

A Study on the Mixed Use of Power Conversion Elements of Propulsion Control Devices in Railway Train

Dongwon Lim¹, Hanmin Lee² and Jinhan Lee³

1. Leekun Industrial Systems Co., Ltd., 42-110 Gyeongbook daero Baramgolgil, Gyeong-gi-do 12070, Korea

2. Energyin Co., Ltd., 176 Cheoldobangmulgwan-ro, Uiwang-si, Gyeonggi-do 16105, Korea

3. Busan Transportation Corporation, Jungang-daero 644beon-gil 20, Busan 47353, Korea

Abstract: A study is under way to apply the main power conversion element of the C/I device, the propulsion control unit of variable voltage and variable frequency (VVVF), to the electric vehicle by changing it from gate turn off thyristor (GTO) to insulated gate bipolar transistor (IGBT). In an early study, a combination of GTO and IGBT was tested on electric vehicles. The IGBT method was applied to 1 coach and the GTO method was applied to the remaining coaches. As a result of the test, a lack of traction force occurred due to an imbalance in output current. This phenomenon was determined to be caused by differences in the operational characteristics of the two types of power devices. This is due to the different response performance of the IGBT inverter vehicle and switching signal of the controller that drives the existing GTO inverter. When two power devices are used in a train, it is necessary to match the response performance between coaches. Interface board was manufactured and installed on the coach with IGBT and tested. The interface board is designed to have the characteristics of matching signals between the controller and the gate drive unit (GDU). As a result, the same switching response performance was achieved between GTO type and IGBT type coaches. The performance of using a mix of two power devices was verified. Therefore, normal driving performance and comfortable ride were maintained during the operation of the train.

Key words: Propulsion control system, inverter, VVVF, GTO, IGBT.

1. Introduction

The variable voltage and variable frequency (VVVF) propulsion control system of gate turn off thyristor (GTO) type was first introduced in Seoul Subway Line 4 in the early 1990s and has been introduced and operated by many other urban railway operators. Since the VVVF propulsion control of GTO type has been in use for more than 20 years, the failure is increasing due to the aging of the device. Therefore, the urban railway operating institution is improving the propulsion control system sequentially with insulated gate bipolar transistor (IGBT) device applied [1, 2]. However, it is difficult to reflect the budget because of the high cost of replacing the system. Currently, the Busan Transportation Corporation is conducting a practical study to replace the propulsion control device of the

GTO type with the IGBT type. This study seeks to make IGBT C/I STACK so that it can be structurally and circuitarily mixed with the existing GTO type and to apply the IGBT STACK development to the train using the controller of the existing GTO type. It is a study that allows the inverter propulsion control device of GTO type and IGBT type to be used simultaneously in a train when replaced by 1 coach units of a train.

At the beginning of the research, IGBT type production was tested by mixing GTO type with electric vehicle. There was an imbalance between the vehicle with IGBT type and the vehicle with GTO type applied and the output current. In the corresponding coach with IGBT, the vibration of the vehicle caused by a lack of traction force occurred, and the propulsion was impossible. The difference in the operating characteristics of the two types of power devices installed in the train has occurred. It has been identified that the switching pulse of the controller that drives the

Corresponding author: Hanmin Lee, Ph.D., research fields: power quality, propulsion control device and ESS.

existing GTO inverter and the switching pulse of the IGBT vehicle are different. This could not be solved simply by changing the power device from GTO to IGBT. Therefore, it is at the core of this research project to identify the characteristics of each power element and ensure that the same switching pulse appears. The switching pulse characteristics of different power devices should be identical. The switching pulse output from the existing GTO controller was converted to a coach with IGBT applied. So we made an interface board to make IGBT equivalent switching pulse performance to GTO. The interface board was installed between the controller and the gate drive unit (GDU). The interface board program was produced using CPLD (CMOS programmer logic device). The interface board converts the time of the output signal for the GTO controller switching input signal. Therefore, the interface board has the same response characteristics as the GTO vehicle. Input and output signals are electrically insulated by allowing them to be transmitted and received by light. Through this research and development, the GTO propulsion control unit can be replaced on a coach basis.

