Power Quality Measurements of Distribution Systems with LRT Ultra-Fast Charging Infrastructures

Chun-Lien Su Hai-Ming Chin
Department of Marine Engineering
National Kaohsiung Marine University
Kaohsiung City 805, Taiwan
cls@webmail.nkmu.edu.tw;
hmsho@mail.nkmu.edu.tw

Rong-Ceng Leou
Department of Electrical Engineering
Cheng Shu University
Kaohsiung City 833, Taiwan
k0535@gcloud.csu.edu.tw

Chien-Hung Lin
Taiwan Power Research Institute
Taiwan Power Company
Taipei City 100, Taiwan
u621363@taipower.com.tw

***Abstract*—The introduction of catenary-free light rail transits (LRTs) in currently urban transportation systems becomes tendency and attractive alternative to traditional fuel cars and LRTs with overhead contact systems. This type of LRT trains are powered through onboard energy storage systems which are elements in an infrastructure that supplies electric energy for recharging of the LRT trains, which requires a higher charger power and current due to the fixed at-station charge duration of tens of seconds. It has been much more concern over power quality issues caused by the LRT. It is necessary to understand the influence of LRT charging impact on distribution systems before they are operated in scale. In this paper, a field power quality measurement of a practical distribution system connected to a LRT system with 6 traction substation stations and 1 depot traction substation station is carried out. Some of measured results of voltage/current trend, harmonics, and voltage deviations are presented and discussed.**

Keywords—transportation electrification; fast charging; power quality; harmonics; impact study

I. INTRODUCTION

One of the solution for mitigating urban carbon dioxide emission, congestion and harmful human health effects is to develop sustainable and energy efficient multi-type transportation systems from public applications to individual requirements. Meanwhile, vehicle electrification is considered as an important product in the overall sustainable urban mobility chain and measure for greenhouse gas reduction. In this context, light rail transit (LRT) is urban public transport using rolling stock similar to a tramway and has been especially popular in recent years due to their lower capital costs and increased reliability compared to mass rapid transit and heavy rail systems. A new generation of LRT is an automotive vehicle primarily propelled by more traction motors that draw from a rechargeable energy storage device in which the power supply for the system is catenary free [1].

Unlike the existing ground power supply system, which supplies power to the vehicle continuously while in operation, the catenary-free LRT power supply system charges banks of onboard supercapacitors or batteries during station stops. The system is capable of delivering thousands kW of power, or thousands of currents at a direct current (dc) low voltage level in a tens of seconds charging cycle, well within typical station dwell time, with the system notifying the driver when the onboard power storage solution is completely charged [2,3].

One of few electric vehicle drawbacks is that the associated battery chargers are power electronic circuits which, due to their nonlinear nature, can produce deleterious harmonics effects on electric utility distribution systems [4,5]. The most common LRT battery is the energy storage equipment with electric double-layer capacitors (EDLC) and NiHM type with capacities of about hundreds of kilowatt-hours. This increases in energy per mile which implies a higher charger power and current due to the fixed at-station ultra-fast charge duration. The new load would worsen the already harmonic distortion existing in the distribution system. All of the resultant effects will dictate the design of the LRT interface devices and the way that future power network will be constructed and operated.

This paper presents the results of power quality field measurements of catenary-free LRT ultra-fast charging infrastructures to evaluate their harmonic distortion and voltage deviation impacts on an existing medium voltage distribution system. This paper is divided into four sections. Section II reviews the configuration of LRT ultra-charging infrastructures. Section III presents the measured results of the system under study. Finally, section IV summarizes the overall conclusions of the study.

II. CONFIGURATION OF LRT ULTRA-FAST CHARGING INFRASTRUCTURES

This paper focuses on the discussion of the catenary-free LRT ultra-fast charging system and its impacts on voltage deviation and harmonics of distribution systems connected to the LRT traction substation station (TSS). For this purpose, a practical LRT system that is the world's first light rail vehicle system on a fully catenary-free route of 8.7 km is selected for the study [6]. Fig. 1 show the phase I route that consists of 14 stations, 6 traction substation stations, and 1 depot traction substation station. The TSS and onboard energy storage system for the LRT are described as follows.

