Measurement and Characterization of DC Harmonics on the Taipei MRT System

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

Abstract-- The dc 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.

Keywords—Mass rapid transit system, harmonics, 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. Four lines (Tamshui line, Chungho line, Hsintien line, and Panchiao line) presently operate. The TMRTS is a 750dcV third rail metro railway. Its power is supplied from Taipower's bulk supply substations (BBS)(3 ϕ , 60Hz and 161/22kV); power is then fed to traction supply substations (TSS)(22kV) via two zig-zag rectifier transformers [1]. The zig-zag windings allow the phase of the primary voltage to be shifted by +7.5° or –7.5°. All TSSs were originally equipped with two 24-plus converter units to supply 750V dc through the third rail to trains. The railroad tracks are the return path of the loading current. Figure 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. So, a well-planned and compromised interface between them must be made.

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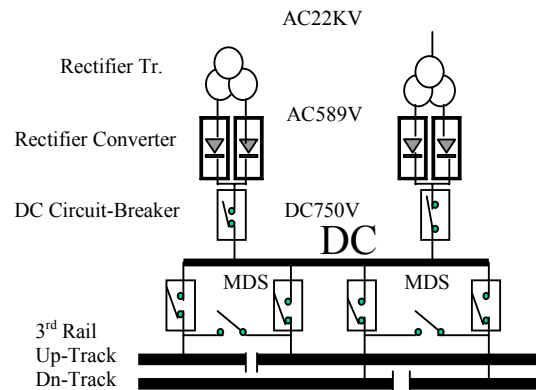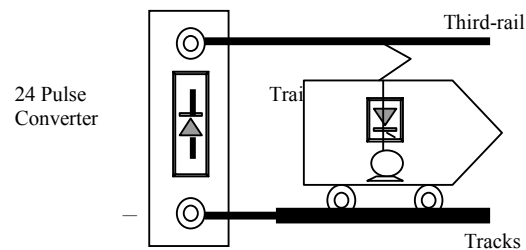

Fig.1. 22KVAC-750VDC traction power system.

Fig.2. Schema of traction power system.

exist in the MRTS. The harmonic currents of 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 TMRTS and will characterize the dc harmonics of the TMRTS.

The rest 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 dc harmonic on an inverter. Section IV presents a novel dc harmonic measurement method for field measurement. The field measurement of the dc harmonic on the TMRTS is performed under various dynamic operations. Moreover, this work reports the analysis and characterization of the dc

harmonics on the TMRTS. Conclusions are finally drawn in the last section.

II. LAYOUT OF TRACTION POWER SUPPLY SYSTEM

Figure 1 illustrates the layout of power supply system, with dedicated 161kV Taipower transmission lines to BSS (161kV/22kV). The 22kV ac power of the TSS (22kV/589V) comes from the low-tension side of the BSS, via power cables. TSS includes two transformers with three phase to six phase winging, to convert ac power from 22kV to 589V; the primary winding is in △ connections and the secondary winding is in △ and Y connections. Figure 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° and of +7.5° 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 750V 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 VVVF 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 sixteen induction motors (DM1 and M2). Table 1 lists the ratings of the motor in TMRTS. A car (DM1 And DM2) has four 200Hp three-phase induction motors, driven by two variable-voltage variable-frequency (VVVF) GTO inverters [1,8].
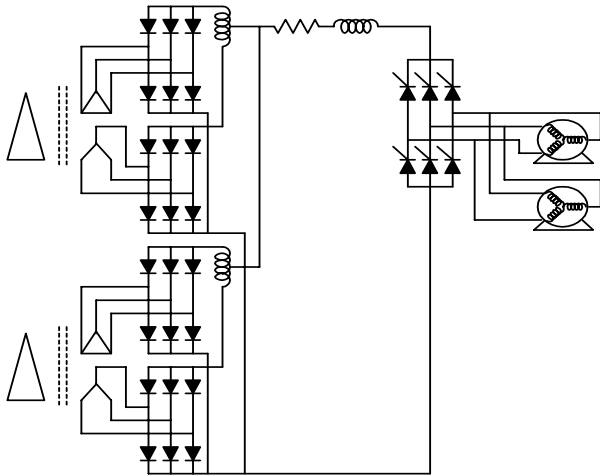

Fig.3. 24 Pulse DC Traction Power.