2. Interface Board for GTO/IGBT

2.1 Comparison of Characteristics of Power Devices

2.1.1 Characteristics of GTO

GTO is a thyristor that has the ability to turn off the current in the reverse direction to the gate. GTO is mainly used for pulse width modulation (PWM) controlled VVVF inverters and auxiliary power units (SIVs) for driving induction motors. The GTO must have a diode, resistor, and snubber circuit to reduce the spike voltage that occurs temporarily between Anode and Cathode when turning off (Fig. 1). So the surrounding circuit becomes complicated. GTO has a longer time (tail time) than IGBT from turning off to when the voltage between Anode and Cathode is fully stable. Therefore, switching frequency is difficult to increase. Noise caused by GTO switching is relatively large compared to noise caused by IGBT switches.

When a thyristor sends current to a P-type semiconductor, the NPN transistor works. The PNP transistor is operated by the NPN transistor. Since then, the NPN semiconductor base is continuously powered by the PNP transistor, it continues to self-maintain even if the base is turned off, so all transistors work. However, GTO is a thyristor that allows power to be cut off from the base when switching is required from DC power. GTO has the disadvantage of increasing power consumption or heating because the gate current is large for turning off, and the gate current is all heat loss. In addition, the GTO has a large heat loss because the turn-on and turn-off time by switching is longer than the IGBT. Table 1 shows the data sheets of the GTO elements currently being used on VVVF trains. The turn-on time of GTO is up to 10 μs and the turn-off time is up to 30 μs [3, 4].

2.1.2 Characteristics of IGBT

IGBT is a bipolar transistor with high speed switching characteristics of Power-MOSFET. IGBT is a power semiconductor device that has high internal pressure and high flow characteristics. Unlike power transistors, IGBT does not have a thermal negative. Therefore, there is a feature that does not cause problems in the area of safe operation, called secondary surrender. In addition, IGBT has excellent switching characteristics and high allowable junction temperature (Table 2). The IGBT has a simple circuit because the gate is isolated and has high input impedance, allowing voltage-controlled drives. In the case of turn-on of IGBT, the channel is formed by giving the gate a pulse voltage of the plus, and the current is supplied to the base of the PNP transistor, and IGBT is in a state of flux. In case of turn-off of IGBT, if the signal voltage is removed from the gate, the channel disappears and the IGBT becomes blocked. The turn-on and turn-off time of IGBT is much shorter than that of GTO, enabling fast switching and reducing heat loss by switching compared to GTO. The turn-on time of IGBT is up to 3.5 μs , and the turn-off time is up to 5.5 μs (Table 3) [5-7].

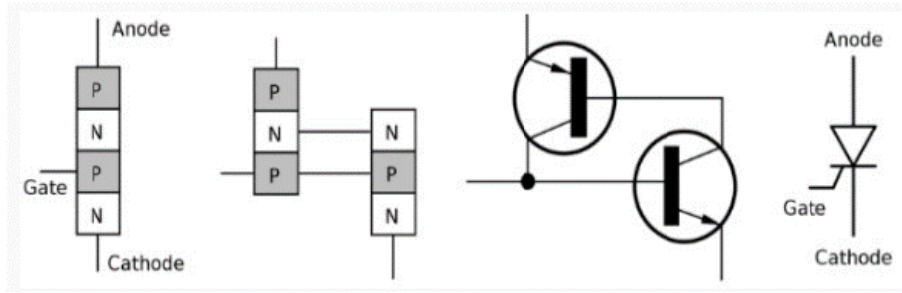


Fig. 1 GTO thyristor inner circuit.

Table 1 GTO (FG3000DV-90DA) electrical characteristics.

