Measurement and Characterization of Harmonics on the Taipei MRT DC System

Ying-Tung Hsiao, *Member, IEEE,* and Kuang-Chieh Lin

***Abstract*—The harmonics of the propulsion power supply system on the Taipei Mass Rapid Transit System (TMRTS) are characterized. This study applies a new measurement method based on the railway magnetic field measurement technique, to record the dc current harmonics of the TMRT system under various operating conditions. Analysis of the data obtained through these field measurements reveals the presence of both typical and atypical harmonics while the trains are running. The monitored information from the TMRTS during dynamic operation helps engineers (planners) to identify how many orders and levels of harmonics may be present.**

***Index Terms*—Harmonics, mass rapid transit system (MRTS), railway magnetic field, traction power system.**

I. Introduction

In 1997, the Taipei Mass Rapid Transit System (TMRTS) was opened as the first heavy-capacity transit line in Taiwan, R.O.C. Four lines (Danshui Line, Zhonghe Line, Xindian Line, and Bannan Line) presently operate. The TMRTS is a 750-V dc third-rail metro railway. Its power is supplied from Taipower's bulk supply substations (BSS) (3ϕ, 60 Hz, and 161/22 kV); power is then fed to traction supply substations (TSSs) (22 kV) via two zigzag rectifier transformers [1]. The zigzag windings allow the phase of the primary voltage to be shifted by $+7.5^{\circ}$ or -7.5°. All TSSs were originally equipped with two 24-plus converter units to supply 750 V dc through the third rail to trains. The railroad tracks are the return path of the loading current. Figs. 1 and 2 depict the scheme of the traction power supply system. The running rails are not only used as the return current path but also to carry signaling for traffic control, via impedance bonds. Therefore, the railroad includes controls signals, propulsion power, harmonics, and other electromagnetic noise. These signals may be compatible or may interfere with each other. Therefore, a well-planned and compromised interface between them must be made.

In this study, a harmonic survey of the TMRTS on the dc side was performed under various dynamic operations. The work elucidates a new harmonic measurement method, based on the railway magnetic field measurement technique to identify harmonics on dc currents and assess the extent to which harmonics exist in the MRTS.

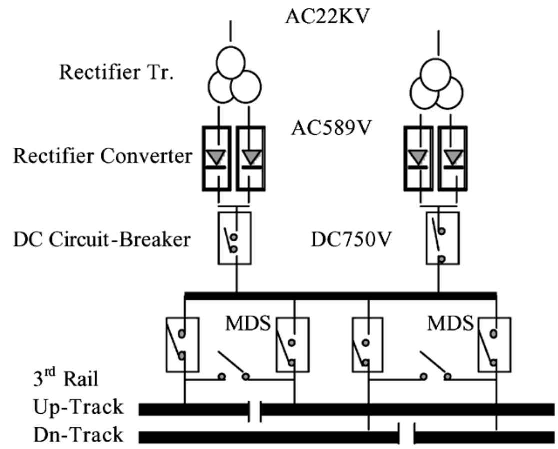

Fig. 1. 22-kVac–750-V dc traction power system.

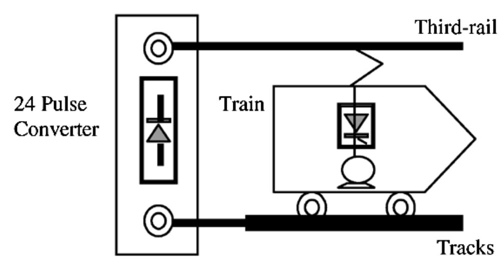

Fig. 2. Schema of traction power system.

The harmonic currents of the MRTS can normally be predicted by simulated analysis methods, for example, [2]–[7]. However, most systems involved in these methods are ideal or approximations and neglect some parameters, due to the complexity or constraints on the real system. Some useful information is evidently lost from the simulation results, as can be seen from the field measurement data. This paper will present the results of the field monitoring of the TMRTS and will characterize the harmonics of the TMRTS on the dc side.

The remainder of this paper is organized as follows. Section II introduces the layout of the traction power supply system. Section III describes the theoretical method for prediction the harmonics on an inverter of its dc side. Section IV presents a novel harmonic measurement method for field measurement. The field measurement of the harmonics of the TMRTS on the dc side is performed under various dynamic operations. Moreover, this work reports the analysis and characterization of the harmonics of the TMRTS on the dc side. Conclusions are finally drawn in Section V.

