Traction Circuit System of Gauge Changing Train

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This paper describes the traction equipment of the electrical motive units (EMUs) of Gauge Changing Train (GCT). These state-of-the-art EMUs are equipped with downsized direct drive type permanent magnet synchronous motors (PMSMs) for traction to run at five supply voltages in Japan, including Shinkansen and conventional narrow-gauge lines. The paper also illustrates the test results of operation on Shinkansen and conventional narrow-gauge lines and on a gauge-changing section that connects different gauge lines.

Keywords : propulsion system, gauge change train, direct drive traction motor, permanent magnet synchronous traction motor control

1. Introduction

In Japan, the high speed Shinkansen network is being expanded to cope with the development of regional economy. However, it requires an enormous amount of expenses to construct new lines of the standard 1,435 mm gauge and to convert conventional 1067 mm narrow gauge line to standard gauge lines. To solve this problem, a Gauge Change Train (GCT) that operates through different gauge sections is being developed by Railway Technical Research Institute based on the R&D contract with Japan Railway Construction Public Corporation under the supervision of Ministry of Land, Infrastructure and Transport.

In the propulsion system, GCT has special features such as wheel-mounted type direct drive type PMSMs, operating in supply voltage sections of 25 kV 50 Hz, 25 kV 60 Hz, 20 kV 50 Hz, 20 kV 60 Hz AC and 1.5kV DC, and running through the gauge changing section which connects different gauge lines. We have been developing a propulsion system with novel traction power converters, which meets the specification of GCT. In addition, the traction power converter must be designed small enough to be equipped under the small car bodies of 20 m in length for narrow gauge conventional lines, even though it is capable to output sufficient power for operation at 300 km/h on Shinkansen sections.

This paper illustrates the design of traction power converter and the control strategy of traction equipment of GCT. We introduce the test results both at a high speed section and a narrow gauge conventional line to verify the basic function of the propulsion system and also refer to the operating results in the gauge changing section to verify the control strategy.

2. Overview of propulsion system.

2.1 Specification of propulsion system.

The specifications of propulsion system are based on vehicle running performance, for instance, the maximum speed, acceleration, grade, braking performance and so on. In addition, specified items of the vehicle are also taken into consideration. We assume the specification of GCT with regard to the propulsion system shown in Table1, which is likely to be required for GCT, though the revenue service line of GCT has not yet been decided. GCT has two rating performance levels in Table1, one for Shinkansen lines and the other for conventional narrow gauge lines. The rating power of traction motors is set for a wheel.

Tractive effort curves which are based on Table1, are shown in Fig.1. Two kinds of tractive effort curves are to be switched for Shinkansen section or the narrow gauge section, though the brake effort is common for both

Table 1 Required specification of propulsion system

Gauge	Standard	Narrow
Length of car body [m]	20	
Mass of vehicle [t]	40	
Axle [tf]	10	
Ratio of motor car and trailer car	All motored cars	
Acceleration [km/h/s]	2.0	1.6
Deceleration [km/h/s]	Max 2.7	
Maximum speed [km/h]	130	300
Maximum speed at test [km/h]	160	350
Wheel radius [mm]	New860, Warn800	
Rating power of traction motor [kw]	60 (1Hr)	95 (Cont)
Rating rotational speed of traction motor [rpm]	675	1560

Fig. 1 Traction performance of GCT

sections. This performance is typical for conventional Shinkansens and inter city service trains in Japan.

2.2 Composition of traction equipment

A Simplified power circuit schematic of the GCT is given in Fig.2. The total equipment is roughly divided into three parts, input circuit, motor traction circuit and auxiliary power circuit. The input circuit contains a vacuum circuit breaker (VCB), main transformer (MTr) and the PWM rectifier for AC supply and, a high speed circuit breaker (HCB) and input LC filters, for DC supply. The motor traction circuit contains voltage source type three-level adjustable voltage adjustable frequency (AVAF) inverters, load conductors and PMSM type traction motors.