Symbol	Parameter	Test conditions	Limits			Unit
			Min	Typ	Max	
V_{TM}	On-state voltage	$T_j = 125^\circ\text{C}$, $I_{TM} = 3000\text{A}$, Instantaneous measurement	-	-	4.0	V
I_{RRM}	Repetitive peak reverse current	$T_j = 125^\circ\text{C}$, V_{RRM} Applied	-	-	300	mA
I_{DRM}	Repetitive peak off-state current	$T_j = 125^\circ\text{C}$, V_{RRM} Applied, $V_{GK} = -2\text{V}$	-	-	150	mA
I_{RG}	Reverse gate current	$T_j = 125^\circ\text{C}$, $V_{RG} = 17\text{V}$	-	-	300	mA
dv/dt	Critical rate of rise of off-state voltage	$T_j = 125^\circ\text{C}$, $V_D = 2250\text{V}$, $V_{GK} = -2\text{V}$	1000	-	-	V/ μs
t_{gt}	Turn-on time	$T_j = 125^\circ\text{C}$, $I_{TM} = 3000\text{A}$, $I_{GM} = 40\text{A}$, $V_D = 2250\text{V}$	-	-	10	μs
t_{gq}	Turn-off time	$T_j = 125^\circ\text{C}$, $I_{TM} = 3000\text{A}$, $V_{DM} = 3375\text{V}$, $d_{GO}/d_i = -40\text{A}/\mu\text{s}$	-	-	30	μs
I_{GOM}	Peak gate turn-off current	$V_{RG} = 17\text{V}$, $C_s = 6.0\mu\text{F}$, $L_s = 0.3\mu\text{H}$	-	670	-	A
V_{GT}	Gate trigger voltage	DC METHOD : $V_D = 24\text{V}$, $R_L = 0.1\Omega$, $T_j = 25^\circ\text{C}$	-	-	1.5	V
I_{GT}	Gate trigger current		-	-	4000	mA
R_{th}	Thermal resistance	Junction to fin	-	-	0.015	$^\circ\text{C}/\text{W}$

Table 2 IGBT (MBN1500E33E2) electrical characteristics.

ELECTRICAL CHARACTERISTICS

Item		Symbol	Unit	Min.	Typ.	Max.	Test Conditions
Collector Emitter Cut-Off Current		I_{CES}	mA	-	-	12	$V_{CE} = 3,300\text{V}$, $V_{GE} = 0\text{V}$, $T_j = 25^\circ\text{C}$
				-	20	60	$V_{CE} = 3,300\text{V}$, $V_{GE} = 0\text{V}$, $T_j = 125^\circ\text{C}$
Gate Emitter Leakage Current		I_{GES}	nA	-500	-	+500	$V_{GE} = \pm 20\text{V}$, $V_{CE} = 0\text{V}$, $T_j = 25^\circ\text{C}$
Collector Emitter Saturation Voltage		$V_{CE(sat)}$	V	2.5	2.95	3.5	$I_C = 1,500\text{A}$, $V_{GE} = 15\text{V}$, $T_j = 125^\circ\text{C}$
				-	3.1	-	$I_C = 1,500\text{A}$, $V_{GE} = 15\text{V}$, $T_j = 150^\circ\text{C}$
Gate Emitter Threshold Voltage		$V_{GE(TH)}$	V	5.5	6.3	7.5	$V_{CE} = 10\text{V}$, $I_C = 1,500\text{mA}$, $T_j = 25^\circ\text{C}$
Input Capacitance		C_{ies}	nF	-	195	-	$V_{CE} = 10\text{V}$, $V_{GE} = 0\text{V}$, $f = 100\text{kHz}$, $T_j = 25^\circ\text{C}$
Internal Gate Resistance		R_{ge}	Ω	-	1.3	-	$V_{CE} = 10\text{V}$, $V_{GE} = 0\text{V}$, $f = 100\text{kHz}$, $T_j = 25^\circ\text{C}$
Switching Times	Rise Time	t_r	μs	1.6	2.0	2.6	$V_{CC} = 1,650\text{V}$, $I_C = 1,500\text{A}$ $L_s = 100\text{nH}$ $R_G = 2.7\Omega / 2.7\Omega$, $C_{GE} = 330\text{nF}$ (3)
	Turn On Time	t_{on}		2.0	3.0	3.5	
	Fall Time	t_f		0.9	1.7	2.6	
	Turn Off Time	t_{off}		2.7	4.4	5.5	
Peak Forward Voltage Drop		V_{FM}	V	2.2	2.6	3.0	$I_F = 1,500\text{A}$, $V_{GE} = 0\text{V}$, $T_j = 125^\circ\text{C}$
				-	2.6	-	$I_F = 1,500\text{A}$, $V_{GE} = 0\text{V}$, $T_j = 150^\circ\text{C}$
Reverse Recovery Time		t_{rr}	μs	0.2	0.8	1.2	$V_{CC} = 1,650\text{V}$, $I_F = 1,500\text{A}$, $L_s = 100\text{nH}$ $T_j = 125^\circ\text{C}$
Turn On Loss	$E_{on(10\%)}$	J/P		-	2.9	3.6	$T_j = 125^\circ\text{C}$
	$E_{on(full)}$			-	3.2	-	$T_j = 150^\circ\text{C}$
Turn Off Loss	$E_{off(10\%)}$	J/P		-	2.2	2.6	$T_j = 125^\circ\text{C}$
	$E_{off(full)}$			-	2.4	-	$T_j = 150^\circ\text{C}$
Reverse Recovery Loss	$E_{rr(10\%)}$	J/P		-	1.4	1.9	$T_j = 125^\circ\text{C}$
	$E_{rr(full)}$			-	1.7	-	$T_j = 150^\circ\text{C}$

