THE STUDY OF MODELING AND HARMONIC FILTERING IN AC ELECTRIC RAILWAY SYSTEMS

KONGTUN KRITSANASUWAN

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THE STUDY OF MODELING AND HARMONIC FILTERING IN AC ELECTRIC RAILWAY SYSTEMS

Suranaree University of Technology has approved this thesis submitted in partial fulfillment of the requirements for a master's degree.

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คำสำคัญ: รถไฟฟ้ากระแสสลับ/รูปแบบโครงสร้างรถไฟฟ้า/ฮาร์มอนิก/ตัวกรองแบบพาสซีฟ/ค่าความเพี้ยนฮาร์มอนิก

วิทยานิพนธ์นี้เสนอรูปแบบและการจำลองการกำจัดฮาร์มอนิกในระบบส่งกำลังของรถไฟฟ้ากระแสสลับ Airport Rail link สายชานเมืองสีน้ำเงิน ในวิทยานิพนธ์เสนอกรณีศึกษา 3 กรณีเพื่อให้เห็นถึงวิธีการกำจัดฮาร์มอนิกแบบต่างได้ได้แก่ การปรับเปลี่ยนรูปแบบของระบบส่งจ่ายกำลังไฟฟ้า การจำลองผลการกำจัดฮาร์มอนิกโดยใช้ข้อมูลฮาร์มอนิกที่ได้จากการวัดและการจำลองผลการกำจัดฮาร์มอนิกโดยใช้ข้อมูลฮาร์มอนิกที่ได้จากลักษณะฮาร์มอริกที่เกิดจากการแปลงกระแสไฟฟ้าของวงจรคอนเวอร์เตอร์โดยจำลองการติดตั้งตัวกรองฮาร์มอนิกแบบพาสซีฟ 4 แบบ ได้แก่ ตัวกรองฮาร์มอนิกแบบปรับคลื่นเดียว ตัวกรองฮาร์มอนิกแบบแบนพาส ตัวกรองฮาร์มอนิกแบบไฮพาส และตัวกรองฮาร์มอนิกแบบซี ทำการจำลองผลการติดตั้งตัวกรองแบบพาสซีฟที่สถานีไฟฟ้าและบนรถไฟในโปรแกรมจำลองแมทแลปเพื่อหาแนวโน้มและประสิทธิภาพการกำจัดฮาร์มอนิกที่จะเกิดขึ้นที่สถานีไฟฟ้า โดยผลลัพธ์จากการจำลองจะนำมาเปรียบเทียบและหาประสิทธิภาพการกำจัดฮาร์มอนิก อีกทั้งยังเทียบมาตรฐานข้อกำหนดสำหรับการควบคุมฮาร์มอนิกในระบบไฟฟ้ากำลัง IEEE519-2014 นอกจากนี้ในการจำลองการติดตั้งตัวกรองแบบพาสซีฟยังมีการเสนอแนวทางการออกแบบตัวกรองแบบซีฟทั้ง 4 แบบเพื่อใช้กับระบบไฟฟ้ากำลังได้อย่างเหมาะสมและสามารถกำจัดฮาร์มอนิกในลำดับที่ต้องการอย่างมีประสิทธิภาพ. ซึ่งจากผลการจำลองพบว่ากรณีศึกษาที่ 1 การเพิ่มจำนวนจุดเชื่อมต่อระหว่างสายส่งและการเพิ่มจำนวนรางส่งผลให้ค่าความต้านทานสายส่งลดลงส่งผลต่อทำให้ปริมาณฮาร์มอนิกที่สถานีไฟฟ้าลดลงเล็กน้อย กรณีศึกษาที่ 2 การนำข้อมูลจากการวัดมาจำลองเพื่อเปรียบเทียบประสิทธิภาพการกำจัดฮาร์มอนิกพบว่าตัวกรองพาสซีฟแบบซี สามารถลดปริมาณฮาร์มอนิกที่สถานีไฟฟ้าได้มากที่สุดและเมื่อเปรียบทียบตำแหน่งที่ติดตั้งตัวกรองระหว่างที่สถานีไฟฟ้าและบนรถไฟพบว่าติดตั้งตัวกรองแบบพาสซีฟบนรถไฟสามารถลดปริมาณฮาร์มอนิกที่สถานีไฟฟ้าได้มากกว่า และกรณีที่ 3 การใช้ข้อมูลลักษณะฮาร์มอริกที่เกิดจากการแปลงกระแสไฟฟ้าของวงจรคอนเวอร์เตอร์ พบว่าตัวกรองพาสซีแบบซีและการติดตั้งตัวกรองบนรถไฟสามารถปริมาณฮาร์มอนิกที่สถานีไฟฟ้าได้มากกว่าเช่นเดียวกับกรณีที่ 2

สาขาวิชา วิศวกรรมไฟฟ้า ลายมือชื่อนักศึกษา กองทุน กฤษณสุวรรณ

ปีการศึกษา 2565 ลายมือชื่ออาจารย์ที่ปรึกษา

KONGTUN KRITSANASUWAN : THE STUDY OF MODELING AND HARMONIC FILTERING IN AC ELECTRIC RAILWAY SYSTEMS
THESIS ADVISOR : PROF. Dr. THANATCHAI KULWORAWANICHPONG, Ph.D., 199 PP.

Keyword: AC railway/Railway topology/Harmonic/Power passive filter/Total harmonic distortion.

This thesis presents a model and simulation of harmonic elimination in the AC railway system of the Blue Line Airport Rail Link. In this thesis, 3 case studies are proposed to illustrate different harmonic elimination methods, as follows: modifications to the topology of the power transmission system, simulation of the harmonic elimination effect using the harmonic data obtained from the measurements, and simulation of the harmonic elimination results using harmonic data obtained from harmonic characteristics caused by the conversion of electricity on the converter circuit on the train. by simulating the installation of four types of passive filters, namely single-tuned filters, band-pass filters, high-pass filters, and a C-type filter. The installation of passive filters at substations and on-board was simulated in a MATLAB simulation program. The simulation results will be compared to determine the harmonic elimination efficiency and complies with the IEEE 519-2014 requirements for harmonic control in electric power systems. In addition, four passive filter design guidelines are proposed to be suitable for the power system and to effectively eliminate the harmonics in the desired sequence. From the simulation results, it was found that in Case Study 1, increasing the intermediate track sectioning between power feeders and increasing the number of tracks. as a result, the impedance of the transmission line is reduced and the amount of harmonics at the substation is slightly reduced. Study 2: Using the data from the measurements to simulate harmonic elimination efficiency, it was found that the C-type passive filter can reduce the amount of harmonics at the substation the most, and when comparing the location of the filter installed between the substation and on-board, it was found that installing a passive filter on-board can reduce the amount of harmonics the most. and case 3, using the harmonic characteristics resulting from the electrical conversion of the converter circuit. It was

found that the passive c-type filter and the installation of the filter on-board can reduce the amount of harmonics at the substation more. Same as case 2.

School of Electrical Engineering

Academic Year 2022

Student's Signature Kongtun Kritsangasuwan

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Kongtun Kritsanasuwan

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LIST OF ABBREVIATIONS

PCC	=	point of common coupling
TDD	=	total demand distortion
TDDi	=	total demand distortion of current
THD	=	total harmonic distortion
THDv	=	total harmonic distortion of voltage
TF	=	Tuning point of the filter
VSC	=	Voltage source converters
DC	=	Direct Current
AC	=	Alternating Current
FS	=	Feeder Substation
MPTS	=	Mid-Point track sectioning
ITS	=	Intermediate track sectioning
ITSC	=	Intermediate track sectioning cable
BT	=	Booster transformer
AT	=	Autotransformer
ARL	=	Airport Rail Link
OCS	=	Overhead Catenary System
TPS	=	Traction Power Substation
PWM	=	Pulse width modulation
4QC	=	PWM-controlled 4-quadrant converter
STF	=	Single-Tuned filter
HPF	=	High-pass filters
BPF	=	Band-pass filters
CF	=	C-type filters
FT	=	Traction force
F_{grad}	=	Slope resistance
F_R	=	Resistance Force
S_{con}	=	Train Power Consumption
S_{tr}	=	Tractive power

LIST OF ABBREVIATIONS (Continued)

S_{aux}	=	Auxiliary power
TE	=	The tractive effort
v	=	The electric vehicle speed
TSS	=	A traction substation
Tr	=	The train
Zf	=	harmonic filter
Qc	=	Reactive power of the capacitor
F	=	System frequency
h	=	Tuning point of the filter
V	=	System voltage
Q	=	Quality factor

CHAPTER 1
INTRODUCTION

1.1 General Introduction

The growing demand for public transportation has resulted in the development of numerous configurations of power supply systems for electric railway networks, as well as the fast development of high-speed trains with massive power capacity, high operating speed, and density. Harmonic distortions have long been a source of concern for power companies and electric railways resulting from the power-electronic energy conversion of the electric railway system, such as those caused by diode rectifiers, voltage source converters (VSC), and other electrical equipment onboard. These can cause harmonic distortion, which has an impact on the overall power quality of the electric train system. As a result, examining the power quality of electric trains is critical for improving and resolving these challenges.

1.2 Problem Statement

At present, there are several electric trains in Thailand that use AC voltage of 25kV and frequency 50Hz, such as the airport rail link, Express line (Red) and City lines (Blue). In this research, The ARL City Line will be used as an example. To study the behavior and quantity of harmonics in the AC power distribution system while in service. The harmonic sample from the Chinese high-speed train model CHR380A will be used in the simulation. In addition, the research presents two patterns of harmonic reduction occurring in the railway power feeding system. The model is the styling of the railway power feeding system and the use of passive harmonic filters. Then compare the efficiency of each harmonic reduction and compare with IEEE519-2014 standard.

1.3 Research Objectives

The main objective of this research is to study the effects and give examples of harmonic reduction methods in the railway power feeding system, the research objectives are divided into two topics as follows.

1) Study the effects of harmonics from Power feeding circuit topology in the AC electric railway system.

2) Study the harmonic elimination effect from the installation of passive harmonic filters in the AC railway power feeding system.

1.4 Scope and Limitations

The proposed conception was simulated within certain limitations and is shown as follows.

1) Compare the simulation results of the total harmonic distortion that changes when the topology changes. In the case of increasing the number of ITS and tracks

2) Compare the total harmonic distortion simulation results at the substation before and after installing the passive harmonic filter.

3) Refer to the IEEE 519-2014 Voltage Harmonic Standard as a specification for regulating the number of harmonics in power systems.

4) The proposed conception was simulated in a MATLAB environment. Using various parameter data and simulating the movement of the AC electric train on the ARL electric train city line.

5) Using multi-train train simulation.

6) The railway power feeding system in the simulation uses a single conductor system.

7) Use the harmonic data of the high-speed rail CRH380A of the Chinese electric train as a reference.

1.5 Research Benefits

A benefit of this research is provided to study the nature of harmonics occurring in railway power feeding system, their effects in various ways, and to introduce examples of harmonic reduction or elimination. that happened to reduce problems in the power quality of the railway power feeding system.

1.6 Thesis Outline

The organization of this research are as follows. In Chapter 2, the literature review is discussed. About AC railway system, Harmonic in AC railway system and other review. In Chapter 3, Method of AC Railway and Harmonic Filter about Train Movement Model and calculation, Power Flow Calculation, Topology of AC Railway Power Feeding system, Harmonic Calculation and Passive Filter Design. In Chapter 4, Simulation Result, About Train movement simulation, Circuit Topology, Case study: Measurement Data and Case study: Input voltage harmonics of the four-quadrant converter with passive power filter and In Chapter 5 Conclusion and Future work.

1.7 Chapter Summary

In this chapter presents the general introduction of the ARL City line AC electric train system serving Thailand, the origins, and effects of harmonic power quality problems, and proposes ways to manage or mitigate harmonic problems. that occur in the railway power feeding system. Furthermore, the research objective, scope and limitation, and research benefit it also has been presented in this chapter.

CHAPTER 2
LITERATURE REVIEW

2.1 Chapter Overview

This chapter is divided into 2 topics. The first topic is descripted in Section 2.2, AC Railway System, which are a detailed description of the AC Railway power feeding system and service information and parameters of the ARL city line electric train used in this study as a test system. The second topic as in Section 2.3 describes the harmonics in the AC electric train system. The sources and effects of the harmonics are explained in Section 2.3.1. Section 2.3.2 describes harmonic distortion and standards related to harmonic quantities in railway power feeding system. In addition, section 2.3.3 explains various types of harmonic filters to compare the efficiency of harmonic reduction in the railway power feeding system.

2.2 AC Railway System

The railway system has a long history and is a large system. It has evolved into one of the most popular forms of public transportation over the past century. The demand for rail transport is increasing year by year from both short- and long-haul passenger and freight travel. Due to the demand for better drive efficiency, speed of service, luxury, and reliability. It's a good choice to use electrification for the train system. that can meet the needs of those passengers and is already widely used in transportation systems around the world.

There are two types of electrical systems that are used to drive electric vehicles today are Direct Current (DC) and Alternating Current (AC), and there are two types of electrical supply to the trains for mobility is third rail system and overhead wire system. The third rail system has the advantage of being aesthetically pleasing to install due to its low installation level. It does not affect the line pollution (visual impact) but has limitations in safety. This system is often used on subways or mass transit systems in non-living cities through running tracks. For overhead contact lines, they are opposite each other. It is installed at a high level. Affects visual pollution but can be used with higher voltage levels than the third rail. Suitable for long distance train operation (T. Kulworawanichpong, 2004)

In the alternating current train system, the most commonly used AC electric power system is the 25 kV voltage. For example, the City Line Airport Rail Link in Figure 2.1, also known as a 25 kV single-phase system. The frequency will be chosen according to the power distribution system. There will be different parts according to the power generation system of each country. Some countries use a frequency of 16 2/3 Hz as a power distribution system in the past that is still used by some European countries today. Some countries use 50 Hz and some use 60 Hz, etc. In large countries such as the United States, the frequency is 25 Hz. In addition, 50 kV AC electric trains are also installed, but are not widely used. Used in some countries (Nakhon, 2016)

Figure 2.1 The City Line Airport Rail Link

In Thailand, the railway system receives voltage 115kv through a transformer to a 25kv 50Hz dual-phase AC voltage system. The structure of the electric power cable system in Figure 2.2 consists of the structure of the conductors. The over-the-air wiring harness powers the electric vehicle with a contact wire (C) and catenary wire. (catenary), also known as messenger wire (messenger wire) to serve to fix the contact feeder to the least swing, making this type of power supply compatible with the main electric system. The two wires will have electricity flowing through and are connected by wires. Vertically connected conductors are called drop wires. The electric train draws electricity from the contact feed line through sliding contacts. A contact made of graphite is designed to be mounted on the roof of an electric vehicle called a pantograph, as shown in Figure 2.3.

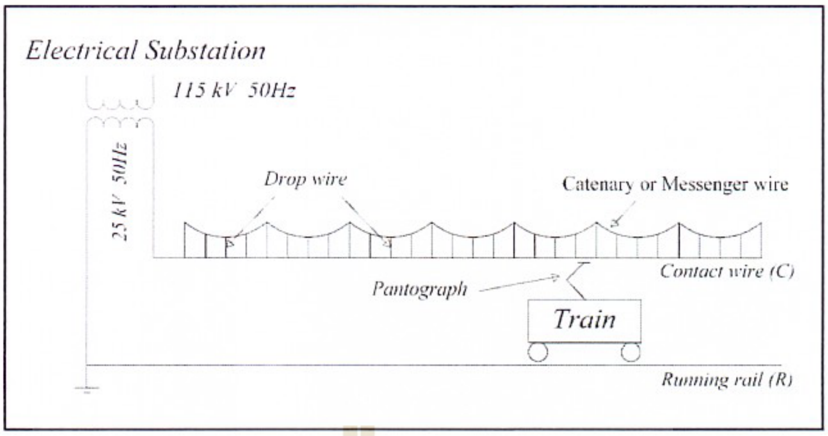


Figure 2.2 The structure of the electric power cable system

The pantograph is a very important point because it is the point where the electric train and the power distribution system come into contact. The pantograph is usually raised and lowered by high-pressure compressed air. The movement into contact with and separation from the contact line must be very fast to prevent damaging sparks. Because the AC electric train system operates at high voltage. The driven power station has a long feeding range, so the stations can be installed far apart. Typically, the propulsion power stations are approximately 50-100 km apart, depending on the selected power distribution system and the congestion of the trains on the route. (T. Kulworawanichpong, 2004)

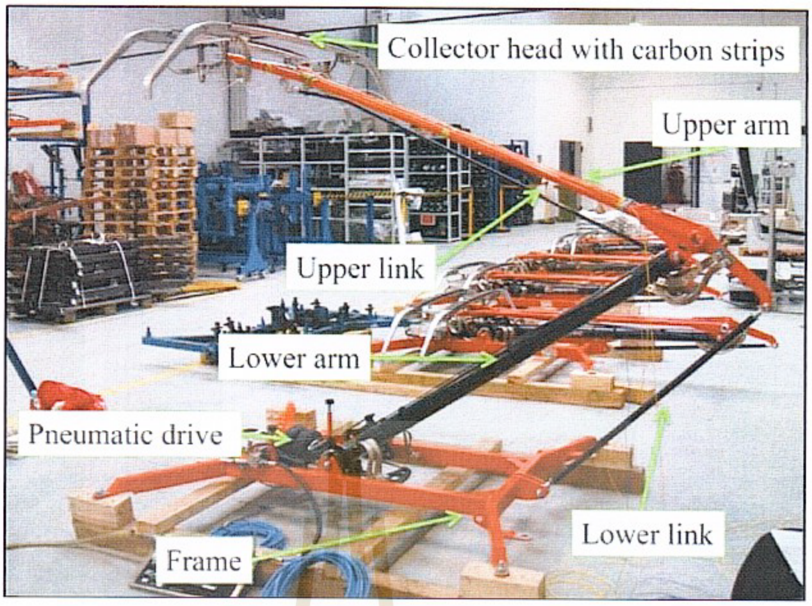


Figure 2.3 Pantograph
(Zdziebko, Paweł, Adam Martowicz, and Tadeusz Uhl. "Multi-domain approach to modeling pantograph-catenary interaction.", 2022)

2.2.1 The configuration of AC railway power feeding system

There are many different forms of AC railway power feeding system in the power transmission industry. especially one-phase railway power feeding system where the AC distribution station is directly connected to the three-phase high-voltage grid system, the 25 kV single-phase railway power feeding system is currently the UK power transmission standard. Each UK substation consists of two transformers sized 132/25 (currently 275/25 kV or 400/25 kV in the new system) with the high voltage side connected to the grid system. The 3-phase and low-voltage side are connected to the single-phase busbars. In Figure 2.4 is a diagram of the overhead feeding of a 25 kV two-rail system in the UK. FS: Feeder Substation, MPTS: Mid-Point track sectioning, and ITS : Intermediate track sectioning

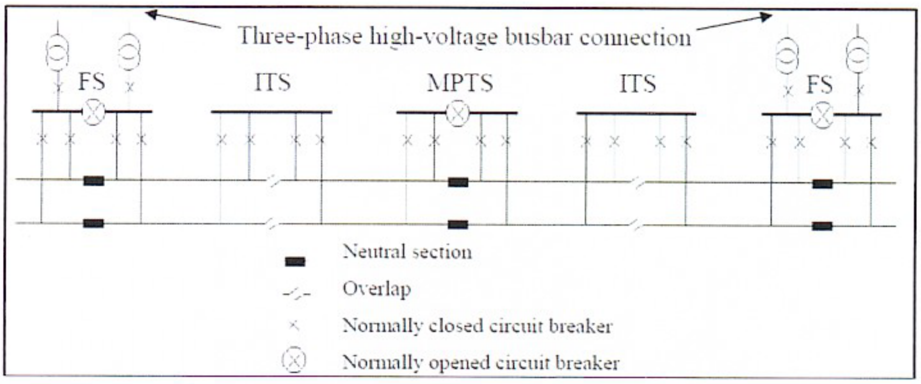


Figure 2.4 Diagram of the overhead feeding of a 25 kV two-rail system in the UK.

The configuration of a single-phase AC power system requires a neutral section to divide the distribution system at the substation and at the MPTS into two. The MPTS network is approximately centered on the substation spacing. In addition, between the center of the power station and the MPTS there is an ITS to be able to install some power equipment such as SVC or power factor adjustment devices or filters. (T. Kulworawanichpong, 2004)

AC traction power feeding systems have been developed in various forms to address many problems that arise in power feeding systems such as loss reduction, leakage current and electromagnetic interference. There are four types of power feeding systems: a single--phase direct feeding system, a booster transformer (BT) feeding system, Autotransformer feeding system and Co-phase traction feeding system.

2.2.1.1 Single-phase direct feeding system

Because of its basic layout, a single-phase direct feeding system is the most basic type of traction power supply. There is no need for extra equipment because the commonly used single-phase transformer is used. one pair of grid phases is sent to the primary side of the traction transformer, which reduces the input voltage to a traction level.

As seen in Figure 2.5, direct feeding without return conductor, the traction current returns to the traction substation through the running rails. Some of the return current can leak into the ground and flow through other metal structures before returning to the traction station. resulting in corrosion of those structures, power loss in the feeding line, voltage drop at the feeding line's end, and electromagnetic interference to the communication circuit. The magnitude of the leakage current depends on the traction current and the rail-to-earth conductivity. The basic solution to reduce this leakage current is to use conductors parallel to the running rails and connect them to the rails every 5-6 km to allow this leakage current to flow back to the power supply station through this return conductor, shown in Figure 2.6 Direct feeding with return conductor, despite using this method but still a small leakage current occurred. (Kritsada Mongkoldee, 2020).

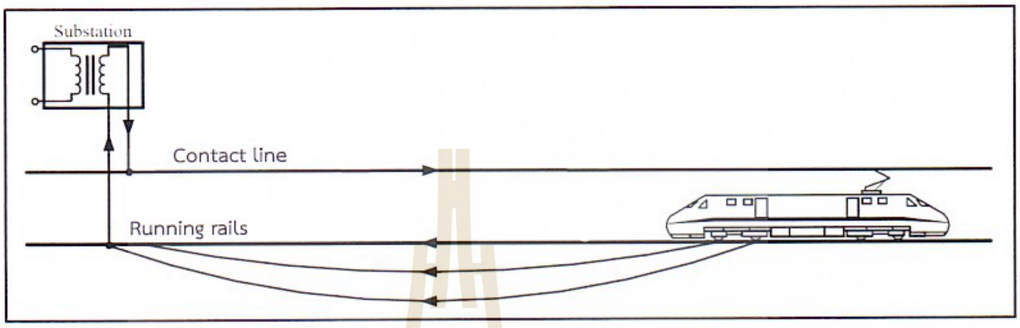


Figure 2.5 Direct feeding without return conductor.
Modified from: Friedrich, K., Rainer, P., Axel, S., and Egid, S. (2009). Contact lines for electric railways (2nd ed.). Erlangen: Publicis Publishing.

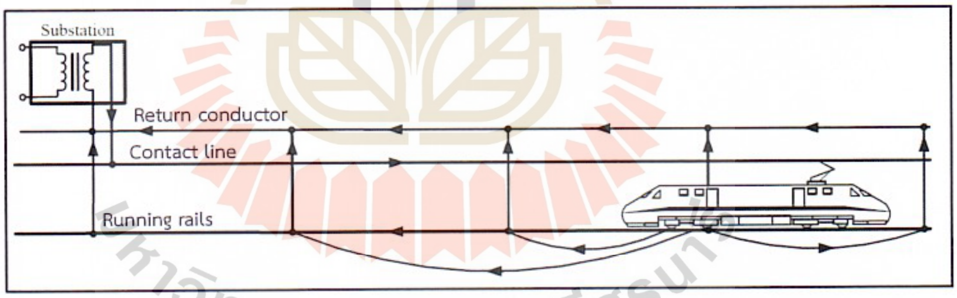


Figure 2.6 Direct feeding with return conductor.
Modified from: Friedrich, K., Rainer, P., Axel, S., and Egid, S. (2009). Contact lines for electric railways (2nd ed.). Erlangen: Publicis Publishing.

2.2.1.2 Booster transformer feeding system.

Even though the single-phase traction feeding system with the return conductor can reduce leakage current, the impact on the nearby signaling system remains unresolved. As a result, a booster transformer (BT) feeding system is proposed to reduce the interference. The idea behind employing BT is to think of it as a current transformer with a 1:1 turn ratio. To use the properties of the current flowing in the primary and secondary windings are equal. As a result, the magnetic field is most balanced. Installing a BT transformer every 1-2 km reduces the interference effect by approximately 50%. But the problem that follows is the voltage drop. Therefore, the problem must be solved by adding a capacitor to the return conductor circuit. If the BT transformer rating is 200-800 A or 100-800 kVA, the optimal distance to install the BT transformer is every 3-4 km as shown in Figure 2.7. A booster transformer power supply system. (Yasu Oura, 1998)

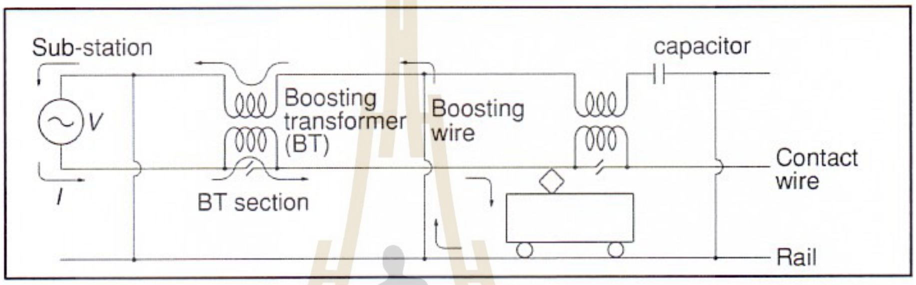


Figure 2.7 A booster transformer power supply system.
(Oura Yasu, Yoshifumi Mochinaga, and Hiroki Nagasawa. "Railway electric power feeding systems." Japan railway & transport review 16.10 (1998): 48-58.)

2.2.1.3 Autotransformer feeding system.

The autotransformer (AT) system is the most efficient way to power trains in an overhead exposed conductor system. And has been popular in the main rail system and high-speed trains as shown in Figure 2.8. AT that are used with a coil ratio of 1:1 is installed every 8-15 km distance, allowing the distance of the power distribution station to be as far as 50 -100 km. This is particularly good at reducing inductive interference in telephone lines. In Japan, the AT is constructed with a 1:1 turn ratio, and the substation feeding power is double that of the overhead line. This technology is suited for high-speed and high-capacity electric vehicles because neither large voltage drops nor arcing sections are present. (Yasu Oura, 1998)

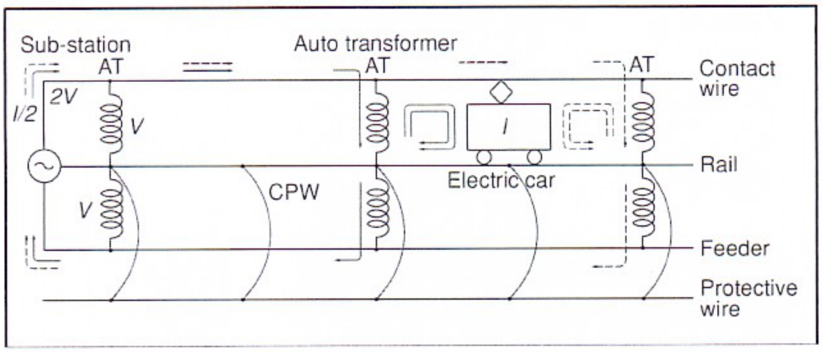


Figure 2.8 Autotransformer (AT) system

(Oura Yasu, Yoshifumi Mochinaga, and Hiroki Nagasawa. "Railway electric power feeding systems." Japan railway & transport review 16.10 (1998): 48-58.)

2.2.1.4 Coaxial cable feeding system.

The Coaxial cable feeding system as shown in Figure 2.9 depicts a coaxial cable installed along the train as part of the coaxial cable feeding system. The inner conductor is linked to the contact wire and the outside conductor is attached to the rail every few kilometers. The cable itself is quite costly, but its conductor architecture is straightforward, making it perfect for usage in confined spaces. Japan is the only nation to employ this approach. In compared to the overhead line, the coaxial power cable's round-trip impedance is exceptionally low. Consequently, the load current in the coaxial power cable is amplified by the connection to the overhead line. This results in a distribution of rail current comparable to that of the AT feeding system, hence greatly minimizing inductive interference in telecom lines. (Yasu Oura, 1998)

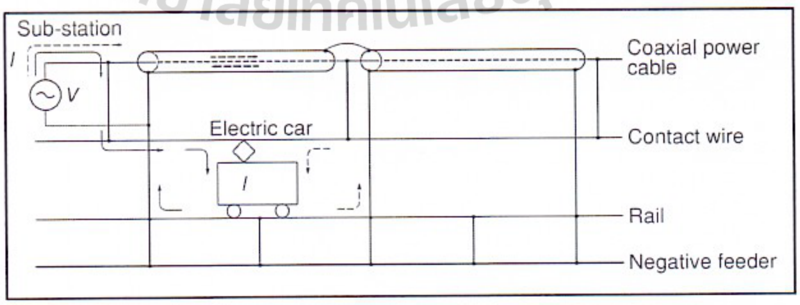


Figure 2.9 Coaxial cable feeding system.

(Oura, Yasu, Yoshifumi Mochinaga, and Hiroki Nagasawa. "Railway electric power feeding systems." Japan railway & transport review 16.10 (1998): 48-58.)

2.2.2 City line Airport Rail Link information

The data of the ARL electric train will be used as a model train in the simulation in this research. The technical feasibility of the traction power supply for the ARL project with 25kV/50Hz has been investigated by means of an electrical network calculation basing on simulated train operation with the simulation program MATLAB. The following paragraphs summaries the essential input data for the simulation of the electrical network and the train operation of the line. (Siemens Limited, 2007)

2.2.2.1 Route

Length of the line: 28.3 km.

Number of passenger stations: 8 Stations

Number of traction substation: 1 substation

The following table 2.1 gives the passenger station names. The initial stage of the ARL system will comprise 8 passenger stations in total.

Table 2.1 Passenger station names

Station name	3 letter code	Location (km)
Phaya Thai	PTH	0.000
Ratchaprarop	RPR	0.908
Makkasan City Line	MAS	3.134
Ramkhamhaeng	RKH	7.480
Hua Mak	HUM	11.833
Ban Thap Chang	BTC	17.183
Lat Krabang	LKB	23.033
Suvarnabhumi (Terminal 1)	SVB	28.193

2.2.2.2 Parameters of the ARL City Line train used in the simulation.

The following table 2.2 shows the parameters used to calculate the ARL City Line train model V03 (year 2022), which are outlined for all simulations.

Table 2.2 Parameters used to calculate the ARL City Line train model V03 (year 2022)

Parameter	Value	Unit
Maximum acceleration	1.00	m/s^2
Maximum deceleration	0.88	m/s^2
Maximum velocity	160	Km/h
Train mass	131	Ton
Passenger mass	44.9	Ton
Maximum tractive effort	200.0	kN
Maximum braking effort	144.0	kN
Power auxiliary	200	kVA
Efficiency motor and inverter	0.82	-
Davis's equation $A + Bv + Cv^2$	$0.0162 \cdot \frac{N}{kg} \cdot m_{train} + 0.00017 \cdot \frac{1}{s} \cdot v \cdot m_{train} + 4.144 \cdot \frac{kg}{m} \cdot f_{tunnel} \cdot v^2$	

2.2.2.3 Overhead Catenary System

Contact wire: Cu 107mm² (20% abrasion)

Messenger wire: Bz 70mm²

Return Conductor: E-Al 120mm²

Rails: UIC 60, 15%

Admittance Catenary: 0.0949 + j0.5877 Ω/km

Admittance Rail: 0.0289 + j1.8539 Ω/km

Figure 2.10 Configuration of Overhead Catenary System shows a cross section of the considered OCS including all relevant horizontal and vertical measures of conductors and running rails.

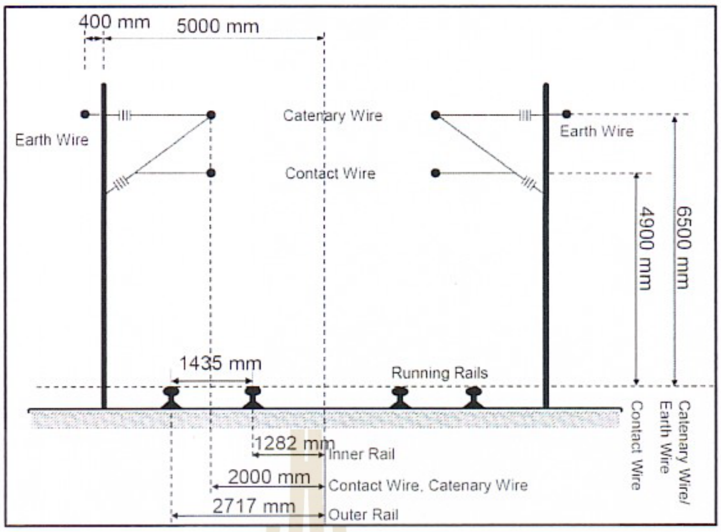


Figure 2.10 Configuration of Overhead Catenary System

2.2.2.4 Traction Power Substation (TPS)

The entire line of "ARL Bangkok" is fed by one TPS with two 20 MVA transformers, located at km 8.078 near the passenger station Ramkham Haeng. Table 2.3 shows the parameters of ARL Traction Power Substation and the substation infeed with two transformers is shown in Figure 2.11.

Table 2.3 the parameters of ARL Traction Power Substation

Parameter	Value	Unit
Short-circuit capacity	2.7	GVA
No-load voltage	25	kV
Rail to Earth conductance	0.1	S/km

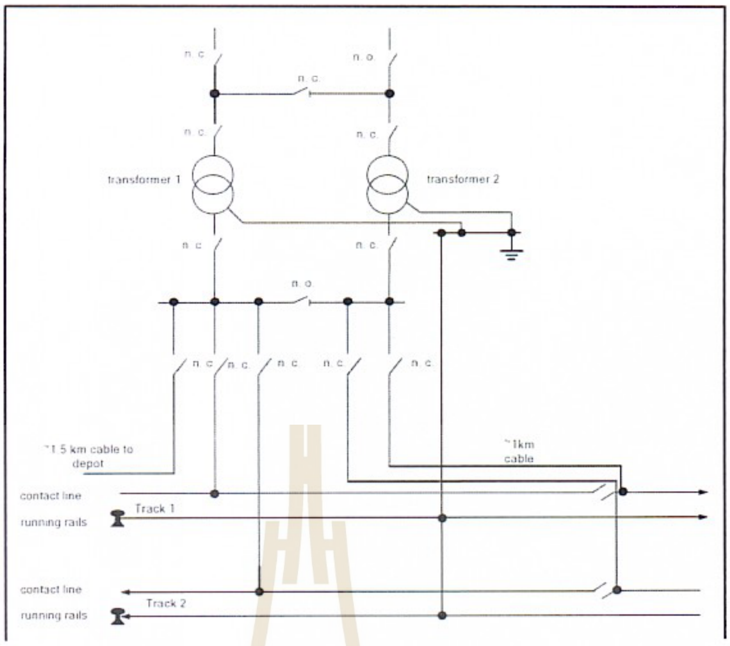


Figure 2.11 The substation infeed with two transformers

2.3 Harmonics in AC railway system

2.3.1 Harmonics Source and effect

Harmonic is a signal whose frequency is a certain number of fundamental frequencies, e.g., fundamental frequency is 50 Hz, harmonic is 100, 200, etc. The fundamental frequency is called the 1st harmonic, and the other harmonics are obtained by multiplying the integer by the fundamental frequency. For the harmonics that occur in the AC electric power system. It has been increasingly highlighted by the rapid development of electric trains, especially high-speed trains.

