consideration of the above, a model was created in which the effects of magnetic shields and car body structures inter alia are taken into account. This model is now being used to calculate car-borne magnetic fields through the finite element method or other means. Figure 6 gives an example of this analysis model. On board magnetic fields can be calculated by supplying electric current to the trolley wire, rail, filter reactor, etc. in this model, and by taking into account the materials, thickness, etc. of the magnetic shield etc. of this model.

An example of the analysis around the filter reactor is shown in Fig.7. Also, the analysis results for the floor surface of the railway vehicle together with results for the case where there is no magnetic shield, are shown in Fig.8. From these results, it can be seen that the magnetic field is much lower toward the center of the magnetic shield on

![Fig. 7 Example of an analysis of on-board magnetic fields](Image)

![Fig. 8 Example of analysis results on the floor, over a filter reactor](Image)

![Fig. 9 Comparison of measured values and analytical values from the analysis model (floor over a filter reactor)](Image)
top of the filter reactor and reaches a peak around the outside edge of the magnetic shield.

To verify the validity of this magnetic field analysis, it was compared with magnetic field measurements carried out on a test vehicle on the RTRI test line. The results of this comparison between the measured values on the top of the filter reactor and calculated values by vehicle magnetic field analysis, are shown in Fig.9. The results generally agreed, even near ferromagnetic material such as the magnetic shield, demonstrating that it is possible to predict the magnetic field on railway vehicles by performing this type of magnetic field analysis.

4.2 Dosimetry

The “basic restrictions” in the ICNIRP guidelines, for the low-frequency magnetic field are designed to evaluate electric field strength in the human body. However it is difficult to measure electric field strength in the actual body. Therefore a voxel human model is employed and a method is being developed to determine the electric field intensity in the body on railway vehicles by calculation. The two voxel human models used for this purpose were the Japanese models designed by the National Institute of Information and Communications Technology (adult male model “TARO,” adult female model “HANAKO,” etc.). These dummies are numerical models of the human body comprising 2 mm sided ‘voxel’ cubes. An adult male model is composed of $320 \times 160 \times 866$ voxels. An ID number is assigned to each of 50 kinds of tissues in the body, and naturally this ID number is also assigned to each voxel.

The detail calculation method is as follows. The human body is regarded as the aggregation of cubes composed of a resistor, the electromagnetic field in the model is replaced with the voltage and current of the electrical network and the calculation is performed using a method of solving the network equations called impedance method (Fig.10). For this calculation, it is necessary to assign the electric constant of the conductivity, etc. to each voxel. Here, a conductivity called Gabriel electric constant [10] was adopted, which is often used in electrical calculations concerning the living body.

Figure 11 shows the example of a case analysis where the magnetic field corresponding to the reference levels in ICNIRP (200 μT / 50 Hz) were given to the Japanese male model as a uniform magnetic field. The results of this analysis demonstrate that the maximum induced electric field strength in the human body did not exceed the basic restrictions in the ICNIRP for commercial frequencies (Central nervous system tissue of the head: 0.02 V / m, all tissues of the head and body: 0.4 V / m). In turn this outcome illustrates that even if the living body is exposed to a uniform magnetic field corresponding to the reference levels in ICNIRP, the maximum induced electric field strength in the human body does not exceed the basic restrictions.

This method therefore permits the estimation of the intensity of the electric field induced in the body by a low frequency magnetic fields through calculation and without the actual measurement.

5. Conclusions

The movement toward standardization of low-frequency magnetic fields is gathering pace both in Japan and other countries. Progress in revising the international ICNIRP guidelines for electromagnetic field is also making headway, and new regulations have come into force in Japan to regulate magnetic field generated by power equipment. Low-frequency magnetic fields on railway vehicles are now
also covered and the EN and IEC recommend method for their measurement while in Japan, the standard governing this topic has been revised.

In this background, RTRI has carried out research to develop measurement methods and means to predict low-frequency magnetic fields.

RTRI has developed a hand-held magnetic field visualization device to measure low frequency magnetic fields, to determine magnetic field distribution on railway vehicles.

Furthermore, a method was developed to predict low-frequency magnetic fields, using a model for the analysis of magnetic fields on railway vehicles considering the conductor-like properties of a vehicle body structure and ferromagnetic material such as magnetic shields, which was used in turn to design a technique for magnetic field analysis by finite element method. Then, in order to verify the validity of those techniques, magnetic field measurement were carried out on a test vehicle on the RTRI test line, which confirmed magnetic field measurements on a magnetic shield located on top of equipment, such as a filter reactor, generally coincide with the calculated values. A quantitative evaluation technique for calculating the amount of electricity induced in a human body from low-frequency magnetic fields was then developed using a voxel model.

Figure 12 illustrates how the research and development from this paper have been incorporated into the process to determine compliance with ICNIRP guidelines. The items outlined in red were introduced in this paper. Although ICNIRP guidelines have no legal force in Japan at present, it is important to be aware of these guidelines, since they have become international de-facto standards.

In this way, RTRI has established a method for measuring and evaluating magnetic fields on railway vehicles consistently, while continuously watching trends both in Japan and in other countries. This research will be continued in order to be able to properly assess low-frequency magnetic fields.

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Authors

Yoshihito KATO
Senior Researcher, Electromagnetic Systems Laboratory, Maglev Systems Technology Division
Research Areas: Electromagnetic Systems

Hitoshi HASEGAWA, Ph.D.,
Laboratory Head, Cryogenic Systems Laboratory, Maglev Systems Technology Division
Research Areas: Electromagnetic Systems