Table 3 GTO & IGBT characteristics comparison.

		GTO ↻	IGBT ↻
Name ↻		Gate Turn-off Thyristor ↻	Insulated Gate Bipolar Transistor ↻
Shape ↻			
Rated specification ↻		4500V/3000A ↻	3300V/1500A ↻
element composition ↻		self-protection type Thyristor ↻	FET + Transistor ↻
Switching frequency ↻		Max. 500Hz ↻	Max. 2kHz ↻
Characteristics ↻	Protection function ↻	None ↻	None ↻
	Installation ↻	Complexity ↻	Simple ↻
	Structure and Capacity ↻	Complexity/Heavy ↻	Simple/Lightness ↻
	Maintenance ↻	Inconvenience (requires stack assembly) ↻	Convenience (on-site action possible) ↻
	Insulation ↻	Separate Insulation Material Required ↻	self-insulation ↻
	Parallel connection ↻	Complexity ↻	Simple ↻

2.2 Function of Interface Board

2.2.1 Behavior of the Interface Board

The interface board consists of Figs. 2-4.

The interface board receives the switching pulse of the GTO controller as input. The interface board outputs by varying the cycle of the switching pulse by giving a delay time. The interface board transmits an output signal to the GDU.

After the input signal of the GTO controller is on by the interface board, the output signal is on after TD (ON) time. After the input signal of the GTO controller is off by the interface board, the output signal is off after the TD (OFF) time.

2.2.2 Comparison of the Behavior of IGBT Devices with Interface Boards and the Behavior of GTOs

We checked the behavior of the GTO element in the propulsion control system in the train. As shown in the waveform (Fig. 6), even when the start signal is off, the turn-off time and tail time of the GTO do not

immediately turn off the Van voltage and show an energized state for a certain time.

As a result of checking the behavior of the IGBT, the Van voltage waveform is immediately switched off. The IGBT's power-on time is shorter than that of the GTO. Install the interface board on the IGBT coach to match the same output on the GTO applied coach and IGBT applied coach for the switching signal output from the GTO controller. The interface board adjusts the On and Off Delay Time and adjusts the U-X phase's interphase lead time. The IGBT coach has the same result as the existing GTO coach performance, enabling it to meet the traction power of the train. After the interface board has applied On and Off Delay Time, the waveform (Fig. 7) represents the Van voltage of the IGBT for the interphase switching signal.

2.3 Comparative Measurement of Data through Field Test Runs

The test trains are configured with GTO C/I STACK

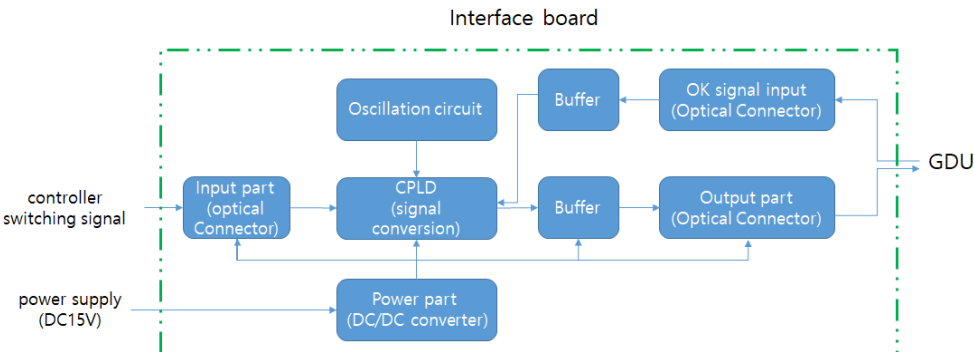


Fig. 2 Interface board block diagram.

