Requirements and Transition of Onboard Reactors

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Technological progress continues to advance, particularly in the field of active components such as semiconductors. This progress has enabled us to reduce the size and weight of traction inverters for railway vehicles. On the other hand, problems remain with passive components such as reactors. In particular, onboard reactors are required to be considered not only as reactor units but also as part of a whole trainset. Therefore, as a determining factor, it is essential for reactors to be small and light. This paper focuses on problems such as flux leakage and resonance, which are unintentionally caused by onboard reactors, and explains changes in inductance values of reactors, so that this investigation informs further investigations.

Key words: onboard reactor, flux leakage, resonance, protection coordination, input filter reactor

1. Introduction

In Japan, SiC MOS-FET (Silicon Carbide Metal-Oxide-Semiconductor Field-Effect Transistor) is introduced into traction inverters from the mid-2010s [1, 2]. SiC MOS-FET, which are a type of semiconductor, are capable of high frequency operation. Moreover, SiC MOS-FET withstands high breakdown voltages. These characteristics reduce the traction inverter in size and weight. However, even though the semiconductor components for switching is smaller and lighter, there it is still possible to reduce the overall size and weight of passive components, such as reactors, capacitors, and circuit breakers. Industry focuses on improving the reactors (inductors). Various attempts have been executed regarding materials, shapes, and evaluation. There is also demand for smaller and lighter components for onboard reactors used in railways. However, the coefficients of reactors are determined by power supply equipment on ground. This hinders attempts to reduce the size and weight of reactors. Therefore, investigations into reactors requires consideration not only for the characteristics of reactor themselves, but also of the trainsets they will be used on. Investigation should contain categorization, requirements and transition for reactor, but there are no comprehensive references for onboard reactors. At the time of the former JNR (Japan National Railway), there were documents specializing transformers and reactors. It should be noted that the time when the document was compiled is the time when power semiconductors began to be applied to railway vehicles.

From these backgrounds, it is useful to summarize the requirements and changes of onboard reactors in order to improve their efficiency and reduce their size. This paper focuses on the requirements and transition of currently used onboard reactors. In Chapter 2, this paper categorizes onboard reactor. Chapter 3 and Chapter 4 deals with the problems caused by onboard reactor. Specifically, this paper refers to flux leakage and resonance in Chapter 3. These matters are the problems, which are caused by the onboard reactor unintentionally at the design phase. Chapter 4 covers the topic of the electrical protection coordination, which is the one of the requirements of input filter reactors. This paper therefore not only presents concepts aimed at improving reactors, but also describes past countermeasures, and the transition in inductance values of input filter reactors.

2. Categorization of reactor

Before describing the requirements of reactor, the following is a brief summary of the important properties of a reactor:

- Smoothing (prevention of high frequency)
- Sustaining (continuity of current)

This paper categorizes reactors structurally in Section 2.1. In Section 2.2, this paper introduces currently used reactors.

2.1 Structural categorization

Depending on their core material, reactors are divided into air-core reactors and iron-core reactors. Iron-core reactors are divided into core-type and shell-type based on the shape of the iron-core. This division between different types is same as for transformers. Depending on their magnetic circuit, they are then classified as closed-core type, open core-type, or gap type.

The cooling methods are air-cooling and oil-cooling. Air-cooling systems are sub-divided into natural air-cooling and forced-air cooling. Oil-cooling systems are sub-divided into natural oil-cooling, oil-circulation, and oil-circulation air-cooling. These categories again, are the same as for transformers.

2.2 Currently used onboard reactors

This section describes currently used reactors. The four kinds of reactors currently used are:

- (1) Input filter reactor for DC vehicle
 - (2) For AC vehicle (smoothing / sustaining reactor)
 - (3) AC reactors for auxiliary power unit (APU)
 - (4) Smoothing reactor for DC-DC conversion system
- The role of each reactor is described below.

2.2.1 Input filter reactor for DC vehicle

In the past (before 1970s), filter reactors meant reactors working by suppressing induced voltage on a signal line when the thyristor rectifier of AC vehicles was operating. The filter of the AC vehicle consists of a capacitor and a resistor. An attempt was executed to improve the performance of the filter by increasing the capacity of the capacitor. However, no increase in the capacity of the capacitor was achieved. The result led to loading the reactor onboard. The role of these older reactors differed from current ones. The input filter reactor for DC vehicle begins at the introduction of the armature

chopper system.