On 25kV and 20 kV AC supplies, three sets of three-

level PWM rectifier are used to produce a stabilized 1.8 kV DC link voltage for each three-level inverter. With 1.5 kV DC supply, power is fed via an input LC filter to the traction inverters. Traction inverters convert the DC voltage to three phase AVAF AC power to control traction motors. Each traction motor is individually controlled by each traction inverter, because the frequency of the inverter output voltage must principally be synchronized with the rotating frequency and the phase angle of the PMSM. Load conductor is equipped to disconnect PMSMs and traction inverters in the case of malfunction on either side.

2.3 Traction power converter

Figure 3 illustrates a rough sketch and dimension of the power traction converter. Each power converter consists of a PWM rectifier unit, eight sets of traction AVAF inverter and two control units. The specification of the traction converters is shown in Table 2. As a semiconductor switching device, IGBT is used both for rectifier and inverter for downsizing, because IGBT generates less switching loss than GTO and can eliminate items such as clamps and the snubber circuit which are required for GTO design.

PWM rectifiers have a three-level voltage source circuit configuration and 2.5 V-1.0 kA IGBT is utilized. The switching frequency of IGBT in the rectifier is 1,050 Hz, which is high enough to prevent a harmonics current

Fig. 3 Dimension of power traction converter

Fig. 2 Traction circuit diagram for GCT

ACDCg: Change gear to switch
AC and DC.

VCB: Vacuum Circuit Breaker.

HCB: High Speed Circuit Breaker

MTr: Main Transformer.

FL: Filter Inductor.

PWM Rec: PWM Rectifier.

INV:AVAF Inverter.

LK: Load Contactor

SM:(PM) Synchronous Motor

Thy Rec: Thyristor Rectifier.

Aux INV: Auxillary Inverter

Table 2 Specification of traction power converter

Converter	Items	Specification
PWM Rectifier	Type	Voltage souce, three level PWM
	Device	IGBT 2500 V-1000 A
	Power [kVA]	2500
	Input voltage	AC. single phase, 50[Hz]or 60[Hz] 885 ~ 925[V]
	Output voltage[V]	DC. 1800
	Switching frequency [Hz]	Asynchronous PWM, 1050
AVAF Inverters	Type	Voltage souce, Three level PWM
	Device	IGBT 1700 V-400 A
	Power [kVA]	300
	Output voltage[V]	DC. 1800
	Input voltage	AC. Three phase, 0 ~ 200[Hz] Max210[A] 0 ~ 1450[V]
	Switching frequency [Hz]	0 ~ 1500

problem in the AC supply line. In addition, PWM rectifier can principally achieve the highest power factor at the primary side of the main transformer.

The traction inverter also has a three-level voltage source circuit configuration and 1.7 kV-400 A IGBT is utilized. The switching frequency in the inverters is 1.5 kHz in the low and middle speed ranges and corresponds to the inverter output frequency in the high speed range to reduce the switching loss of IGBT.

3. Specific features at control

3.1 PMSM control strategy

PMSMs are controlled by AVAF inverters with field orientated control strategy for the quick torque response. Figure 4 illustrates an outline of PMSM traction motor control system. In the field orientated control strategy, the motor current is controlled by separating two components based on the d-q axis coordinate which is synchronized with the rotation of the PM field flux. The d axis current i_d is regarded as a magnetizing current which mainly controls flux, and the motor torque is proportional to the q axis current i_q . The automatic current regulator (ACR) compensates for error between the current command and actual current. Control functions specified to railway vehicle traction, such as, wheel slip control, anti-overvoltage control at regenerative brake and beat-less control, are available by regulating current commands. In the controller, the measured three-phase currents are transformed into i_d and i_q by using the rotating angle θ which is detected and processed by the resolver and RD converter. In ACR, the armature reactance voltage is

compensated for by feed forward compensation by using the command current instead of measured currents to avoid the harmonics problem included in the motor current. The current error is compensated for by PI compensator $C_{PI}(s)$. In the ACR in Fig.4, if the time constant is given as T_d , current step response can be a one-order delay with the time constant of T_d , giving gains as in equations (1) to (6), where, $G_f(s)$ is the one-order delay filter which simulates the delay of the actual currents.