A. Traction Substation Station

The TSS is an essential component in an infrastructure that is response for supplying electric power to the LRT. Fig. 2

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shows the topologic relationship of TSSs and stations in Fig. 1. According to the currently catenary-free LRT charging techniques, the dc 750 V charging, belong to quick charging, is most common seen [1]. Due to the requirements of dc fast charging on the station and supply reliability, two sets of three-phase rectifier are used for the TSS and DTSS. For other loads, three-phase 380V and single-phase 220V are used. Fig. 3 shows the configuration of power supply for the LRT. The simplified on-line diagram of DTSS and TSS1 in Fig. 3 is shown in Fig. 4.

Fig. 1 The catenary-free LRT route under study [6]

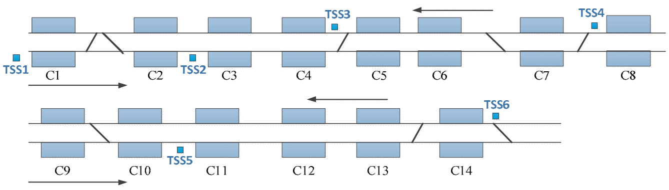


Fig. 2 Topologic relationship of TSSs and stations in Fig. 1

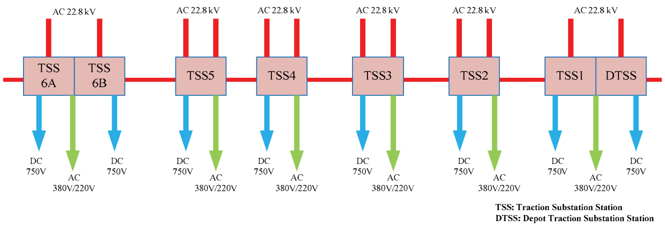


Fig. 3 Voltage level of traction power systems

B. *Onboard Energy Storage System*

The existing overhead contact system (OCS) supplies power to the vehicle continuously while in operation. An alternative to these solutions is the use of on-board energy storage systems which charge banks of onboard supercapacitors and/or batteries during station stops. These technologies emerged not in order to avoid the existence of overhead wires, but to improve the energy efficiency of light rail systems by using of regenerative braking. Each train is equipped with two modules of rapid charge accumulator (ACR) OCS-free system which consists of DC/DC converter, filtering inductor and capacitor, energy storage modules of supercapacitor and battery, control unit, and cooling unit. The supercapacitors can be fully charged, while the train is stopped in a station, in around 20 seconds [7]. In addition, the system recovers the energy stored on the journey and the braking energy too [8]. It can be complemented with batteries as backup for solving supercapacitor's failure situations. Fig. 5 shows the simplified circuit of onboard energy storage systems in the catenary-free LRT train.