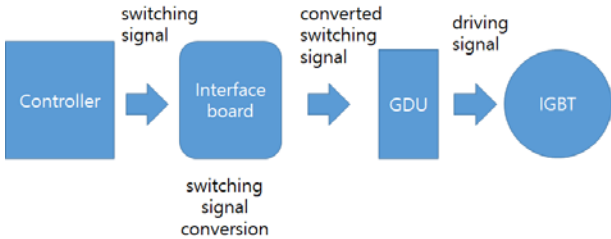


Fig. 3 Interface board movement diagram.

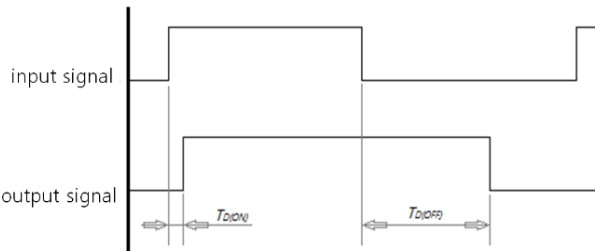


Fig. 4 Interface board input signal delay output.

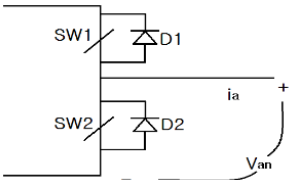


Fig. 5 Arm constant output circuit.

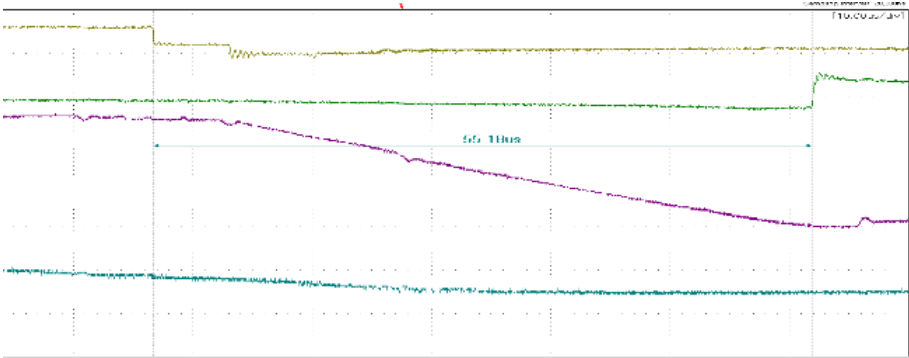


Fig. 6 GTO constant output waveform.