A DC vehicle having a power semiconductor in its traction circuit always has an input filter reactor (Fig. 1). Two reactors exist for the traction circuit and for the auxiliary circuit. The former is employed as an air-core reactor, and the latter is an iron-core reactor. A current of 1000 A or more flows through the input filter reactor in the traction circuit. Moreover, the inductance of the reactor should guarantee high self-inductance in large current such as short-circuit accident. Therefore, an air-core reactor is employed for the input filter reactor in the traction circuit. The role of an input filter reactor is as follows:

- Low pass filter between vehicle and catenary
 - Disturbance suppression (for voltage sudden change)
 - Prevention of inrush-current (when the vehicle starts to operate)
 - Protection coordination with power substation
- This paper deals with protection coordination in Chapter 4.

2.2.2 For AC vehicle (smoothing / sustaining reactor)

In general, AC vehicles have reactors (Fig. 2). Different roles and arrangements are assigned depending on the circuit configuration. When rectification was performed by diode rectifiers (~1980s), reactors were located on the load side of the rectifier. The reactors were responsible for smoothing. Nowadays, four-quadrant-converters (4QC or PWM (Pulse Width Modulation) rectifiers) are employed for AC vehicles. The reactors are located on the catenary (power supply) side. The reactors in 4QC are responsible for sustaining. The reactors in the boost chopper operate in a similar way to AC vehicle reactors, which employ 4QC. The reactors of the AC vehicles, which employ 4QC, are substituted by the leakage inductance of the transformer. Therefore, these inductors are often omitted.

2.2.3 AC reactors for auxiliary power unit (APU)

Apart from the traction inverters, another inverter is also equipped for lightning, air-conditioning, compressors and control (Fig. 3). These inverters are called SIV (Static Inverter) in Japan, and APU (Auxiliary Power Unit) overseas. The beginning of the SIV for APU is in 1968. The SIV is widely employed for APU from 1990s. For a DC vehicle, the APU generates three-phase 440 V from DC 1500 V. This three-phase 440 V is insulated and transformed via a transformer. On the load side of the transformer, an AC reactor is arranged to suppress ripple. In the actual vehicle, this reactor, the input filter reactor and the transformer for the auxiliary circuit are united.

2.2.4 Smoothing reactor for DC-DC conversion system

In principle, it is impossible to use a transformer for DC voltage conversion. DC voltage conversion is performed by a DC-DC conversion system, which consists of power semiconductor components and magnetic components.

The former performs the switching, while the latter are mainly responsible for smoothing. For railway vehicles, DC-DC conversion systems are utilized for driving DC motors and for converting voltage (conversion between source voltage and inverter input voltage). The configurations are shown in Fig. 4. The former was employed in the 1970s-1980s, the latter is now being used for onboard energy storage mainly. The configuration of circuits is also different between the two. In 1970s-1980s, since power semiconductors were

Fig. 1 Input filter reactor for DC vehicle

(a) Diode rectify (- 1980s)

(b) PWM rectify (1990s-)

Fig. 2 Reactor for AC vehicle

* Reactors for APU is mainly employed iron-core type.
* HVAC : Heating, Ventilation, and Air Conditioning

Fig. 3 AC Reactor for APU

(a) Armature chopper (1970s-1980s)

(b) Bidirectional chopper (1990s-)

Fig. 4 Smoothing reactor for DC-DC conversion system

expensive, the number of semiconductors was minimized. The configuration of the circuit was designed only in one directional current flow. To protect the power semiconductors from flashover current, the power semiconductors were located at the negative side of traction circuit. Since semiconductors were not self-extinguishing devices, commutation was forced in the whole circuit. Switching between powering and braking was performed by contactors, not by semiconductors. There was vehicle, which employed bidirectional choppers to satisfy the limit of the outbreak voltage in power semiconductors in 1991. Bidirectional choppers consisted of an upper-arm and a lower-arm, with a leg configuration structure. Vehicles with loaded energy storage systems then began to appear in 2010s. These energy storage systems required DC-DC converter systems, which included reactors for smoothing current, for voltage conversion and current adjustment. Since current semiconductors are capable of self-extinguishing and operate at high frequency, current reversal is easy with the upper and lower arm configuration. The configuration of the upper and lower arm is the same as in traction inverters.

The requirement of reactor in 2010s is also different from that of 1970s-1980s. Table 1 compares armature choppers and bidirectional choppers. In 1970s-1980s, due to the configuration of circuit, it was necessary to avoid discontinuous current mode (DCM) at a light load. The value of the inductance was determined by the DCM, not through protection coordination with the ground substation. In general, an air-core reactor is employed for a DC vehicle, an iron-core reactor is employed for some vehicles, which employ armature chopper systems for miniaturization and weight reduction. Currently, since the operations of the upper and lower arms in each leg complement each other, the current is continuous, and it is no longer necessary to consider DCM.