Harmonic Current is the current in the wires in the electrical system. They arise from devices with non-linear characteristics, which can be loads or sources, or are caused by thyristor control devices or pulse width modulation (PWM) devices in electric power and harmonic currents. The reactance of various devices in the system, such as the reactance of the transmission line or the reactance of the capacitors connected to the system to improve the power factor and voltage, create a voltage. Harmonic Voltage in the electric power transmission system makes it a major problem for the power transmission system. The electric power transmission system is characterized by an RLC circuit. Multiple resonance frequencies can be found, which will result in more harmonic current amplification in the power transmission system.

An example of a graph of measured voltage and current under resonance frequency. As shown in Figure 2.12 (Haitao Hu, 2018)

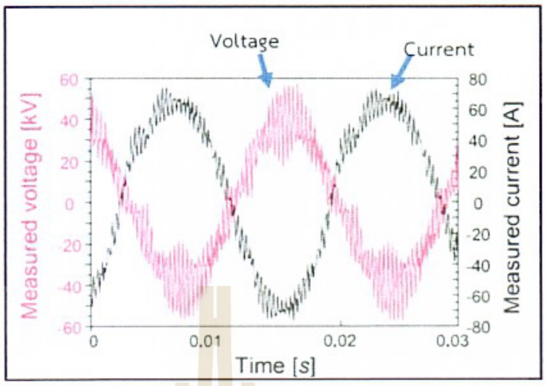


Figure 2.12 An example of a graph of measured voltage and current under resonance frequency

Harmonic Problem Sources in AC railway systems as shown in Figure 2.13 can be divided into 3 types as follows. (Haitao Hu, 2018)

1) Background voltage harmonics are typically below 20 per unit (p.u.), i.e., the fifth, seventh, eleventh, and thirteenth harmonics, and are caused by the harmonic injections of nonlinear devices connected to the utility power system. They may be measured without train operations in a new RES. Moreover, the series resonance may amplify the background harmonics.

2) Harmonic resonance is stimulated by the interplay of capacitive and inductive elements/parameters and energized by the nonlinear train's current injection. Two conditions are necessary to stimulate a harmonic resonance.

a) At certain frequencies, the inductance and capacitance of the system are equal.

b) A linked harmonic source encompasses one or more of these resonance frequencies.

3) High-speed trains' PWM-controlled 4-quadrant converter (4QC) generates characteristic harmonics around the integer switching frequencies. Harmonics of the standard electric train are characterized by an abundance of low-frequency odd harmonics. In addition to various harmonic spectra, different types of electric trains may exhibit distinct harmonic behaviors due to their equivalent output admittance.

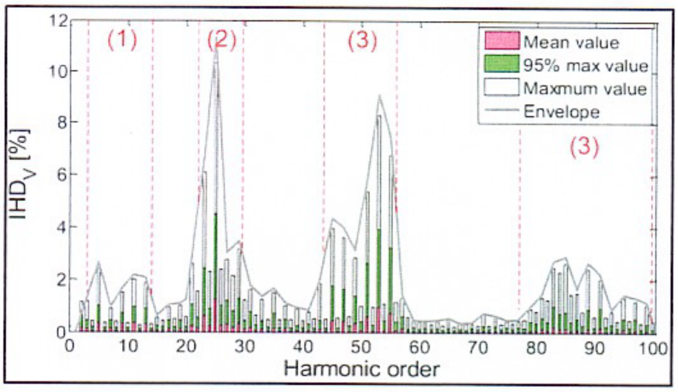


Figure 2.13 Type of Harmonic Problem Sources in AC railway system

Examples of harmonic effects on electrical systems and equipment

1) Capacitor - Connecting capacitors and reactance to the system is likely to cause parallel resonance conditions between the capacitor and reactance of the system when the load is not considered. It is linear as a source of harmonic currents. If parallel resonance occurs at the same or similar frequency as the harmonic frequency of the nonlinear load, it will cause There is a large amount of current flowing between the system reactance and the capacitor reactance, and this current is combined with the harmonic current of the nonlinear load. This causes a voltage drop across the reactance of the system. For this reason, the voltage distortion is very large. Therefore, the capacitor size selection method should avoid the size that produces the same resonant frequency or close to the harmonic frequency.

2) Relay Protection - The distortion waveform will affect the performance of the protection relay. This may cause the relay to not function properly when voltage transformers are required and especially current transformers to transmit harmonic distortions to the relay system. Current transformers are normally operated at load current levels, but when high fault currents are present, they will saturate the iron core of the current transformer causing a distortion signal into the relay system. Therefore, this distortion may cause the relay to disconnect the circuit incorrectly in the event of a fault or it may cause trouble for the power user. by ordering to cut off the circuit while there is no fault occurring in the electrical system.

3) Transformer - The effect of harmonics in the power system on transformers is that there is an increase in heat in the form of more power losses. which are losing these include: Loss of coil This power loss is heated in the conductor and surface phenomenon, power loss due to eddy currents in the windings. The power loss in this section increases with the square of the load current and the square of the frequency

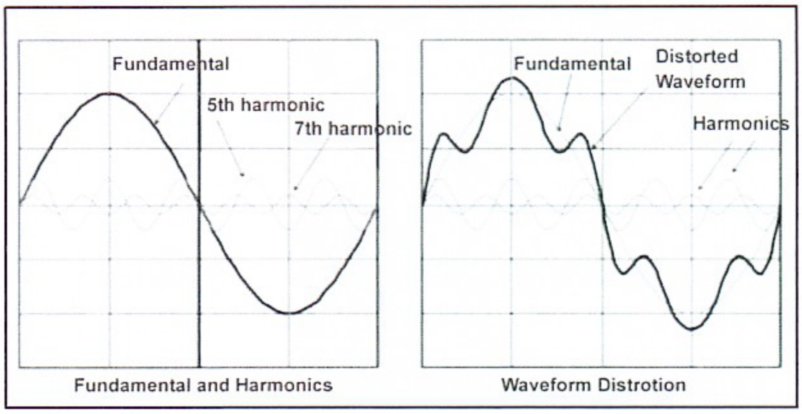
and other losses As the magnetic flux passes through the metallic components of the transformer, these losses increase with frequency when the transformer is heated above a certain value, shortening the life of the transformer.

4) Electronic devices - Harmonic distortion can affect the operation of many electronic devices, such as electronic circuits used to monitor fundamental frequency zero voltage when harmonics at primary frequency occur. dung as a result, this electronic circuit malfunctions or occurs with electronic power supplies that use the crest of the voltage to charge filter capacitors. But the harmonic frequency and the phase relationship between the fundamental voltage and the distorted harmonic voltage can cause the crest to rise or flatten. As a result, the power supply has an unstable output voltage at or below the required voltage level. Therefore, other devices that need to be powered by this power supply will be less efficient. It can affect video or television or loads that require constant voltage.

5) Telephone Interference - When the telephone line is installed on a pole near the power line, there is a chance that interference from the power line can interfere with the telephone communication system and if harmonics are included in the system. Harmonic frequencies can cause more problems than fundamental frequencies, resulting in communication failures or interference in the communication system.

2.3.2 Harmonics Distortion and standard

A harmonic is a sine wave component of a signal or periodic quantity whose frequency is an integer multiple of the fundamental frequency (50 Hz) in a power system, such as a harmonic. The 5th harmonic has a frequency of 250Hz, and the 7th harmonic has a frequency of 350Hz, shown in Figure 2.14(a) Fundamental and Harmonics.



(a) (b)

Figure 2.14 Harmonics Distortion Waveform
(https://www.apt4power.com/2021/07/22/total-harmonic-distortion-thd/, Retrieved September 8, 2022)

And the harmonic effect when combined with the fundamental frequency signal with the size (Amplitude) and the phase angle (Phase Angle) causes the signal to change in size and have a distorted signal. away from the sine wave signal as shown in Figure 2.14(b) Waveform Distortion.

Mathematically, Fourier series can be used to describe harmonic characteristics where a signal or periodic function can be distributed as the sum of trigonometric functions where the frequencies are also denoted periodic functions. f(t) as in the equation (2.1) (Watcharapong,2016)

$$f(t) = a_0 + \sum_{n=1}^{\infty} a_0 \cos(n\omega_0 t) + \sum_{n=1}^{\infty} b_n \sin(n\omega_0 t) \tag{2.1}$$

When

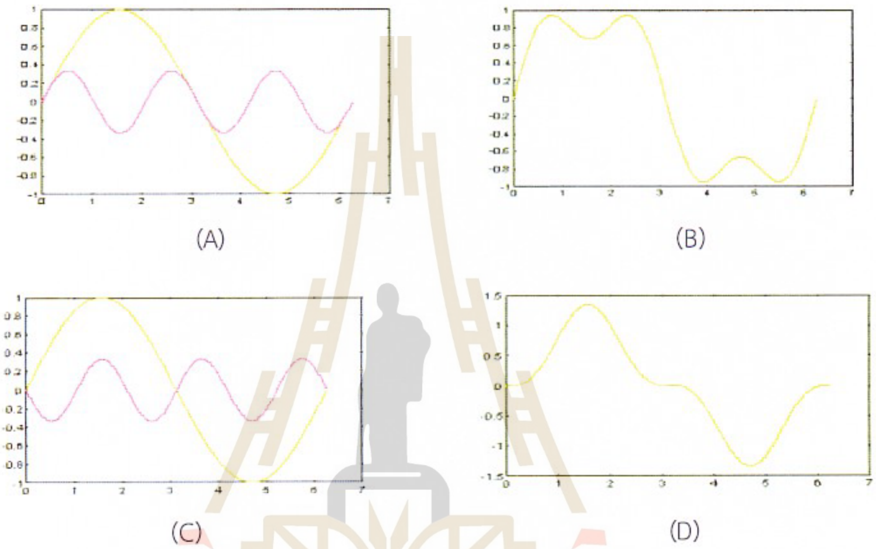
$$a_0 = \frac{1}{T}\int f(t)dt$$

$$a_n = \frac{2}{T}\int f(t)\cos n\omega_0 t dt$$

$$b_n = \frac{2}{T}\int f(t)\sin n\omega_0 t dt$$

where T is the one period of the signal and n is a positive integer. In the case where n = 0, this is the fundamental frequency or in the case where n is greater than zero, this frequency is called an order n harmonic. It can be both an even and an odd sequence.

Figure A and Figure C represent a sine wave signal of the fundamental frequency and a sine wave of the 3rd harmonic, and Figure B and Figure D represents the distortion produced by combining the sine wave at the fundamental frequency with the 3rd harmonic sine wave.



(A) (B) (C) (D)

$$f(t) = \sin(x) - \frac{1}{3}\sin(3x)$$

Because harmonics have caused damage in the power system in many ways, so the standards bodies have planned to prevent and promulgated standards for harmonics to control the amount of harmonics. Monique in the electrical system and some countries have modified the standard for use within the country itself.

In this research, the standard IEE519-2014 is used. It is a standard on Recommended Practice and Requirements for Harmonic Control in Electric Power Systems, detailing both voltage harmonics and current harmonics related to electric train simulation in this research as shown in the table below at 2.4 and 2.5.

Table 2.4 shows voltage distortion limitations; all values should be expressed as a percentage of the rated power frequency voltage at the point of common connection (PCC). This is true for voltage harmonics with frequencies that are integer multiples of the power frequency. (IEEE 519 ,2014)

Table 2.4 Voltage distortion limits

Bus voltage V at PCC	Individual harmonic (%)	Total harmonic distortion THD (%)
V ≤ 1.0 kV	5.0	8.0
1 kV < V ≤ 69 kV	3.0	5.0
69 kV < V ≤ 161 kV	1.5	2.5
161 kV < V	1.0	1.5

Table 2.5 shows the current distortion limitations for systems rated from 120 V to 69 kV. The restrictions in this subclause apply to users connected to systems with rated voltages ranging from 120 V to 69 kV at the PCC. All values should be expressed as a percentage of the maximum demand current, IL. This current value is determined by the PCC and is calculated as the total of the currents corresponding to the greatest demand for the preceding twelve months divided by twelve. Table 2.5 is applicable to harmonic currents with frequencies that are integer multiples of the power frequency.

Table 2.5 Current distortion limits for systems rated 120 V through 69 kV.

Maximum harmonic current distortion in percent of I_L						
Individual harmonic order (odd harmonics)						
I_{SC}^{a}/I_L^{b}	$3 \leq h < 11$	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h \leq 50$	TDD[c]
< 20	4.0	2.0	1.5	0.6	0.3	5.0
20 < 50	7.0	3.5	2.5	1.0	0.5	8.0
50 < 100	10.0	4.5	4.0	1.5	0.7	12.0
100 < 1000	12.0	5.5	5.0	2.0	1.0	15.0
> 1000	15.0	7.0	6.0	2.5	1.4	20.0

[a]I_{sc} = maximum short-circuit current at PCC

[b]I_L = maximum demand load current (fundamental frequency component) at the PCC under normal load operating conditions

[c]TDD = Total demand distortion, the ratio of the root mean square of the harmonic content, considering harmonic components up to the 50th order and specifically excluding interharmonics, expressed as a percent of the maximum demand current. Harmonic components of order greater than 50 may be included when necessary.

2.3.3 Harmonic Filter

Adding a filter to a system to limit or reduce the harmonics is a highly efficient method. Limiting harmonics to very low dimensions Multiple filters may be required, resulting in higher investment costs. When applying filters to solve harmonic problems, one must consider the purpose or size of the harmonics to be reduced to a greater extent and how many filters should be used first. To go into the details of choosing a filter size, consider the type of filter first. The harmonic filters are divided into active filter and passive filter (AIDA ENGINEER ,2004)

Active filter is a harmonic filtering device consisting of a power electronic device and a computer circuit together. It measures the harmonics in the power system, analyzes the results, and produces harmonics of equal order and quantity but opposite direction. and supply that current to offset the harmonic current in the system until no harmonic current is present or reduced. The active filter is designed as an optional standard module. It has the flexibility to filter any harmonic from the 2nd to 50th harmonic, and up to 15-20 harmonic sequences simultaneously. The problem with this type of filter is that it is much more expensive than passive, so the harmonic problem must be carefully analyzed before deciding which equipment to fix.

Passive filter is a harmonic filtering device that consists of a primary resistor (R), reactor (L), and capacitor (C) that are designed to have R, L, and C values relative to each other. Based on the principle of series resonance like a short circuit, it has low impedance for harmonic frequencies but is similar to a normal load based on a 50 Hz system frequency. The disadvantage of passive filters is that they are only designed to suit certain load conditions. If the load or electrical system is changed from the one that was originally designed, it will greatly affect the operation. In this research, 4 harmonic filters are presented as follows. (J.C. Das, 2015)

2.3.3.1 Single-Tuned Filter

Series filters, also known as single-tuned or notch filters, are the most popular in the industry. This filter is adjusted to suppress a single frequency and is developed around three parameters: the harmonic current order that must be blocked, the capacitive reactive power that it will give, and its quality factor. During the design phase, the voltage level and fundamental frequency provided by the system must also be addressed. Figure 2.15 depicts the series or single-tuned filter's circuit architecture as well as a typical impedance characteristic.

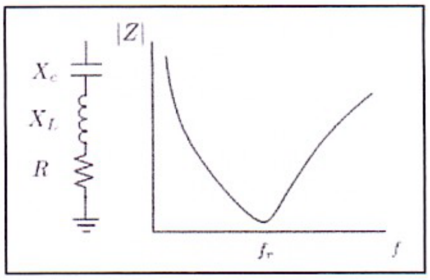


Figure 2.15 Single-tuned filter's circuit architecture and a typical impedance characteristic

2.3.3.2 High-pass Filter

High-pass filters, as shown in Figure 2.16, are utilized to suppress a larger range of frequencies than a single tuned filter, hence lowering the size of the components and preventing capacitive power factor when the system is not loaded. This filter is designed to have an impedance characteristic that is flat for high frequencies.

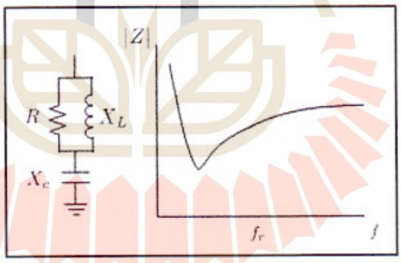


Figure 2.16 High-pass filter's circuit architecture and a typical impedance characteristic

2.3.3.3 Band-Pass Filter

Band-pass filters are uncommon in the industry, but this component may be used to simulate high-order or double-tuned filters. This component may be used to simulate filters with a high order. Figure 2.17 depicts the double-tuned filter, which is a combination of a band-pass filter in series with an inductor and a capacitor. This filter is perhaps the most common. Combining the parallel resonance of the band-pass filter with the series resonance of the inductor and capacitor combination, this sort of filter operates. As seen in Figure 2.17, two more resonance frequencies are available for selection. This setup results in a cheaper filter than the parallel combination of two separate series filters.

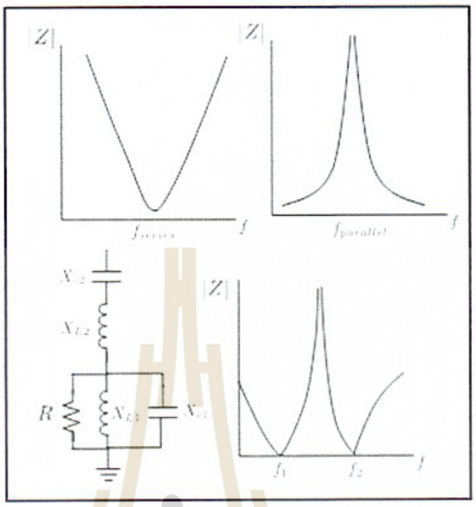


Figure 2.17 Double-pass filter's circuit architecture and a typical impedance characteristic

2.3.3.4 C-Type Filter

C-type filters, as shown in Figure 2.18, are second-order filters that may suppress harmonic currents with lower losses than series filters or band-pass filters. The L and C components, which are parallel to the resistor, resonate at the fundamental frequency, which enables this capacity. Consequently, the fundamental current that flows through the damping resistor is minimized. Due to their intrinsically flat impedance profile above the tuned frequency, c-type filters also work well in suppressing high-frequency harmonics.

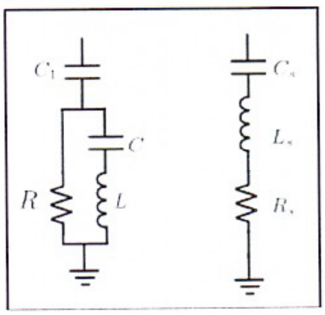


Figure 2.18 C-type filter's circuit architecture

2.4 Other Review

Hamed Kaleybar (2019) An Inclusive Study and Classification of Harmonic Phenomena in Electric Railway Systems investigates and classifies harmonic phenomena based on ERS type, effective factors, origins of formation, destructive consequences, and compensatory strategies. It gives researchers and engineers a perfect view of ERS harmonic difficulties. They categorized harmonic phenomena by effective factors, causes, destructive consequences, and compensatory strategies. The main indices are LOH, LFO, PHR, SHR, and HI. These phenomena are mitigated via control and compensators. Depending on the type of running ERS, harmonic phenomena can vary.

Hanmin Lee (2006) Korean High-Speed Railway Harmonic Analysis Using the Eight-Port Representation Model gives a high-speed railway harmonic analysis model. Since harmonic current runs via the catenary system, it must be modeled to analyze harmonic current amplifications and overall harmonic distortion. In this work, the line constants of five conductors in the catenary system were determined using the reduction approach, and each Korean high-speed railway subsystem was modeled by the eight-port representation. The accuracy of the harmonic analysis model was verified by comparing simulation results to field test data from the Korean high-speed railway. Also shown are the high-speed railway's harmonic characteristics.

Davor Vujatovic (2006) Harmonics Generated from Railway Operation reports on high-speed railway harmonics. Installing power electronic compensators, notably static VAR compensators (SVC), in the railway system during infrastructure upgrades may not be an easy solution. Better approaches and methods will be discussed. To offset the principal downside of SVC compensators, such as the harmonic currents introduced into the railway catenary due to their non-linear properties. Harmonics content was studied by analyzing a vast volume of high-speed train data. The recommended approach could limit SVC's negative effects on rail and electrical systems.

El Hajji Moine (2019) Harmonic analysis caused by static converters of the railway high-speed train and its impact on the track circuit This paper deals with the study of the electromagnetic interference in the railway field, especially the disturbance generated by static converters such as the rectifiers and the inverters used in train propulsion systems. The focus of this work is modeling and simulating the electrified railway propulsion drive equipped with a two-level NPC PWM inverter and rectifier for harmonics analysis and their impact on the railway signaling, especially track circuit, and proposing a solution to reduce the EM disturbance.

Wensheng Song (2016) High-Frequency Harmonic Resonance Suppression on a High-Speed Railway Using an LCL Filter. This article proposes adopting a single-phase grid-side PWM converter with an LCL filter in high-speed trains to reduce resonance excitation. The LCL filter's total inductance value is supposed to be the same as that of the L-type filter, with only a tiny capacitor added. This design fits the traction converter system's space and weight constraints. In this work, a 27.5-kV 50-Hz autotransformer-fed power-supply system and grid-side LCL filter-based converters are modeled and simulated in real-time HIL. The proposed approach stops TPSS from resonating at high frequencies.

Zhengyouhe (2016) Power quality in high-speed railway systems have caused severe voltage and current aberrations in the traction power supply system (TPSS) and the linked power system. Nonlinear and dynamic trains make power quality (PQ) calculations and evaluations problematic. Unbalance, reactive power, harmonics, harmonic resonance, and low-frequency voltage fluctuations are HSR PQ concerns. This article gives a summary of power quality difficulties based on reported documentation and field testing, and details the modeling of the TPSS in China's HSR systems to explore PQ issues. Throughout railway electrification history, many mitigating strategies have been used to improve PQ performance. New power-electronics technologies have led to the creation of unique PQ solutions. The article compares PQ improvements using various power quality.

B. Lutrakulwattana (2015) Harmonic Resonance Assessment of 1×25kV, 50Hz Suvarnabhumi Rail Link Traction Power Supply Harmonic resonance in railway traction power supply systems (TPSS) can cause voltage distortion, overvoltage on capacitive devices, overheating of electrical components, and EMI in communication circuits. Harmonic resonance in railway TPSS must be assessed. This work gives a modeling and simulation-based harmonic resonance assessment of Thailand's first AC-electrified railway line, Suvarnabhumi Airport Rail Link (SARL). The model includes genuine ESS and OCS parameters.

Ahmed S. Abbas (2019) Comprehensive Parametric Analysis of Single Tuned Filter in Distribution Systems. Single-tuned harmonic filters (STFs) are employed in distribution systems to reduce harmonic distortion and associated negative effects. This work gives a parametric analysis for the STF to investigate filter performance. Changing the quality factor, tuned frequency, and filter size can modify the filter's impedance-frequency curve. This article examines how distribution system factors affect the filter's harmonic pass band. The offered analysis can assist designers understand the STF's operation and performance and select the right filter parameter values to improve STF performance and accomplish certain mitigation characteristics. MATLAB performs simulation analyses.

Ashlin Gloria Reginald (2015) Harmonic Analysis and Its Mitigation Using Different Passive Filters. Electronics emit harmonics. Harmonic distortion, caused by harmonics, degrades power quality. Passive or active filters reduce harmonics. Active filters effectively compensate harmonic currents and voltages, but they're pricey. For small installations, passive filters are preferable over active filters. In this paper, a harmonic filter for a non-linear load is designed and developed. Based on proposed ways to suppress harmonics, different filter topologies are created. Recent THD data showed 128%. The full system is simulated with SIMULINK to verify procedures.

M I Fahmi (2018) Harmonic reduction by using single-tuned passive filter in plastic processing industry. Non-linear industrial loads might cause inconsistent harmonics that don't meet IEEE 519-1992 standards. This paper covers using single-tuned passive filters to reduce plastics processing harmonics. The MATLAB/Simulink simulation resulted in 15.55% total harmonic distortion (THD), which can be reduced to 4.77% harmonics per IEEE 519–1992 standards. Simulation results show that a single-tuned passive filter can reduce the current 82.23% harmonic and other harmonics between 7% and 8%.

2.5 Chapter Summary

Chapter 2 presents a search for research literature related to the research conducted. which makes them aware of the relevant research guidelines Methodology that other researchers have applied research findings and proposals to apply and develop to research.

CHAPTER 3
Method of AC Railway and Harmonic Filter

3.1 Chapter Overview

This chapter discusses the calculation and design methods involved in this research, including Train Movement Model and calculation, Power Flow Calculation, Topology of AC electric train system, Harmonic Calculation, and Passive Filter Design.

3.2 Train Movement Model and calculation

The calculation of train movement is based on Newton's Second Law in equation (3.1) and the force acting on the train as shown in the free object diagram of train movement Figure 3.1, consists of tractive effort and friction force. The driving force of the train is the traction force (FT), and the friction force is the rolling resistance of the wheels, aerodynamic resistance, and slope resistance (Fgrad) in equation (3.3). The combination of rolling resistance, aerodynamic resistance, and other resistance (FR) is summarized in Davies's equation as shown in (3.2)

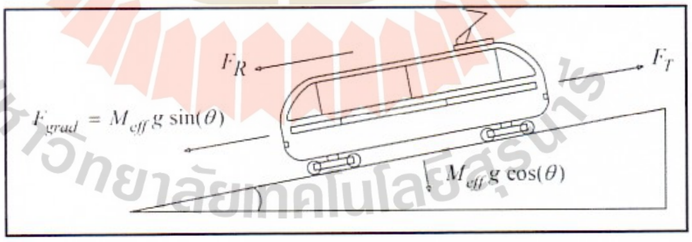


Figure 3.1 The free object diagram of train movement.

When M_{eff} is effective mass (kg)

θ is the angle of track inclination.

a is the train acceleration.

g is the acceleration due to gravity (9.8 m/s^2)

A, B, C are Davis's coefficients.

v is the train speed (m/s)

Davis's equation of ARL

$$0.0162 \cdot \frac{N}{kg} \cdot m_{train} + 0.00017 \cdot \frac{1}{s} \cdot v \cdot m_{train} + 4.144 \cdot \frac{kg}{m} \cdot f_{tunnel} \cdot v^2$$

The movement of the electric train in this research, the movement patterns of electric trains, as shown in Figure 3.2, will be considered in 3 modes of operation.

1) Acceleration mode is when the electric train receives power through a contact line to increase the torque of the motor in a standby state. The electric train operates with the specified acceleration when leaving the station. Until reaching the specified speed or according to the designed distance, the electric train will run in constant speed mode.

2) Constant speed mode is the way an electric train moves at a constant speed while keeping its operating speed at zero acceleration until reaching the braking distance before stopping at the train station.

3) Brake mode is where the train's movement will reduce its speed with latency, i.e., the acceleration is negative in the range greater than zero to the maximum latency. To park at the passenger terminal or reduce the speed so that the train speed does not exceed the specified working speed.

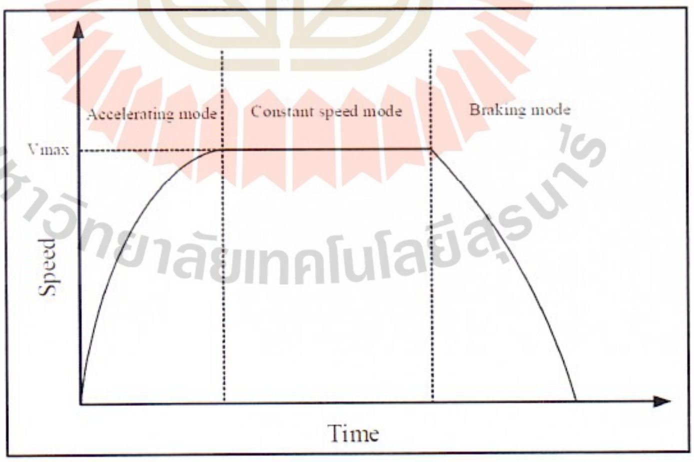


Figure 3.2 The movement patterns of electric trains.

The speed and distance of the electric vehicle in different modes can be calculated in equation (3.4) and (3.5)

$$v_{t+1} = v_t + a\Delta t \tag{3.4}$$

$$s_{t+1} = s_t + v_{t+1}\Delta t + \frac{1}{2}a\Delta t^2 \tag{3.5}$$

When

v_{t+1}, v_t are the speed of electric trains after and before adjustment (m/s).

s_{t+1}, s_t are the positions of the electric train after and before adjustment (m).

Δt is the time step (s)

a is the acceleration (m/s^2)

The Train Power Consumption (S_{con}) in mobility consists of two parts: Tractive power (S_{tr}) and auxiliary power (S_{aux}) generated by lighting, air conditioning systems, transmission systems, etc., and the tractive effort depends on the traction value of the electric vehicle in motion (TE), the electric vehicle speed (v) and the conversion efficiency of mechanical energy into electrical energy (η), as in equation (3.6).

$$S_{con} = S_{tr} + S_{aux} \tag{3.6}$$

$$S_{tr} = \begin{cases} \frac{TEv}{\eta} & ;a > 0 \\ 0 & ;a = 0 \\ TEv\eta & ;a < 0 \end{cases}$$

3.3 Power Flow Calculation

The voltage solution of a powered power distribution system is calculated using an AC single-conductor system model. As shown in Figure 3.3 and AC single-conductor system circuit. As shown in Figure 3.4, it consists of a traction substation (TSS), feeder and train (Tr). A node analysis method was used to facilitate the calculation of the model. and using iterative methods to verify the correctness of the calculated solution. This research uses the current injection method to find the solution for calculating the voltage at the bus. (Kulworavanichphong, 2018) Model of the electric train system in the form of a current the voltage solution can be calculated from the node equations as shown in (3.7).

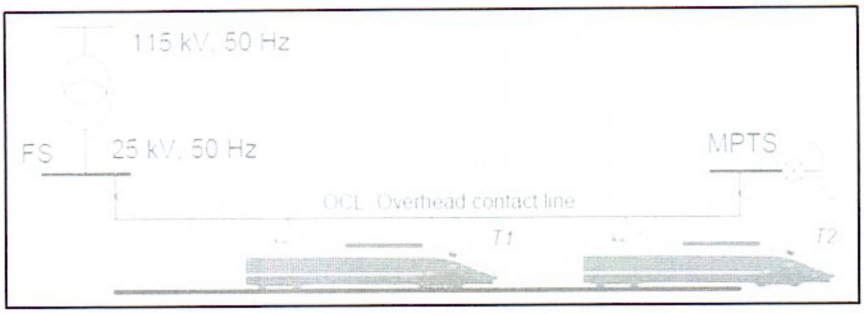


Figure 3.3 AC single-conductor system model

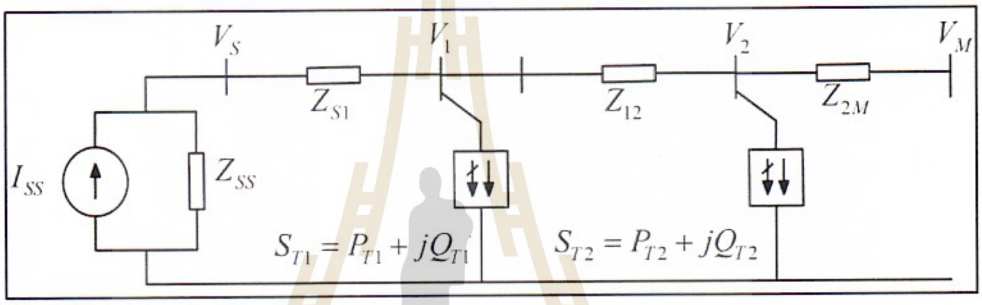


Figure 3.4 An AC single-conductor system circuit

$$[V] = [Y]^{-1}[I] \tag{3.7}$$

With this calculation, the system matrix equation is therefore formed.

$$\begin{bmatrix} V_{SS,1} \\ \vdots \\ V_{SS,N} \\ V_{Tr,1} \\ \vdots \\ V_{Tr,M} \end{bmatrix} = \begin{bmatrix} Y_{1,1} & Y_{1,2} & \cdots & Y_{1,q} \\ Y_{2,1} & Y_{2,2} & \cdots & Y_{2,q} \\ \vdots & \vdots & \ddots & \vdots \\ Y_{p,1} & Y_{p,1} & \cdots & Y_{q,q} \end{bmatrix}^{-1} \begin{bmatrix} I_{SS,1} \\ \vdots \\ I_{SS,N} \\ I_{Tr,1} \\ \vdots \\ I_{Tr,M} \end{bmatrix}$$

where [Y] is the aggregation of each bus's sub-conductance matrix which Consists of a sub-conductance matrix at the power station location [Y_{SS}]. The sub-conductance matrix of the contact line between bus p to q [Y_{pq}], the sub-conductance matrix of the rail-to-ground contact line at buses p and q [Y_{pp}] and [Y_{qq}], and the electric train conductor [Y_{Tr}] matrix is shown in the equation (3.8) – (3.11) respectively.

$$Y_{pq} = \frac{1}{(L_p - L_q)z_L} \tag{3.8}$$

$$Y_{pp} = Y_{qq} = 0 \tag{3.9}$$

$$Y_{SS,N} = \frac{1}{z_{SS,N}} + \frac{1}{(L_p - L_q)z_L} + 0 \tag{3.10}$$

$$Y_{Tr,M} = \frac{1}{(L_p - d)z_{L,p}} + \frac{1}{(L_q - d)z_{L,q}} \tag{3.11}$$

Where

L is the bus position (m)

z_L is the conductor rail Impedance (Ω/m)

z_{SS} is the short-circuit Impedance of the traction station (Ω/m)

I_{SS} is the current of the traction station (A)

I_{Tr} is the current of the electric train (A)

p, q are the bus number

N is the power station number.

M is the electric train number.

The short circuit Impedance and the electric power of the substation can be calculated from equation (3.12) – (3.14).

$$z_{SS} = \frac{(V_{nl})^2}{S_{ss}} \tag{3.12}$$

$$I_{ss} = I_s - \frac{V_{ss}}{z_{ss}} \tag{3.13}$$

$$I_s = \left(\frac{S_{ss}}{V_{nl}}\right)^* \tag{3.14}$$

Where

V_{nl} is the load voltage of the power station (V).

I_{SS} is the short-circuit current at the power station (A).

S_{ss} is the short-circuit power at the power supply station (VA).

The electric current value of the electric train is calculated from Equation (3.15).

$$I_{Tr} = \left(\frac{S_{Tr}}{V_{Tr}} \right)^* \tag{3.15}$$

Where

V_{Tr} is the electric vehicle voltage (V).

S_{Tr} is the electric power of the train (VA).

In this research the calculation of the voltage solution in the electric train system is through a process of solving the problem with the equation Current injection method (Kulworawanichpong, 2015). The operation uses a calculation interval of every 0.5 s. The position and power of the electric train will change according to the train's operating mode. This method depends on the equilibrium current equation. (Current-balance equation) at each bus as in equation (3.16).

$$I_{ss,i} - \left(\frac{S_{T,j}}{V_j} \right)^* = \sum_{i=1}^{N} Y_{k,ij} V_i \tag{3.16}$$

3.4 Topology of AC Railway Power Feeding system

Simulation of the effect of changing the topology of the railway power feeding system on the harmonic load at the traction station. In this research, two topology simulation models are presented. A model of increasing the connection points between power grids and a model of increasing the number of rails of the electric train system. To be a case study to find out how to reduce the amount of harmonics that occur in the railway power feeding system.