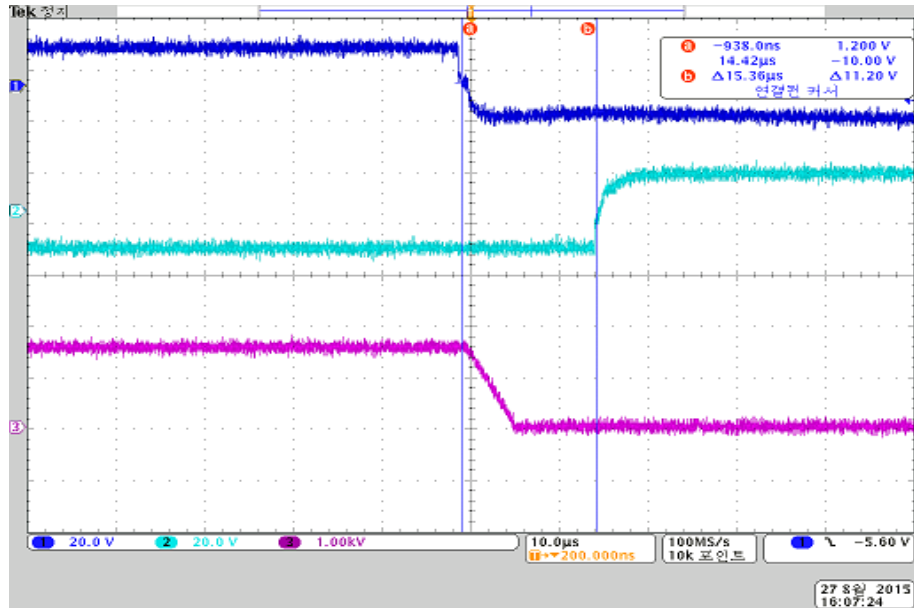


Fig. 7 IGBT constant output wave (dead time 15 μ s with a delay time of the interface B/D).

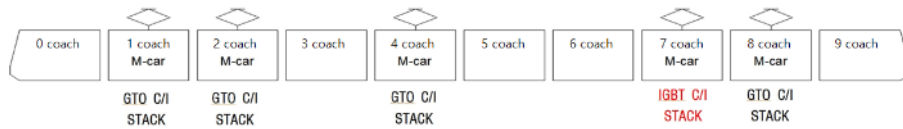


Fig. 8 The configuration of the train.

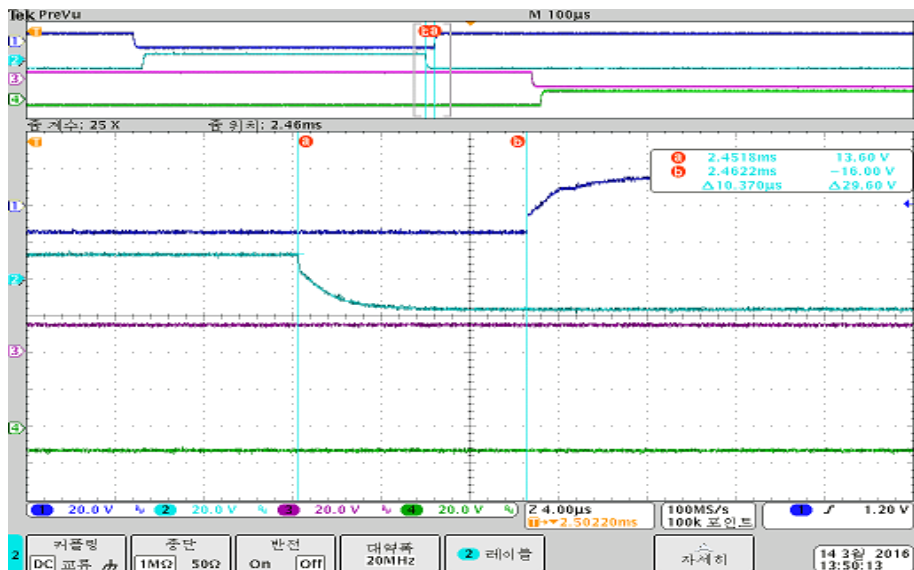


Fig. 9 IGBT dead time adjustment via the interface B/D.

(4 coaches) and IGBT C/I STACK (1 coach) as shown in Fig. 8. The data for FC voltage, U phase output current, and vibration acceleration (JERK) were measured by testing in the field.

The dead time was approximately 10 μ s applied in the field test.

The vibration acceleration (Jerk) was measured in the field test. As a result, the vibration acceleration (Jerk) of the GTO coach and IGBT coach was equal to or below the specified value of 8.0 m/s^3 . It has also been confirmed that the ride quality of the train is fairly stable.