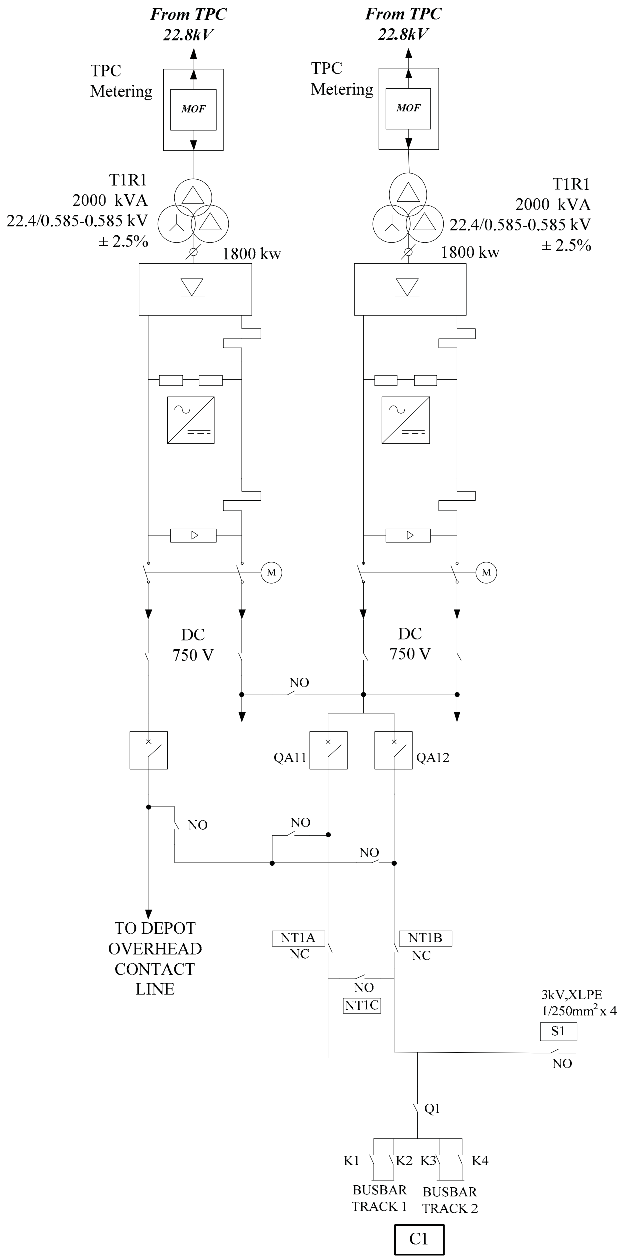


Fig. 4 Simplified on-line diagram of DTSS and TSS1 in Fig. 3

III. Power Quality Measurement Results and Discussions

In order to investigate the power quality impacts on distribution systems connected with LRT ultra-fast charging infrastructures, the TSS 1 and DTSS had been selected for actual measurements that are carried on three-phase four wire 22.8 kV medium-voltage distribution system, which is shown in Fig. 6. Two power quality analyzers were installed in measured points A and B, respectively. The measurement was performed for a time period of one week in order to capture different power quality measurements under different charging and system loading conditions and the results are compared to the limits defined in the standards [9,10]. The measurement results focus on harmonics and voltage deviation which are two of main power quality issues concerned by the utility because of some sensitive industrial customers connected to the same feeder. For the harmonics, the measurement method is based on the IEC 61000-4-7 standard [11]. Two indexes including total harmonic distortion (THD) and total demand distortion (TDD) defined in [12] are calculated and compared.

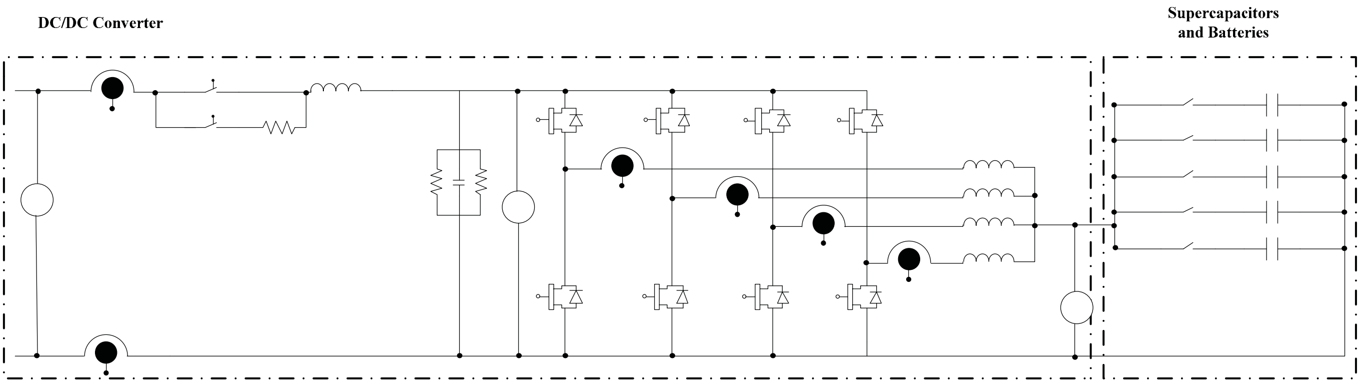


Fig. 5 Simplified circuit of onboard energy storage systems used in the LRT train