TABLE 1
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

Figure 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 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.
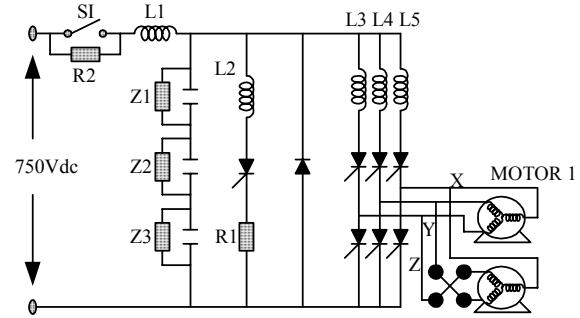

Fig. 4. VVVF Inverter on Train Circuit

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 PWM mode has a control frequency from 0 to 35 Hz and control speed from 0 to 22KPH. (2) The quasi six-step mode has a control frequency from 35 to 67Hz and control speed from 22 to 42 KPH. (3) The six-step mode has a control frequency above 67Hz and control speed is from 42 to 90KPH.

The maximum speed of the motor is 400 RPM at a control frequency of 133Hz. The speed limit under manual operation without automatic train protection (ATP) is 96 KPH. For the TMRTS, the speed limit is set at 90kPH in the six-step mode, and at 80kPH 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_{ac}, where f_{ac} is the fundamental ac frequency [10]. Consequently, the harmonics of the dc current due to the rectifier are at frequencies:

$$h = pn \pm 1 \quad n=1,2,3\dots \qquad (1)$$

where h is 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.

$$I = \frac{4\sqrt{3}}{\Pi} Id\left[\cos\omega t - \frac{1}{23}\cos 23wt + \frac{1}{25}\cos\omega t - \frac{1}{47}\cos 47\omega t +\dots\right] \quad (2)$$

where I_d denotes the dc current and I represents the ac phase current. From Eq. (2), the ideal order of harmonics is 1, 23, 25, 47, 49, … . 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 of obtained from Eq. (2). The dc

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harmonic properties of the traction power for MRTS cannot be analyzed only by theoretical prediction.

IV. MEASUREMENTS AND CHARACTERIZATION OF DC HARMONICS

Figure 5 presents the configuration of the control and measurement system for the TMRT system. The receiver coil is installed under a cab, 9.1cm from the railroad. The loading current of the trains is output from the negative port of the car to the railroad, via the wheels. The receiver coil can sense the magnetic file induced from the current of the railroad, including the loading current of trains and the carry signal. Thus, the control system must be closed to exclude its signal to measure the dc current harmonic of the propulsion power on the third railroad. The harmonics of the loading current vary with the train's speed. Accordingly, in this work, the measurements are made when the train is (1) standing by without running, (2) running at a low speed (3) running at a medium speed and (4) running with a high speed.
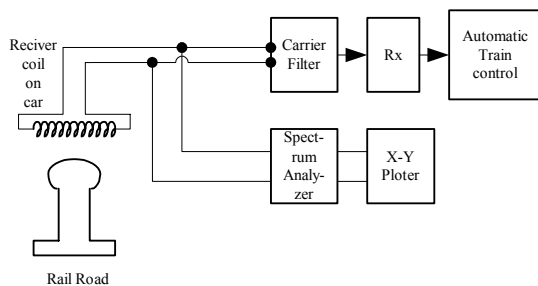
Fig.5. Measurement of DC traction power harmonics.