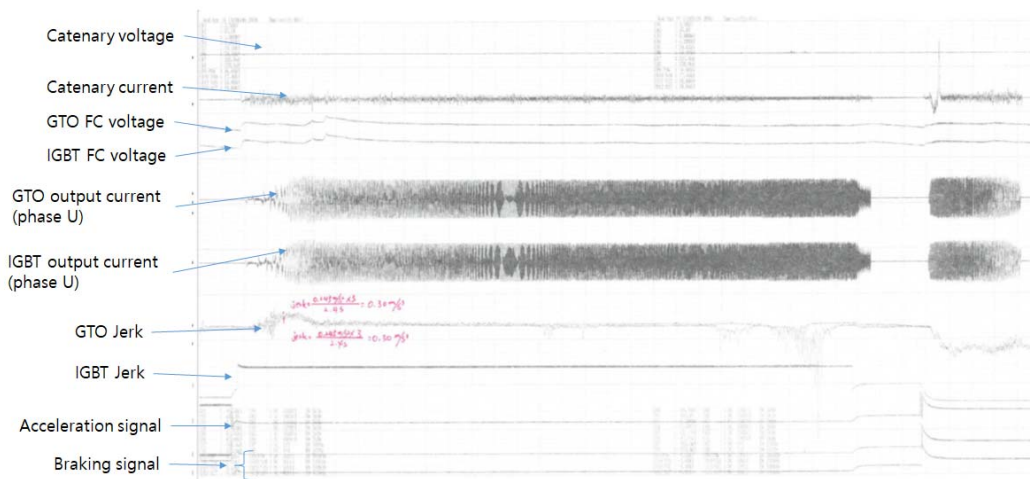


Fig. 10 Mains commissioning measured waveform.

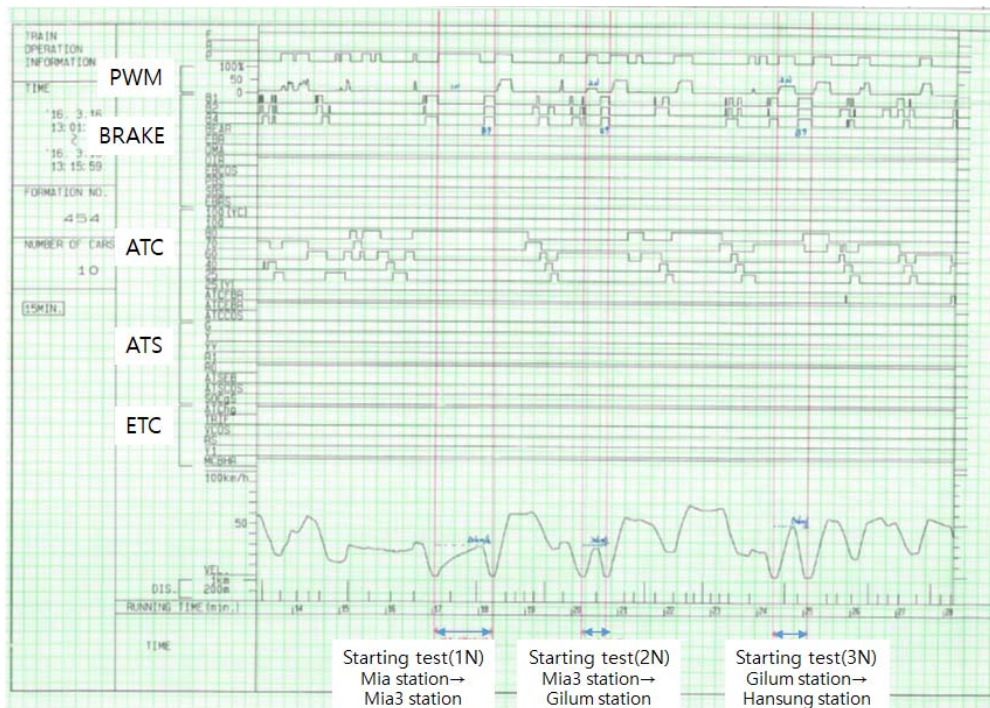


Fig. 11 Train service record.

3. Conclusion

The existing GTO type (4 coaches) and the developer IGBT type (1 coach) were mixed and installed on the VVVF train of the GTO type. Compatibility has been verified through field test. The performance of mixing different power conversion devices was secured through field operation. IGBT C/I (Converter/Inverter) STACK and its components have been built. The IGBT type has been verified by

applying it to all 5 coaches of power vehicles to verify compatibility with existing GTO type controllers on a train basis. The test result confirmed good operation performance. By prototype using IGBT element, existing GTO type controllers have been verified for compatibility in coach and train units. Instead of the maintenance type, which replaces the entire system at a huge cost, the IGBT type per coach is expected to be an efficient alternative to maintenance.

Acknowledgments

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