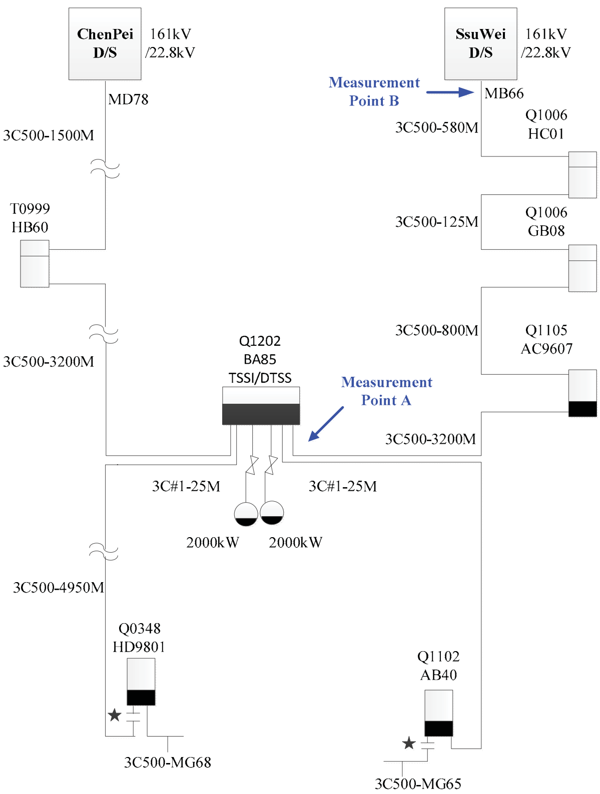
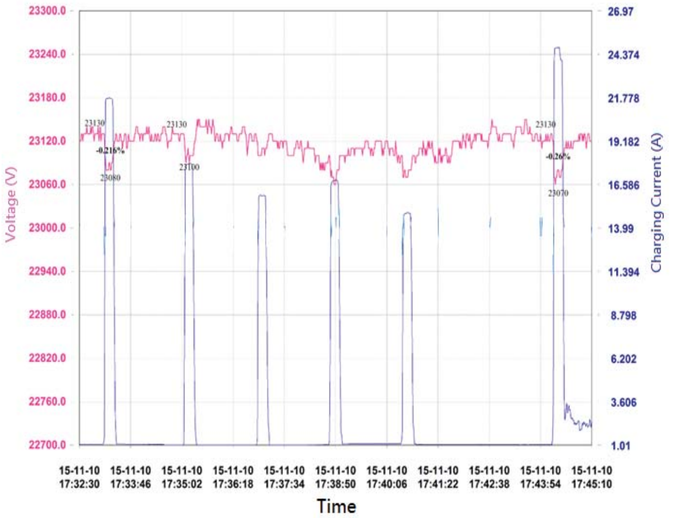