3.4.1 model of increasing the Intermediate track sectioning between power feeders.

A model of increasing the Intermediate track sectioning is an experiment to observe the behavior of the harmonic quantities occurring at the power distribution substation during railway service. The total feeder line distance of the ARL electric train is 28.3 km. It will be tested in 4 cases, including Case 1 open loop at the end-point track, normal power feeding system As shown in Figure 3.5, Case 2 close loop at the end-point track causing the railway power feeder line to 1 loop over a total distance of 28.3 km. as shown in Figure 3.6, Case 3 ITS 1 point divides railway power feeder line distance 28.3 km into equal 2 loops as shown in Figure 3.7 and Case 4 ITS 2 points divide the railway power feeder line distance 28.3km into 3 equal loops as shown in Figure 3.8.

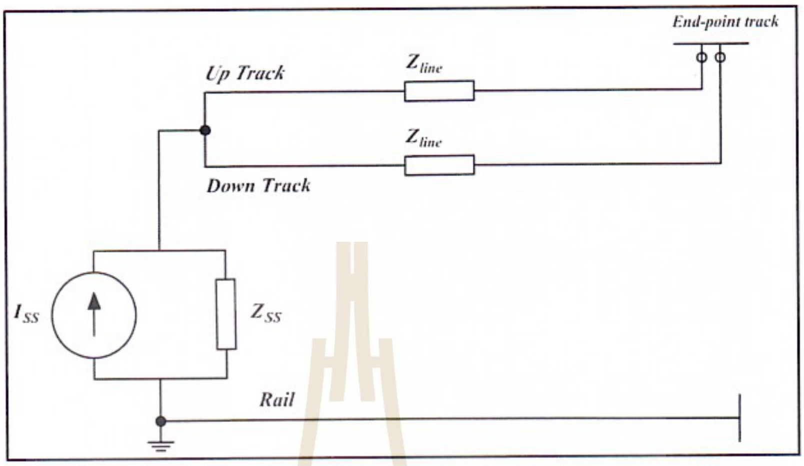


Figure 3.5 Case 1 open loop at the end-point track, normal power feeding system.

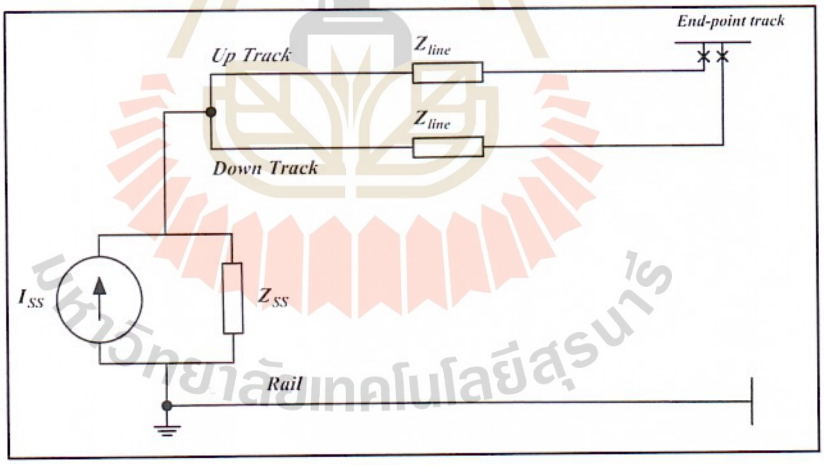


Figure 3.6 Case 2 close loop at the end-point track causing the railway power feeder line to 1 loop over a total distance of 28.3 km.

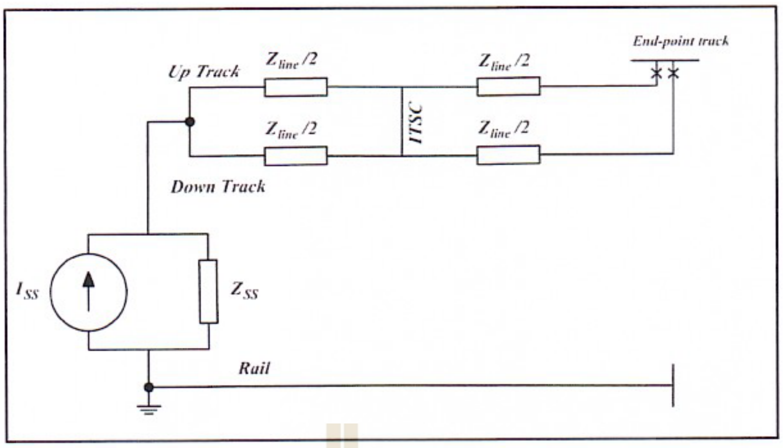


Figure 3.7 Case 3 ITS 1 point divides railway power feeder line distance 28.3 km into equal 2 loops

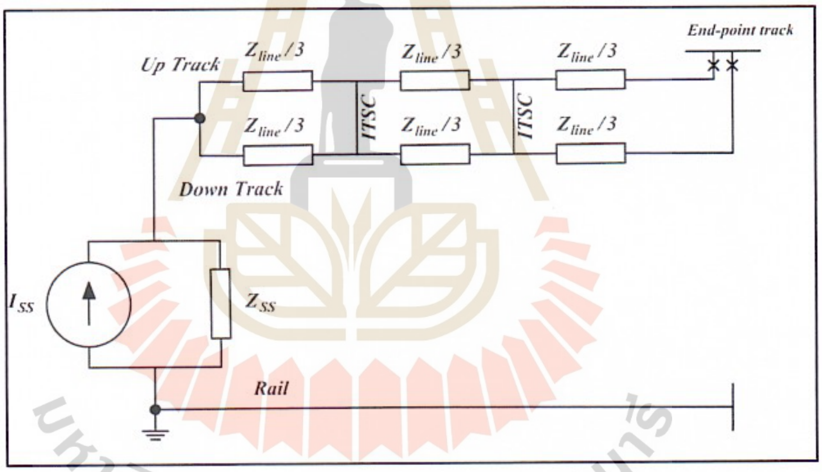


Figure 3.8 Case 4 4 ITS 2 points divide the railway power feeder line distance 28.3km into 3 equal loops.

3.4.2 A model of increasing the number of tracks of the electric train system.

A model of increasing the number of tracks of the electric train system is an experiment to observe the behavior of the harmonic quantities occurring at the power distribution station. The number of railway tracks that are in use today are either 1-track, 2-track, 4-track or 6-track. For testing in this research, 2-track and 4-track models that are commonly used in electric train systems are used. Comparison of the harmonic quantity at the power distribution station that changes with the number of track s by the 2-track and 4-track electric train system models are shown in Figure 3.9-3.10.

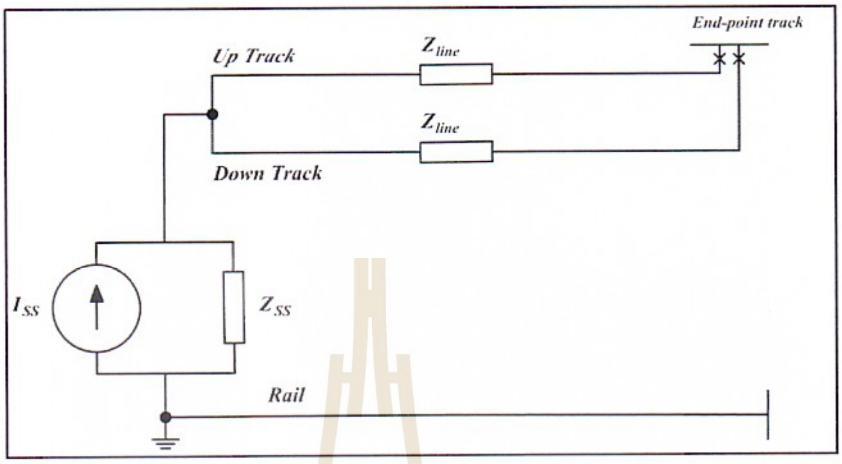


Figure 3.9 2-track electric train system models.

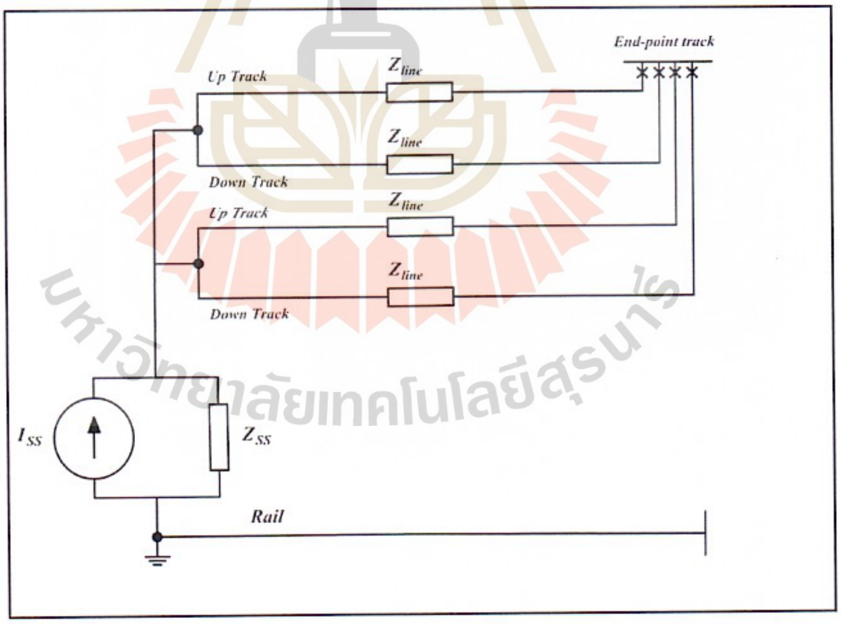


Figure 3.10 4-track electric train system models.

3.5 Harmonic Calculation

In general, parameters of all conductor systems are described in fundamental frequency. Since reactance or susceptance of the power feeding conductors, such as overhead contact system, running rails or return cables, are frequency-dependent, a method of frequency scanning can be employed by varying the frequency used starting from 50 Hz (fundamental: f1) to any high frequency of the form n×50 Hz (n×f1), where n is a positive integer. This cause a set of linear system equations needed to be solved at a given harmonic order (n) of frequency.

Power flow calculation model for calculating harmonics as shown in Figure 3.11. There is a change from the normal power flow calculation which is to change the electric train to be the source of harmonic current and then send it through the feeder line to the substation acting like a load without power supply. After that, calculate the amount of voltage and harmonic current occurring at the power station.

$$\omega_n = 2\pi n f_1 \qquad ; n = 1, 2, 3, \ldots$$

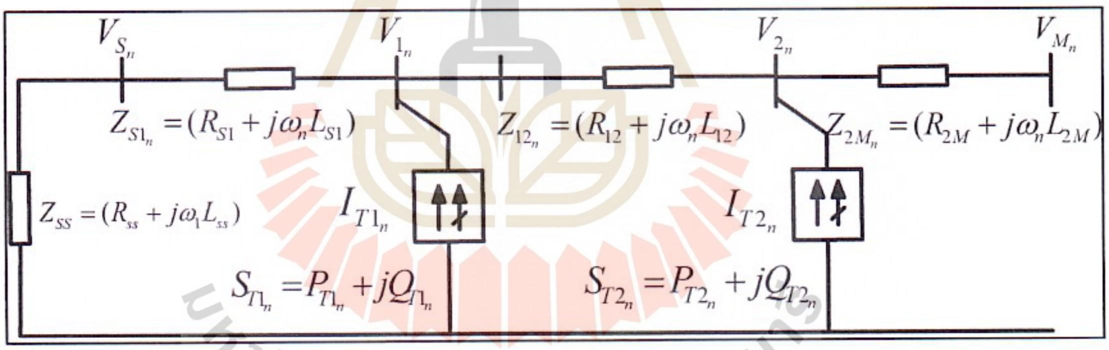


Figure 3.11 Power flow calculation model for calculating harmonics.

In this research, a current injection calculation method is used to calculate the bus voltage in each order as well as the power flow calculation in normal or fundamental conditions. The electric train model calculations are in terms of harmonic currents that change with each order. The impedance of the contact line is in terms of the Y bus that changes with each order but at the substation there is a fixed impedance at fundamental frequency (n=1). Therefore, the bus voltage values for each order can be calculated in terms of node equations as shown in equation (3.17).

$$[V_n] = [Y_n^{-1}][I_n] \qquad (3.17)$$

For calculating harmonic distortion at 25kV substation, the total harmonic distortion (THD) is the ratio of the root mean square of the harmonic content, considering harmonic components up to the 50th order and specifically excluding interharmonics, expressed as a percent of the fundamental. Harmonic components of order greater than 50 may be included, when necessary, THD is used to calculate the total harmonic distortion for voltage (THDv) following equation (3.18) and can be compared to the IEEE 519-2014 standard.

$$THD_v = \frac{\sqrt{\sum_{n=2}^{\infty} V_n^2}}{V_1} \tag{3.18}$$

Where

V1 is values of the fundamental harmonic of voltage.

Vn is values of non-fundamental harmonics of voltage.

The total demand distortion (TDD) is the ratio of the root mean square of the harmonic content, considering harmonic components up to the 50th order and specifically excluding interharmonics, expressed as a percent of the maximum demand current. Harmonic components of order greater than 50 may be included when necessary. TDD is used to calculate the total harmonic distortion for current (TDDi) following equation (3.19) and can be compared to the IEEE 519-2014 standard.

$$TDD_i = \frac{\sqrt{\sum_{n=2}^{\infty} I_n^2}}{I_{\max}} \tag{3.19}$$

Where

I_{max} is the fundamental maximum demand current.

I_n is values of non-fundamental harmonics of current.

3.5.1 Case study: Topology Power Feeding

For the determination of harmonic quantities in the case of changes in topology increasing the intermediate track sectioning. It will be considered in the form of the equivalent circuit to study the change in impedance of the railway power feeder line. By the case of 1 loop, the equivalent circuit is as shown in Figure 3.12; by the case of 2 loop, the equivalent circuit is as shown in Figure 3.13; and by the case of 3 loop, the equivalent circuit is as shown in Figure 3.14. The impedance of the railway power feeder line, which changes with the distance of each loop multiplication scheme circuit is as shown in Figure 3.15.

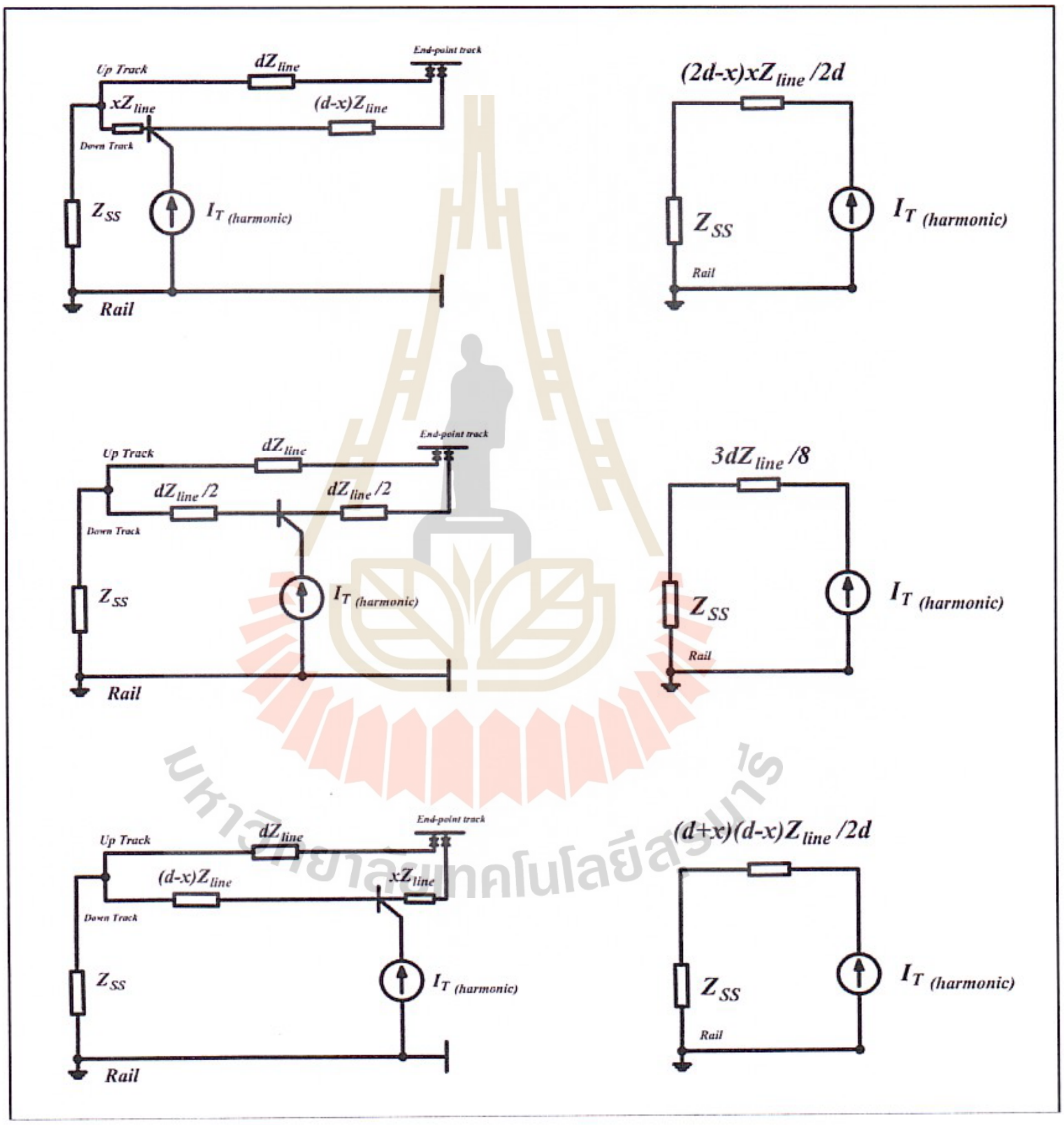


Figure 3.12 The equivalent circuit of 1 loop.

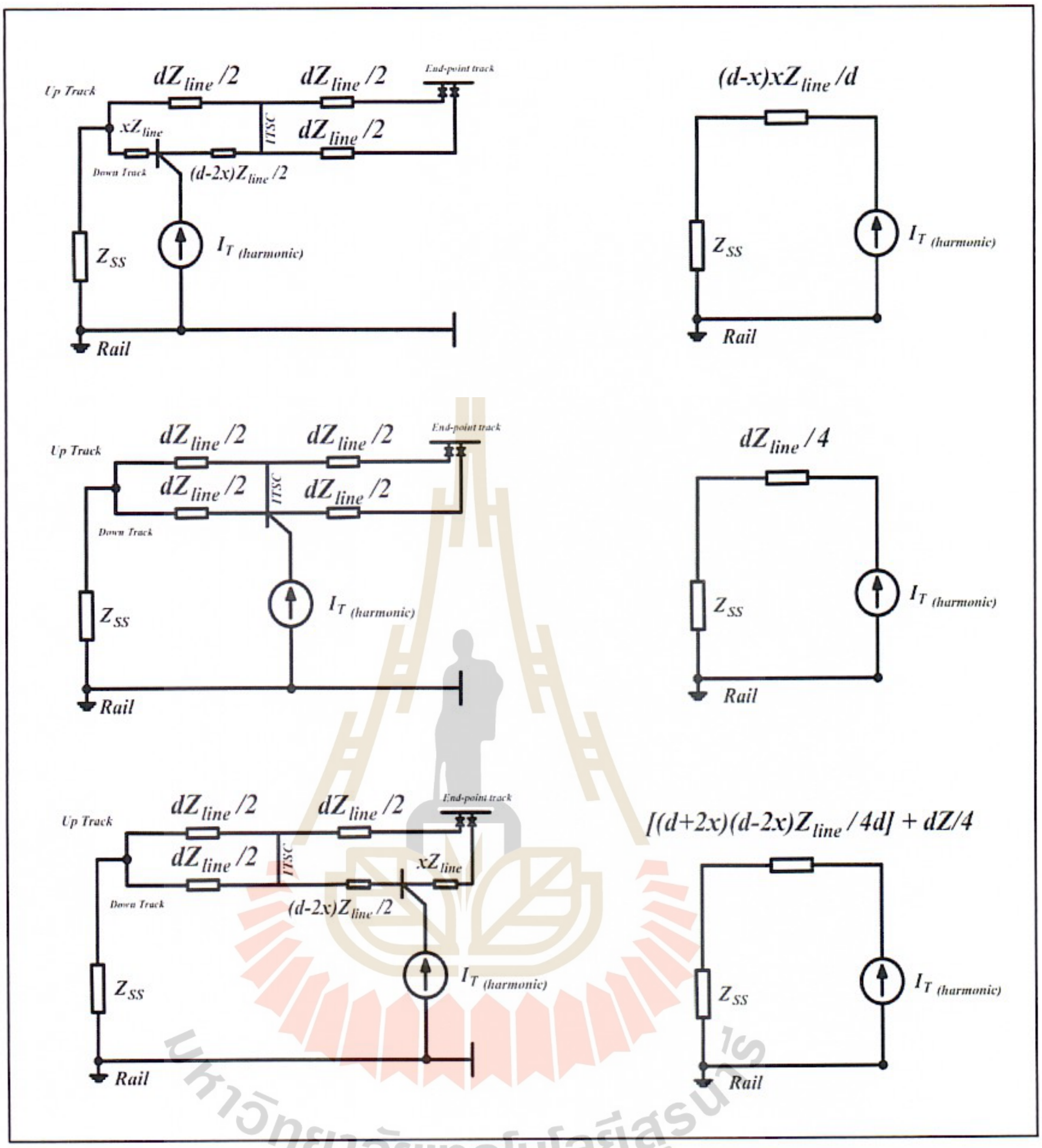


Figure 3.13 The equivalent circuit of 2 loop.

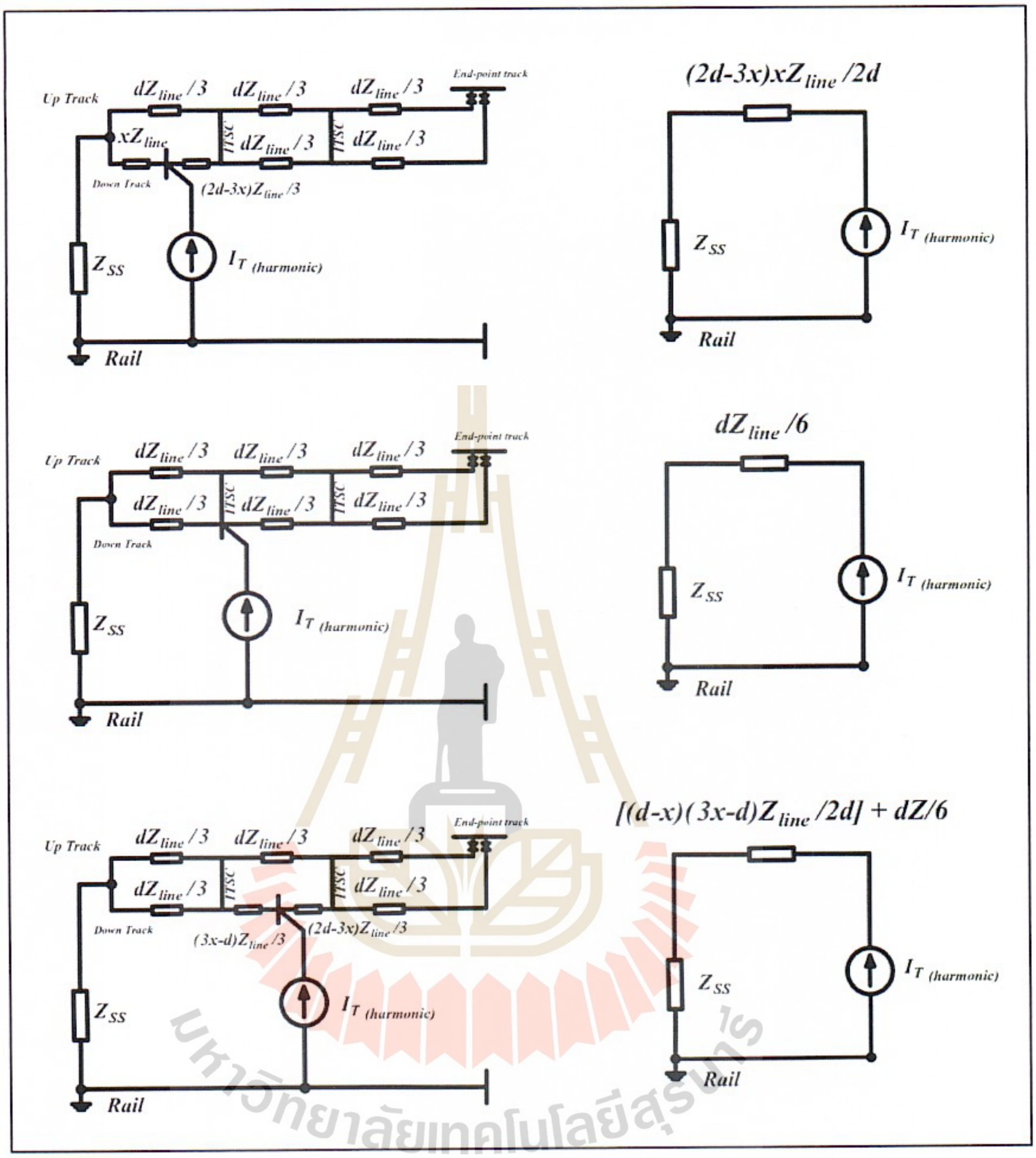


Figure 3.14 The equivalent circuit of 3 loop.

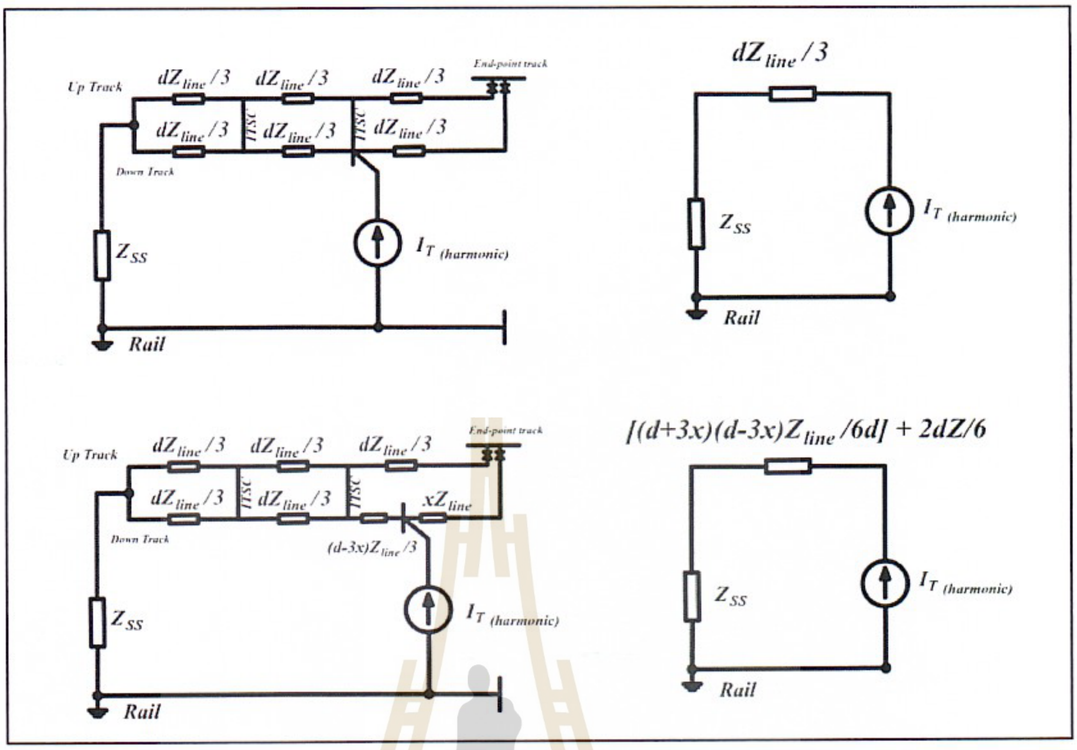


Figure 3.14 The equivalent circuit of 3 loop. (continue)

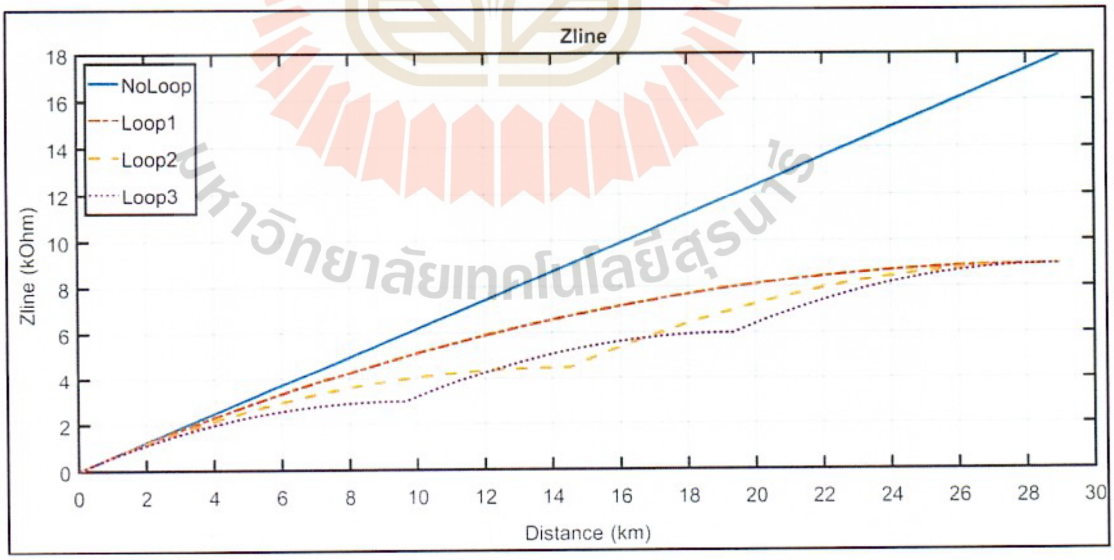


Figure 3.15 The impedance of the railway power feeder line, which changes with the distance of each ITS multiplication scheme.

For the determination of harmonic quantities in the case of changes in topology increasing the number of tracks of the electric train system. It will be considered in the form of the equivalent circuit to study the change in impedance of the railway power feeder line. Figure 3.16 shows the equivalent circuit of a railway system with an increase in the number of tracks to 4 tracks. Figure 3.17 shows the impedance of the railway power feeder line which changes with distance in the case of 2-track and 4-track.

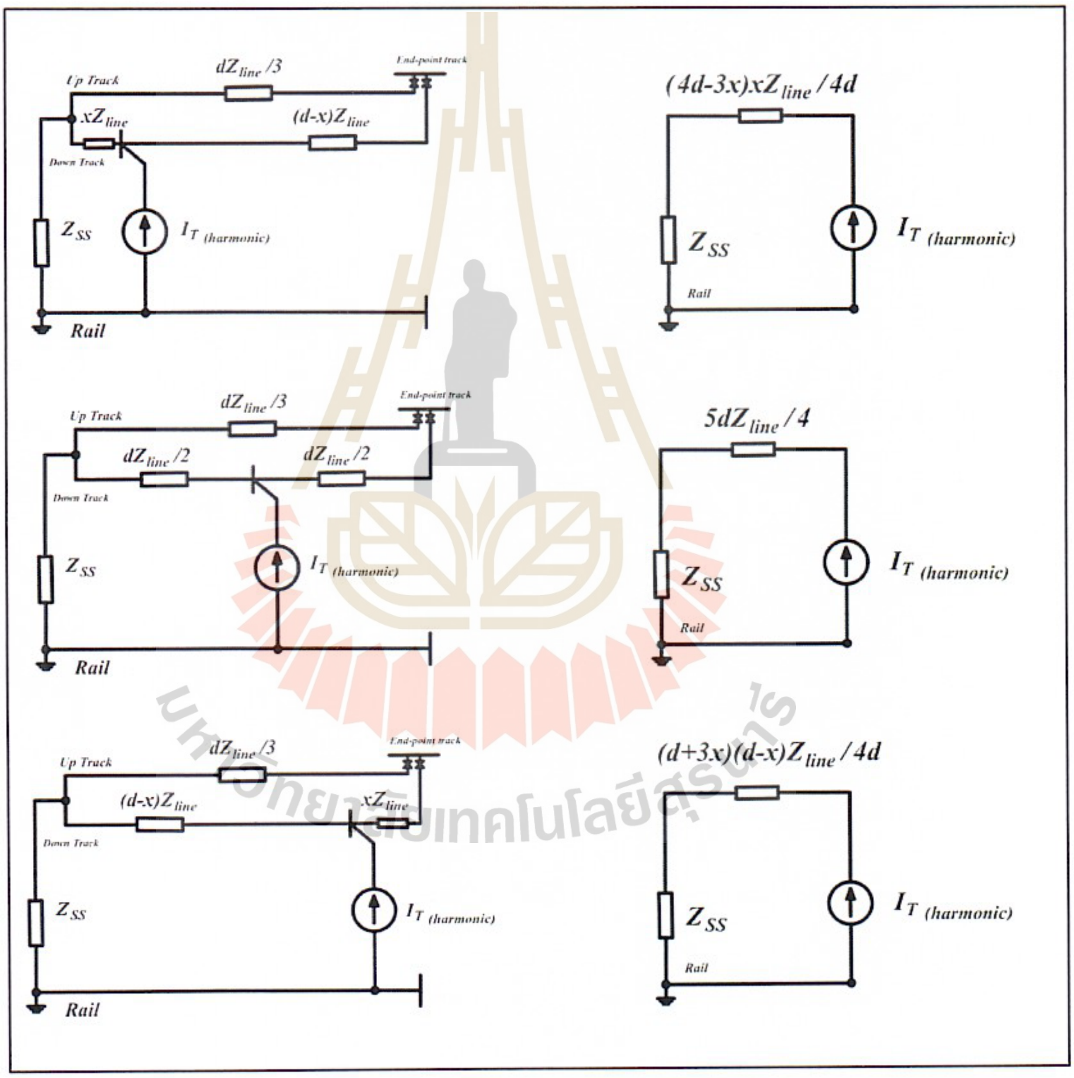


Figure 3.16 The equivalent circuit of a railway system with an increase in the number of tracks to 4 tracks.