Paper ICPSD-03IAS30-1, presented at the 2003 Industry Applications Society Annual Meeting, Salt Lake City, UT, October 12–16, and approved for publication in the IEEE Transactions on Industry Applications by the Power Systems Engineering Committee of the IEEE Industry Applications Society. Manuscript submitted for review October 15, 2003 and released for publication July 1, 2004. This work was supported in part by the National Science Council of the Republic of China under Grant NSC 91-2213-E-032-031.

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Digital Object Identifier 10.1109/TIA.2004.836224

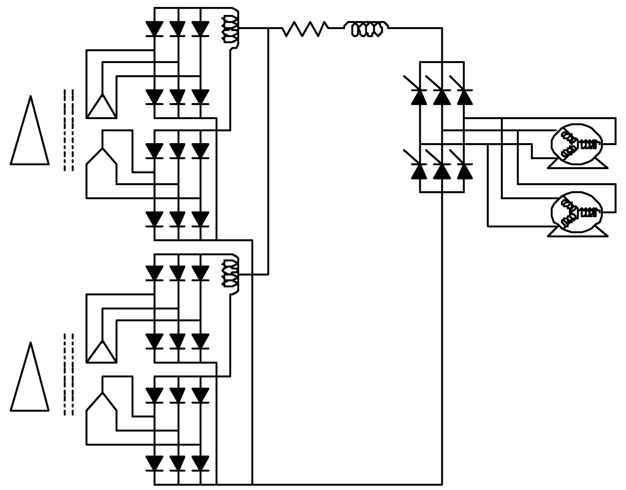

Fig. 3. 24-pulse dc traction power.

TABLE I
RATINGS OF THE DRIVING MOTORS

Types	Inverter	Voltage (AC)	Speed (rpm)	Power (kW)	Gear-ratio	Control frequency
1	GTO	507	1658	147	6.6667	0~133Hz
2	GTO	478	2050	230	6.8125	0~133Hz

II. LAYOUT OF TRACTION POWER SUPPLY SYSTEM

Fig. 1 illustrates the layout of the power supply system, with dedicated 161-kV Taipower transmission lines to the BSS (161 kV/22 kV). The 22-kV ac power of the TSS (22 kV/589 V) comes from the low-tension side of the BSS, via power cables. The TSS includes two transformers with three-phase-to-six-phase winding, to convert ac power from 22 kV to 589 V; the primary winding is in $\triangle$ connections and the secondary winding is in $\triangle$ and Y connections. Fig. 3 shows the two transformers with two parallel 12-pulse rectifiers to form a 24-pulse rectifier unit. The primary winding is not with phase shift. The two secondary windings have phase shifts of -7.5° and $+22.5^\circ$, and of $+7.5^\circ$ and -22.5°, respectively. They are combined to yield a phase shift of 15°, and are fed to two parallel 12-pulse rectifiers, to supply 24-pulse 750-V dc traction power.

The high-capacity TMRTS operates with six-car trains (four motor cars and two trailer cars) [8]. Each train is accompanied by a driver for handling unexpected incidents. The six cars of a train are arranged as: 1) DM1 (with a driver room and one variable-voltage variable-frequency (VVVF) gate-turn-off thyristor (GTO) inverter unit); 2) T (trailer); 3) M2 (with one VVVF GTO inverter unit); 4) M2; 5) T; and 6) DM1. In summary, each train includes two driver rooms (DM1), four inverter units (DM1 and DM2), and 16 induction motors (DM1 and M2). Table I lists the ratings of the motor in the TMRTS. A car (DM1 And DM2) has four 200–hpp three-phase induction motors, driven by two VVVF GTO inverters [1], [8].

Fig. 4 illustrates the circuit of the VVVF inverter that is composed of: 1) six GTO sets; 2) low-pass filter (inductance L1 and *R–C* sets); and 3) breaking circuit (R1 and R2) [9]. R1, in series with a GTO, is used to receive the breaking energy and dissipate it as heat. The electric braking of motor drives is achieved

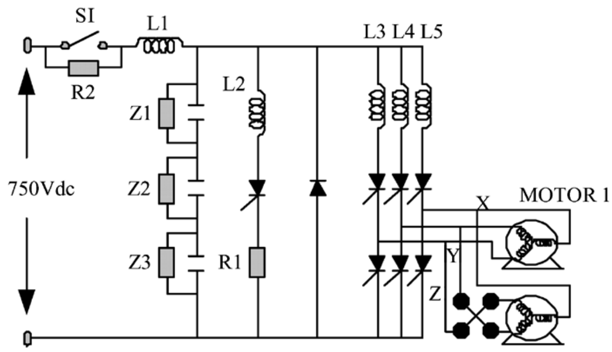

Fig. 4. VVVF inverter on train circuit.

by causing the motor to act as a generator. The voltage of the input port of the inverter set may be increased and the rising voltage can be dissipated by R2, by opening switch S1.