This section describes the role of currently used reactors. Among these, reactors operating with large capacities, and involving other equipment and ground systems, moreover which still have problems are as follows:

- Input filter reactor for DC vehicles
 - Smoothing reactors for DC-DC conversion systems
- The difference between the two is shown in the Table 2.

3. Problems caused by onboard reactors and requirements of reactors

This chapter explains the requirements of onboard reactors. Onboard reactors can cause two main types of problem, listed below. Both problems have unintended influences on other devices without designer's intention. These problems and countermeasures are listed as follows:

- Flux leakage
- Resonance

3.1 Flux leakage

From the point of the protection coordination and the value of load current, air-core reactors are generally preferred for traction circuits on DC vehicle. An air-core reactor utilizes space for the magnetic circuit. This situation is peculiar to onboard reactors for traction circuits. Therefore, the magnetic field, which is caused by the reactor, is required not to affect the other onboard equipment and the equipment on the ground. It is also necessary to consider the magnetic field inside the vehicle.

Table 1 Comparison between armature choppers and bidirectional choppers

	Armature chopper	Bidirectional chopper
Era	1970s-1980s	1990s-
Use	Motor control	Voltage conversion
Configuration of semiconductor	Minimum unit	Upper and lower arm
Self-extinguish	No	Yes
Commutation	Whole circuit	Semiconductor itself
Switching (Powering and braking)	Contactors	Semiconductor itself
Duty factor	Not constant	Constant
Design consideration	DCM (Discontinuous Current Mode)	Protection coordination

Table 2 Difference between input filter reactor and smoothing reactor

	Filter reactor	Smoothing reactor
Car	Vehicles driven by power semiconductors	Vehicles that require DC voltage conversion
Use	Low pass filter	Voltage conversion
Frequency	Wide bandwidth	Specific (Chopper frequency)

3.1.1 Magnetization of rail and the direction of the reactor

The problem dealt with in this section is common to vehicles equipped with open-core reactors regardless of the core material of the reactors. As shown in Section 2.2.2, when propulsion system used diode rectifiers (-1980s), reactors were located on the load side of the rectifier. These reactors were of open-core type, which caused a specific problem: due to flux from the smoothing reactor, rails were magnetized [3]. This phenomenon was observable on routes on routes used by ED 75s (one of AC locomotives manufactured in 1963-1976). The magnetized rail led to signal failures. According to a survey at that time, the magnetized rail, which was caused by these locomotives, attracted iron powder from the brake shoe. Due to this phenomenon, the insulation of the track circuit was shorted, and the signal remained red. ED 75 reactors were open-core type, with an inductance of 10 mH. As a countermeasure, the direction of the reactor was inverted on half the locomotives. The problem was caused by AC locomotives, the same problem can be caused by DC vehicles, which have air-core reactors. Therefore, this countermeasure is still being used today.

When propulsion system shifted to AC motors with direct inverters, the directions of the input filter reactor are various (vertical direction, rail direction and sleeper direction). Now, the problem of magnetic field exists inside the vehicle, the direction of the reactor is mainly in the rail direction or sleeper direction.

3.1.2 The countermeasures for flux leakage inside vehicles

Research into magnetic fields in vehicles due to flux leakage was conducted and measured in the 1990s.

Regarding magnetic fields, internationally the “GUIDELINES FOR LIMITING EXPOSURE TO TIME-VARYING ELECTRIC, MAGNETIC, AND ELECTROMAGNETIC FIELDS (1 Hz to 100 kHz)” were revised in 2010 by ICNIRP (International Commission on Non-Ionizing Radiation Protection) [4]. In Japan, the investigation of protection guidelines for high-frequency electromagnetic fields began in 1985 by the former Ministry of Posts and Telecommunications (now MIC: Ministry of Internal Affairs and Communications), the guidelines were enacted in 1990. The “Radio Protection Guidelines” were enacted in 2017 with the revision of the Radio Law Enforcement Regulations to be consistent with the ICNIRP guidelines revised in 2010 [5]. This procedure made the ICNIRP guidelines a mandatory standard. Although the level of magnetic flux inside vehicles is below the levels specified in the guidelines, it must be considered the impact on cardiac pacemakers. Since cardiac pacemakers are required not to malfunction at 1 mT, and therefore, the standard value of the magnetic flux at the floor on a vehicle should be below 1 mT.