$$G_f(s) = 1/(T_d s + 1) \dots\dots\dots (1)$$

$$G_{pid}(s) = K_{ACRPid} + K_{ACPI}/s \dots\dots\dots (2)$$

$$G_{pld}(s) = K_{ACRPd} + K_{ACRI}/s \dots\dots\dots (3)$$

$$K_{ACRPd} = L_d/T_d \dots\dots\dots (4)$$

$$K_{ACRP_d} = L_d / T_d \dots\dots\dots (5)$$

$$K_{ACRI d} = R_m / T_d \dots\dots\dots (6)$$

where, L_d and L_q donate the armature winding d axis and q axis inductance, and R_m is the armature winding resistance.

Fig. 4 Diagram of PMSM control system.

3.2 Beat-less control

On the AC fed traction circuit, the DC link voltage between the PWM rectifier and the AVAF inverter fluctuates due to the single phase AC voltage feeding. It interferes with the inverter output AC current and causes overcurrent and torque fluctuation, which is the so called beat-phenomenon. At the traction system on GCT, the beat less control shown in Fig. 5 is used for the PMSM drive system for the first time.

3.3 Gauge changing section control strategy

At the gauge changing section, the guide rail along both sides of track, instead of the wheel and rail, supports the mass of the vehicle. On this occasion, the wheels are suspended and the traction motor is unloaded. Under this condition, wheels could easily slip and damage the rail. Anti-slip control, which is originally employed for slip and skid protection, copes with this potential problem and the speed limiter which stops powering if the speed exceeds its set limit, is added to back up the ineffectiveness of the anti slip control.

Fig. 5 Beat-less control system.

4. Test results

4.1 Running test at high speed.

On the high speed test line at Transportation Technology Center Inc. (TTCI), Colorado, U.S, we carried out high speed running tests to verify the appropriate operation of the propulsion system under the condition of AC 25 kV supply voltage. In Fig. 6, traction system works appropriately up to 246 km/h and the anti-slip control system reduces the q axis current 2 and 4 to minimize the loss of tractive efforts. Through this test, we verified the appropriate operation of the traction system for PMSMs in the higher speed range over 200 km/h.

The waveforms at 100 Hz of inverter frequency in Fig. 6 is enlarged in Fig. 7 to verify the beatless control. The amplitude of motor currents does not fluctuate even though the DC link voltage fluctuates by the doubled frequency. The beatless control strategy in Fig. 5 is verified to appropriately operate through the running test.

4.2 Running test at narrow gauge section.

In addition to the high speed running tests, we also carried out running tests on a conventional narrow gauge line electrified at AC20 kV. In Fig. 8, we verified that the traction system is operated appropriately to accelerate GCT up to 130 km/h. During brake application from 130 km/h to a stop, regenerative brake works and anti-skid control system reduces motor currents to avoid skids on the wheels. Through this test, we verified the appropriate operation PMSMs from start to higher speed running on the conventional narrow-gauge section.

4.3 Running through the gauge changing section

In the gauge changing section, the anti-slip control is effective enough to reduce motor currents to avoid the over speed of the wheels in Fig. 9. The motor current is

Fig. 6 Running test in the standard gauge test line

Fig. 7 Voltage and currents wave at 100 Hz inverter frequency.

reduced to prevent the overspeed of the wheels, when the bogie approaches the gauge changing section. Then the motor current recovers properly when the bogie runs through the gauge changing section. This result verifies the appropriate operation of the control strategy for the gauge changing section.

Fig. 8 Running test at 130 km in the narrow gauge section

5. Conclusion

In this paper, we have introduced an outline of propulsion system for GCT and its control feature characterized by the application of PMSM type traction motors and the running at a gauge changing section. Through

Fig. 9 Running test at the gauge changing section

the tests results, the general control performance for PMSMs and the special features for GCT both are verified to appropriately operate as the designers intended. We also performed a running test in the DC 1.5 kV section and verified the appropriate results as well. The propulsion system for GCT is now being prepared for a prototype version.