A. The 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 - 1080Hz), 19th - 47th (1140 - 2820Hz) and 48th - 73th (2880 - 4380Hz). Figures 6 to 8 depict the harmonics of the three groups. In Fig.6, the first order (60Hz) harmonic is −5.31dB and the others are under −25dB. Summarizing the above data, the amplitude of the odd harmonic is greater than that of the even harmonic. Most harmonics are above −60dB. However, the some even order harmonics, such as the 18th, 24th, 30th, and 40th are greater than −60dB. In particular, some even order harmonics are multiples of the 6th harmonic (360Hz) and are summarized in Table 2.

TABLE 2
HARMONICS WHOSE FREQUENCIES ARE MULTIPLES OF 360HZ

Orders	Frequency	Amplitude
6th	360 Hz	-51.44 dB

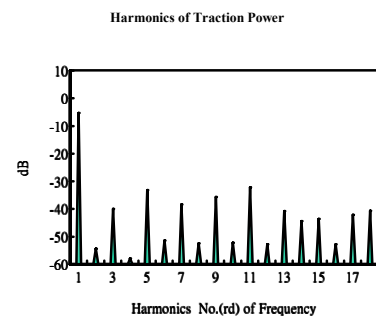| 12th	720 Hz	-52.76 dB
18th	1080 Hz	-40.65 dB
24th	1440 Hz	-37.25 dB
30th	1800 Hz	-34.22 dB
36th	2160 Hz	-23.94 dB
42th	2520 Hz	--
48th	2880 Hz	--
54th	3240 Hz	-29.50 dB
60th	3600 Hz	-31.56 dB
66th	3960 Hz	-42.50 dB
72th	4320 Hz	-40.86 dB

Harmonics of Traction Power

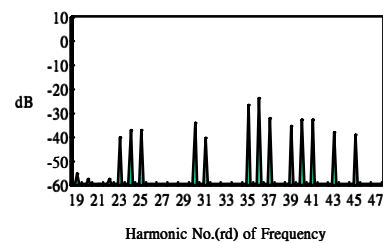Fig. 6. Harmonics (1-17th) under the standing train cases.

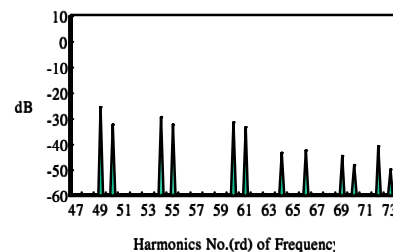Fig. 7. Harmonics (19-47th) under the standing train cases.

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

B. The train runs at low and medium 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

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Table 3 and 4 [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 to 10 KHz to exclude the radio frequency. The measured data concerning the train during dynamic operation shows that the harmonics vary with the speed and location of the train. The data vary over a large range, and so are divided into two groups, which are (1) low and medium speed (0-40 KPH) and (2) high speed (65-80 KPH). The high-speed case is discussed below.

For the low and medium speed cases, the train runs in ATO mode with a speed from 0 KPH to 25 KPH and then from 25KPH to 40KPH. Figures 9 and 10 illustrate the harmonic spectrum of the 1st-49th and 53th-198th, respectively.

The rate of change of the harmonic amplitude decreases with as the order of the harmonic increases, because of the effect of the low-pass filter and PWM control 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 dc harmonic of the propulsion power supply system varies with many factors such as the train's status, impedance of the propulsion system, filters, operation of the inverter, and others.

From figure 9 and 10, it is interested 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 is gradually appeared. It is affected by the blanking time during the GTO switch turn-off and turn-on as well as the delay time of communication angle of inverters.