Each inverter set is loaded with two motors in different phase sequences. The two motors run in opposite directions and should be combined in opposite directions to drive a car. The VVVF inverter has three operation modes: 1) the pulsewidth-modulation (PWM) mode has a control frequency from 0 to 35 Hz and control speed from 0 to 22 km/h; 2) the quasi-six-step mode has a control frequency from 35 to 67 Hz and control speed from 22 to 42 km/h; and 3) the six-step mode has a control frequency above 67 Hz and control speed is from 42 to 90 km/h.

The maximum speed of the motor is 400 r/min at a control frequency of 133 Hz. The speed limit under manual operation without automatic train protection (ATP) is 96 km/h. For the TMRTS, the speed limit is set at 90 km/h in the six-step mode and at 80 km/h in the ATP mode.

III. DC CURRENT HARMONICS

The harmonic frequencies on the dc side of an n-pulse naturally commutated converter are multiples of $nf_{\rm ac}$, where $f_{\rm ac}$ is the fundamental ac frequency [10]. Consequently, the harmonics of the dc current due to the rectifier are at frequencies

$$h = pn \pm 1 \qquad n = 1, 2, 3 \ldots. \tag{1}$$

where h represents the order of harmonic frequencies, p denotes the pulse number of rectifiers for a 24-pluse inverter, and the dc current harmonic is expressed as a Fourier series, as follows:

$$I = \frac{4\sqrt{3}}{\Pi} I_d \left[\cos \omega t - \frac{1}{23} \cos 23\omega t + \frac{1}{25} \cos 25\omega t - \frac{1}{47} \cos 47\omega t + \ldots \right] \tag{2}$$

where I_d denotes the dc current and I represents the ac phase current. From (2), the ideal order of harmonics is $1, 23, 25, 47, 49, \ldots$. In fact, the harmonic on the traction power is affected by the train loading, distance of the train from the feeding point, and other loading from the induction circuit. Therefore, the order and level of these harmonics may be different from those obtained from (2). The harmonics properties of the traction power for the MRTS cannot be analyzed only by theoretical prediction.

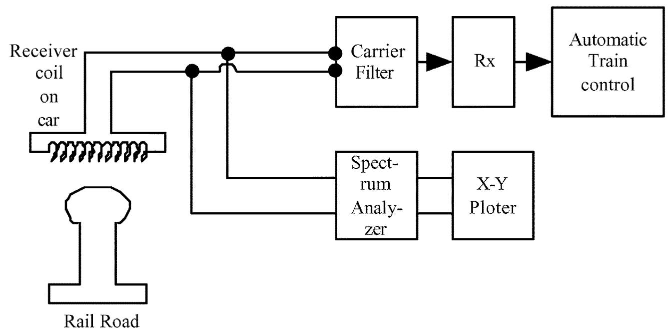

Fig. 5. Measurement of dc traction power harmonics.

IV. Measurements and Characterization of Harmonics on the DC Side

The measurements of the harmonics of the TMRT system on the dc side are held in the Peitou Depot Test Track and Bannan Line, respectively, wherein the measurements of the Peitou Depot Test Track employ one train with six cars during daytime, regardless of the load variation between the ac side of the traction power supply and the ac side of the power substation. This measurement is to proceed in the case of no other trains in operation. As such the measurements of the Bannan Line during the nighttime in the case of no other trains employ one train (six cars), regardless of the load factor of the ac side.

Fig. 5 presents the configuration of the measurement system for the TMRT system. The receiver coil is installed under the pilot cab, 9.1 cm from the railroad. The traction current is transferred from the third track to the trains, and then output from the trains into the rails through the wheels of the trains, hereinafter returning to the negative polarity of the traction power supply. The magnetic file induced from the traction current in the tracks utilizes the receiver coil to sense it. The receiver coil connects with a spectrum analyzer for analyzing the harmonic components of the traction current.