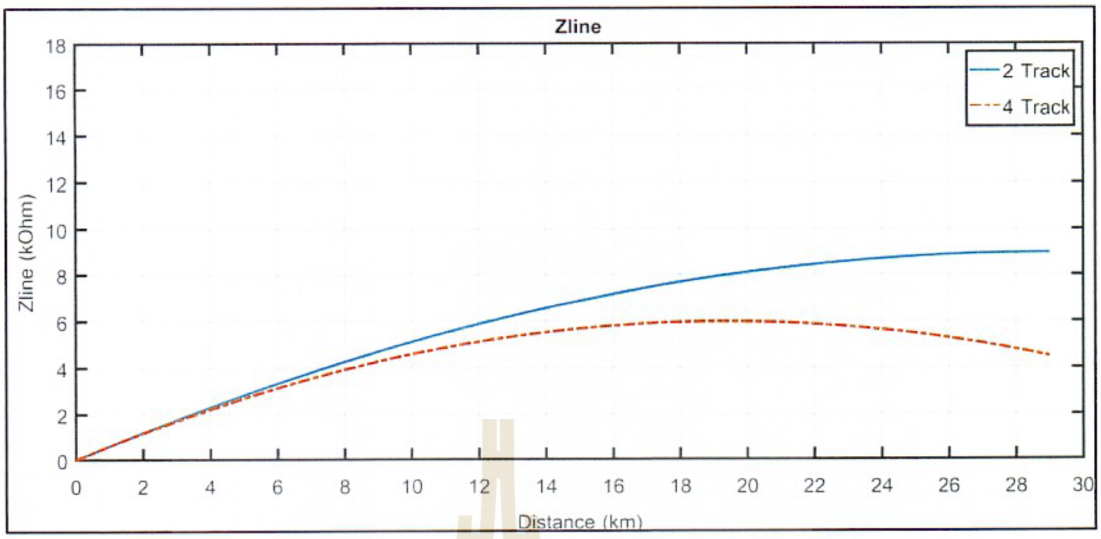


Figure 3.17 The impedance of the railway power feeder line which changes with distance in the case of 2-track and 4-track.

3.5.2 Case study: Measurement Data

The amount of harmonic current produced by the electric train will be taken from the value sample of the harmonic current of the high-speed electric train from China, model CHR380A, as shown in Figure 3.18 and in Figure 3.19, to compare the proportion of the harmonic current. in various orders to suit the ARL train simulation system in this research by comparing the maximum current of trains in normal state. (H. Hu,2015)

Har. Order	Mag. [A]	Ang. [deg]	Har. Order	Mag. [A]	Ang. [deg]	Har. Order	Mag. [A]	Ang. [deg]	Har. Order	Mag. [A]	Ang. [deg]	Har. Order	Mag. [A]	Ang. [deg]	Har. Order	Mag. [A]	Ang. [deg]
1	127.3	0	11	0.8271	-21.37	21	0.2924	-134.32	31	0.1230	134.01	41	0.1469	21.93	51	2.3297	2.83
2	0.9265	103.25	12	0.1101	-157.55	22	0.1849	-50.75	32	0.1139	95.75	42	0.0127	-97.62	52	0.0728	-40.80
3	2.1747	116.88	13	0.6158	-147.27	23	0.0971	74.1411	33	0.2622	-42.59	43	0.2230	96.34	53	2.1778	62.04
4	0.3581	72.49	14	0.2713	10.91	24	0.3774	-149.02	34	0.0623	82.82	44	0.0430	160.99	54	0.1041	74.28
5	0.9183	147.13	15	0.3856	-8.59	25	0.3370	-65.66	35	0.1090	65.49	45	0.4277	4.39	55	1.2922	-61.16
6	0.2770	139.42	16	0.2774	-19.42	26	0.0641	114.47	36	0.0900	-178.85	46	0.0892	94.60	56	0.1212	-31.06
7	2.0031	-156.40	17	0.2757	-131.11	27	0.1858	-111.47	37	0.0563	167.46	47	0.9697	-101.02	57	0.1851	-115.60
8	0.2555	152.82	18	0.2775	139.33	28	0.1067	-34.01	38	0.0840	139.45	48	0.0752	-159.97	58	0.0087	-31.30
9	1.4280	101.31	19	0.5897	54.54	29	0.1413	-74.79	39	0.1282	97.60	49	1.9844	-40.84	59	0.1159	138.06
10	0.2134	-104.32	20	0.3763	93.58	30	0.0884	-97.50	40	0.0503	153.88	50	0.0544	-107.04	60	0.0742	9.38

Figure 3.18 The graph sample of the harmonic current of the high-speed electric train from China, model CHR380

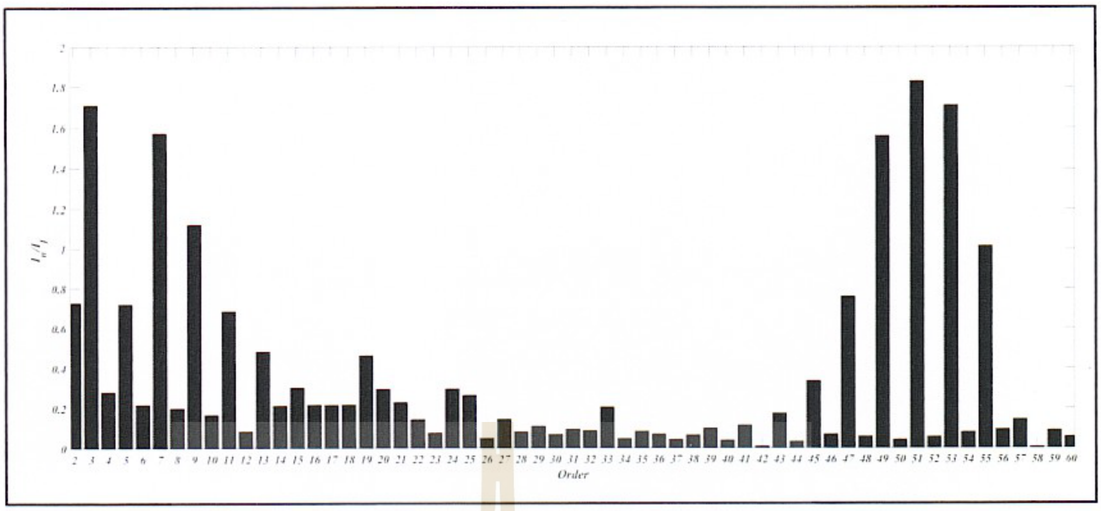


Figure 3.19 The graph sample of the harmonic current of the high-speed electric train from China, model CHR380A

3.5.3 Case study: Four-quadrant converter's harmonic modelling

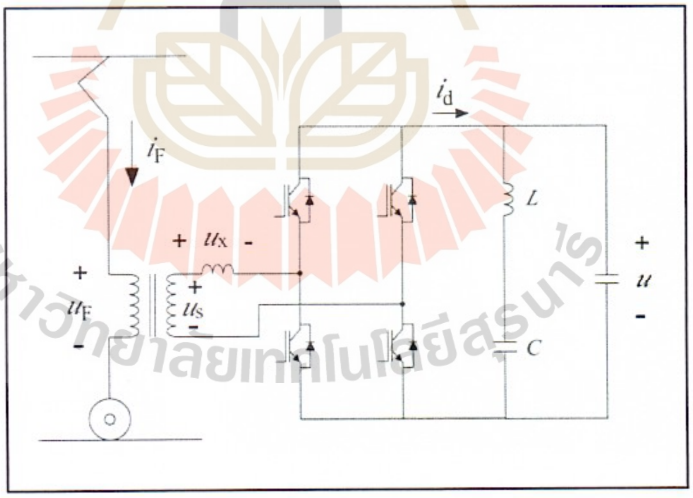


Figure 3.20 Four-quadrant converter equivalent circuit

In a four-quadrant converter equivalent circuit in Figure 3.20 the transformer secondary winding is connected between the outputs of two-quadrant choppers (similar to the inverter phase modules). With the usual (unipolar) PWM control with two inverse reference functions, the pulsed bridge voltage us contains harmonics with the frequencies in equation (3.20). (Steimel,2014)

$$f=\left[2\cdot h\cdot N_Z\pm(2g-1)\cdot f_F\right]\quad for\quad g,h=1,2,3,... \tag{3.20}$$

With the pulse number Nz and line frequency fF; the amplitudes can be described approximately as in equation (3.21).

$$u_{S2kN\pm(2m-1)}=\mp U_d\left\{\frac{4N_Z}{\pi(2hN_Z\pm(2g-1))}\right\}\cdot J_{\pm(2m-1)}\left\{2hN_z\pm(2g-1)\cdot k_1\cdot\frac{\pi}{2N_Z}\right\} \tag{3.21}$$

J_V is the Bessel function of order **V**). The harmonics of the line current are limited by the leakage inductivity of the transformer and the line impedance.

To present that graphically, a 50-Hz, 25-kV application with fivefold switching (Nz = 5, fz = 250 Hz) is chosen as an example in simulation; the normalized short-circuit voltage of the transformer is 44 %, that of the line is neglected

Figure 3.21 shows the spectra of the converter voltage and of the line current (on the primary side of the transformer) of 4q-C. The dominating spectral lines in the vicinity of 2·fz = 500 Hz can be easily recognized. The interference current r.m.s. value with a fundamental train current of 123.5 A.

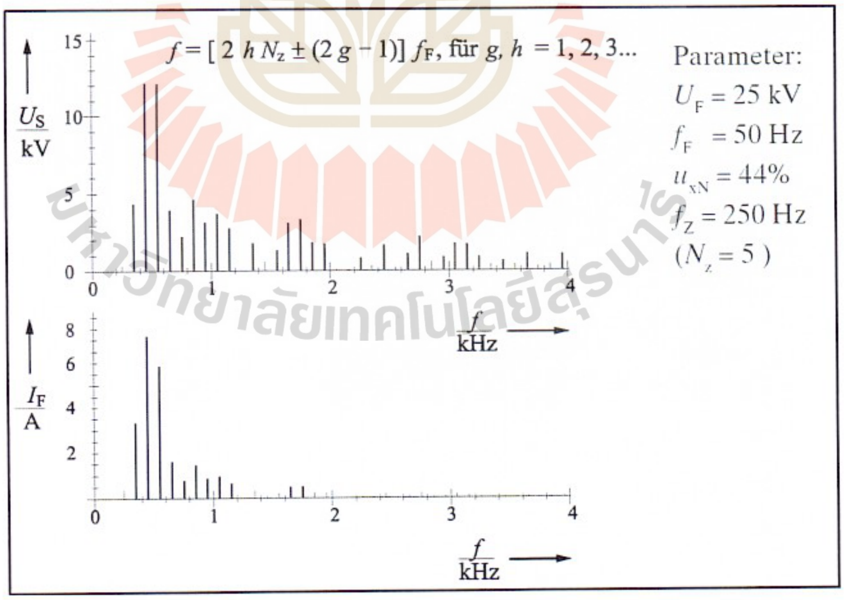


Figure 3.21 Spectra of voltage of 4q-C (r.m.s. values)

3.6 Passive Filter Design

Adding filters to the system to limit or reduce the harmonics is a highly efficient method. Limiting harmonics to very low dimensions may require multiple filters, which incur a high investment cost. When applying filters to solve harmonic problems, one must consider the purpose or size of the harmonics to be reduced to a greater extent and must know how many filters should be used or their size. Therefore, it must be calculated to be suitable for that electrical system. In this research, the design method of passive harmonic filters will be presented.

Passive harmonic filters can be constructed using three main components: a capacitor (C), an inductor (L), and a resistor (R). They are connected to make a series or parallel resonance circuit. To obtain a circuit with very low or very high impedance at the resonance frequency or tuning frequency. The equivalent impedance of a harmonic filter (Z_f) in the case that a passive filter is installed at the substation is represented in Figure 3.22. and the equivalent impedance of a harmonic filter (Zf) in the case that a passive filter is installed On-board is represented in Figure 3.23. The harmonic filter is usually connected to the system in parallel.

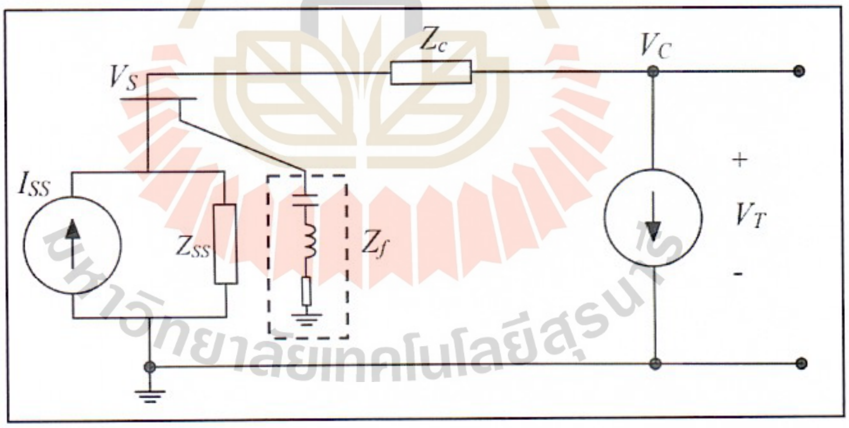


Figure 3.22 The equivalent impedance of a harmonic filter (Zf) in the case that a passive filter is installed at the substation.

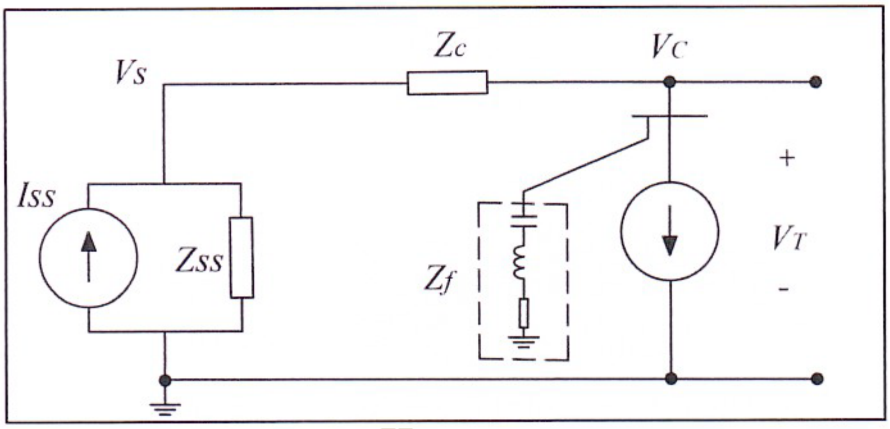


Figure 3.23 The equivalent impedance of a harmonic filter (Zf) in the case that a passive filter is installed On-board.

3.6.1 Single-Tuned Filter (STF)

This filter is based on three variables: A capacitor (C), a reactor (L), and a resistor (R) are linked in series and are tuned to suppress a single frequency. The harmonic current order that necessitates blocking, as well as the capacitive reactive power and quality factor that it will give. During the design process, the voltage level and fundamental frequency provided by the system must also be recognized. The impedance of the filter is as follows in equation (3.21) and the circuit schematic of STF is shown in Figure 3.24.

$$Z_f = R_f + j(X_L - X_c) \tag{3.21}$$

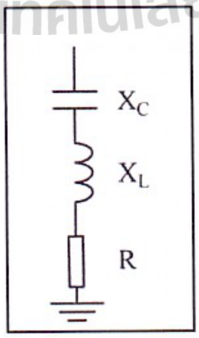


Figure 3.24 Single-Tuned Filter

In conclusion, the values utilized to define the input parameters are as follows:

Q_c : Reactive power of the capacitor (kVARs)

F : System frequency (Hz)

h : Tuning point of the filter

V : System voltage (kV)

Q : Quality factor

The quality factor determines the bandwidth and the filtering deepness at the notch frequency. The quality factor has an impact on this filter, which shows that, as Q is increased, the sharpness of the tuning increases whereas the bandwidth decreases. As Q is decreased, we notice an enlargement of the bandwidth as opposed to the deterioration of the tuning sharpness.

For Single-Tuned Filter, it is the ratio of the filter's reactance and resistance. Between 30 and 60 is a normal range for Q. Therefore, Q=30 was chosen for the design. (Abbas,2019)

To compare the harmonic filtering efficiency of these 4 types of passive filters, in this report, the value of Q=30 was chosen to be used in the design of these 4 types of filters.

Design steps of the single tuned passive filter.

1) Select the tuned harmonic order (h) to be reduced by the filter.

2) Find the reactive power of the capacitor (Q_c).

3) Calculate the L and C as shown in (3.22), (3.23), (3.24), and (3.25)

$$X_c = \frac{V^2}{Q_c} \quad (3.22) \qquad C = \frac{1}{2\pi f X_c} \quad (3.23)$$

$$X_L = \frac{X_c}{h^2} \quad (3.24) \qquad L = \frac{X_L}{2\pi f} \quad (3.25)$$

4) Select the Quality factor, this report selects Q = 30.

5) Calculate the R as shown in (3.26) and (3.27)

$$X_n = \sqrt{\frac{L}{C}} \qquad (3.26) \qquad\qquad R = \frac{X_n}{Q} \qquad (3.27)$$

3.6.2 Band-Pass Filter (BP)

This element is useful for modeling high-order filters. A capacitor (C), a reactor (L), and a resistor (R) are linked in parallel. The design order and design values have the same values as the design of STF. The impedance of the filter is as follows in equation (3.28) and the circuit schematic of the band-pass filter is shown in Figure 3.25. (Nassif, 2007)

$$Z_f = \left(\frac{1}{R} + \frac{1}{jX_L} + jX_c\right)^{-1} \qquad (3.28)$$

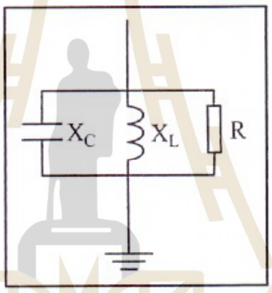


Figure 3.25 Band-pass filter

3.6.3 High-Pass Filter (HP)

For high frequencies, this filter is designed to have a flat impedance characteristic. The design order and design values have the same values as the design of STF. The impedance of the filter is as follows in equation (3.29) and the circuit schematic of the High-pass filter is shown in Figure 3.26.

$$Z_f = \left(\frac{1}{R} + \frac{1}{jX_L}\right)^{-1} + jX_c \qquad (3.29)$$

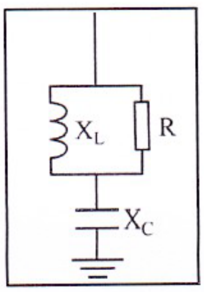


Figure 3.26 High-pass filter

3.6.4 C-Type Filter

C-type filters are second-order filters that may suppress harmonic currents with lower losses than a series or band-pass filter. The L and C components, which are parallel to the resistor, resonate at the fundamental frequency, which explains this capacity. As a result, the fundamental current flowing through the damping resistor is kept to a minimum. Another advantage is that, because of their essentially flat impedance profile above the tuned frequency, c-type filters are good at suppressing high-frequency harmonics. The impedance of the filter is as follows in equation (3.30) and the circuit schematic of the band-pass filter is shown in Figure 3.27.

$$Z_f = \left(\frac{1}{R} + \frac{X_{C2}}{1 - X_L X_{C2}}\right)^{-1} + \frac{1}{jX_{C1}} \quad (3.30)$$

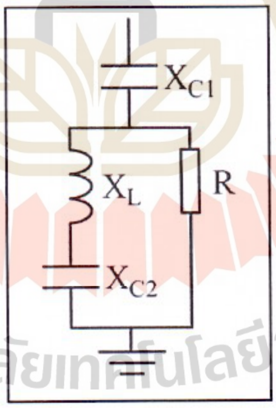


Figure 3.27 C-type Filter.

Design steps of C-type filter. (Paul S.,2022)

1) Find the reactive power of the capacitor (Q_c).

2) Calculate the X_{C1} and the C1 as shown in (3.31) and (3.32)

$$X_{C1} = \frac{(kV)^2}{Q_c} \quad (3.31) \qquad C1 = \frac{1}{2\pi f X_{C1}} \quad (3.32)$$

3) Calculate the X_L, L, X_{C2} and $C2$ as shown in (3.33), (3.34), (3.35), and (3.36)

$$X_L = \frac{X_{C1}}{h^2 - 1} \qquad (3.33)$$

$$L = \frac{X_L}{2\pi f} \qquad (3.34)$$

$$X_L = X_{C2} \qquad (3.35)$$

$$C2 = \frac{1}{2\pi f X_{C2}} \qquad (3.36)$$

4) Select the Quality factor, this report selects Q = 30.

5) Calculate the R as shown in (3.37)

$$R = Q_f h X_L \qquad (3.37)$$

In the case that a passive filter is installed at the Substation, the value of Y_{ss} will be given to Equation 3.38.

$$Y_{SS,N} = \frac{1}{z_{SS,N}} + \frac{1}{(L_p - L_q)z_L} + 0 + \frac{1}{z_{hf}} \qquad (3.38)$$

In the case that a passive filter is installed at On-board, the value of Y_{Tr} will be given to Equation (3.39).

$$Y_{Tr,M} = \frac{1}{(L_p - d)z_{L,p}} + \frac{1}{(L_q - d)z_{L,q}} + \frac{1}{z_{hf}} \qquad (3.39)$$

In the simulation, the number of system nodes is equal to the number of power stations plus the number of moving trains. The location of the electric train is not considered when it is the same as the power station location. The procedure for determining the voltage solution by the current injection method can be described as follows Figure 3.28 the procedure for current injection method.

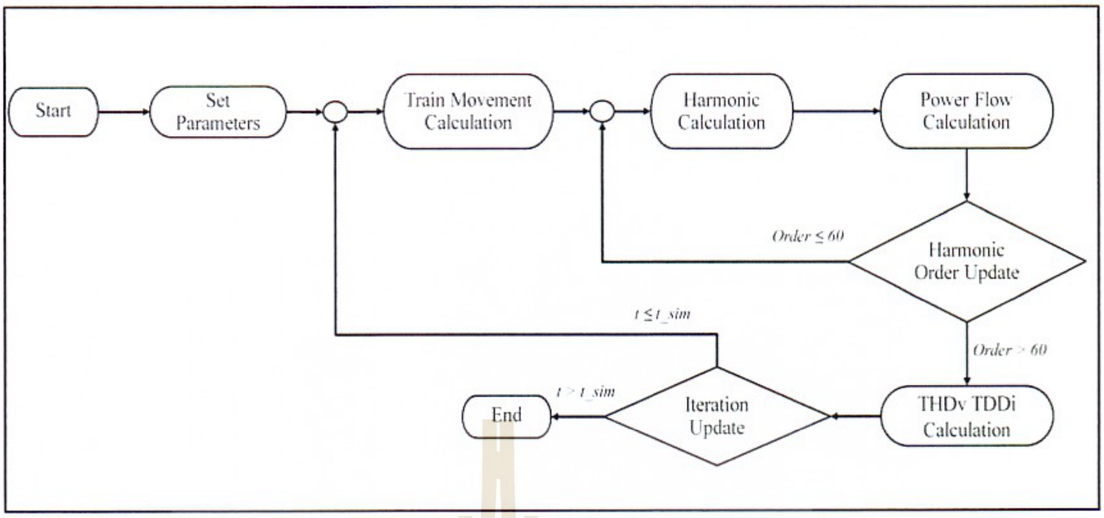


Figure 3.28 The procedure for current injection method

3.7 Chapter Summary

This chapter discusses the Train Movement Model and calculations that will be used to understand the train movement characteristics and to calculate the distance, speed, and force. Discuss Power Flow Calculation for Single Conductor AC railway system. Understood in the topology of AC rail systems with an increasing number of ITS and track that the change in line impedance with distance in the form of a equivalent circuit has an effect on harmonics in the railway system. In addition, harmonic calculations are described in the cases of measurement data and 4QC. Finally, describe the design process of four types of passive harmonic filters: STF, BP, HP, and C-Type.

CHAPTER 4
Simulation Result

4.1 Chapter Overview

Chapter 4 simulation results This chapter presents the simulation results of various case studies, such as the simulation results of the train in the condition without the passive filter installed, the simulation results of the topology modification case studies, the simulation results of passive filter installation in cases where harmonic values are obtained from measurements, and the simulation results of passive filter installation in cases where harmonic values are obtained from the Four-Quadrant converter. Also, the simulation results were compared to the effectiveness of reducing harmonics at the substation for each tuning order and installation location of the filter at both the substation and on-board.

4.2 Train movement simulation

The results of a simulation on ARL city line trains using the MATLAB program. This even takes 1 hour to simulate train service with 20 trains, 8 passenger stations, and a 28-kilometer distance between the origin station and the destination station. AC power is supplied to the train via a single conductor from a single AC substation. A simulation of the train movement by determining the speed of travel from the design and from the train parameters in Chapter 2 is shown in Figure 4.1-4.5.

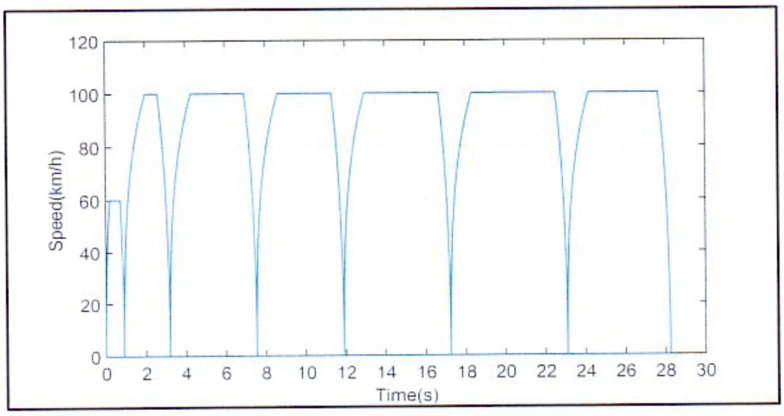


Figure 4.1 Speed and Position of the ARL City Line

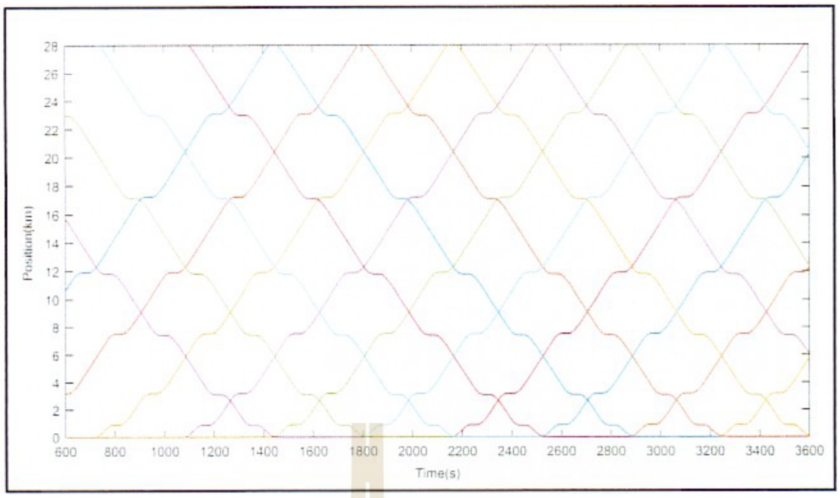


Figure 4.2 Position and Time of ARL City Line multi-trains.

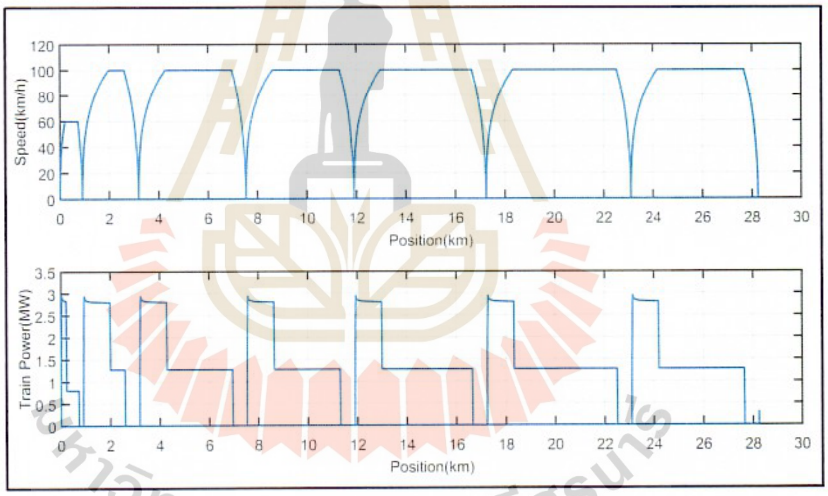


Figure 4.3 Speed and Position of ARL City Line and Train Power and Position of ARL City Line

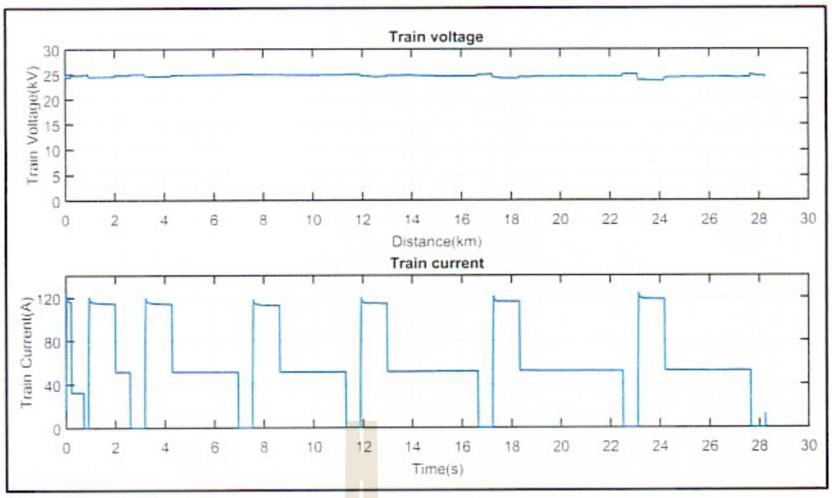


Figure 4.4 Train Voltage and Position of ARL City Line and Train Current and Position of ARL City Line.

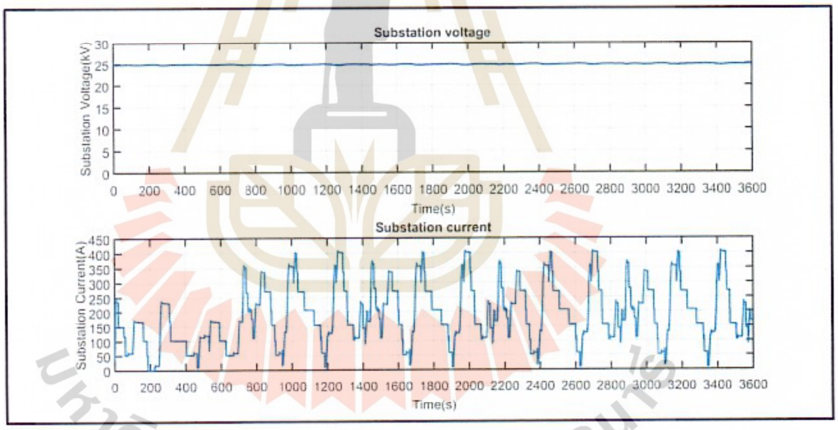


Figure 4.5 Substation Voltage and Time of ARL City Line and Substation Current and Time of ARL City Line.

In case study: Measurement data. There is also the effect of simulating the movement of trains. The train will release the harmonic current through the railway power feeding system to the power station. The amount of harmonic produced is the amount of harmonic sample from the China high-speed train CHR380A that is adjusted for the proportion of the harmonic current in accordance with the moving current of the ARL City Line electric train. The simulation results are shown in Figure 4.6-4.11.

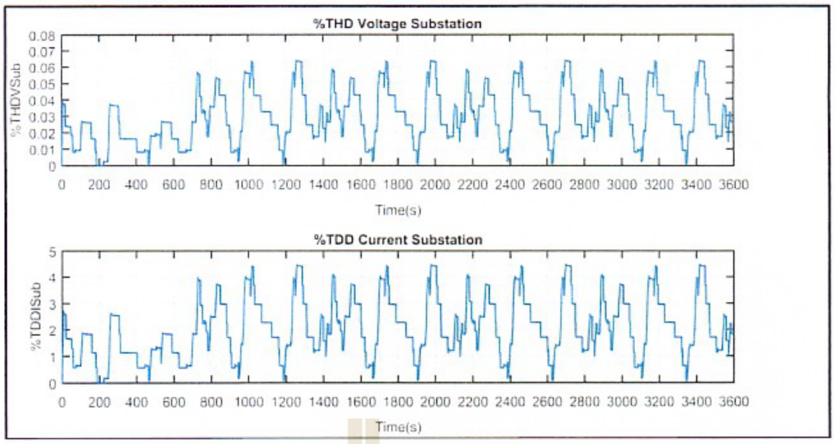


Figure 4.6 Total Harmonic Distortion Voltage at substation and Total Harmonic Distortion Current at substation

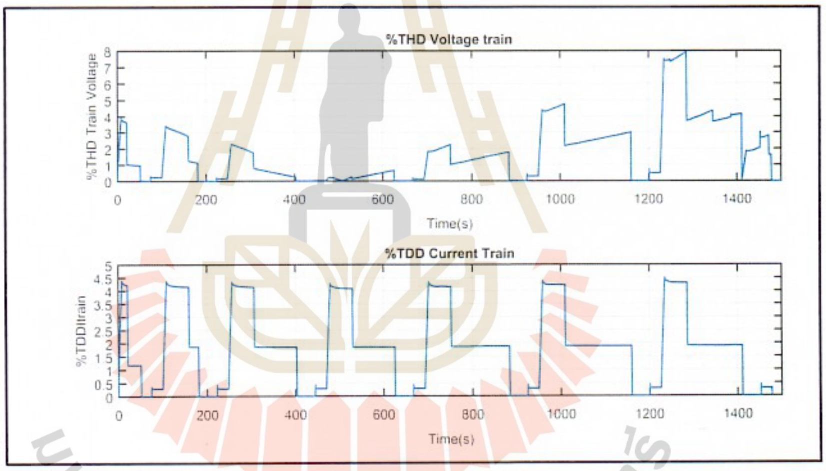


Figure 4.7 Total Harmonic Distortion Voltage at Train and Total Harmonic Distortion Current at Train

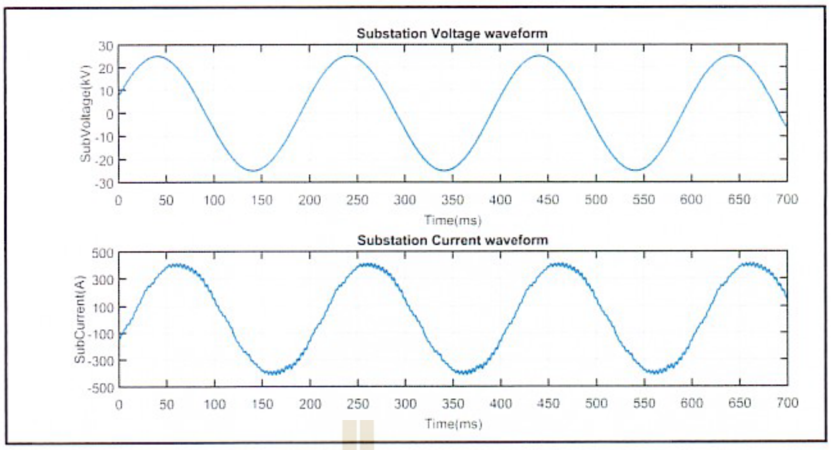


Figure 4.8 Harmonic Distortion Voltage at substation and Harmonic Distortion Current at substation wave form

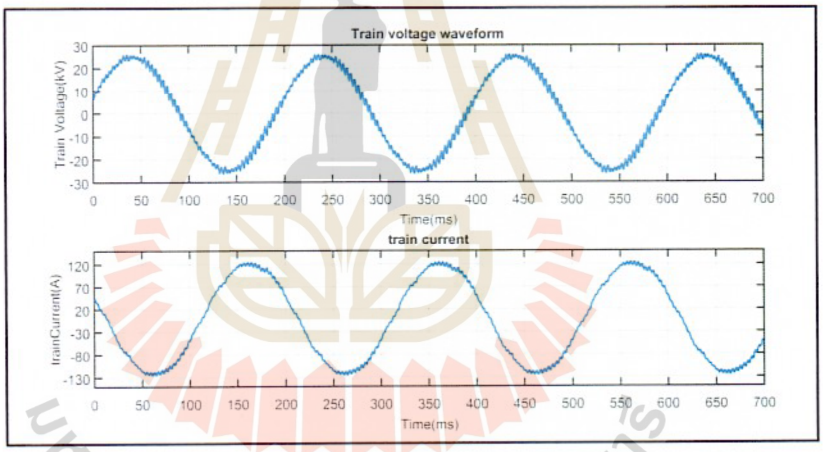


Figure 4.9 Harmonic Distortion Voltage at Train and Harmonic Distortion Current at Train wave form

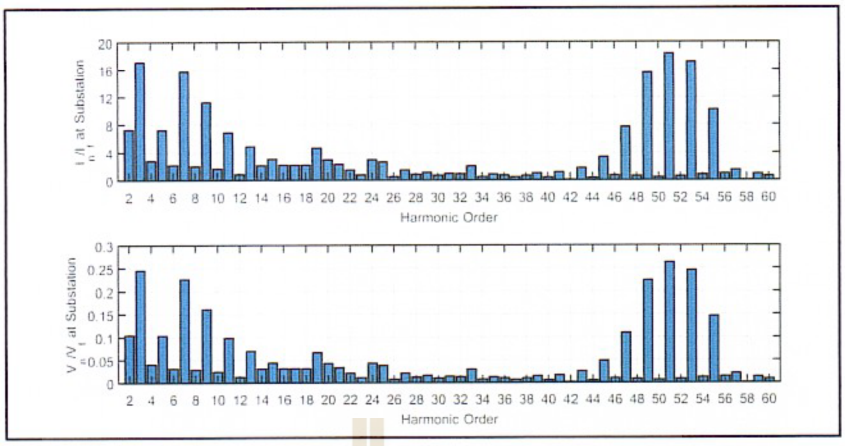


Figure 4.10 Harmonics spectrum of Current and Voltage at the Substation.