As a measure against magnetic field inside vehicles, shield plates have been installed just above input filter reactors. Vehicles manufactured in around 1991 were the first to settle have shield-plates (9 mm-25 mm) installed above their input filter reactors. Because of changes in cooling methods, it became necessary to install shield plates. When vehicles employing traction inverters were introduced, the cooling system of the input filter reactor was mainly a forced air cooling using a blower. Since the blower outer plate also served as a shield, initially no shield plate was required. There is no blower for natural wind cooling, so a shield plate is required. This transition overlaps with the first half of the 1990s when there was a shift from forced wind cooling to natural wind cooling. Currently, an input filter reactor and a shield plate are mounted as a set, and the shield plate is one of the factors that hinders the reduction in size and weight.

3.2 Resonance

Vehicles must be compatible with signaling systems and feeding systems, therefore, resonance from inductance and capacitance also must be considered.

The RTRI of the JNR examined the impact of onboard armature chopper systems on ground equipment, in 1967. JNR conducted tests with different coefficients of filter circuit, on test vehicles. Low frequency resonance (10 Hz-30 Hz) was observed during these experiments. Before the Teito Rapid Transit Authority (Now: Tokyo Metro) vehicles with armature chopper systems ran on JNR lines, the examination was also conducted. These examinations led to determine the coefficient of the reactor inductance and that of the capacitor capacitance. The determined values are shown in section 4.2.2. In Europe, the resonance frequency is defined in EN 50388 [6]. If the resonance frequency is outside the defined frequency, consultation with infrastructure managers is required. These values are designated by TSI ROC&PAS (Technical Specifications for Interoperability relating to the ‘rolling stock - locomotives and passenger rolling stock’) [7]. Since TSIs are mandatory standards for achieving interoperability in Europe, the value of the resonance frequency shall be compelled in Europe.

- DC motors with chopper: 20 Hz to 40 Hz
- AC motors with chopper + inverter: 20 Hz to 30 Hz
- AC motors with direct inverter: 10 Hz to 30 Hz

For example, the inductance and the capacitance of the JNR207 Series (a DC vehicle, which has AC motors with direct inverters manufactured in 1986) are 10 mH, 7600 μ F respectively. From these

values, the frequency of resonance is 18.25 Hz, which complies with EN 50388.

4. The relationship between the input filter reactor and the protection coordination

Since it is difficult for us to distinguish load current from short-circuit current for DC vehicle, protection coordination is an important issue for DC vehicle. This chapter examines a key requirement for input filter reactors, which ensure protection coordination for the ground substation.

4.1 Protection coordination

To establish the protection coordination, a power supply grid compels us to follow certain requirements:

- Protective relays are provided to ensure protection wherever a failure occurs.
- Overlap protective sections are provided to avoid existing unprotected sections.
- When a failure occurs, it is necessary to limit the protected area in order to minimize the section of the failure. Normal operation is required in other sound areas. To establish the requirement, the protective relays are operated with a time difference.
- The electric vehicle corresponds to the lowest level (the load side) of the feeding system. The requirements of the protection coordination between the vehicle and the feeding system are as follows.
- Distinguish the feeding system into gradual protection ranges and cooperate so that lower grade systems can protect them sooner than other upper grade systems.
- When a failure such as a short circuit occurs in a vehicle, the system first tries to assure protection through the vehicle itself. If this is not possible, the system tries to protect it via the electric grid.
- Overlapped protected sections are provided with a vehicle and a power system to ensure that no unprotected sections are created.
- Since it is necessary to minimize sections suffering a power interruption, the protective system does not operate outside the faulty section, such as the ground or other cars.

An example of how protection between the vehicle and the feeding system is shown in Fig. 5. When a failure such as a short circuit occurs in a vehicle, the protection is required to be completed in the vehicle itself. The specifications of the onboard circuit breaker and the inductance value of the input filter reactor are determined in accordance with these requirements. Protection coordination in the field was investigated in the 1990s, when there was a wide vari-

Fig. 5 Protection coordination between the vehicle and the feeding system

ety of propulsion systems in use.

4.2 The transition of the protection coordination and the input filter reactor

4.2.1 Protection coordination and circuit breakers

In order to investigate protection coordination, it is necessary to examine circuit breakers in more detail, whether on the vehicle or on the ground. When propulsion system was the DC motors with switched resistors before 1970s, protection coordination was assured with a circuit breaker either on the vehicle or on the ground. Progress in onboard circuit breakers was achieved with the arrival of the 101 series (a DC vehicle) and the ED 60 (a DC locomotive). These vehicles employed “CB14,” which was the newest onboard circuit breaker at that time. Vacuum circuit breakers and semiconductor circuit breakers were also developed in the 1990s. Now trains are equipped with deion grid circuit breakers, which are capable of self-extinguishing arcs inside itself.