There are also the carrier signals of the audio-frequency track circuit in the railroad, therefore, the carrier signal system in the tracks must first be shut off when measuring and, thus, the measuring harmonics are the traction power harmonics.

The measurements are made when the train is: 1) standing by without running; 2) running at a low speed; and 3) running at a high speed.

A. Train Is Standing by Without Running

After the train runs, it stands on the railroad while the carry control signal is turned off but the loadings (for example, air conditioning and lights) of the train are on. Thus, the generated harmonics from the VVVF inverter and the motor driver can be excluded.

The measurement data are divided into three groups, which are 1st–18th (60–1080 Hz), 19th–47th (1140–2820 Hz), and 48th–73rd (2880–4380 Hz). Figs. 6–8 depict the harmonics of the three groups. In Fig. 6, the first-order harmonic (60 Hz) is -5.31 dB and the others are under -25 dB. Summarizing the above data, the amplitude of the odd harmonics is greater than that of the even harmonic. Most harmonics are above -60 dB. However, some even-order harmonics, such as the 18th, 24th, 30th, and 40th are greater than -60 dB. In particular, some even-order harmonics are multiples of the 6th harmonic (360 Hz) and are summarized in Table II.

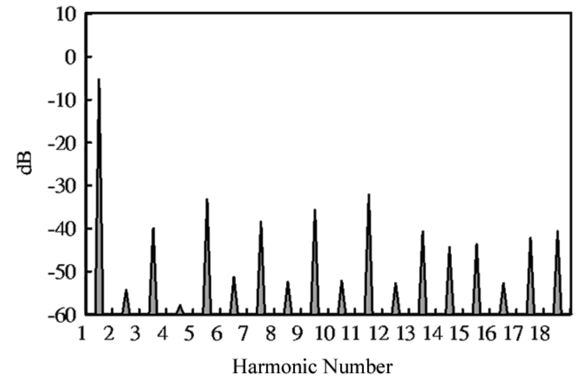

Fig. 6. Harmonics (1st–18th) under the standing train cases.

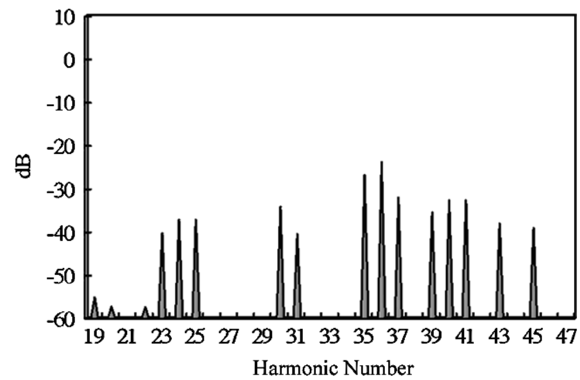

Fig. 7. Harmonics (19th–47th) under the standing train cases.

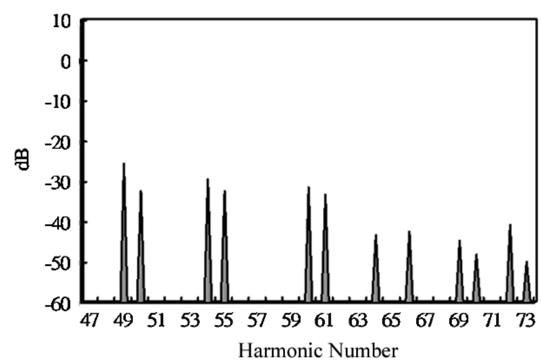

Fig. 8. Harmonics (47th–73rd) under the standing train cases.

B. Train Runs at Low Speed

In this case, the train is operating in the ATO mode. The audio-frequency track circuits of the wayside control unit runs to transmit the control carry signals (speed code) specified in Tables III and IV [11] to control the speed of the train. During the measurement, the VVVF inverter is turned on to drive the motor while the train speed is controlled by the speed code specified by the signal control center. These measurement data include the harmonics of propulsion power, control signal, and loading of the trains' equipment. Therefore, in analyzing the spectrum of these data, the control frequency is limited to 0–10 kHz to exclude the radio frequency. The measured data concerning the train during dynamic operation show that the harmonics vary with the speed and location of the train. The data vary over a