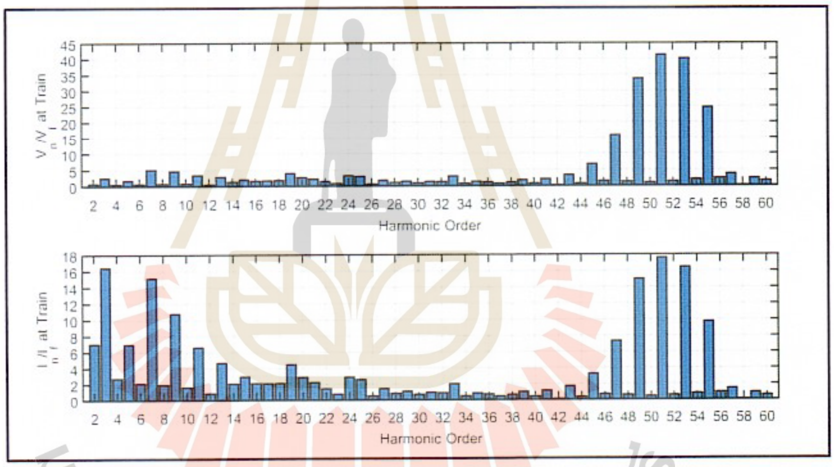


Figure 4.11 Harmonics spectrum of Voltage and Current at On-board.

Tables 4.1 and 4.2 show the results of simulation and comparison with IEEE. Table 4.1 shows the minimum, average and maximum voltage Total Harmonic Distortion values obtained from simulations both at the substation and on the train and compared to IEEE519-2014 voltage harmonic standards. Table 4.2 shows the minimum, average and maximum values of the substation harmonic currents from the simulation by dividing the harmonic sequences into groups for comparison with the IEEE519-2014 harmonic currents standard.

Table 4.1 The minimum, average and maximum THD voltage values obtained from simulations both at the substation and on the train and compared to IEEE519-2014.

Bus voltage V at PCC 25 kV	THD Substation (%) (Simulation)	THD Train (%) (Simulation)	THD (%) IEEE519-2014 Standard
Min	0.00	0.00	5.00
Average	0.03	0.70	5.00
Max	0.07	7.92	5.00

Table 4.2 The minimum, average and maximum values of the substation harmonic currents distortion from the simulation and comparison with the IEEE519-2014.

Maximum harmonic current distortion in percent of I_L						
Individual harmonic order (odd harmonics) at Substation						
I_{SC}^{a}/I_{L}^{b} *(100 < 1000)*	$3 \le h < 11$	$11 \le h < 17$	$17 \le h < 23$	$23 \le h < 35$	$35 \le h \le 50$	TDD[c]
Min	0.00	0.00	0.00	0.00	0.00	0.00
Average	1.29	0.45	0.32	0.25	0.83	2.07
Max	2.80	0.97	0.70	0.53	1.79	4.48
IEEE514-2014	12.0	5.5	5.0	2.0	1.0	15.0

In case study: Four-quadrant converter's harmonic modelling. There is also the effect of simulating the movement of trains. The train will release the harmonic current through the railway power feeding system to the traction station. The amount of harmonics generated by the converter is in accordance with section 3.5.3. that is adjusted for the proportion of the harmonic current in accordance with the moving current of the ARL City Line electric train. The simulation results are shown in Figure 4.12-4.17.

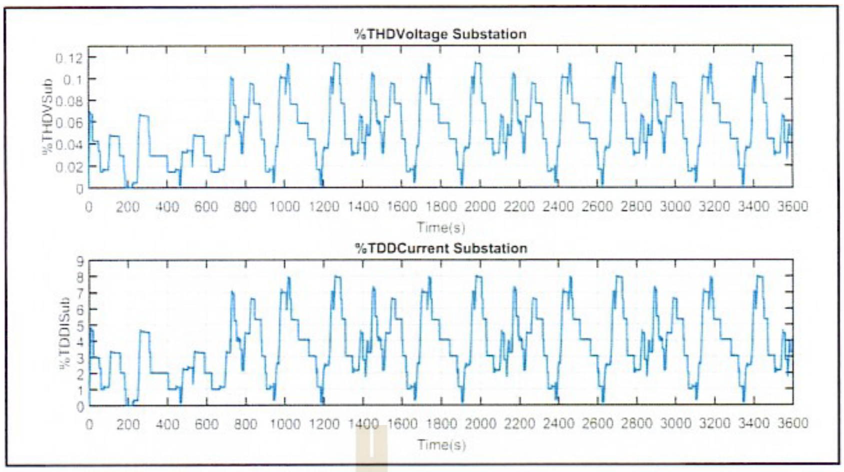


Figure 4.12 Total Harmonic Distortion Voltage and Current at substation in case study: Four-quadrant converter's harmonic modelling

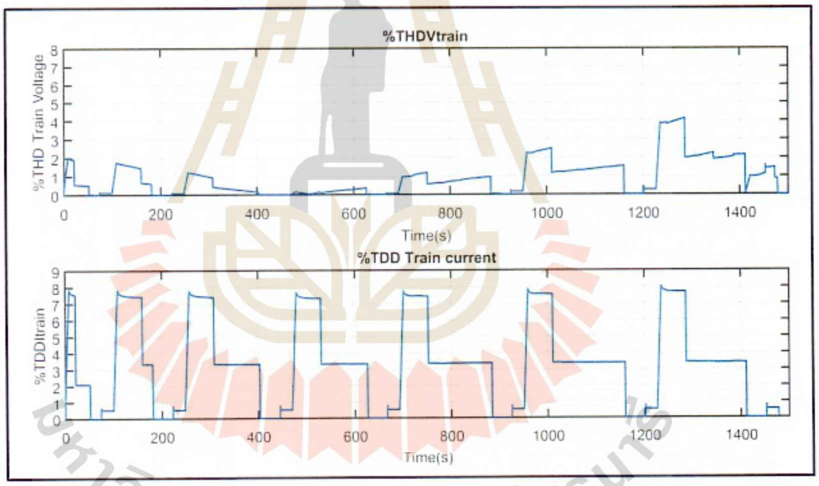


Figure 4.13 Total Harmonic Distortion Voltage and Current at train in case study: Four-quadrant converter's harmonic modelling

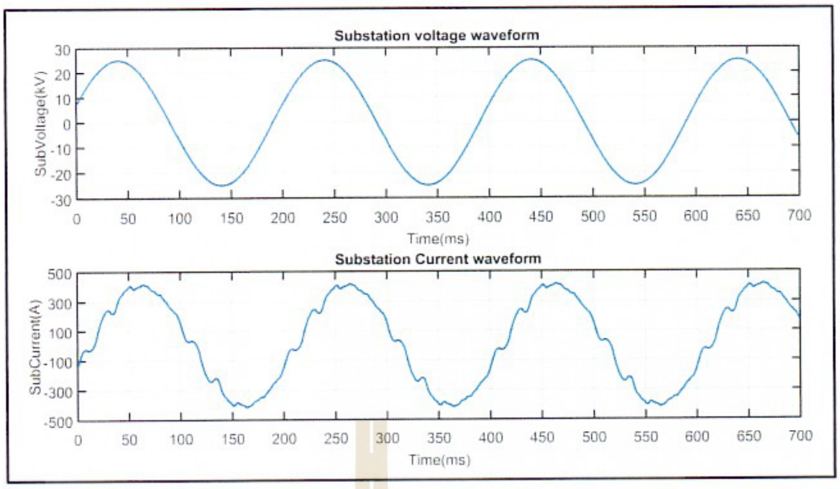


Figure 4.14 Harmonic Distortion Voltage and Current at substation wave form in case study: Four-quadrant converter's harmonic modelling

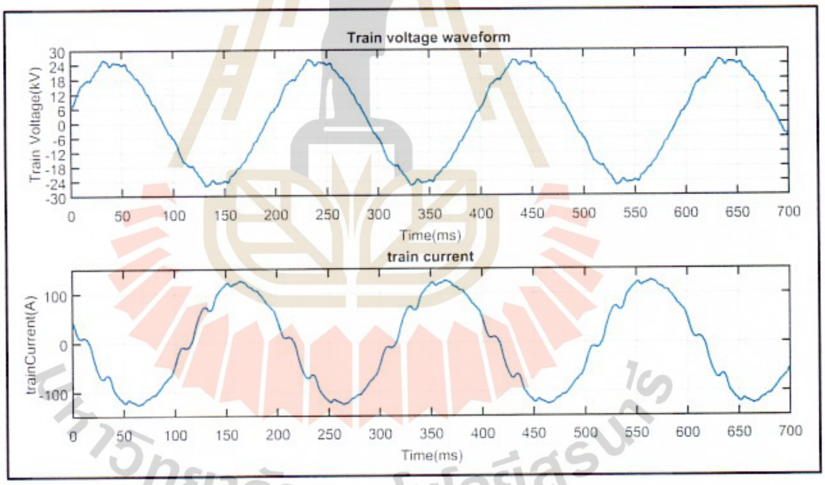


Figure 4.15 Harmonic Distortion Voltage and Current at train wave form in case study: Four-quadrant converter's harmonic modelling

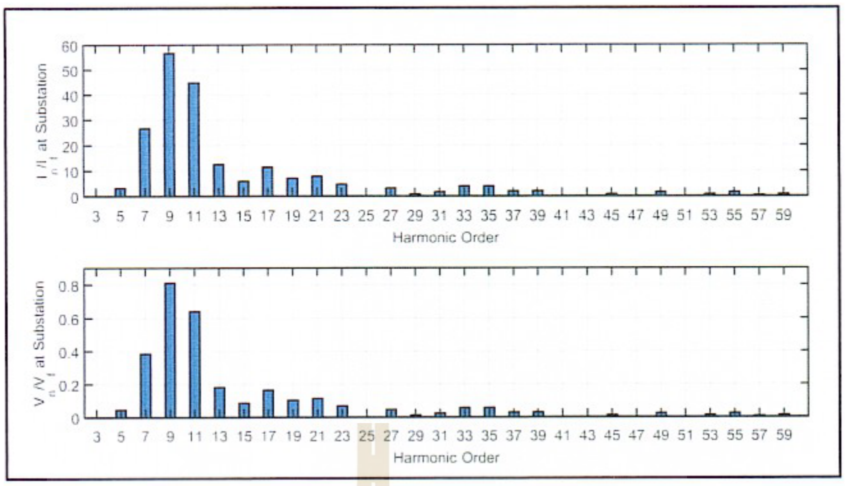


Figure 4.16 Harmonics spectrum of Current and Voltage at the Substation in case study: Four-quadrant converter's harmonic modelling.

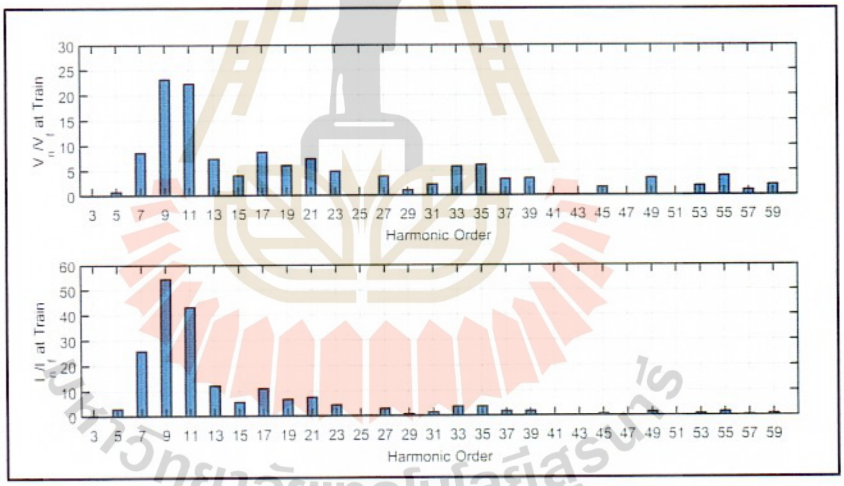


Figure 4.17 Harmonics spectrum of Current and Voltage at the train in case study: Four-quadrant converter's harmonic modelling.

Tables 4.3 and 4.4 show the results of simulation and comparison with IEEE. Table 4.3 shows the minimum, average and maximum voltage Total Harmonic Distortion values obtained from simulations both at the substation and on the train and compared to IEEE519-2014 voltage harmonic standards. Table 4.4 shows the minimum, average and maximum values of the substation harmonic currents from the simulation by dividing the harmonic sequences into groups for comparison with the IEEE519-2014 harmonic currents standard.

Table 4.3 The minimum, average and maximum THD voltage values obtained from simulations both at the substation and on the train and compared to IEEE519-2014

Bus voltage V at PCC 25 kV	THD Substation (%) (Simulation)	THD Train (%) (Simulation)	THD (%) IEEE519-2014 Standard
Min	0.00	0.00	5.00
Average	0.05	0.37	5.00
Max	0.11	4.12	5.00

Table 4.4 The minimum, average and maximum values of the substation harmonic currents distortion from the simulation and comparison with the IEEE519-2014.

Maximum harmonic current distortion in percent of I_L						
Individual harmonic order (odd harmonics) at Substation						
I_{SC}^{a}/I_{L}^{b} *(100 < 1000)*	$3 \leq h < 11$	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h \leq 50$	TDD[c]
Min	0.00	0.00	0.00	0.00	0.00	0.00
Average	3.56	2.23	0.75	0.38	0.24	1.36
Max	7.70	4.82	1.62	0.81	0.51	8.03
IEEE514-2014	12.0	5.5	5.0	2.0	1.0	15.0

4.3 Circuit Topology

4.3.1 Increasing the Intermediate track sectioning between power feeders' result.

According to the analysis in Section 3.5.1, a comparative simulation of the increase in the number of ITS in the railway system will affect the impedance of the railway power feeder line. The simulation results showed that when comparing the results of the number of ITS in the form of 1-loop, 2-loop, and 3-loop in a total length of 29 km, it was found that when the value of the railway power feeder line impedance decreased, the average voltage at the train increased and the current value used by the train decreased, resulting in table 4.5 and 4.6the THDv at the substation in the normal railway system having the highest value of 0.064. When 1-loop THDv decreases by 1.56%, 2-loop THDv decreases by 1.56%, and 3-loop THDv decreases by 3.12% according to Figure 4.18 Total Harmonic Distortion Voltage and Current at substation Increasing the ITS.

And at the train, the THDv in the normal railway system has the highest value of 7.921. when 1-loop THDv decreases by 34.09%, when 2-loop THDv decreases by 42.46%, and 3-loop THDv decreases by 45.23%. according to Figure 4.19 Total Harmonic Distortion Voltage and Current at train Increasing the ITS When compared to the IEEE 519-2014 standard, it was found that the THDv value of the trains in the normal railway system exceeds the standard, but other values are still within the standard, according to table 4.5. and table ภใ

In addition, the TDDi value at the substation decreased by 0.78% when 1-loop TDDi was added, 0.98% when 2-loop TDDi was added, and 1.05% when 3-loop TDDi was added. When compared to the standard IEEE 519-2014, it was found that the TDDi value, the harmonic order of 35–50, in the normal train system exceeds the standard values, but other values are within the standard values, according to Table 4.7 and table 4.8

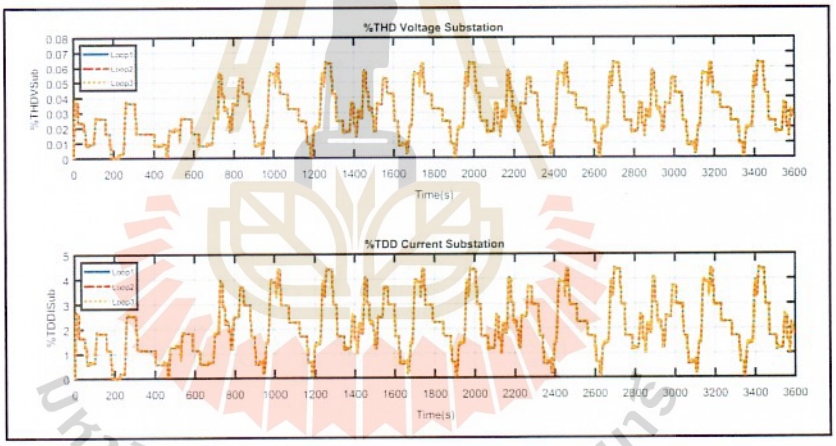


Figure 4.18 Total Harmonic Distortion Voltage and Current at substation Increasing the ITS.

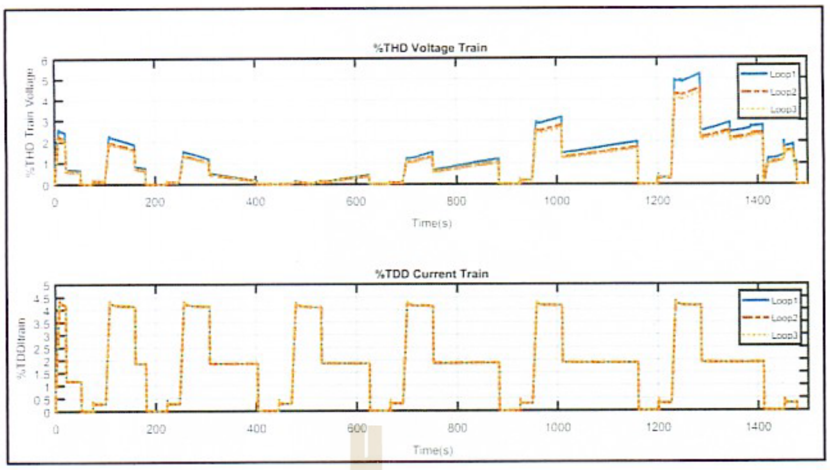


Figure 4.19 Total Harmonic Distortion Voltage and Current at train Increasing the ITS.

Table 4.5 THD Voltage Substation Comparison Results of Increasing the Intermediate track sectioning at the Substation.

Bus voltage *V* at PCC 25 kV	THD Substation (%) (Simulation)				THD Train (%) (Simulation)				THD (%) IEEE519-2014 Standard
	No Loop	1 Loop	2 Loop	3 Loop	No Loop	1 Loop	2 Loop	3 Loop	
Minimum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	5.00
Average	0.030	0.029	0.029	0.028	0.698	0.465	0.407	0.388	5.00
Maximum	0.064	0.063	0.063	0.062	7.921	5.221	4.558	4.338	5.00

Table 4.6 Percent reduction in THD Voltage Substation Comparison Results of Increasing the Intermediate track sectioning at the Substation with No-Loop

Bus voltage *V* at PCC 25 kV	Percent reduction in THD Substation compared to No Loop. (%) (Simulation)			Percent reduction in THD Train compared to No Loop. (%) (Simulation)		
	1 Loop	2 Loop	3 Loop	1 Loop	2 Loop	3 Loop
Minimum	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Average	3.33%	3.33%	6.67%	33.38%	41.69%	44.41%
Maximum	1.56%	1.56%	3.12%	34.09%	42.46%	45.23%

Table 4.7 TDD current Substation Comparison Results of Increasing the Intermediate track sectioning at the Substation.

Maximum harmonic current distortion in percent of I_L												
Individual harmonic order (odd harmonics) at Substation												
I_{SC}/I_L *(100 < 1000)*	$3 \le h < 11$				$11 \le h < 17$				$17 \le h < 23$			
	No Loop	1 loop	2 loops	3 loops	No Loop	1 loop	2 loops	3 loops	No Loop	1 loop	2 loops	3 loops
Minimum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Average	1.293	1.286	1.284	1.284	0.448	0.446	0.445	0.445	0.319	0.317	0.316	0.316
Maximum	2.800	2.777	2.772	2.770	0.971	0.963	0.961	0.960	0.689	0.684	0.683	0.682
IEEE514-2014	12.0				5.5				5.0			

Maximum harmonic current distortion in percent of I_L												
Individual harmonic order (odd harmonics) at Substation												
I_{SC}/I_L *(100 < 1000)*	$23 \le h < 35$				$35 \le h \le 50$				TDD			
	No Loop	1 loop	2 loops	3 loops	No Loop	1 loop	2 loops	3 loops	No Loop	1 loop	2 loops	3 loops
Minimum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Average	0.245	0.243	0.243	0.243	0.827	0.823	0.822	0.821	2.071	2.061	2.058	2.057
Maximum	0.530	0.526	0.525	0.524	1.791	1.777	1.774	1.772	4.484	4.449	4.440	4.437
IEEE514-2014	2.0				1.0				15.0			

Table 4.8 Percent reduction in TDD current Substation Comparison Results of Increasing the Intermediate track sectioning at the Substation with No-Loop

Maximum harmonic current distortion in percent of I_L									
Individual harmonic order (odd harmonics) at Substation									
I_{SC}/I_L *(100 < 1000)*	$3 \le h < 11$			$11 \le h < 17$			$17 \le h < 23$		
	1 loop	2 loops	3 loops	1 loop	2 loops	3 loops	1 loop	2 loops	3 loops
Minimum	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Average	0.54%	0.70%	0.70%	0.45%	0.67%	0.67%	0.63%	0.94%	0.94%
Maximum	0.82%	1.00%	1.07%	0.82%	1.03%	1.13%	0.73%	0.87%	1.02%

Table 4.8 Percent reduction in TDD current Substation Comparison Results of Increasing the Intermediate track sectioning at the Substation with No-Loop (Continued)

Maximum harmonic current distortion in percent of I_L									
Individual harmonic order (odd harmonics) at Substation									
I_{SC}/I_L (100 < 1000)	$23 \le h < 35$			$35 \le h \le 50$			TDD		
	1 loop	2 loops	3 loops	1 loop	2 loops	3 loops	1 loop	2 loops	3 loops
Minimum	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Average	0.82%	0.82%	0.82%	0.48%	0.60%	0.73%	0.48%	0.63%	0.68%
Maximum	0.75%	0.94%	1.13%	0.78%	0.95%	1.06%	0.78%	0.98%	1.05%

4.3.2 Increasing the number of tracks of the electric train system result.

According to Section 3.5.1, the comparative simulation results of increasing the number of railway tracks will affect the Impedance of the railway power feeder line. The simulation results show that when comparing the results between 2-track s and 4-tracks according to Figure 4.20 and 4.21, it was found that when the value of the railway power feeder line Impedance decreased, the average voltage at the train increased and the current value used by the train decreased, resulting in the THDv value at the substation decreasing by 1.563% and the value at the train decreasing by 50.764%. When compared to the standard IEEE 519-2014, it was found that the THDv is still in the standard, as shown in Table 4.8.

In addition, the TDDi was found to be reduced by 0.781% at the substation when the number of tracks was increased to 4 tracks. Compared to the IEEE 519-2014 standard, the TDDi was found to be within the standard. According to table 4.9

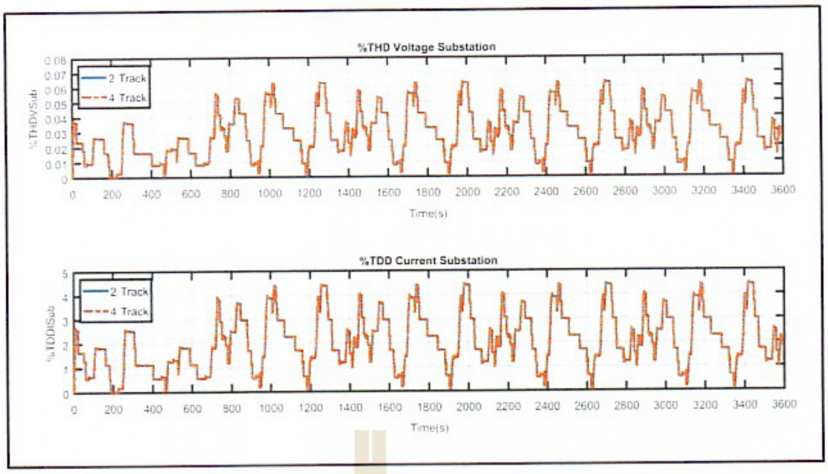


Figure 4.20 Total Harmonic Distortion Voltage and Current at substation Increasing the number of tracks.

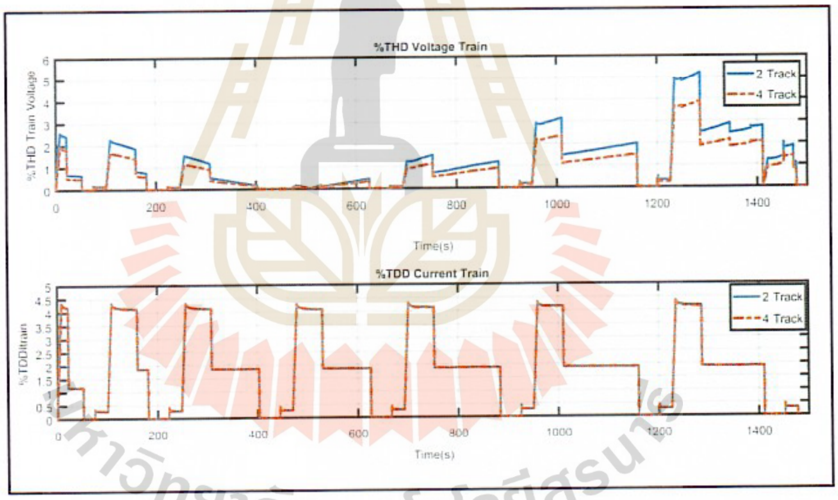


Figure 4.21 Total Harmonic Distortion Voltage and Current at train Increasing the number of tracks.

Table 4.9 THD Voltage Substation Comparison Results of Increasing the number of tracks at the Substation.

Bus voltage V at PCC 25 kV	THD Substation (%) (Simulation)			THD Train (%) (Simulation)			THD (%) IEEE519-2014 Standard
	2 tracks	4 tracks	Reduce (%)	2 tracks	4 tracks	Reduce (%)	
Minimum	0.00	0.00	0.00%	0.00	0.00	0.00%	5.00
Average	0.030	0.028	6.667%	0.698	0.349	50.000%	5.00
Maximum	0.064	0.063	1.563%	7.921	3.900	50.764%	5.00

Table 4.10 TDD current Substation Comparison Results of Increasing the number of tracks at the Substation.

Maximum harmonic current distortion in percent of I_L												
Individual harmonic order (odd harmonics) at Substation												
I_{SC}/I_L (100 < 1000)	$3 \le h < 11$		$11 \le h < 17$		$17 \le h < 23$		$23 \le h < 35$		$35 \le h \le 50$		TDD	
	2 tracks	4 tracks	2 tracks	4 tracks	2 tracks	4 tracks	2 tracks	4 tracks	2 tracks	4 tracks	2 tracks	4 tracks
Minimum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Average	1.293	1.286	0.448	0.446	0.319	0.317	0.245	0.243	0.827	0.823	2.071	2.060
Maximum	2.800	2.777	0.971	0.963	0.689	0.684	0.530	0.526	1.791	1.777	4.484	4.449
IEEE514-2014	12.0		5.5		5.0		2.0		1.0		15.0	

Table 4.11 Percent reduction in TDD current Substation Comparison Results of Increasing the number of tracks at the Substation with No-Loop

Maximum harmonic current distortion in percent of I_L						
Individual harmonic order (odd harmonics) at Substation						
I_{SC}/I_L (100 < 1000)	$3 \le h < 11$	$11 \le h < 17$	$17 \le h < 23$	$23 \le h < 35$	$35 \le h \le 50$	TDD
	Reduce (%)	Reduce (%)	Reduce (%)	Reduce (%)	Reduce (%)	Reduce (%)
Minimum	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
Average	0.541%	0.446%	0.627%	0.816%	0.483%	0.531%
Maximum	0.821%	0.824%	0.726%	0.755%	0.781%	0.781%

4.4 Case study: Measurement Data

4.4.1 Installing Passive Filters at the Substation

4.4.1.1 Passive filters design result.

Based on the simulation of the train movement, a passive harmonic filter can be designed with a maximum reactive power of substation (Qc) value of 6254.3kVar, a system voltage (V) of 25kV, a system frequency (F) of 50Hz, and the quality factor (Q) is set to 30 for comparison with different types of passive filters. And the Tuning point of the filter (TF) value is chosen to reduce the harmonic amount in the order of 3,7,51 and 53 as the order with the highest harmonic content. The design results for reducing the several of harmonics at the Substation of various passive filters are shown in Table 4.12-4.15.

Table 4.12 The design results of Single-tuned filter installed at the substation.

Single-tuned Filter	TF = 3	TF = 5	TF = 51	TF = 53
R (Ω)	$2.22x10^{-3}$	$1.33x10^{-3}$	$1.31x10^{-4}$	$1.26x10^{-4}$
L (H)	$7.07x10^{-5}$	$2.54 x10^{-5}$	$2.45 x10^{-7}$	$2.26 x10^{-7}$
C (F)	$1.59x10^{-2}$	$1.59x10^{-2}$	$1.59x10^{-2}$	$1.59 x10^{-2}$

Table 4.13 The design results of Band-Pass filter installed at the substation.

Band-Pass Filter	TF = 3	TF = 5	TF = 51	TF = 53
R (Ω)	$2.00x10^{0}$	$1.20x10^{0}$	$1.18x10^{-1}$	$1.13x10^{-1}$
L (H)	$7.07x10^{-5}$	$2.54x10^{-5}$	$2.45x10^{-7}$	$2.26x10^{-7}$
C (F)	$1.59x10^{-2}$	$1.59x10^{-2}$	$1.59x10^{-2}$	$1.59x10^{-2}$

Table 4.14 The design results of High-Pass filter installed at the substation.

High-Pass Filter	TF = 3	TF = 5	TF = 51	TF = 53
R (Ω)	$2.00x10^{0}$	$1.20x10^{0}$	$1.18x10^{-1}$	$1.13x10^{-1}$
L (H)	$7.07x10^{-5}$	$2.54x10^{-5}$	$2.45x10^{-7}$	$2.26x10^{-7}$
C (F)	$1.59x10^{-2}$	$1.59x10^{-2}$	$1.59x10^{-2}$	$1.59x10^{-2}$

Table 4.15 The design results of C-Type filter installed at the substation.

C-Type Filter	TF = 3	TF = 5	TF = 51	TF = 53
R (Ω)	9.99×10^{-1}	6.00×10^{-1}	5.88×10^{-2}	5.66×10^{-2}
L (H)	3.98×10^{-5}	1.33×10^{-5}	1.22×10^{-7}	1.13×10^{-7}
C1 (F)	4.25×10^{-2}	3.82×10^{-2}	3.25×10^{-2}	3.25×10^{-2}
C2 (F)	8.49×10^{-2}	1.53×10^{-1}	1.62×10^{0}	1.69×10^{0}

In addition, a graph that shows the results of calculating the total Impedance of the passive filter (Zf) installed at the substation in various harmonic sequences at various TF points and various types of passive filters as shown in Figure 4.22-4.25.

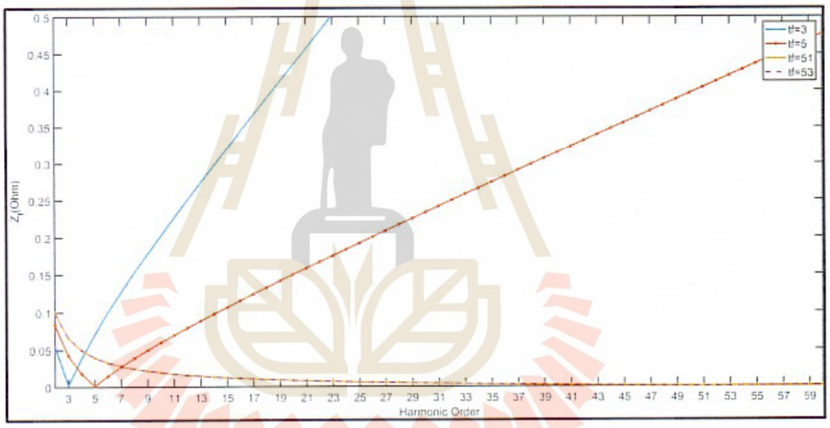


Figure 4.22 Total Impedance of the Single-Tuned filter (Zf) installed at the substation in various harmonic order.

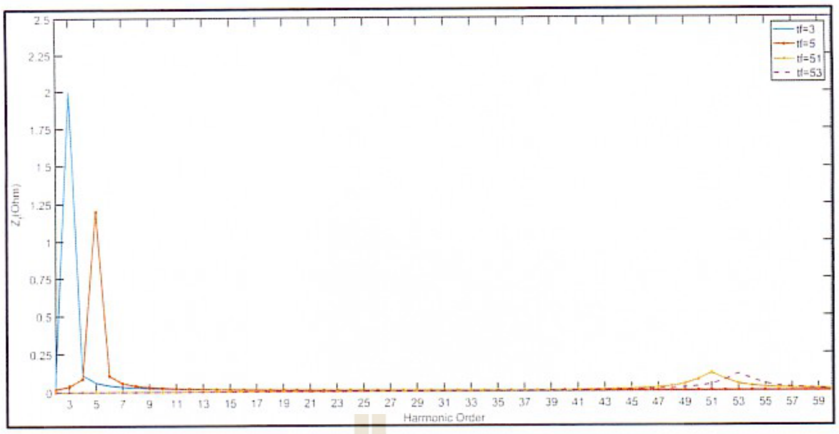


Figure 4.23 Total Impedance of the Band-Pass filter (Zf) installed at the substation in various harmonic order.