4.2.2 Input filter reactors and protection coordination

The input filter reactors, which suppress steep current changes, are essential for protection coordination.

The reactors are also installed on the ground. The inductance value of ground reactors are mainly 1.1 mH in Japan, and 2 mH in Europe. EN 50388 designates the conditions which lead to tripping at the substation.

As for the inductance value of input filter reactors, EN 50388 does not designate specific values. It specifies that the impedance of the input filter reactor shall exceed 0.3Ω at 50 Hz. The corresponding value of the inductance is not designated in Japan. For the development of onboard armature chopper systems, the JNR and Teito Rapid Transit Authority conducted studies including tests with different coefficients of filter and elements. As a result, an inductance of 8 mH and capacitance of 3200 μF were employed for Series 6000 used by the Teito Rapid Transit Authority (in 1968). The reasons are as follows:

- It is larger than the internal inductance (4 mH) of the traction motor.
- Resonance frequency is less than 50 Hz.
- The overvoltage generated at the time of load cutoff is less than the withstand voltage ($1300 \text{ V} \times 4 / 1.1 = 4730 \text{ V}$) of the thyristor.

The problems of the armature chopper system and the specifications of the armature chopper system are summarized in [8]. The abovementioned reasons are also indicated by the author of [8] in another Japanese reference. Table 3 shows an example of the coefficient of an armature chopper system.

The changes of the inductance values for input filter reactors after introduction of inverter control vehicles is explained as follows. When propulsion systems began employing AC motors with direct inverters around 1990, input filter reactor inductance was considered to be 12 mH. Today, the inductance value is around 8 mH. For vehicles used in rural areas, the inductance value is around 20 mH. We assume that the value seems to be determined by ground equipment. Table 4 shows the inductance values of input filter reactors of the vehicles, which were manufactured in these days. Copper or aluminum are commonly used as winding material in the reactor, depending on purpose. Aluminum is usually employed when the main purpose is weight reduction. Nowadays, traction circuit efficiency is the focus, therefore copper is often employed. There is

Table 3 The coefficients of armature chopper vehicles

Company	Series	Reactor		Filter capacitor	Year
		Filter	Smoothing		
Teito Rapid Transit Authority	6000	8 mH	5.5 / 8 mH ^{*1}	3200 μF	1968
JNR	201	5 mH	5 mH	3200 μF	1982
Tokyo	10-000	8 mH	8 mH	3200 μF	1971
Kobe	1000	8 mH	8 mH ^{*2}	3200 μF	1976
Nagoya	3000	5 mH	8.8 mH ^{*2}	3200 μF	1977

*1 Depend on manufacturer.

Electromagnetic coupling: 5.5 mH, Non-electromagnetic coupling: 8 mH

*2 Electromagnetic coupling

Table 4 The coefficients of input filter reactor on inverter vehicles

Company	Series	Inductance	Area	Year
Keisei	3000	8 mH	Urban	2002
JR West	125	23 mH	Region	2002
JR East	E129	24 mH	Region	2014
JR East	E235	8 mH	Urban	2015
JR Shikoku	8600	23 mH	Region	2014
Sagami	20000	8 mH	Urban	2017
Keio	5000	8 mH	Urban	2017

comparison article between aluminum and copper.

5. Conclusions

Onboard reactors must be examined not just as independent units, but also as a component in a trainset's entire system. This paper therefore provides an overview of the applications, requirements, and the transitions of reactors, and of how their coefficient values are determined. The findings of this paper are summarized as follows.

- Onboard reactor applications and key observations: Input filter reactors for DC vehicles and smoothing reactors for DC-DC conversion systems used for large currents. Certain problems remain, namely problems which unintendedly impact other types of equipment and ground systems.

- Unintended problems caused by onboard reactors are flux leakage and resonance.

- A DC vehicle having a power semiconductor in its traction circuit always has an input filter reactor mounted. A key requirement for input filter reactors is to include protection coordination for ground substations.

- This paper reviews the transition of the value of the input filter reactor for DC vehicle. When the propulsion systems were DC motors with armature choppers, input filter reactor inductance was around 5 to 8 mH. Today, the inductance value of input filter reactor is around 8 mH. For vehicles used in rural areas, the inductance value is around 20 mH.

This paper shows that there is room for miniaturization and weight reduction of magnetic components. The author hopes that this paper will contribute to achieving reductions in the size and

weight of magnetic components.

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