TABLE II
HARMONICS WHOSE FREQUENCIES ARE MULTIPLES OF 360 Hz

Orders	Frequency	Amplitude
6th	360 Hz	-51.44 dB
12th	720 Hz	-52.76 dB
18th	1080 Hz	-40.65 dB
24th	1440 Hz	-37.25 dB
30th	1800 Hz	-34.22 dB
36th	2160 Hz	-23.94 dB
42th	2520 Hz	--
48th	2880 Hz	--
54th	3240 Hz	-29.50 dB
60th	3600 Hz	-31.56 dB
66th	3960 Hz	-42.50 dB
72th	4320 Hz	-40.86 dB

TABLE III
BLOCK AUDIO FREQUENCY CODE

No.	Block audio frequency	Code rate
F1	2970 Hz	2~3Hz
F2	3330 Hz	2~3Hz
F3	3510 Hz	2~3Hz
F4	3690 Hz	2~3Hz
F5	3870 Hz	2~3Hz
F6	4230 Hz	2~3Hz
F7	4410 Hz	2~3Hz
F8	4950 Hz	2~3Hz

TABLE IV
TRAIN SPEED CONTROL CODE

Speed	Frequency	Code rate
10 KPH	2340 Hz	8.6 Hz
25 KPH	2340 Hz	10.8Hz
40 KPH	2340 Hz	13.6Hz
55 KPH	2340 Hz	16.8Hz
65 KPH	2340 Hz	20.4Hz
80KPH	2340 Hz	27.5Hz
Left door	2340 Hz	5.0 Hz
Right door	2340 Hz	6.6 Hz

large range, and so are divided into two groups, which are: 1) low speed (0–40 km/h) and 2) high speed (65–80 km/h). These cases are discussed below.

For the low-speed cases, the train runs in ATO mode with a speed from 0 to 25 km/h and then from 25 to 40 km/h. Figs. 9 and 10 illustrate the harmonic spectrum of the 1st–49th and 53rd–198th, respectively.

The rate of change of the harmonic amplitude decreases as the order of the harmonic increases, because of the effect of the low-pass filter and PWM control on the propulsion system. Notably, the measured results differ from the simulation results. The simulations generally consider ideal devices and neglect some parameters of the system. In fact, the harmonics of the propulsion power supply system vary with many factors such as the train's status, impedance of the propulsion system, filters, operation of the inverter, and others.

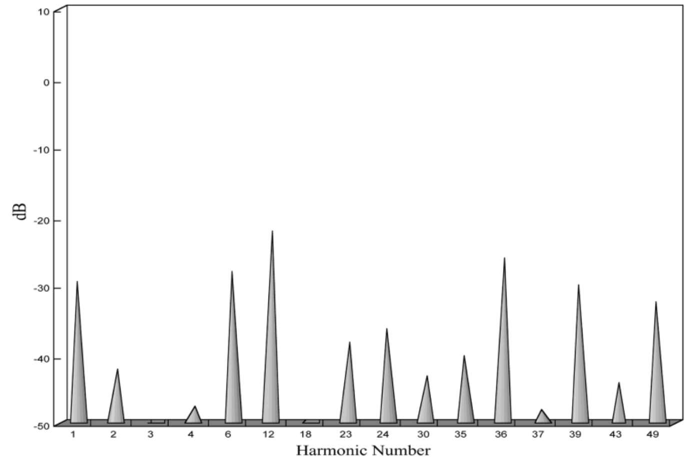

Fig. 9. Harmonics (1st–49th) under the low-speed cases.

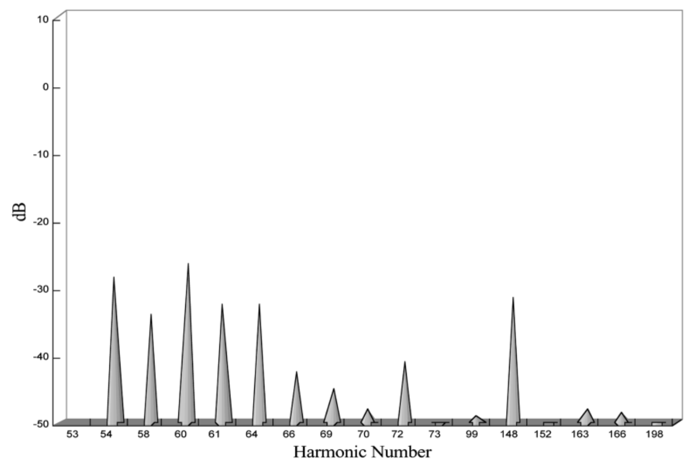

Fig. 10. Harmonics (50th–198th) under the low-speed cases.