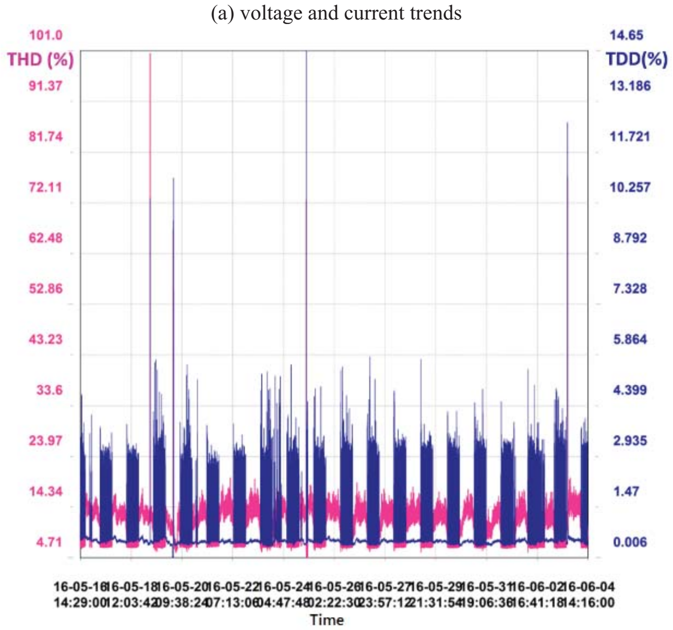
Fig. 6 Simplified one-line diagram of measured distribution system

Fig. 7 shows some of the power quality measurement results in the study. It can be seen from Fig. 7(a) that the voltage mostly varies in the about of ±0.3% ranges that still meet the consideration of the study expected, in which the charging current at the PCC in the 22.8 kV feeder can be about 24.688 A and the active power is about 980 kW. For the harmonic current distortions, the maximum values of the THD and TDD are 101% and 14.65%, respectively, which are beyond the distortion limits for the system. In general. The original recommended practice only addresses steady-state limitations. Since the LRT charging system delivers thousands kW of power in a tens of seconds charging cycle, it is interested to know that the transient conditions exceeding these limitations may be encountered for this type of charging system. For this purpose, two transient harmonic measurements including very short time and short time are defined and suggested in [12]. For the very short time harmonic measurements, the harmonic values can be assessed over a 3-second interval based on an aggregation of 15 consecutive 12 cycle windows for 60 Hz power systems. The 99th percentile value is calculated for each 24-hour period and the harmonic current should be less than 2.0 times the values given in [12], respectively. Figs. 8(a) and 8(b) shows the probability density functions of harmonic current distortions by using the less and more samples, respectively. It can be seen from Figs. 8(a) and 8(b) that the 99th percentile values of TDD are 3.14% and 3.61% for the samples of 1,441 and 80,828, respectively, which are within the 2.0 times the limit of 12%. Due to the ultra-fast charging characteristics for the LRT, it is suggested that an evaluation of very short time harmonic measurements can be used for assessing the LRT charging impact on the distribution system.

Figs. 9 and 10 show the waveform and harmonic spectrum of fast-ultra charging currents at the initial charging stage and steady-state, respectively. Form the analysis results of harmonic spectrum, it can be seen that the main orders of harmonics for the LRT ultra-fast charging current are 11th and 13th. Form the analysis results of charging currents, it is found that an abnormal charging current occurs when the LRT ultra-fast charging system is operated. It may be because a short-circuit phenomenon for the energy conversion circuit in the LRT ultra-fast charging system, which could lead to the system operation security. Figs. 11(a) and 11(b) show that measured charging currents trend and waveforms of abnormal charging currents, respectively. The harmonic spectrums of the abnormal charging currents in Fig. 11(b) are shown in Fig. 12. It is indicated that the main harmonic orders of abnormal charging currents are 2nd, 3th, 4th, and 5th, which are low frequency harmonics. The application of different charging current spectrums for harmonic power flow analysis is the subject for further study.