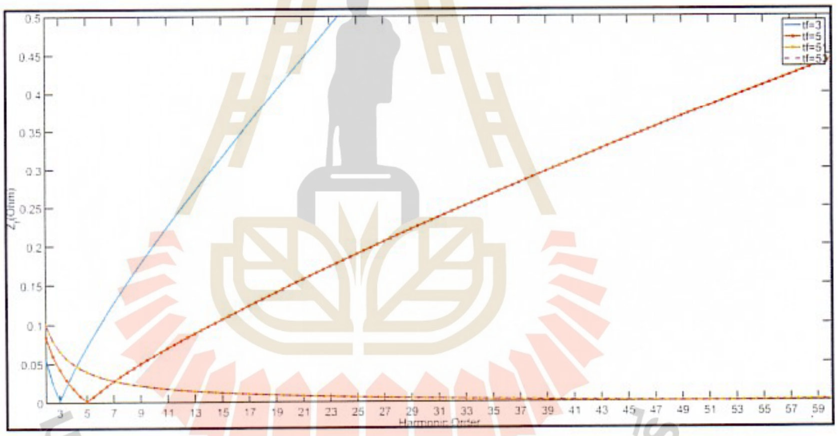


Figure 4.24 Total Impedance of the High-Pass filter (Zf) installed at the substation in various harmonic order.

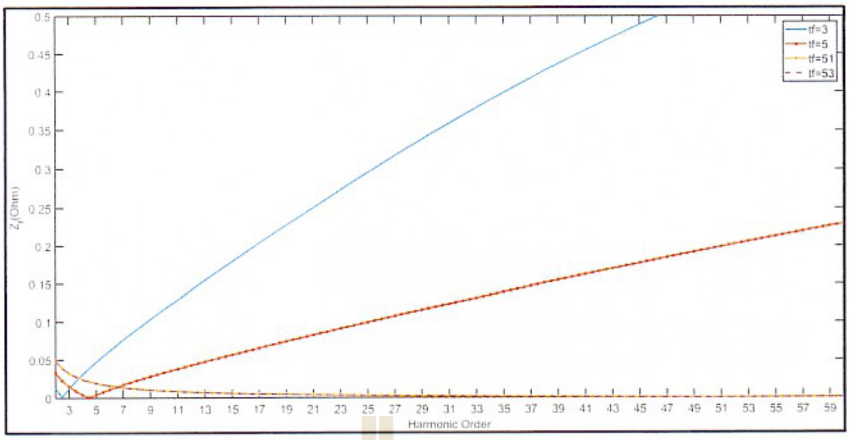


Figure 4.25 Total Impedance of the C-Type filter (Zf) installed at the substation in various harmonic order.

The harmonic results of installing passive filters at the substation. Graphs and tables are included in Appendix A.2.1 The simulation results consist of a simulation of a filter installation at a substation. Four filters were installed: a single-tuned filter (STF), a band-pass filter (BP), a high-pass filter (HP), and a C-type filter (C-type) at TF values of 3, 5, 51, and 53.

4.4.2 Installing on-board Passive Power Filters

4.4.2.1 Passive filters design results

Based on the simulation of the train movement, a passive harmonic filter can be designed with a maximum reactive power of Train (Qc) value of 2,306.40 kVar, a system voltage (V) of 25kV, a system frequency (F) of 50Hz, and the quality factor (Q) is set to 30 for comparison with different types of passive filters. And the Tuning point of the filter (TF) value is chosen to reduce the harmonic amount in the order of 3,7,51 and 53 as the order with the highest harmonic content. The design results for reducing the several of harmonics at the Substation of various passive filters are shown in Table 4.16-4.19.

Table 4.16 The design results of Single-tuned filter installed on the trains.

Single-tuned Filter	TF = 3	TF = 5	TF = 51	TF = 53
R (Ω)	7.87×10^{-3}	4.72×10^{-3}	4.63×10^{-4}	4.46×10^{-4}
L (H)	2.51×10^{-4}	9.02×10^{-5}	8.67×10^{-7}	8.03×10^{-7}
C (F)	4.49×10^{-3}	4.49×10^{-3}	4.49×10^{-3}	4.49×10^{-3}

Table 4.17 The design results of Band-Pass filter installed on the trains.

Band-Pass Filter	TF = 3	TF = 5	TF = 51	TF = 53
R (Ω)	7.09×10^{0}	4.25×10^{0}	4.17×10^{-1}	4.01×10^{-1}
L (H)	2.51×10^{-4}	9.02×10^{-5}	8.67×10^{-7}	8.03×10^{-7}
C (F)	4.49×10^{-3}	4.49×10^{-3}	4.49×10^{-3}	4.49×10^{-3}

Table 4.18 The design results of High-Pass filter installed on the trains.

High-Pass Filter	TF = 3	TF = 5	TF = 51	TF = 53
R (Ω)	7.09×10^{0}	4.25×10^{0}	4.17×10^{-1}	4.01×10^{-1}
L (H)	2.51×10^{-4}	9.02×10^{-5}	8.67×10^{-7}	8.03×10^{-7}
C (F)	4.49×10^{-3}	4.49×10^{-3}	4.49×10^{-3}	4.49×10^{-3}

Table 4.19 The design results of C-Type filter installed at the substation.

C-Type Filter	TF = 3	TF = 5	TF = 51	TF = 53
R (Ω)	7.97×10^{0}	4.42×10^{0}	4.17×10^{-1}	4.01×10^{-1}
L (H)	2.82×10^{-4}	9.40×10^{-5}	8.68×10^{-7}	8.03×10^{-7}
C1 (F)	4.49×10^{-3}	4.49×10^{-3}	4.49×10^{-3}	4.49×10^{-3}
C2 (F)	3.59×10^{-2}	1.08×10^{-1}	11.68×10^{0}	12.61×10^{0}

In addition, a graph that shows the results of calculating the total Impedance of the passive filter (Zf) installed at the substation in various harmonic sequences at various TF points and various types of passive filters as shown in Figure 4.26-4.29.

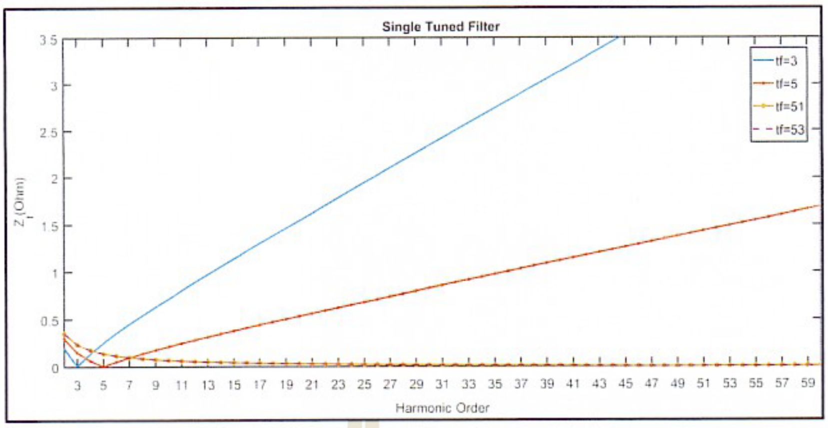


Figure 4.26 Total Impedance of the Single-Tuned filter (Zf) installed on the trains in various harmonic order.

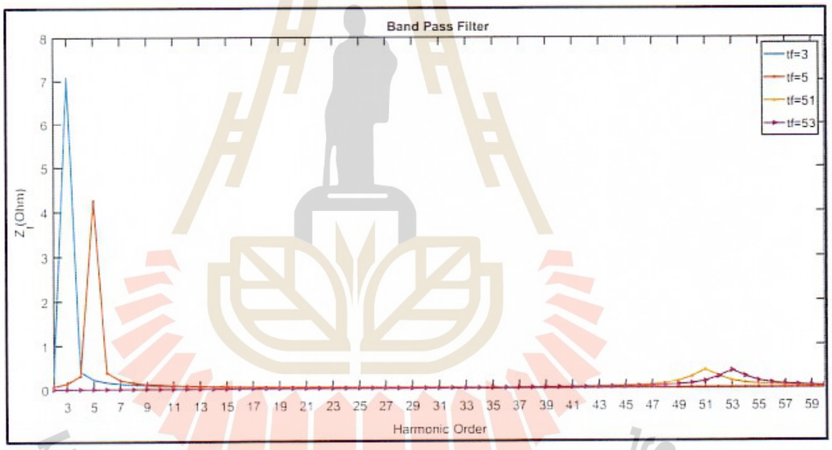


Figure 4.27 Total Impedance of the Band-Pass filter (Zf) installed on the trains in various harmonic order.

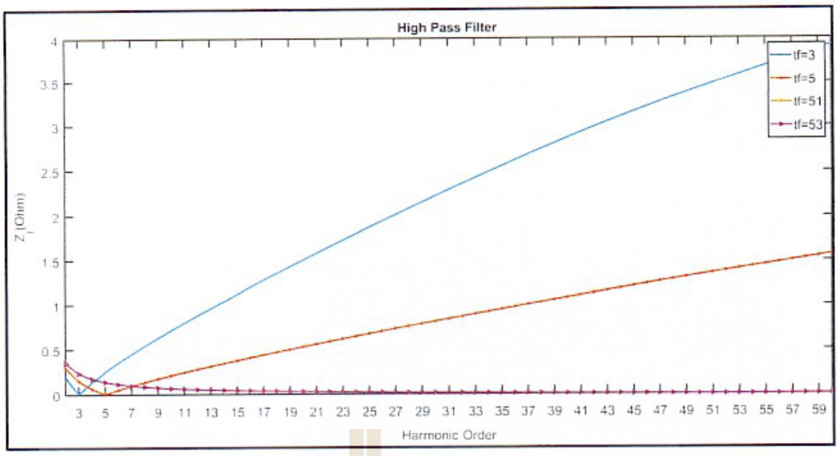


Figure 4.28 Total Impedance of the High-Pass filter (Zf) installed on the trains in various harmonic order.

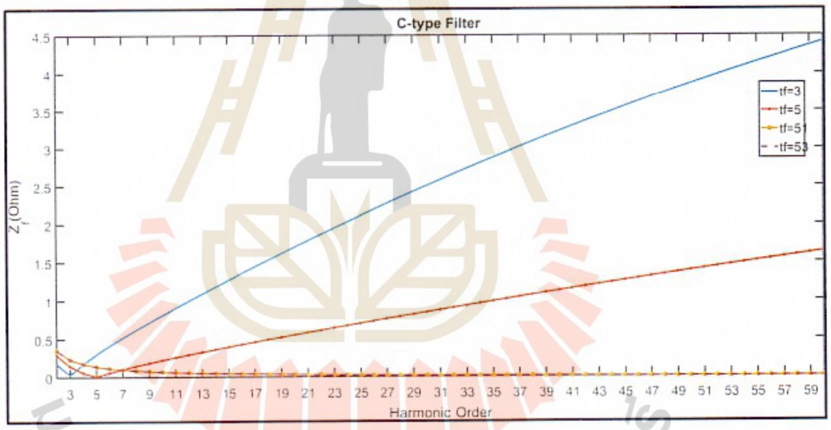


Figure 4.29 Total Impedance of the C-Type filter (Zf) installed on the trains in various harmonic order.

The harmonic results of installing on-board passive filters. Graphs and tables are included in Appendix A.2.2 The simulation results consist of a simulation of a filter installation at a substation. Four filters were installed: a single-tuned filter (STF), a band-pass filter (BP), a high-pass filter (HP), and a C-type filter (C-type) at TF values of 3, 5, 51, and 53.

4.4.3 Comparison Results

The simulation results of different types of passive filter installations at substations can be summarized in Table 4.20 below. Table 4.20 THD Voltage Substation Comparison Results of Installing Power Passive Filters at the Substation STF, BP, HP, and C-type, in which the table shows the percentage reduction after filter installation compared to before filter installation. Through different passives, it was found that the C-type filter had the percentage reduction of the voltage harmonic content at 89.97%, which was the highest. Next is the BP filter, and the percentage of harmonic pressure drop is 88.39%.

In addition, when considering the order of the tuning points of the filter (TF), the percentage of reduction in voltage harmonic content was the highest at TF = 53 with a value of 96.79%, followed by TF = 51. The percentage reduction in voltage harmonic content is 96.08%.

However, the effect of reducing the number of harmonics is consistent with the impedance of the filter. The lower the filter impedance, the more harmonics are reduced entering the substation.

Table 4.20 THD Voltage Substation Comparison Results of Installing Power Passive Filters at the Substation

TF	No-filter	STF		BP		HP		C-type		RMSE
		Value	Reduce (%)	Value	Reduce (%)	Value	Reduce (%)	Value	Reduce (%)	
3	0.07	0.03	57.14%	0.020	71.43%	0.030	57.14%	0.020	71.43%	64.68%
5	0.07	0.015	78.57%	0.007	90.00%	0.020	71.43%	0.008	88.57%	82.49%
51	0.07	0.003	95.71%	0.004	94.29%	0.003	95.71%	0.001	98.57%	96.08%
53	0.07	0.003	95.71%	0.003	95.71%	0.002	97.14%	0.001	98.57%	96.79%
RMSE			83.31%		88.39%		82.10%		89.97%	

** Root Mean Square Error (RMSE) is the square root of the mean square of Error, which is the arithmetic mean of the squares of a group of values

When considering the TDDi value the following table summarizes the simulation results of various types of passive filter installations at power plants. Table 4.21 represents the TDD current Substation Comparison Results of Installing Power Passive Filters at the Substation. STF, BP, HP, and C-type, in which the table shows the percentage reduction after filter installation compared to before filter installation. The different passives found that the C-type filter had the greatest reduction percentage of harmonic current at 89.16%. Next is the BP filter, and the percentage of harmonic pressure drop is 87.43%.

In addition, when considering the order TF that causes the percentage reduction of the harmonic current, the highest value is at TF = 53, with a value of 69.21%, followed by TF = 51. The percentage of reduction in voltage harmonic content is 96.05%.

However, the harmonic reduction effect is consistent with the impedance value of the filter, the lower the filter impedance, the lower the harmonic amount.

Table 4.9 TDD current Substation Comparison Results of Installing Power Passive Filters at the Substation

TF	No-filter	STF		BP		HP		C-type		RMSE
		Value	Reduce (%)	Value	Reduce (%)	Value	Reduce (%)	Value	Reduce (%)	
3	4.48	1.94	56.70%	1.36	69.64%	1.78	60.27%	1.27	71.65%	64.87%
5	4.48	1.07	76.12%	0.51	88.62%	1.01	77.46%	0.61	86.38%	82.32%
51	4.48	0.18	95.98%	0.26	94.20%	0.18	95.98%	0.09	97.99%	96.05%
53	4.48	0.18	95.98%	0.23	94.87%	0.18	95.98%	0.09	97.99%	96.21%
RMSE			82.82%		87.43%		83.74%		89.16%	

When considering THDv at the substation, the simulation results of various passive filter installations on board can be summarized in a table. 4.22 shows the THD voltage substation comparison results of power passive filters installed on board. STF, BP, HP, and C-type, in which the table shows the percentage reduction after filter installation compared to before filter installation. Different passives found that the BP filter had the greatest reduction percentage of voltage harmonic content at 92.9231%. Next up is the HP filter; the percentage of harmonic voltage drop is 90.8312%.

In addition, when considering the order TF that causes the percentage decrease of harmonic voltage content, the highest value is at TF = 53, with a value of 95.3509%, followed by TF = 51. There is a percentage decrease in voltage harmonic content of 96.2273%.

However, the harmonic reduction effect is consistent with the impedance value of the filter, the lower the filter impedance, the lower the harmonic amount.

Table 4.10 THD Voltage Substation Comparison Results of Power Passive Filters Installed On-Board

TF	No-filter	STF		BP		HP		C-type		RMSE
		Value	Reduce (%)	Value	Reduce (%)	Value	Reduce (%)	Value	Reduce (%)	
3	0.07	0.010703	84.7100%	0.010909	84.4157%	0.011002	84.2829%	0.011334	83.8086%	84.3049%
5	0.07	0.008479	87.8871%	0.003397	95.1471%	0.008156	88.3486%	0.008281	88.1700%	89.9396%
51	0.07	0.003421	95.1129%	0.003100	95.5714%	0.003422	95.1114%	0.003421	95.1127%	95.2273%
53	0.07	0.003422	95.1114%	0.002752	96.0686%	0.003424	95.1086%	0.003422	95.1114%	95.3509%
RMSE			90.8112%		92.9231%		90.8312%		90.6741%	

When considering TDDi at the substation, the simulation results of various passive filter installations on board can be summarized in a table. 4.23 shows the THD voltage substation comparison results of power passive filters installed on board. STF, BP, HP, and C-type, in which the table shows the percentage reduction after filter installation compared to before filter installation. Different passives found that the BP filter had the greatest reduction percentage of current harmonic content at 92.2975%. Next up is the HP filter; the percentage of harmonic current drop is 90.0088%.

In addition, when considering the order TF that causes the percentage decrease of harmonic current content, the highest value is at TF = 53, with a value of 94.9278%, followed by TF = 51. There is a percentage decrease in current harmonic content of 94.7932%.

However, the harmonic reduction effect is consistent with the impedance value of the filter, the lower the filter impedance, the lower the harmonic amount.

Table 4.23 TDD current Substation Comparison Results of Power Passive Filters Installed On-Board

TF	No-filter	STF		BP		HP		C-type		RMSE
		Value	Reduce (%)	Value	Reduce (%)	Value	Reduce (%)	Value	Reduce (%)	
3	4.48	0.747383	83.3173%	0.761736	82.9970%	0.768256	82.8514%	0.791429	82.3342%	82.8757%
5	4.48	0.592072	86.7841%	0.237211	94.7051%	0.569474	87.2885%	0.578222	87.0933%	89.0296%
51	4.48	0.238841	94.6687%	0.216431	95.1690%	0.238977	94.6657%	0.238858	94.6683%	94.7932%
53	4.48	0.238954	94.6662%	0.192127	95.7115%	0.239085	94.6633%	0.238967	94.6659%	94.9278%
RMSE			89.9901%		92.2975%		90.0088%		89.8441%	

From Table 4.20 and 4.22, compare the results of harmonic filtering in Table 4.24 showing the THD Voltage Substation Comparison Result of Power Passive Filters Installed Substation and On-Board and Table 4.25 showing the TDD current Substation Comparison Results of Power Passive Filters Installed Substation and On-Board to show the differences in the different harmonic filtering effects of the passive filter installation positions at the substation and On-Board for each passive filter, from the table, it is found that installing a passive filter at a train has a greater effect on reducing harmonics both voltage and current than installing a passive filter at a substation because the installation of a passive filter On-Board is used to eliminate harmonics generated by the source of harmonics, the effect of reducing the amount of harmonics in the railway system is greater and It is the same in all types of passive filters.

Table 4.24 THD Voltage Substation Comparison Result of Power Passive Filters Installed Substation and On-Board

TF	STF		BP		HP		C-type	
	Substation	On-Board	Substation	On-Board	Substation	On-Board	Substation	On-Board
3	57.14%	84.71%	71.43%	84.42%	57.14%	84.28%	71.43%	83.81%
5	78.57%	87.89%	90.00%	95.15%	71.43%	88.35%	88.57%	88.17%
51	95.71%	95.11%	94.29%	95.57%	95.71%	95.11%	98.57%	95.11%
53	95.71%	95.11%	95.71%	96.07%	97.14%	95.11%	98.57%	95.11%
RMSE	83.31%	90.81%	88.39%	92.92%	82.10%	90.83%	89.97%	90.64%

Table 4.25 TDD current Substation Comparison Results of Power Passive Filters Installed Substation and On-Board

TF	STF		BP		HP		C-type	
	Substation	On-Board	Substation	On-Board	Substation	On-Board	Substation	On-Board
3	56.70%	83.32%	69.64%	83.00%	60.27%	82.85%	71.65%	82.33%
5	76.12%	86.78%	88.62%	94.71%	77.46%	87.29%	86.38%	87.09%
51	95.98%	94.67%	94.20%	95.17%	95.98%	94.67%	97.99%	94.67%
53	95.98%	94.67%	94.87%	95.71%	95.98%	94.66%	97.99%	94.67%
RMSE	82.81%	89.99%	87.43%	92.29%	83.74%	90.00%	89.16%	89.84%

4.5 Case study: Input voltage harmonics of the four-quadrant converter with passive power filter

From the simulation results in the case of installing passive filters at substations, it was found that the filter that could reduce the harmonic content the most was the C-type passive filter at TF = 53. Therefore, in the input voltage harmonics of the four-quadrant converter with passive power filter case simulation, the simulation results are, for example, in the case of using a C-type passive filter at TF = 53.

The harmonic results of installing passive filters at the substation and onboard, as well as graphs and tables, are included in Appendix A.2.3 and A.2.4. The simulation results consist of a simulation of a filter installation at a substation and onboard using a C-type passive filter at TF = 53.

From the simulation results in the Input voltage harmonics of the four-quadrant converter with passive power filter case study, Table 4.26 THD Voltage Substation Comparison Results of Installing C-Type Filters TF=53 at the Substation, it was found that the value can reduce the harmonic voltage at the power station from 0.11 to 0.002 or decreased by 98.18%. and in Table 4.17 TDD current Substation Comparison Results of Installing C-Type Filters TF=53 at the Substation, it was found that the harmonic current at the Substation was reduced from 8.03 to 0.09 or decreased by 98.88%.

Table 4.26 THD Voltage Substation Comparison Results of Installing C-Type filters TF=53 at the Substation

TF	No-filter	C-Type	
		Value	Reduce
53	0.11	0.002	98.18

Table 4.27 TDD current Substation Comparison Results of Installing C-Type filters TF=53 at the Substation

TF	No-filter	C-Type	
		Value	Reduce
53	8.03	0.09	98.88

From the simulation results in the Input voltage harmonics of the four-quadrant converter with passive power filter case study, Table 4.28 THD Voltage Substation Comparison Results of Installing C-Type filters TF=53 On-board, it was found that the value can reduce the harmonic voltage at the power station from 0.11 to 0.001 or decreased by 99.09%. and in Table 4.29 TDD current Substation Comparison Results of Installing C-Type filters TF=53 On-board, it was found that the harmonic current at the Substation was reduced from 8.03 to 0.09 or decreased by 98.88%.

Table 4.28 THD Voltage Substation Comparison Results of Installing C-Type filters TF=53 On-board

TF	No-filter	C-Type	
		Value	Reduce
53	0.11	0.001	99.09

Table 4.119 TDD current Substation Comparison Results of Installing C-Type filters TF=53 On-board

TF	No-filter	C-Type	
		Value	Reduce
53	8.03	0.09	98.88

4.5.1 Comparison Results

The harmonic reduction results of both THDv and TDDi with passive filters installed at the substation and On-Board were compared using result tables 4.26 and 4.28. From Table 4.30, THD Voltage and Current Substation Comparison Results of Power Passive Filters Installed at the Substation and On-Board, comparing the harmonic reduction results, it was found that the THDv with the installation of the C-type passive filter On-Board had a reduction of 99.09%, which was higher than the C-type passive filter installed at the substation at 98.18%.

In addition, when comparing the harmonic reduction results of TDDi, it was found that TDDi with the C-type passive filter installed On-Board had a reduction of 98.88% of the harmonic reduction. This is close to the installation of a C-type passive filter at the substation at 98.88%.

The installation of passive filters On-Board provides a greater efficiency in harmonic reduction than the installation at the substation as in the previous case, because the installation of a passive filter On-Board is used to eliminate harmonics generated by the source of harmonics, and this is true of all types of passive filters.

Table 4.30 Percent Reduction of THD Substation Voltage and Substation Current

THDv	C-type	
	Substation	On-Board
53	98.18%	99.09%

TDDi	C-type	
	Substation	On-Board
53	98.88%	98.88%

4.6 Chapter Summary

Chapter 4 simulation results, this chapter presents the simulation results of harmonic reduction in an AC railway system in a total of 3 case studies and then compares them with normal conditions.

In case 1, there are two types of circuit topology in the study. It was found that increasing the number of ITS resulted in the railway power feeder line impedance decreasing as the number of ITS increased, resulting in changes in the voltage and current consumption of the train. When considering the harmonic content, it was found that the THDv and TDDi of the trains will obviously decrease with increasing the number of ITS, while the THDv and TDDi at the power stations tend to decrease as well but not as much. Furthermore, increasing the number of tracks results in a decrease in railway power feeder line Impedance as well as an increase in the number of ITS, causing changes in train voltage and current. Considering the harmonic content, it was found that the THDv and TDDi of the trains will obviously decrease when the number of tracks is increased, whereas the THDv and TDDi at the substations tend to decrease as well, but not much.

Case 2: Harmonics are simulated from measurement data with two studies for the installation of passive filters on-board and at substations, and then the harmonic values are measured at the substation. There are four passive filter designs: STF, BF, HP, and C-type, to eliminate all four high harmonic sequences: 3, 5, 51, and 53. Comparing the harmonic reduction effects of the four types of passive filters, it was found that the passive filter that reduced the most harmonics was the C-type, followed by BH, HP, and STF, respectively, based on the total Impedance of the different filters. The more harmonics that enter the substation, the lower the Impedance of the filter. Comparison of the harmonic reduction effect of the passive filter installation location between the on-board and the substation It has been discovered that installing passive filters on-board can reduce harmonics more effectively than substations. because harmonics can be eliminated from the source of the harmonics on the train before they enter the railway power feeding system.

Case 3: Study of Input Voltage Harmonics of the Four-Quadrant Converter with Passive Power Filter Caused by Electrical Power Conversion Equipment on the Train Use a C-type filter at TF = 53 to reduce the number of harmonics generated and simulate the installation of passive filters on-board and at substations as in Case 3. It was discovered that installing an on-board passive filter, as opposed to installing a harmonic filter at the substation, can reduce the amount of harmonics at the substation more than installing a harmonic filter at the substation, as in Case 3.

CHAPTER 5

Conclusion and Future work

5.1 Conclusion

In this research, model and harmonic elimination were studied. The CITY Line airport rail link movement model was used in the study, which served eight passenger stations over a distance of 28.3 km. There are a total of 10 trains available. Using the model of a single-conductor electric train system and having one power station at a distance of 8.072 km near Ramkhamhaeng Station. Harmonic problems in the railway power feeding systems are still important problems nowadays that need to be solved because they may affect the quality of the railway power feeding systems, the communication system, or the operation of important electronic equipment in the railway system. The main sources of harmonics are non-linear load devices or power converters on board the train; therefore, it is important to analyze and determine how to eliminate these harmonics. In this research, three case studies are proposed to analyze the changing behavior and quantity of harmonics at substations. The simulation results of behavior and quantity of harmonics at substations in an AC railway system are compared to normal conditions in three case studies.

Case 1: A study of increasing the number of ITS in the railway power feeding systems over the same total distance It is found that increasing the number of ITS will result in a decrease in the Impedance of the railway power feeder line, causing the voltage and current usage of the train to change. Decreased value of substation is also decreasing as the number of ITS increases. In addition, increasing the number of tracks also causes the Impedance of the railway power feeder line to decrease. When considering the value of THDv and TDDi at the substation, it decreases with the increase in the number of tracks.

Case 2: Harmonics are simulated from measurement data with two studies for the installation of passive filters on-board and at substations, and then the harmonic values are measured at the substation. It was found that the passive filter that reduced the most harmonics was the C-type, followed by BH, HP, and STF, respectively, based on the total Impedance of the different filters. In addition, it has been discovered that installing passive filters on-board can reduce harmonics more effectively than substations. because harmonics can be eliminated from the source of the harmonics on the train before they enter the railway power feeding system.

Case 3: Study of Input Voltage Harmonics of the Four-Quadrant Converter with Passive Power Filter Caused Use a C-type filter at TF = 53 to reduce the number of harmonics. It was discovered that installing an on-board passive filter can reduce the amount of harmonics at the substation more than installing a harmonic filter at the substation, as in Case 3.

5.2 Future work

This research is a harmonic analysis of the AC electric railway system of the ARL City Line, an urban railway in Thailand. The harmonic analysis and elimination described in this research can also be applied to the high-speed electric railway system, where harmonics are also a major problem. The form of the railway's power feeding system will have different forms of power feeding, such as the autotransformer feeding system, which can change the power feeding system, but the harmonic analysis and elimination method can be used and the model in this research is applicable.

The harmonic analysis in this research can be applied to the DC electric railway system because in the DC electric railway system, converters are used to convert electricity from high-voltage AC to DC voltage. In train movement, it is an important harmonic generator in the DC electric train system, which can take data from measurements or from the resulting harmonic equations to analyze. (Djeghader,2015)

In addition, to filter harmonics using passive filters. In this research, only one tuning point was selected for simulation. In future studies, it may be possible to selectively filter harmonics in the 2nd or 3rd harmonic order simultaneously by paralleling the filters and adding filtering locations

REFERENCE

A. Zynovchenko, J. Xie, S. Jank and F. Klier "Calculations And Measurements Of Harmonic Current Distributions In The Catenary Of Railways With Single-phase A.C." WIT Transactions on The Built Environment, Vol 88 P.10, DOI 10.2495/CR060761, Published 2006.

A.Zupan, T. Teklic and B. Grcic "Modeling of 25 kV Electric Railway System for Power Quality Studies", IEEE Eurocon2013 Conference, DOI:10.1109/EUROCON.2013.6625081, July 2013.

Abbas, A. S., Ali, E. S., El-Sehiemy, R. A., Abou El-Ela, A. A., & Fetyan, K. M. (2019, December). "Comprehensive parametric analysis of single tuned filter in distribution systems". In 2019 21st International Middle East Power Systems Conference (MEPCON) (pp. 465-472). IEEE.

AIDA ENGINEER (2004) , "Substation Equipment and Protective standard" , Volume8 distorting load J.C. Das, Power System Harmonics and Passive Filter Design, John-Wiley & Sons, 2015.

D.Williams (2017). "Understanding, Calculating, andMeasuring Total Harmonic Distortion (THD) ".www.Allaboutcircuits.com/technical- articles/theimportance -of-total-harmonic-distortion/[online].

Das, J. C. (2002). "Power system analysis: Short-circuit load flow and harmonics". CRC press.

Djeghader, Y., Zellouma, L., Labar, H., Toufouti, R., & Chelli, Z. (2015, December). "Study and filtering of harmonics in a DC electrified traway system". In 2015 7th International Conference on Modelling, Identification and Control (ICMIC) (pp. 1-6). IEEE.

Fahmi, M. I., Baafai, U., Hazmi, A., & Nasution, T. H. (2018, February). "Harmonic reduction by using single-tuned passive filter in plastic processing industry". In IOP Conference Series: Materials Science and Engineering (Vol. 308, No. 1, p. 012035). IOP Publishing.

Fahmi, M. I., Baafai, U., Hazmi, A., & Nasution, T. H. (2018, February). "Harmonic reduction by using single-tuned passive filter in plastic processing industry". In IOP Conference Series: Materials Science and Engineering (Vol. 308, No. 1, p. 012035). IOP Publishing.

H. Hu, Y. Shao, L. Tang, J. Ma, Z. He and S. Gao "Overview of Harmonic and Resonance in Railway", IEEE Transactions on Industry Applications (Volume: 54, Issue: 5, Sept.-Oct. 2018), DOI: 10.1109/TIA.2018.2813967, 09 March 2018.

H. Hu, Z. He and S. Gao "Passive Filter Design for China High-Speed Railway with Considering Harmonic Resonance and Characteristic Harmonics", IEEE transactions on power delivery, vol. 30, no. 1, february 2015.

Hassane, M. (2019, April). "Harmonic analysis caused by static converters of the railway high speed train and their impact on the track circuit". In 2019 International Conference on Wireless Technologies, Embedded and Intelligent Systems (WITS) (pp. 1-6). IEEE.

He, Z., Zheng, Z., & Hu, H. (2016). "Power quality in high-speed railway systems". "International Journal of Rail Transportation, 4(2), 71-97.

IEEE Std. 1531. (2003, November). "IEEE Guide for application and specification of harmonic filters." In IEEE Power Engineering Society, Transmission & Distribution Committee.

Institute of Electrical and Electronics Engineers (2014). "IEEE recommended practice and requirements for harmonic control in electric power systems". IEEE.

Kaleybar, H. J., Kojabadi, H. M., Brenna, M., Foiadelli, F., Fazel, S. S., & Rasi, A. (2019, June). "An inclusive study and classification of harmonic phenomena in electric railway systems". In 2019 IEEE International Conference on Environment and Electrical Engineering and 2019 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe) (pp. 1-6). IEEE.

Kulworawanichpong T. (2004). "Optimising AC electric railway power flows with power electronic control", Doctoral dissertation, University of Birmingham.

Kulworawanichpong T. (2018) "Railway Electrification". Documentation for teaching Suranaree University of Technology.University of Technology

Lee, H., Lee, C., Jang, G., & Kwon, S. H. (2006). "Harmonic analysis of the Korean high-speed railway using the eight-port representation model". IEEE Transactions on Power Delivery, 21(2), 979-986.

Lutrakulwattana, B., Konghirun, M., & Sangswang, A. (2015, October). "Harmonic resonance assessment of 1× 25kV, 50Hz traction power supply system for Suvarnabhumi airport rail link." In 2015 18th International Conference on Electrical Machines and Systems (ICEMS) (pp. 752-755). IEEE.

M. Popescu, A.Bitoleanu and M. Dobriceanu "Harmonic current reduction in railway systems", wseas transactions on systems, SSN: 1109-2777, Issue 7, Volume 7, July 2008

Monem, O. A. (2019, September). "Harmonic mitigation for power rectifier using passive filter combination". In IOP conference series: materials science and engineering (Vol. 610, No. 1, p. 012013). IOP Publishing.

Mongkoldee, Kritsada(2020). "Design of railway power conditioner in autotransformer-fed traction power supply system". Diss. School of Electrical Engineering Institute of Engineering Suranaree University of Technology, 2020.

Nakorn Chanthor Sor. (2016) Railway technician. "General knowledge in railway engineering". Development Institute Project National Rail Transportation Technology. Publication 3.

Nassif, A. B., & Xu, W. (2007, September). "Passive harmonic filters for medium-voltage industrial systems": Practical considerations and topology analysis. In 2007 39th North American Power Symposium (pp. 301-307). IEEE.

Oura Yasu, Yoshifumi Mochinaga, and Hiroki Nagasawa. "Railway electric power feeding systems." Japan railway & transport review 16.10 (1998): 48-58.

Paul S. (2022). "Harmonic Filter Design", Northeast Power Systems, Inc.

Reginald, A. G., & Thomas, K. J. (2015). "Harmonic Analysis and Its Mitigation Using Different Passive Filters". Asian Journal of Engineering and Technology, 3(4).

Shah, I. A., Ali, R. K., & Khan, N. (2016). "Design of a C-type passive filter for reducing harmonic distortion and reactive power compensation". Int. J. Softw. Hardw. Res. Eng, 4, 12.

Siemens Limited (2007), "Railway Electrification (REL) Traction Power Supply Attachment A: Traction Power Study and Simulation", Submission No.: TPS/0001, Suvarnabhumi Airport Rail Link and City Air Terminal.

Song, W., Jiao, S., Li, Y. W., Wang, J., & Huang, J. (2016). "High-frequency harmonic resonance suppression in high-speed railway through single-phase traction converter with LCL filter." IEEE Transactions on Transportation Electrification, 2(3), 347-356.

Steimel, A. (2014). "Electric traction: motive power and energy supply". Division Deutscher Industrieverlag.