From Figs. 9 and 10, it is interesting to note that the harmonic frequencies are with shift (different with the characteristic harmonics) due to the inductance loads and the operation of GTO switching. When the frequency of harmonics is over 1 kHz, this phenomenon gradually appears. It is affected by the blanking time during the GTO switch turn-off and turn-on as well as the delay time of the communication angle of the inverters.

C. Train Runs at High Speed

For the high-speed test case, the train runs in the ATO mode, with a speed from 65 to 80 km/h. The speed limit is maintained under 80 km/h by the automatic train protection, and the train is operated in the three states, which are coast, acceleration, and slowdown.

The train's propulsion motor is in the generator mode in the coast state, and in the motor mode in the acceleration and slowdown states.

Fig. 11 indicates the harmonic spectrum of the measured data, which includes harmonics above −60 dB only, and ignores control signals. Notably, most of the harmonics are multiples of the 6th order (360 Hz, 720 Hz, 1080 Hz. . .). Moreover, the amplitudes of the harmonics decrease while the train accelerates, but the harmonics that are multiples of 360 Hz are clearly enhanced, except those of orders 72, 84, 90, and 96 (which do not exceed −60 dB) and might be canceled during the commutation of the inverters.

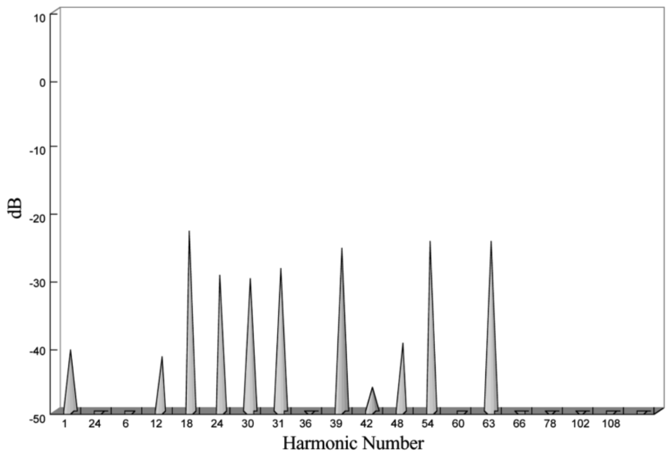

Fig. 11. Harmonics (1st–108th) under the high-speed cases.

TABLE V
HARMONICS WHOSE FREQUENCIES ARE MULTIPLES OF 360 Hz AT LOW AND HIGH SPEEDS

Orders	Frequency (approximation) (Hz)	Standing (dB)	Low speed (dB)	High speed (dB)
6th	360	-51.44	-27.98	-42.02
12th	720	-52.76	-22.35	-23.12
18th	1080	-40.65	-49.56	-29.56
24th	1440	-37.25	-26.33	-30.23
30th	1800	-34.20	-43.24	-28.33
36th	2160	-23.94	-26.21	-25.76
42th	2520	--	--	-40.02
48th	2880	--	--	-24.72
54th	3240	-29.50	-28.65	-58.76
60th	3600	-31.56	-26.52	-24.76
66th	3960	--	-42.50	-53.37
72th	4320	-40.87	-40.82	--
78th	4680	--	--	-56.72
84th	5040	--	--	--
90th	5400	--	--	--
96th	5760	--	--	--
102th	6120	--	--	-50.93
108th	6480	--	--	-57.32

Table V summarizes the harmonics that are multiples of 360 Hz at low and high speeds. The table shows that the amplitudes of harmonics that are multiples of 360 Hz at low train speeds obviously exceed those of the standing train. In particular, the dc propulsion power includes the greatest harmonic with a multiple of 360 Hz when the train is running at high speed.

V. CONCLUSION

Field measurements of dc current harmonics on the TMRTS were made based on the railway magnetic field measurement technique. This paper has presented the characteristics of harmonics on the dc side of the power supply system under various operating conditions. These field measurements reveal the nontypical harmonics present while the trains are operational. Measurements of harmonics on the MRTS should be compiled and shared because important information is missed by simulated analysis. Such sharing would enable planners (or designers) to review their designs, with regard to the orders and levels of harmonics to ensure that the systems run smoothly. Future studies may be done on the detailed comparison of the measured results and the simulation results for this specific system and research the influence on the harmonics on the dc side with respect to the variation of the ac side of the traction power supply (e.g., unbalance).

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