(a) voltage and current trends

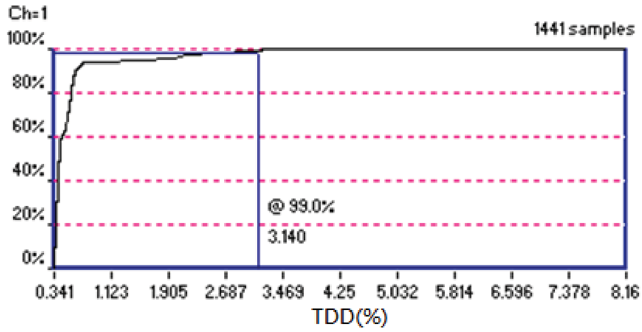


(b) harmonic current indices

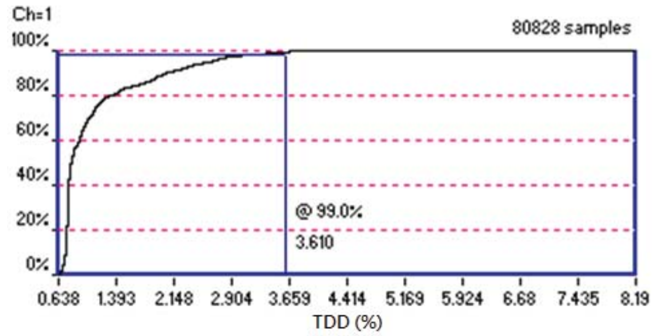
Fig. 7 Power quality measurements for the studied system

IV. CONCLUSIONS

A study for performing the power quality field measurements of a practical distribution system connected to catenary-free LRT ultra-charging infrastructures has been presented. It is found the sources of power quality disturbance in studied cases are mainly from the AC/DC rectifiers used for dc fast charging at the station. Because of this, a large fraction of the voltage deviation and harmonic distortion at a connected bus originates at relatively higher charging currents and smaller dc charging voltages, as observed in the power quality measurements.



(a) less samples



(b) more samples

Fig. 8 Probability density functions of harmonic current distortions

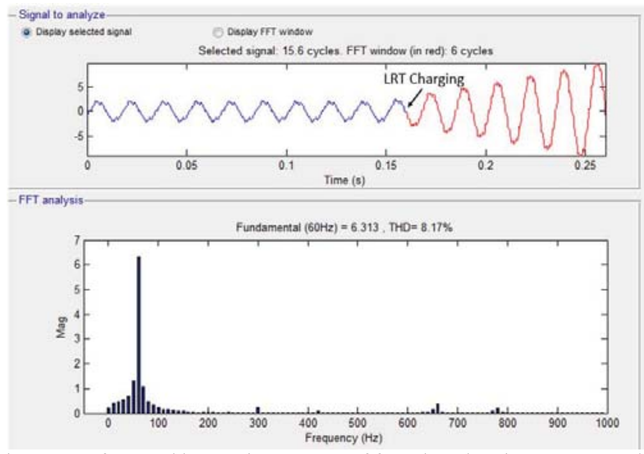


Fig. 9 Waveform and harmonic spectrum of fast-ultra charging currents at the initial charging stage