Vujatovic, D., & Zhang, Q. (2006, June). "Harmonics generated from railway operation". In 2006 IEEE Power Engineering Society General Meeting (pp. 4-pp). IEEE.

Vujatovic, D., & Zhang, Q. (2006, June). "Harmonics generated from railway operation." In 2006 IEEE Power Engineering Society General Meeting (pp. 4-pp). IEEE.

W. Jesadapornpinyo (2016) "Harmonic Analysis for 40th year Sripatum Building"

Y.Wang (2014) "Comparison of Chinese and International Harmonic Interharmonic and Flicker Standards", A thesis submitted to the Graduate Faculty of Auburn University, December 13, 2014

Zdziebko, Paweł, Adam Martowicz, and Tadeusz Uhl.(2020) "Multi-domain approach to modeling pantograph-catenary interaction."

Zynovchenko, A., Xie, J., Jank, S., & Klier, F. (2006). "Calculations and measurements of harmonic current distributions in the catenary of railways with single-phase AC." WIT Transactions on The Built Environment, 88.

APPENDIX A

Results from simulation

A.1 Introduction

The graphical and tabulated results of the simulation result in Chapter 4, consisting of the results of the case study measurement data in Part 1 and Part 2 for the case study input voltage harmonics of the four-quadrant, are collected and displayed in this appendix.

A.2 Part 1 the results of the case study measurement data

A.2.1 Harmonic results of installing passive filters at Substation.

- Single-Tuned filter at TF=3

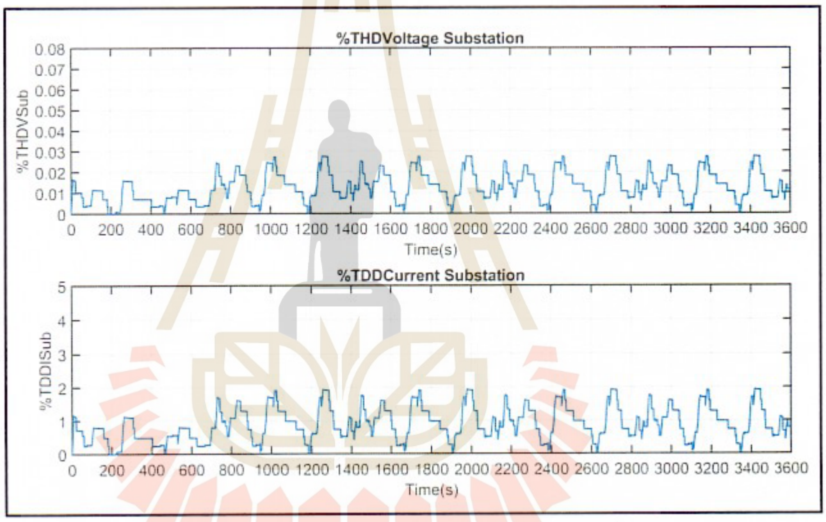


Figure A.1 Total Harmonic Distortion Voltage and Current at substation: STF TF=3

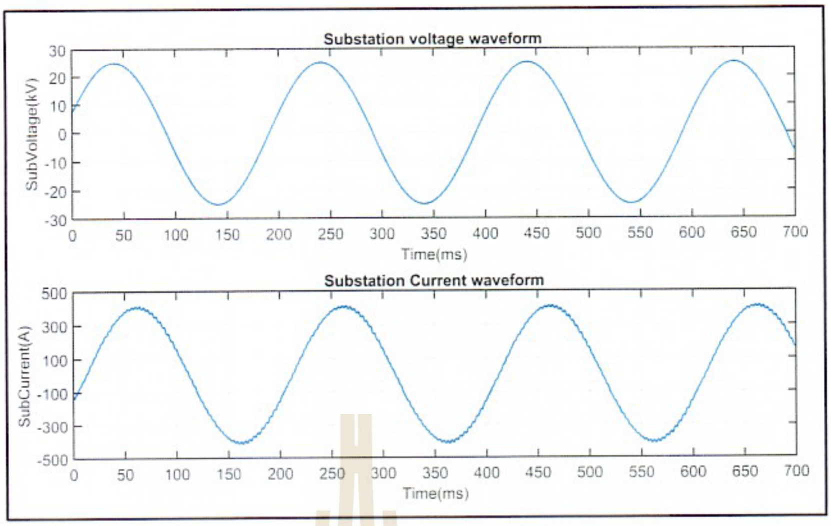


Figure A.2 Harmonic Distortion Voltage and Current at substation wave form: STF TF=3

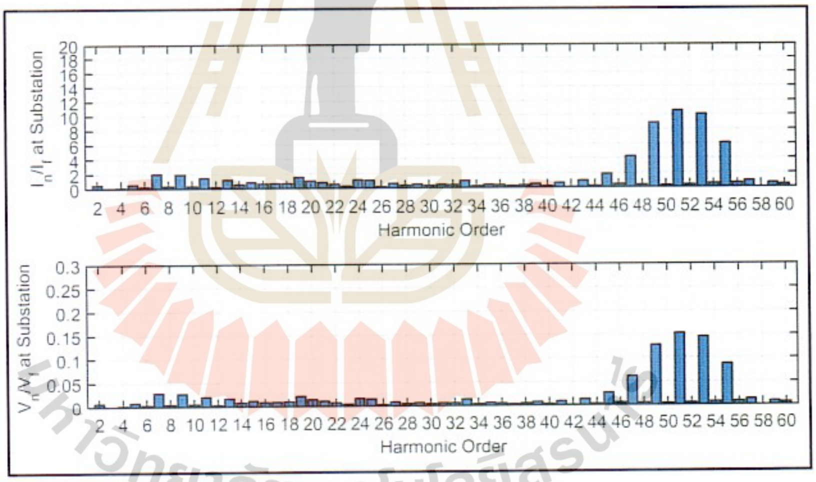


Figure A.3 Harmonics spectrum of Current and Voltage at the Substation: STF TF=3

Table A.1 THD Voltage results of installing Single-Tuned filters TF=3 at the substation

Bus voltage *V* at PCC 25 kV	THD Substation (%) (Simulation)		THD Train (%) (Simulation)		THD (%) IEEE519-2014 Standard
	No Filter	STF	No Filter	STF	
Minimum	0.00	0.00	0.00	0.00	5.00
Average	2.07	0.01	0.70	0.70	5.00
Maximum	4.48	0.03	7.92	7.92	5.00

Table A.2 TDD current results of installing Single-Tuned filters TF=3 at the substation

Maximum harmonic current distortion in percent of I_L												
Individual harmonic order (odd harmonics) at Substation												
I_{SC}/I_L (100 < 1000)	$3 \le h < 11$		$11 \le h < 17$		$17 \le h < 23$		$23 \le h < 35$		$35 \le h \le 50$		TDD	
	No Filter	STF	No Filter	STF	No Filter	STF	No Filter	STF	No Filter	STF	No Filter	STF
Minimum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Average	1.29	0.15	0.45	0.11	0.32	0.11	0.25	0.10	0.83	0.47	2.07	0.90
Maximum	2.80	0.32	0.97	0.23	0.70	0.23	0.53	0.22	1.79	1.01	4.48	1.94
IEEE514-2014	12.0		5.5		5.0		2.0		1.0		15.0	

- Single-Tuned filter at TF=5

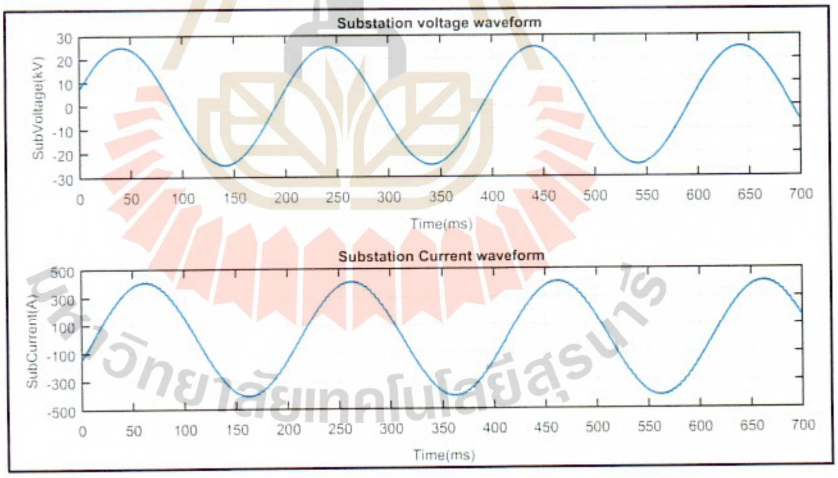


Figure A.4 Total Harmonic Distortion Voltage and Current at substation: STF TF=5

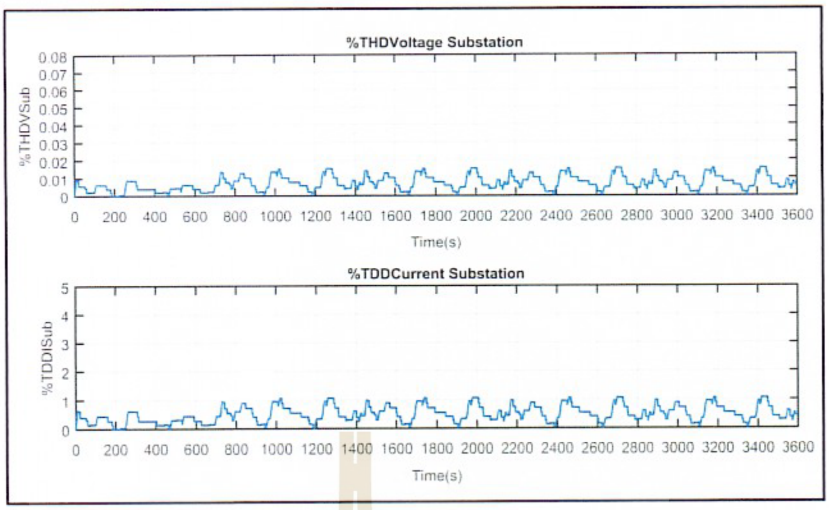


Figure A.5 Harmonic Distortion Voltage and Current at substation wave form: STF TF=5

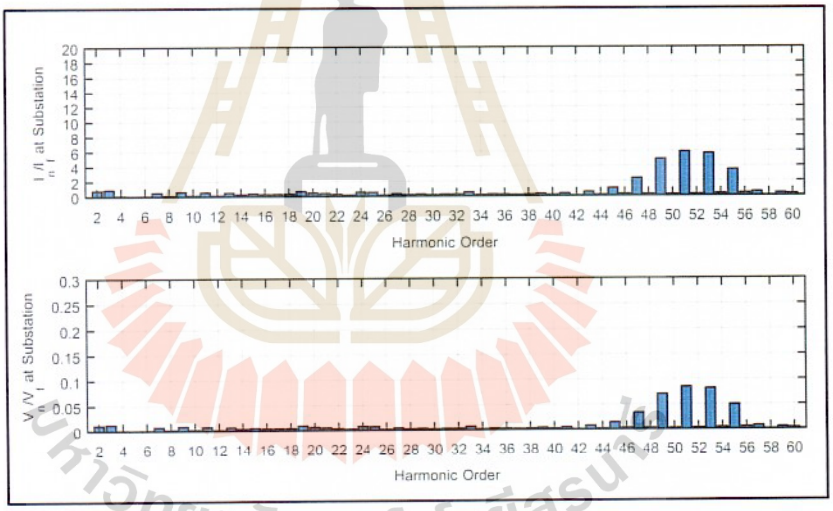


Figure A.6 Harmonics spectrum of Current and Voltage at the Substation: STF TF=5

Table A.3 THD Voltage results of installing Single-Tuned filters TF=53 at the substation

Bus voltage *V* at PCC 25 kV	THD Substation (%) (Simulation)		THD Train (%) (Simulation)		THD (%) IEEE519-2014 Standard
	No Filter	STF	No Filter	STF	
Minimum	0.00	0.00	0.00	0.00	5.00
Average	2.07	0.007	0.70	0.70	5.00
Maximum	4.48	0.015	7.92	7.92	5.00

Table A.4 TDD current results of installing Single-Tuned filters TF=5 at the substation

Maximum harmonic current distortion in percent of I_L												
Individual harmonic order (odd harmonics) at Substation												
I_{SC}/I_L *(100 < 1000)*	3 ≤ *h* < 11		11 ≤ *h* < 17		17 ≤ *h* < 23		23 ≤ *h* < 35		35 ≤ *h* ≤ 50		TDD	
	No Filter	STF	No Filter	STF	No Filter	STF	No Filter	STF	No Filter	STF	No Filter	STF
Minimum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Average	1.29	0.06	0.45	0.04	0.32	0.05	0.25	0.05	0.83	0.26	2.07	0.50
Maximum	2.80	0.13	0.97	0.09	0.70	0.10	0.53	0.10	1.79	0.56	4.48	1.07
IEEE514-2014	12.0		5.5		5.0		2.0		1.0		15.0	

- Single-Tuned filter at TF=51

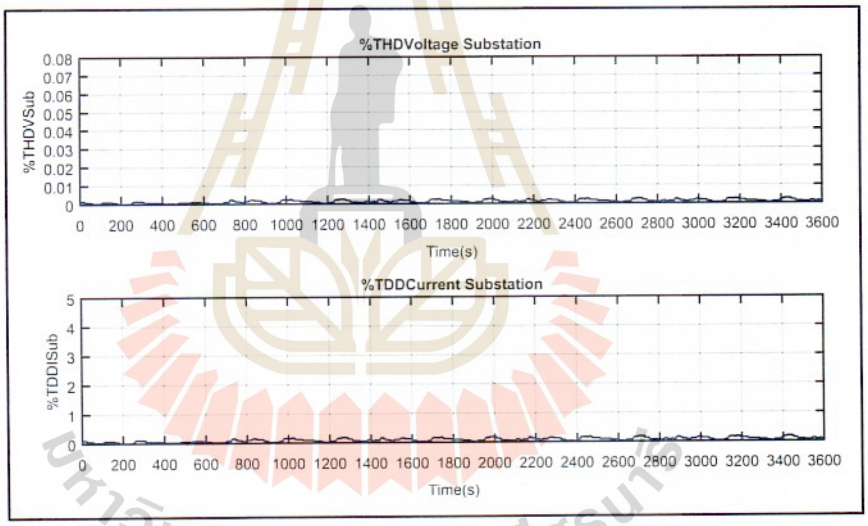


Figure A.7 Total Harmonic Distortion Voltage and Current at substation: STF TF=51

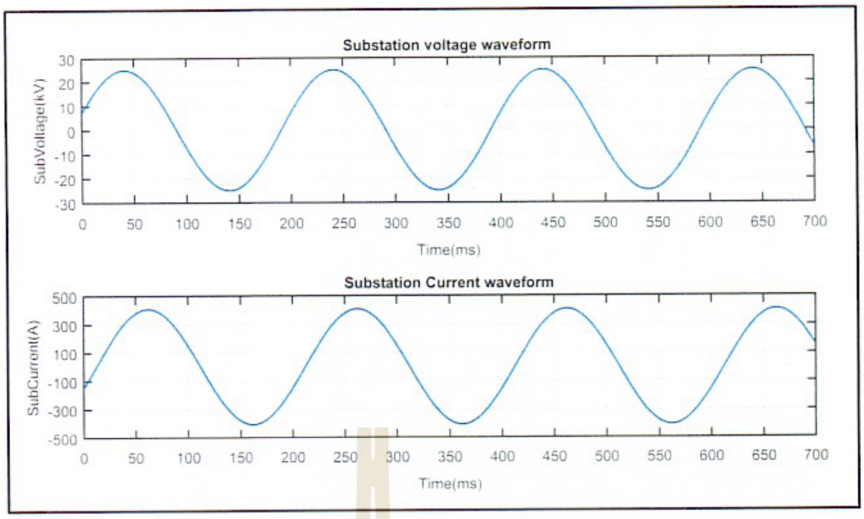


Figure A.8 Harmonic Distortion Voltage and Current at substation wave form: STF TF=51

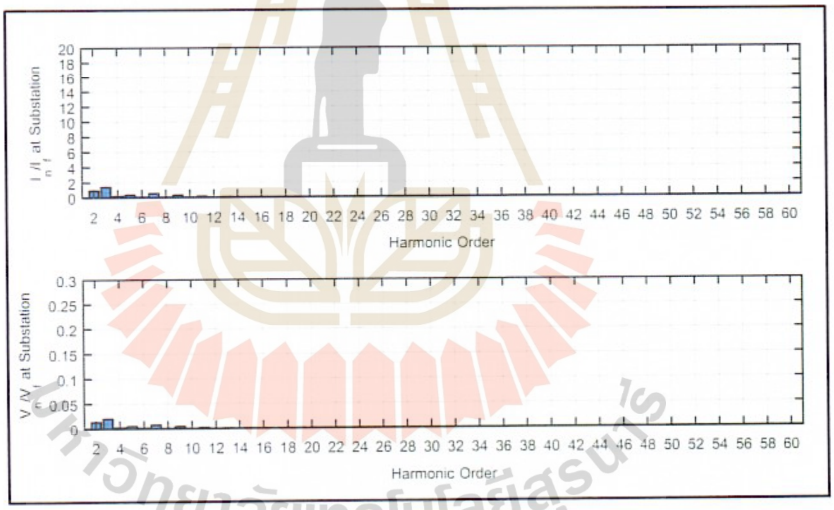


Figure A.9 Harmonics spectrum of Current and Voltage at the Substation: STF TF=51

Table A.5 THD Voltage results of installing Single-Tuned filters TF=51 at the substation

Bus voltage *V* at PCC 25 kV	THD Substation (%) (Simulation)		THD Train (%) (Simulation)		THD (%) IEEE519-2014 Standard
	No Filter	STF	No Filter	STF	
Minimum	0.00	0.00	0.00	0.00	5.00
Average	2.07	0.001	0.70	0.70	5.00
Maximum	4.48	0.003	7.92	7.92	5.00

Table A.6 TDD current results of installing Single-Tuned filters TF=53 at the substation

Maximum harmonic current distortion in percent of I_L												
Individual harmonic order (odd harmonics) at Substation												
I_{SC}/I_L (100 < 1000)	$3 \le h < 11$		$11 \le h < 17$		$17 \le h < 23$		$23 \le h < 35$		$35 \le h \le 50$		TDD	
	No Filter	STF	No Filter	STF	No Filter	STF	No Filter	STF	No Filter	STF	No Filter	STF
Minimum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Average	1.29	0.07	0.45	0.01	0.32	0.003	0.25	0.002	0.83	0.001	2.07	0.08
Maximum	2.80	0.16	0.97	0.02	0.70	0.01	0.53	0.003	1.79	0.001	4.48	0.18
IEEE514-2014	12.0		5.5		5.0		2.0		1.0		15.0	

- Single-Tuned filter at TF=53

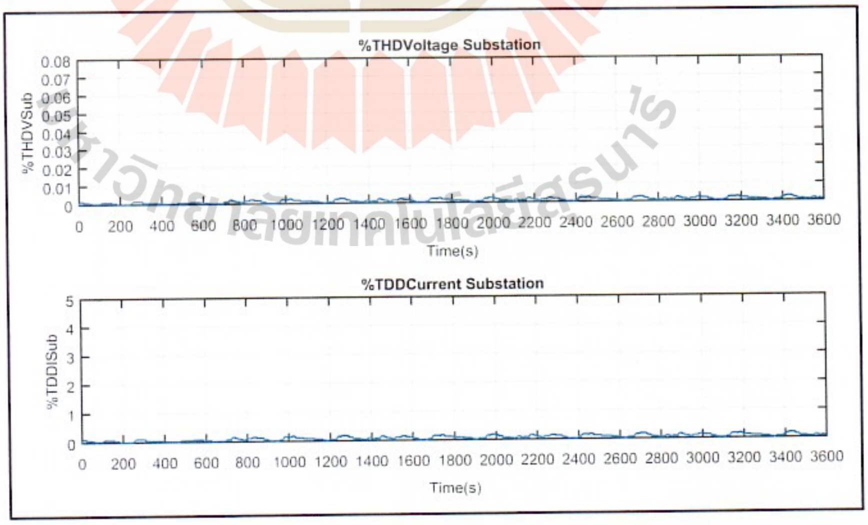


Figure A.10 Total Harmonic Distortion Voltage and Current at substation: STF TF=53

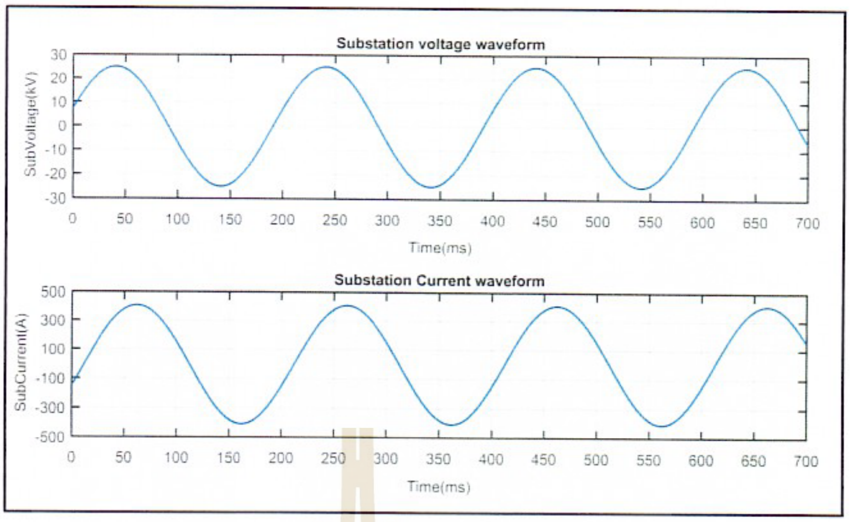


Figure A.11 Harmonic Distortion Voltage and Current at substation wave form: STF TF=53

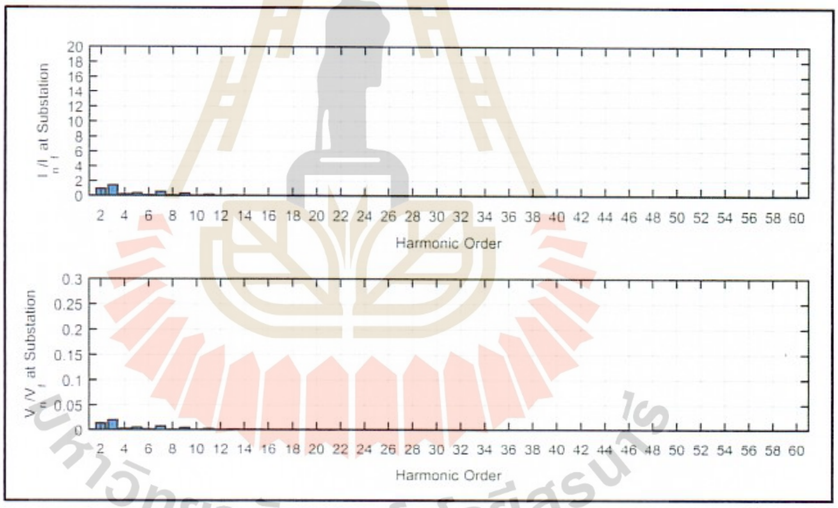


Figure A.12 Harmonics spectrum of Current and Voltage at the Substation: STF TF=53

Table A.7 THD Voltage results of installing Single-Tuned filters TF=53 at the substation

Bus voltage *V* at PCC 25 kV	THD Substation (%) (Simulation)		THD Train (%) (Simulation)		THD (%) IEEE519-2014 Standard
	No Filter	STF	No Filter	STF	
Minimum	0.00	0.00	0.00	0.00	5.00
Average	2.07	0.001	0.70	0.70	5.00
Maximum	4.48	0.003	7.92	7.92	5.00

Table A.8 TDD current results of installing Single-Tuned filters TF=53 at the substation

Maximum harmonic current distortion in percent of I_L												
Individual harmonic order (odd harmonics) at Substation												
I_{SC}/I_L (100 < 1000)	$3 \le h < 11$		$11 \le h < 17$		$17 \le h < 23$		$23 \le h < 35$		$35 \le h \le 50$		TDD	
	No Filter	STF	No Filter	STF	No Filter	STF	No Filter	STF	No Filter	STF	No Filter	STF
Minimum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Average	1.29	0.07	0.45	0.01	0.32	0.003	0.25	0.002	0.83	0.001	2.07	0.08
Maximum	2.80	0.16	0.97	0.02	0.70	0.01	0.53	0.003	1.79	0.002	4.48	0.18
IEEE514-2014	12.0		5.5		5.0		2.0		1.0		15.0	

- Band-Pass filters TF=3

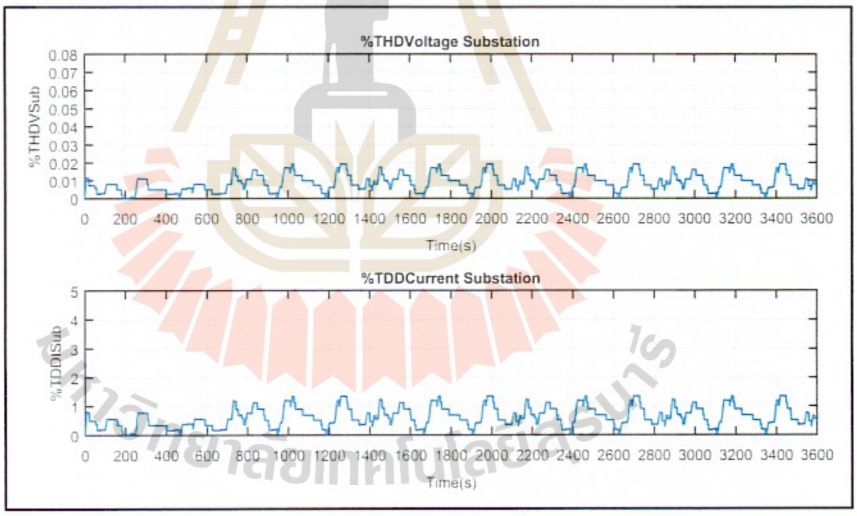


Figure A.13 Total Harmonic Distortion Voltage and Current at substation: BP TF=3

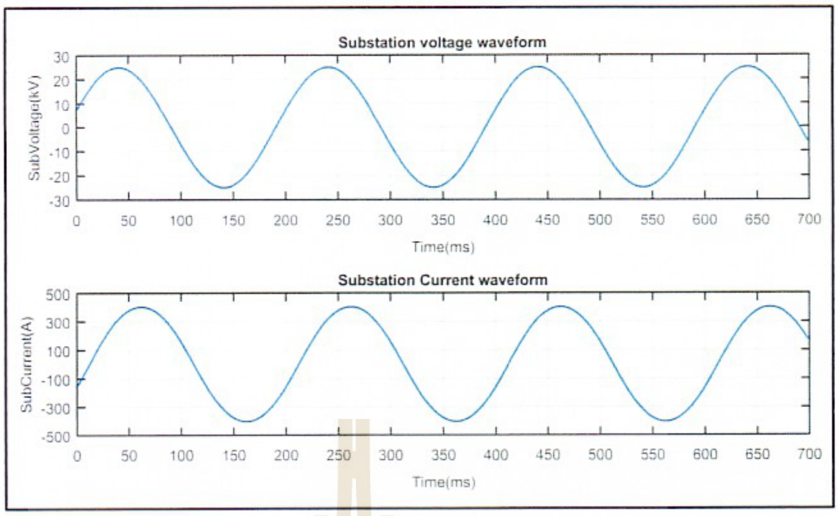


Figure A.14 Harmonic Distortion Voltage and Current at substation wave form: BP TF=3

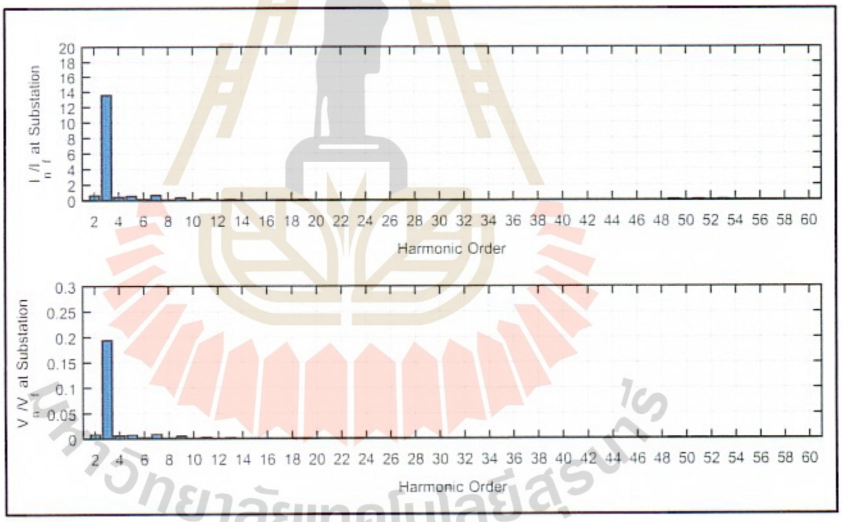


Figure A.15 Harmonics spectrum of Current and Voltage at the Substation: BP TF=3

Table A.9 THD Voltage results of installing Band-Pass filters TF=3 at the substation

Bus voltage *V* at PCC 25 kV	THD Substation (%) (Simulation)		THD Train (%) (Simulation)		THD (%) IEEE519-2014 Standard
	No Filter	BP	No Filter	BP	
Minimum	0.00	0.00	0.00	0.00	5.00
Average	2.07	0.01	0.70	0.70	5.00
Maximum	4.48	0.02	7.92	7.92	5.00

Table A.10 TDD current results of installing Band-Pass filters TF=3 at the substation

Maximum harmonic current distortion in percent of I_L												
Individual harmonic order (odd harmonics) at Substation												
I_{sc}/I_L *(100 < 1000)*	$3 \le h < 11$		$11 \le h < 17$		$17 \le h < 23$		$23 \le h < 35$		$35 \le h \le 50$		TDD	
	No Filter	BP	No Filter	BP	No Filter	BP	No Filter	BP	No Filter	BP	No Filter	BP
Minimum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Average	1.29	0.63	0.45	0.01	0.32	0.004	0.25	0.002	0.83	0.004	2.07	0.63
Maximum	2.80	1.36	0.97	0.02	0.70	0.01	0.53	0.005	1.79	0.01	4.48	1.36
IEEE514-2014	12.0		5.5		5.0		2.0		1.0		15.0	

- Band-Pass filters TF=5

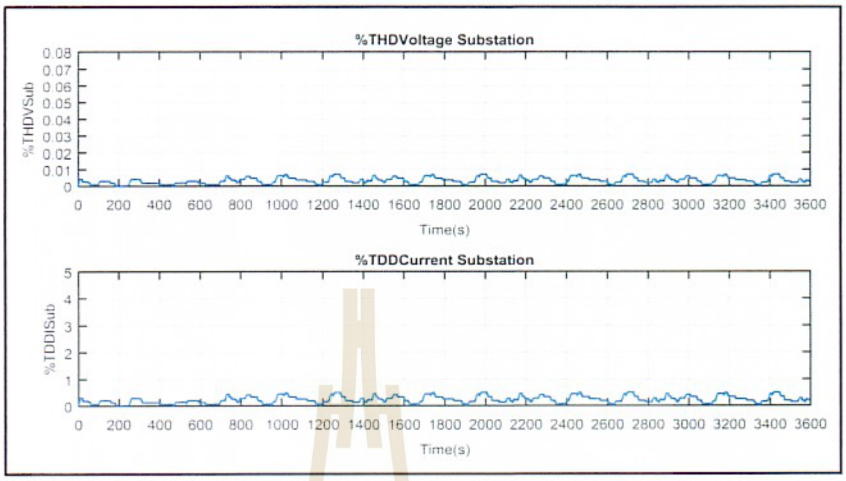


Figure A.16 Total Harmonic Distortion Voltage and Current at substation: BP TF=5

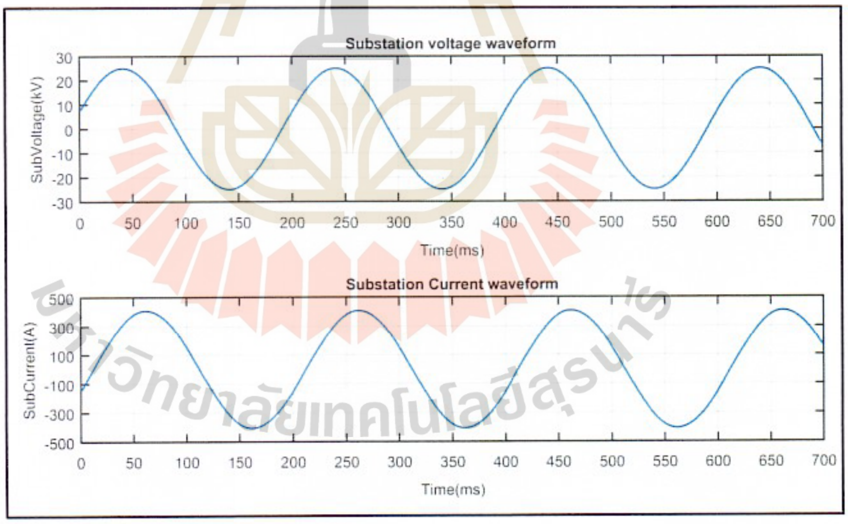


Figure A.17 Harmonic Distortion Voltage and Current at substation wave form: BP TF=5

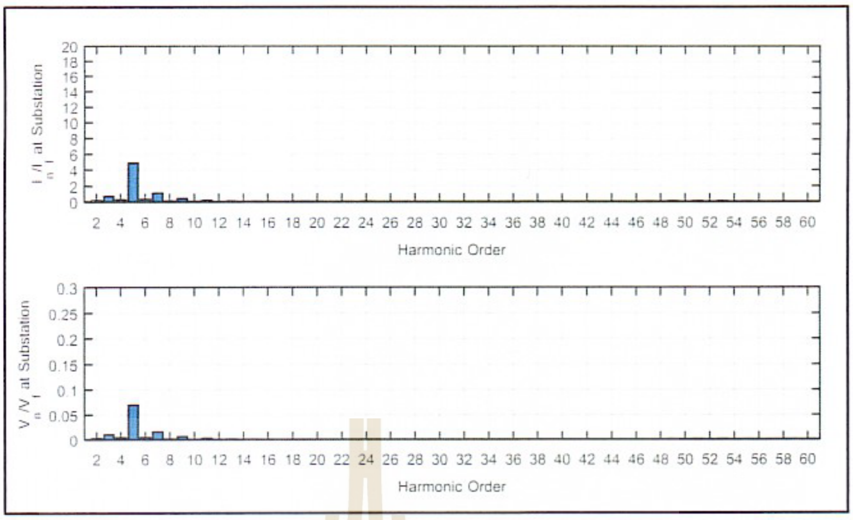


Figure A. 18 Harmonics spectrum of Current and Voltage at the Substation: BP TF=5

Table A.11 THD Voltage results of installing Band-Pass filters TF=5 at the substation

Bus voltage *V* at PCC 25 kV	THD Substation (%) (Simulation)		THD Train (%) (Simulation)		THD (%) IEEE519-2014 Standard
	No Filter	BP	No Filter	BP	
Minimum	0.00	0.00	0.00	0.00	5.00
Average	2.07	0.003	0.70	0.70	5.00
Maximum	4.48	0.007	7.92	7.92	5.00

Table A.12 TDD current results of installing Band-Pass filters TF=5 at the substation