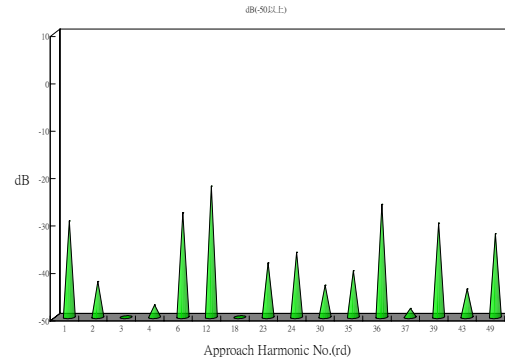| 25 KPH	2340 Hz	10.8Hz
40 KPH	2340 Hz	13.6Hz
55 KPH	2340 Hz	16.8Hz
65 KPH	2340 Hz	20.4Hz
80KPH	2340 Hz	27.5Hz
Left door	2340 Hz	5.0 Hz
Right door	2340 Hz	6.6 Hz

Fig. 9. Harmonics (1-49th) under the low speed cases.
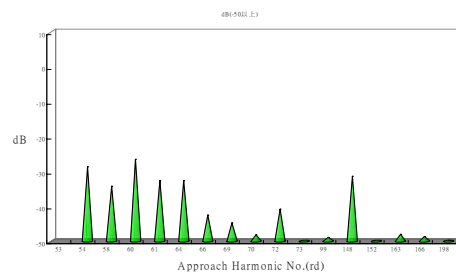
Fig. 10. Harmonics (50-198th) under the low speed cases.

TABLE 3
BLOCK AUDIO FREQUENCY CODE

No.	Block audio frequency	Code rate
F1	2970 Hz	2~3Hz
F2	3330 Hz	2~3Hz
F3	3510 Hz	~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 4
TRAIN SPEED CONTROL CODE

Speed	Frequency	Code rate
10 KPH	2340 Hz	8.6 Hz

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 KPH. The speed limit is maintained under 80 KPH by the automatic train protection, and the train is operated in the three states, which are coast, acceleration and retard.

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.

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

Table 5 summaries the harmonics that are multiples of 360Hz at low, medium and high speeds. The table shows that the amplitudes of harmonics that are multiples of 360Hz at low and medium train speeds obviously exceed those of the standing train. In particular, the dc propulsion power includes

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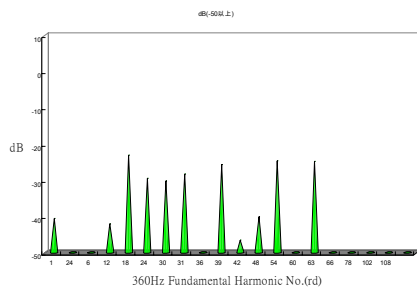the greatest harmonic with a multiple of 360Hz when the train is running at high speed.

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

TABLE 5
HARMONICS WHOSE FREQUENCIES ARE MULTIPLES OF 360HZ AT LOW, MEDIUM AND HIGH SPEEDS.

Orders	Frequency (approximation) (Hz)	Standing (dB)	Low and medium (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

V. CONCLUSIONS

Field measurements of dc current harmonics on the TMRTS are made based on the railway magnetic field measurement technique. This study presents the characteristics of dc harmonics under various operating conditions. These field measurements reveal the non-typical harmonic 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 the systems run smoothly.

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VII. BIOGRAPHIES

Ying-Tung Hsiao received his B.S. degree in electrical engineering from National Taiwan Institute of Technology in 1986, M.S. and Ph.D. degree in electrical engineering from National Taiwan University in 1989 and 1993, respectively. After that, he joined the faculty of ST. John's & ST. Mary's Institute of Technology, Taiwan. He is currently an Associate Professor of Electrical Engineering at Tamkang University, Taiwan. His research interests include power system analysis, optimal theory and motor control.

Kuang-Chieh Lin was born in Kaohsiung, Taiwan in 1960. He graduated from Wu-Feng Technology College in 1980 and received his M.S. degree in electrical engineering from Tamkang University, Taiwan in 2002. His employment experience included the Systemwide E&M Project Office of the Department of Rapid Transit System, TMG, the Synchrotron Radiation Research Center of Executive Yuan, the Pan-Asia Electronics Co, Ltd. Currently he is studying toward his Ph.D. degree in Tamkang University, Taiwan. His research interests include power system analysis and railway electrification design.