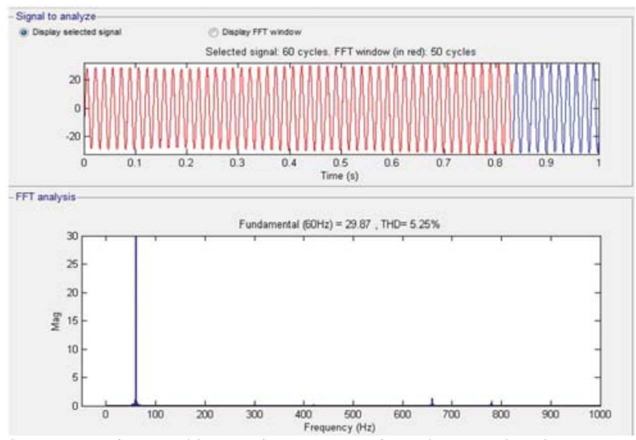
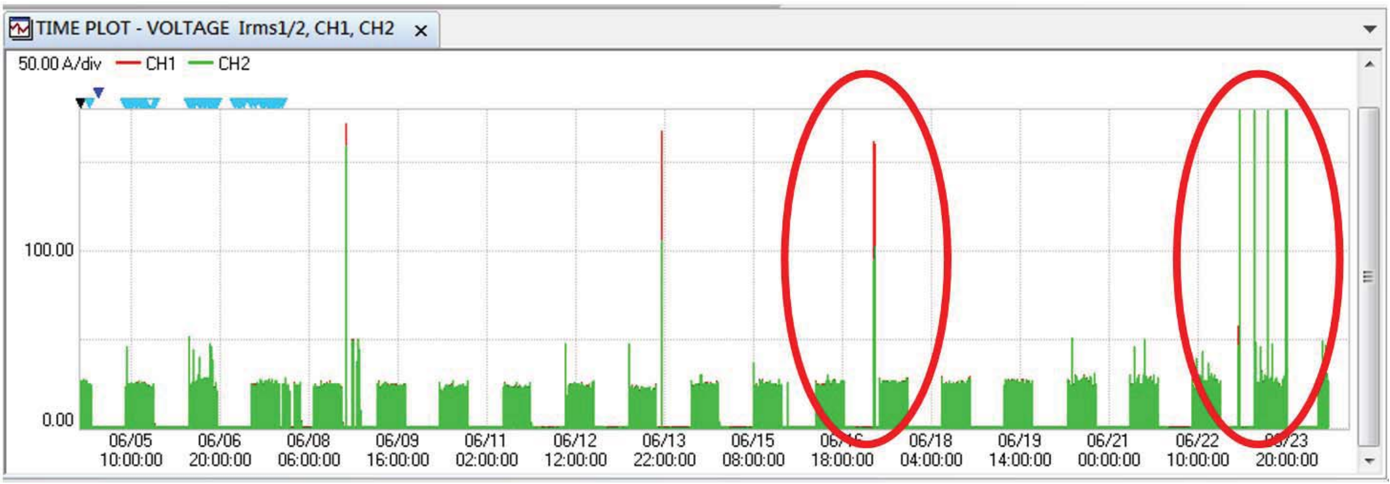


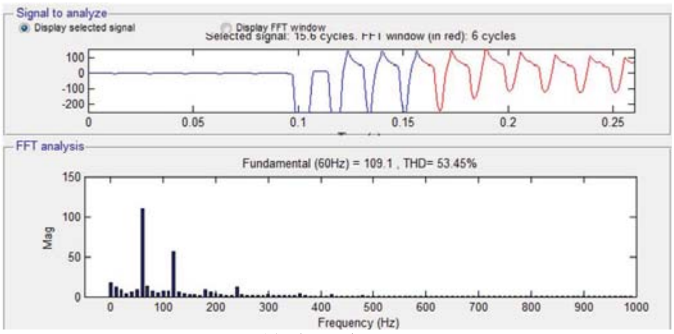
Fig. 10 Waveform and harmonic spectrum of steady-state charging currents



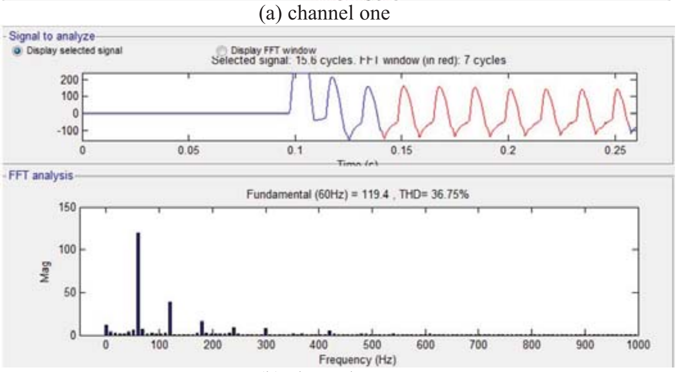
(a) measured charging currents trend

(b) waveforms of abnormal charging currents

Fig. 11 Measured abnormal charging currents



(a) channel one



(b) channel two

Fig. 12 Harmonic spectrum of abnormal charging currents

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