Maximum harmonic current distortion in percent of I_L												
Individual harmonic order (odd harmonics) at Substation												
I_{SC}/I_L (100 < 1000)	$3 \le h < 11$		$11 \le h < 17$		$17 \le h < 23$		$23 \le h < 35$		$35 \le h \le 50$		TDD	
	No Filter	BP	No Filter	BP	No Filter	BP	No Filter	BP	No Filter	BP	No Filter	BP
Minimum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Average	1.29	0.23	0.45	0.01	0.32	0.004	0.25	0.002	0.83	0.004	2.07	0.23
Maximum	2.80	0.51	0.97	0.02	0.70	0.01	0.53	0.005	1.79	0.01	4.48	0.51
IEEE514-2014	12.0		5.5		5.0		2.0		1.0		15.0	

- Band-Pass filters TF=51

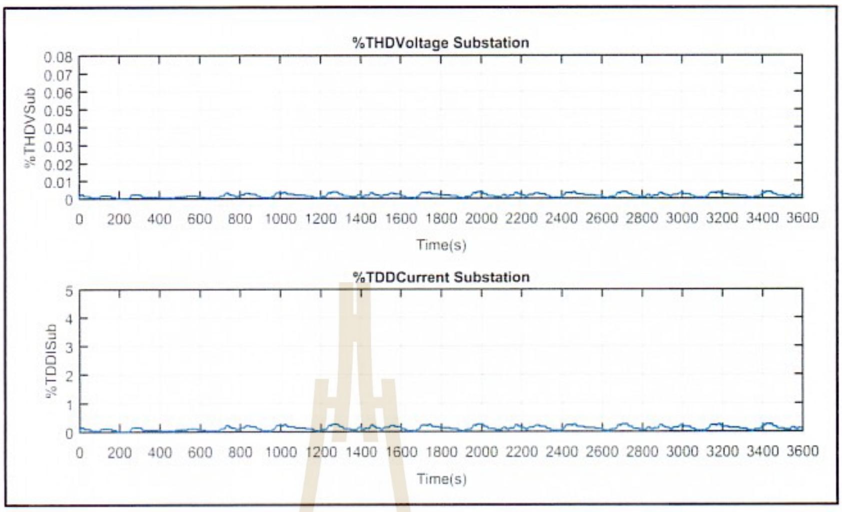


Figure A.19 Total Harmonic Distortion Voltage and Current at substation: BP TF=51

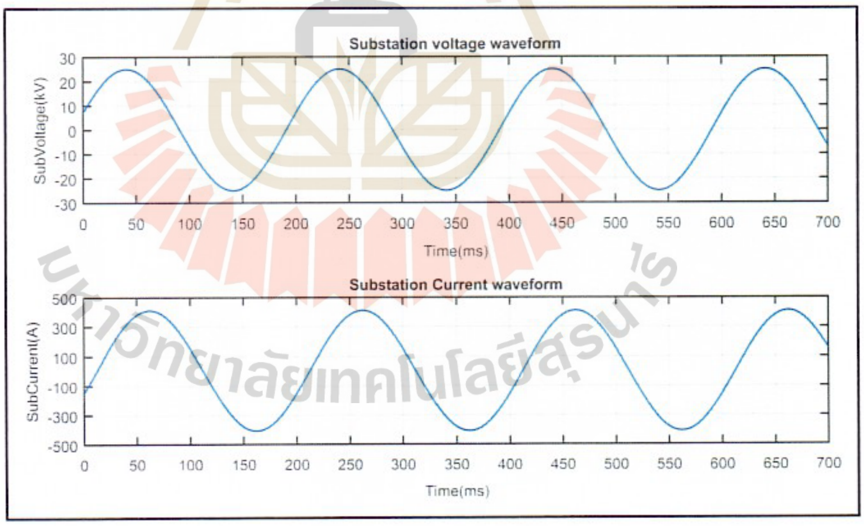


Figure A.20 Harmonic Distortion Voltage and Current at substation wave form: BP TF=51

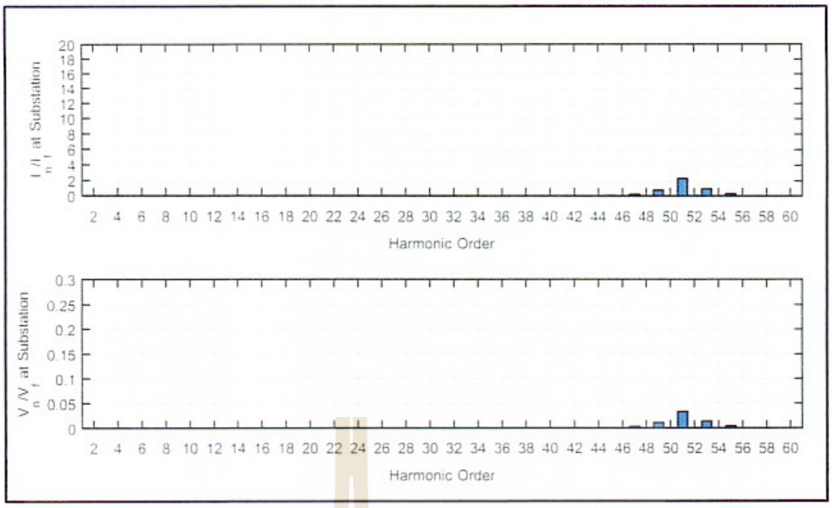


Figure A.21 Harmonics spectrum of Current and Voltage at the Substation: BP TF=51

Table A.13 THD Voltage results of installing Band-Pass filters TF=51 at the substation

Bus voltage V at PCC 25 kV	THD Substation (%) (Simulation)		THD Train (%) (Simulation)		THD (%) IEEE519-2014 Standard
	No Filter	BP	No Filter	BP	
Minimum	0.00	0.00	0.00	0.00	5.00
Average	0.03	0.001	0.70	0.70	5.00
Maximum	0.07	0.004	7.92	7.92	5.00

Table A.14 TDD current results of installing Band-Pass filters TF=51 at the substation

Maximum harmonic current distortion in percent of I_L												
Individual harmonic order (odd harmonics) at Substation												
I_{SC}/I_L (100 < 1000)	$3 \le h < 11$		$11 \le h < 17$		$17 \le h < 23$		$23 \le h < 35$		$35 \le h \le 50$		TDD	
	No Filter	BP	No Filter	BP	No Filter	BP	No Filter	BP	No Filter	BP	No Filter	BP
Minimum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Average	1.29	0.001	0.45	0.001	0.32	0.001	0.25	0.001	0.83	0.04	2.07	0.12
Maximum	2.80	0.001	0.97	0.001	0.70	0.001	0.53	0.001	1.79	0.08	4.48	0.26
IEEE514-2014	12.0		5.5		5.0		2.0		1.0		15.0	

- Band-Pass filters TF=53

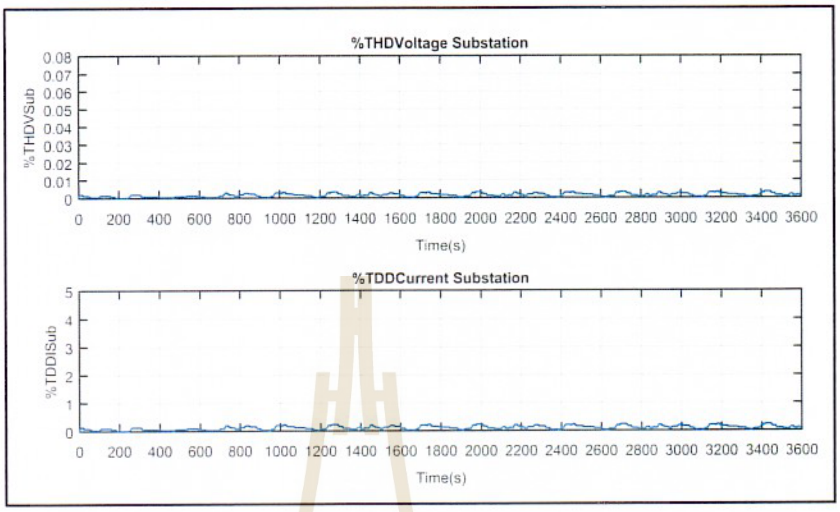


Figure A. 22 Total Harmonic Distortion Voltage and Current at substation: BP TF=53

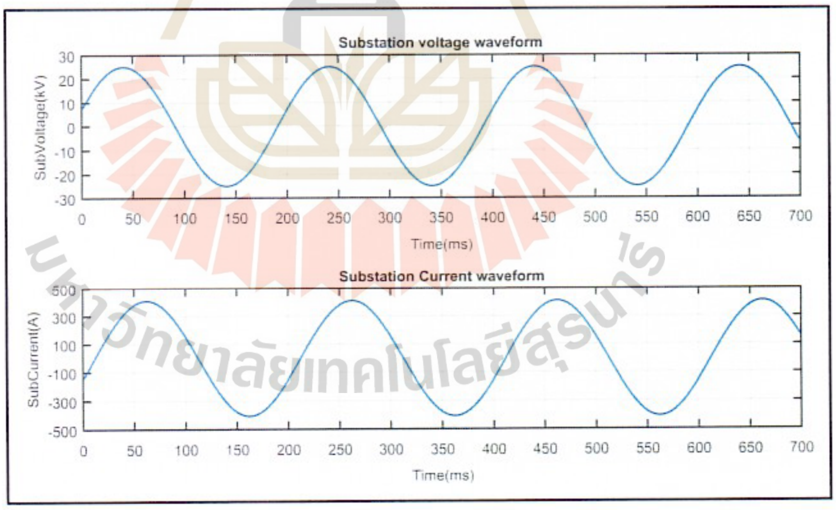


Figure A. 23 Harmonic Distortion Voltage and Current at substation wave form: BP TF=53

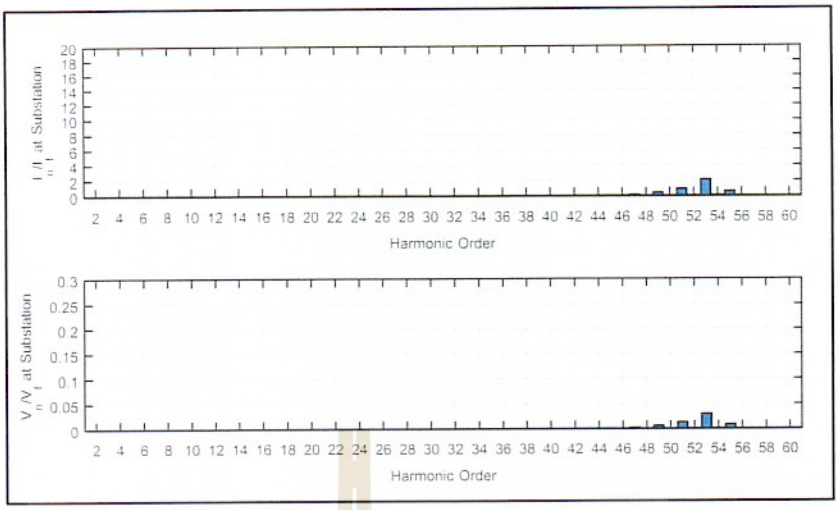


Figure A.24 Harmonics spectrum of Current and Voltage at the Substation: BP TF=53

Table A.15 THD Voltage results of installing Band-Pass filters TF=53 at the substation

Bus voltage V at PCC 25 kV	THD Substation (%) (Simulation)		THD Train (%) (Simulation)		THD (%) IEEE519-2014 Standard
	No Filter	BP	No Filter	BP	
Minimum	0.00	0.00	0.00	0.00	5.00
Average	2.07	0.002	0.70	0.70	5.00
Maximum	4.48	0.003	7.92	7.92	5.00

Table A.16 TDD current results of installing Band-Pass filters TF=53 at the substation

Maximum harmonic current distortion in percent of I_L												
Individual harmonic order (odd harmonics) at Substation												
I_{SC}/I_L $(100 < 1000)$	$3 \le h < 11$		$11 \le h < 17$		$17 \le h < 23$		$23 \le h < 35$		$35 \le h \le 50$		TDD	
	No Filter	BP	No Filter	BP	No Filter	BP	No Filter	BP	No Filter	BP	No Filter	BP
Minimum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Average	1.29	$1x10^3$	0.45	$5x10^4$	0.32	$7x10^4$	0.25	$7x10^4$	0.83	0.02	2.07	0.11
Maximum	2.80	$1x10^3$	0.97	$1x10^3$	0.70	$1x10^3$	0.53	$1x10^3$	1.79	0.04	4.48	0.23
IEEE514-2014	12.0		5.5		5.0		2.0		1.0		15.0	

- High-Pass filters TF=5

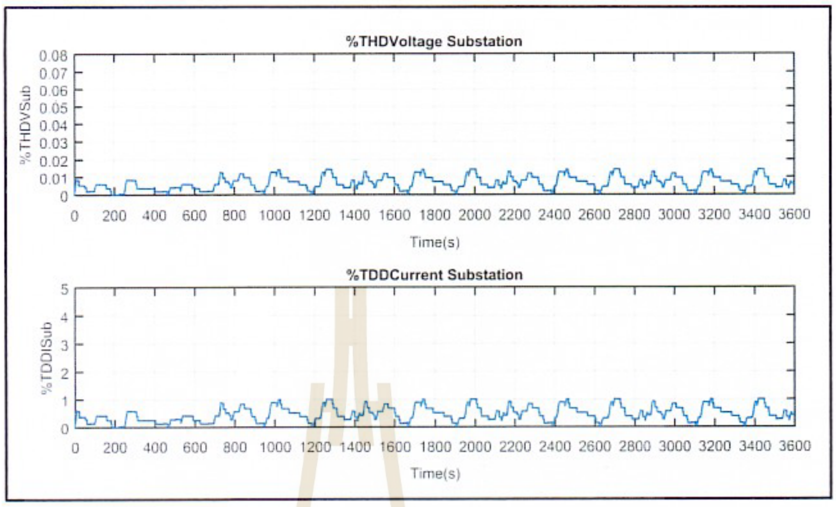


Figure A.25 Total Harmonic Distortion Voltage and Current at substation: HP TF=5

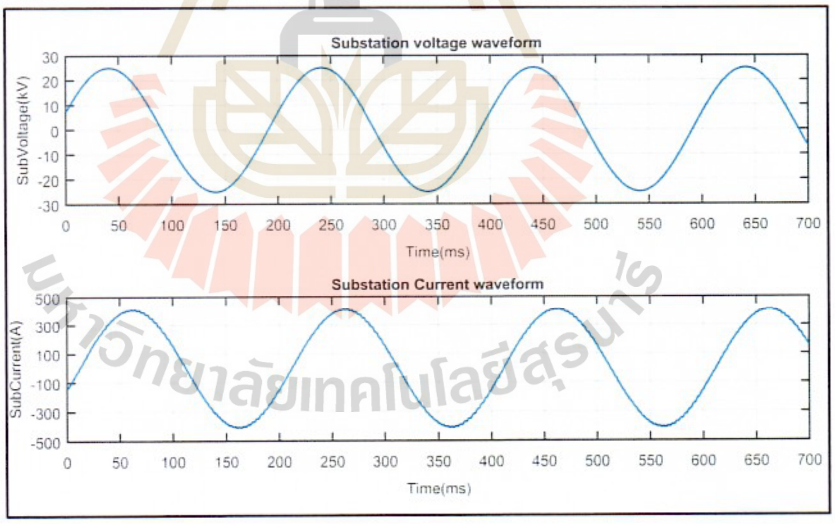


Figure A.26 Harmonic Distortion Voltage and Current at substation wave form: HP TF=5

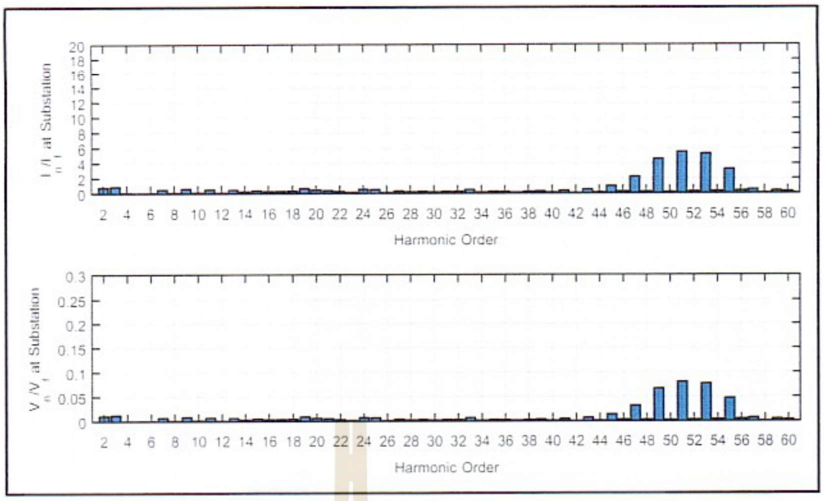


Figure A.27 Harmonics spectrum of Current and Voltage at the Substation: HP TF=5

Table A.17 THD Voltage results of installing High-Pass filters TF=5 at the substation

Bus voltage *V* at PCC 25 kV	THD Substation (%) (Simulation)		THD Train (%) (Simulation)		THD (%) IEEE519-2014 Standard
	No Filter	HP	No Filter	HP	
Minimum	0.00	0.00	0.00	0.00	5.00
Average	2.07	0.01	0.70	0.70	5.00
Maximum	4.48	0.02	7.92	7.92	5.00

Table A.18 TDD current results of installing High-Pass filters TF=5 at the substation

Maximum harmonic current distortion in percent of I_L												
Individual harmonic order (odd harmonics) at Substation												
I_{SC}/I_L (100 < 1000)	$3 \le h < 11$		$11 \le h < 17$		$17 \le h < 23$		$23 \le h < 35$		$35 \le h \le 50$		TDD	
	No Filter	HP	No Filter	HP	No Filter	HP	No Filter	HP	No Filter	HP	No Filter	HP
Minimum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Average	1.29	0.06	0.45	0.04	0.32	0.04	0.25	0.05	0.83	0.24	2.07	0.47
Maximum	2.80	0.13	0.97	0.09	0.70	0.10	0.53	0.10	1.79	0.53	4.48	1.01
IEEE514-2014	12.0		5.5		5.0		2.0		1.0		15.0	

- High-Pass filters TF=51

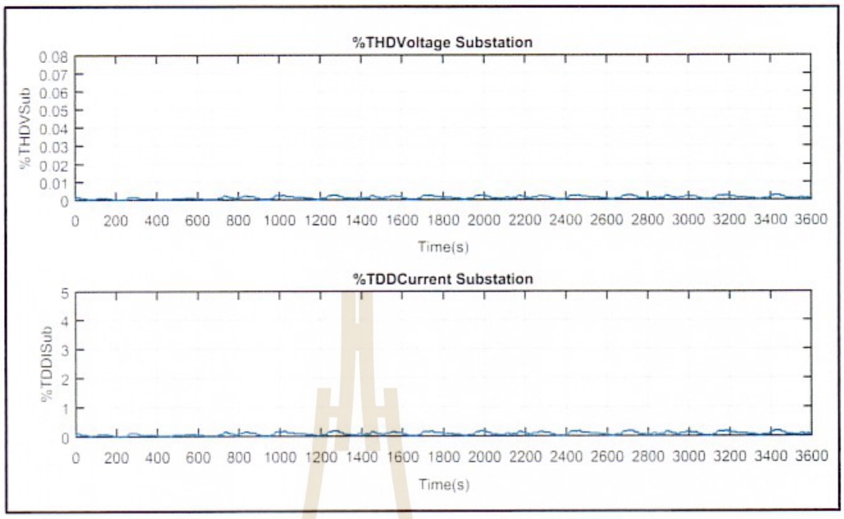


Figure A.28 Total Harmonic Distortion Voltage and Current at substation: HP TF=51

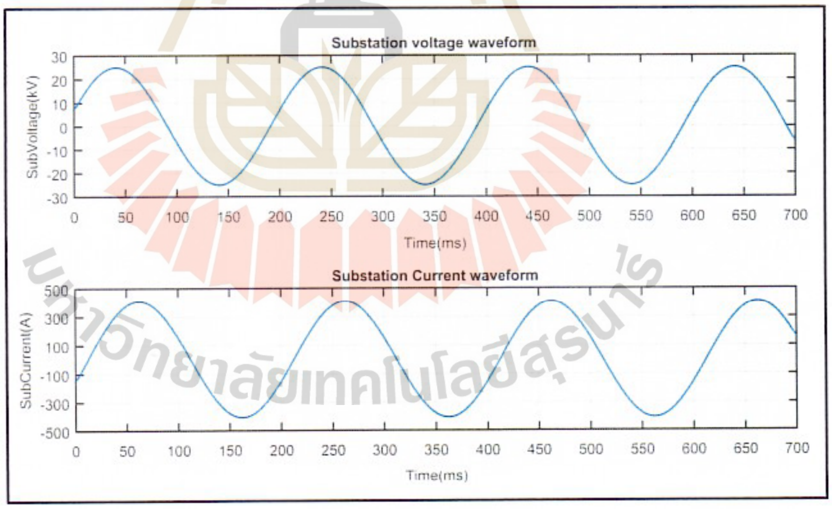


Figure A.29 Harmonic Distortion Voltage and Current at substation wave form: HP TF=51

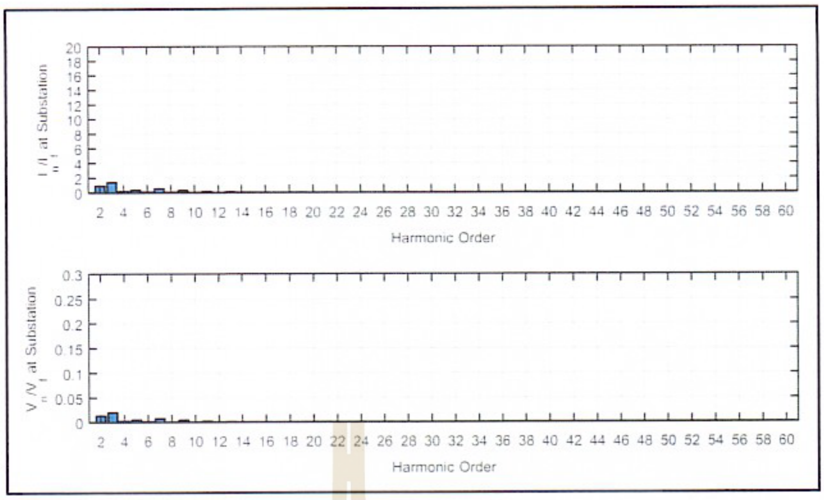


Figure A.30 Harmonics spectrum of Current and Voltage at the Substation: HP TF=51

Table A.19 THD Voltage results of installing High-Pass filters TF=51 at the substation

Bus voltage *V* at PCC 25 kV	THD Substation (%) (Simulation)		THD Train (%) (Simulation)		THD (%) IEEE519-2014 Standard
	No Filter	HP	No Filter	HP	
Minimum	0.00	0.00	0.00	0.00	5.00
Average	0.03	0.001	0.70	0.70	5.00
Maximum	0.07	0.003	7.92	7.92	5.00

Table A.20 TDD current results of installing High-Pass filters TF=51 at the substation

Maximum harmonic current distortion in percent of I_L												
Individual harmonic order (odd harmonics) at <u>Substation</u>												
I_{SC}/I_L *(100 < 1000)*	$3 \le h < 11$		$11 \le h < 17$		$17 \le h < 23$		$23 \le h < 35$		$35 \le h \le 50$		TDD	
	No Filter	HP	No Filter	HP	No Filter	HP	No Filter	HP	No Filter	HP	No Filter	HP
Minimum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Average	1.29	0.07	0.45	0.008	0.32	0.003	0.25	0.001	0.83	$5x10^{4}$	2.07	0.08
Maximum	2.80	0.16	0.97	0.16	0.70	0.007	0.53	0.003	1.79	$1x10^{3}$	4.48	0.18
IEEE514-2014	12.0		5.5		5.0		2.0		1.0		15.0	

- High-Pass filters TF=53

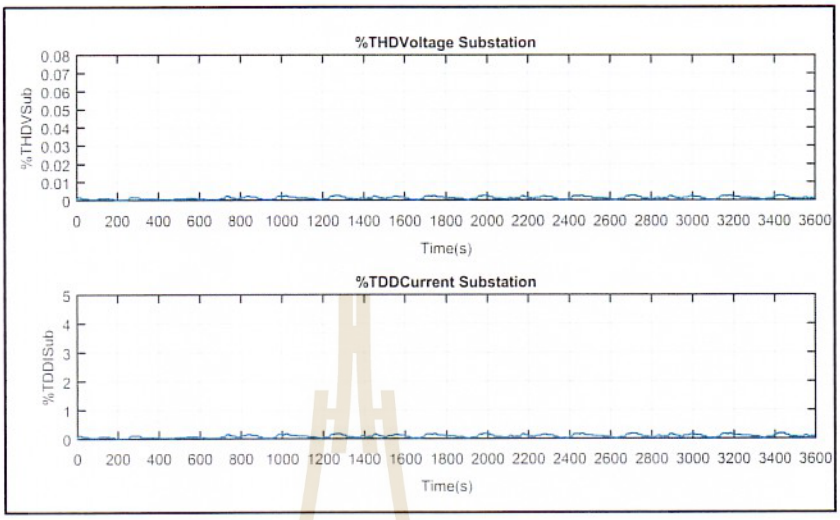


Figure A.31 Total Harmonic Distortion Voltage and Current at substation: HP TF=53

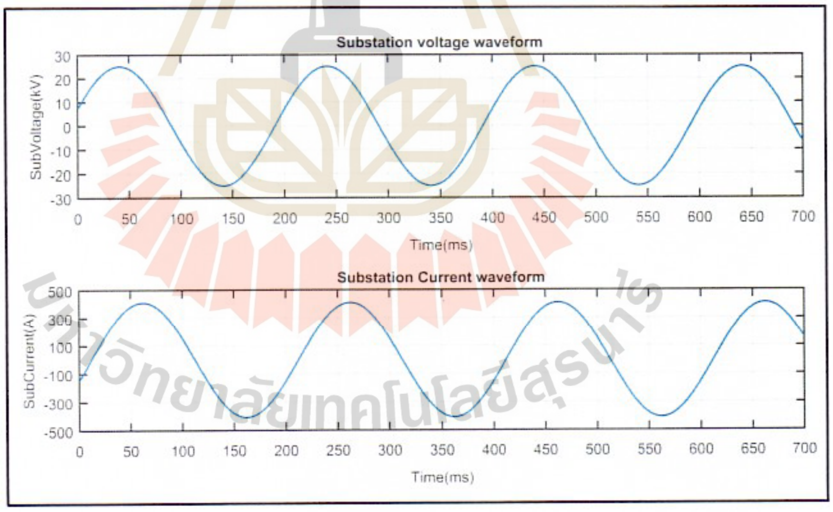


Figure A.32 Harmonic Distortion Voltage and Current at substation wave form: HP TF=53

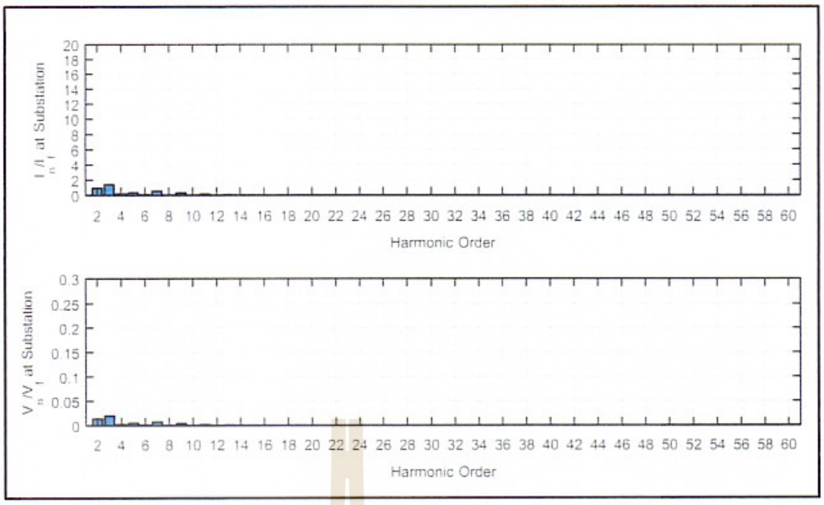


Figure A.33 Harmonics spectrum of Current and Voltage at the Substation: HP TF=53

Table A.21 THD Voltage results of installing High-Pass filters TF=53 at the substation

Bus voltage *V* at PCC 25 kV	THD Substation (%) (Simulation)		THD Train (%) (Simulation)		THD (%) IEEE519-2014 Standard
	No Filter	HP	No Filter	HP	
Minimum	0.00	0.00	0.00	0.00	5.00
Average	2.07	0.001	0.70	0.70	5.00
Maximum	4.48	0.002	7.92	7.92	5.00

Table A.22 TDD current results of installing High-Pass filters TF=53 at the substation

Maximum harmonic current distortion in percent of I_L												
Individual harmonic order (odd harmonics) at Substation												
I_{SC}/I_L (100 < 1000)	$3 \le h < 11$		$11 \le h < 17$		$17 \le h < 23$		$23 \le h < 35$		$35 \le h \le 50$		TDD	
	No Filter	HP	No Filter	HP	No Filter	HP	No Filter	HP	No Filter	HP	No Filter	HP
Minimum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Average	1.29	0.07	0.45	0.01	0.32	0.003	0.25	0.002	0.83	7×10^{4}	2.07	0.08
Maximum	2.80	0.16	0.97	0.02	0.70	0.007	0.53	0.003	1.79	0.002	4.48	0.18
IEEE514-2014	12.0		5.5		5.0		2.0		1.0		15.0	

- C-Type filters TF=3

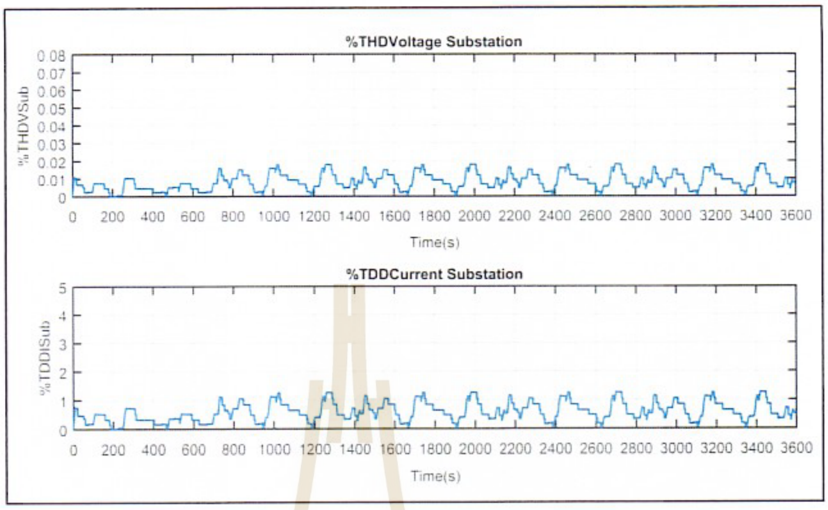


Figure A.34 Total Harmonic Distortion Voltage and Current at substation: C-Type TF=3

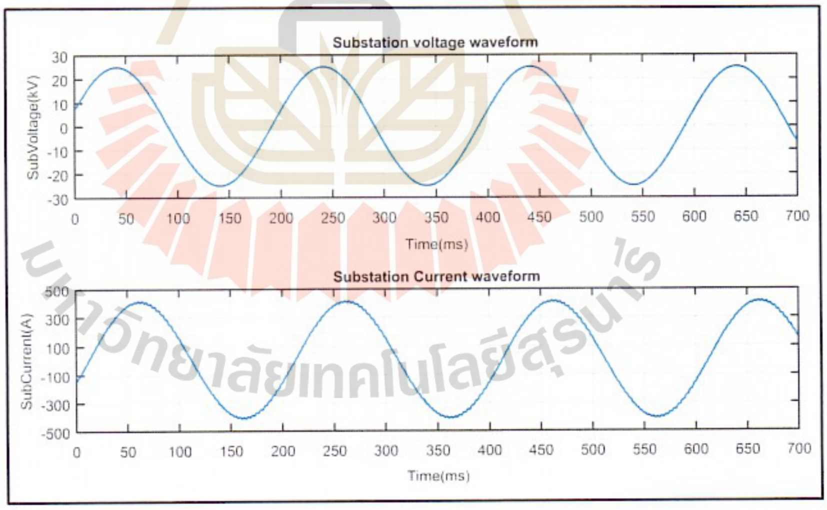


Figure A.35 Harmonic Distortion Voltage and Current at substation wave form: C-Type TF=3

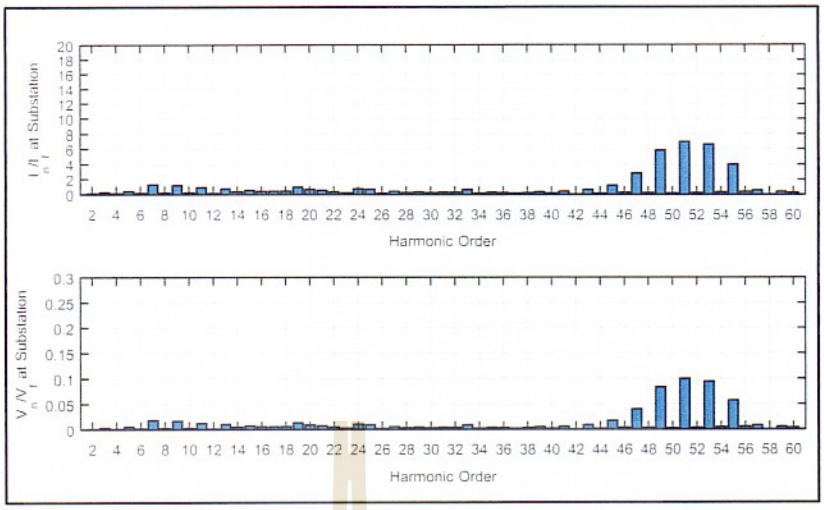


Figure A.36 Harmonics spectrum of Current and Voltage at the Substation: C-Type TF=3

Table A.23 THD Voltage results of installing C-Type filters TF=3 at the substation

Bus voltage V at PCC 25 kV	THD Substation (%) (Simulation)		THD Train (%) (Simulation)		THD (%) IEEE519-2014 Standard
	No Filter	C-Type	No Filter	C-Type	
Minimum	0.00	0.00	0.00	0.00	5.00
Average	0.03	0.01	0.70	0.70	5.00
Maximum	0.07	0.02	7.92	7.92	5.00

Table A.24 TDD current results of installing C-Type filters TF=3 at the substation

Maximum harmonic current distortion in percent of I_L												
Individual harmonic order (odd harmonics) at Substation												
I_{SC}/I_L *(100 < 1000)*	$3 \le h < 11$		$11 \le h < 17$		$17 \le h < 23$		$23 \le h < 35$		$35 \le h \le 50$		TDD	
	No Filter	C-Type	No Filter	C-Type	No Filter	C-Type	No Filter	C-Type	No Filter	C-Type	No Filter	C-Type
Minimum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Average	1.29	0.09	0.45	0.07	0.32	0.07	0.25	0.07	0.83	0.31	2.07	0.59
Maximum	2.80	0.20	0.97	0.14	0.70	0.14	0.53	0.14	1.79	0.66	4.48	1.27
IEEE514-2014	12.0		5.5		5.0		2.0		1.0		15.0	

- C-Type filters TF=5

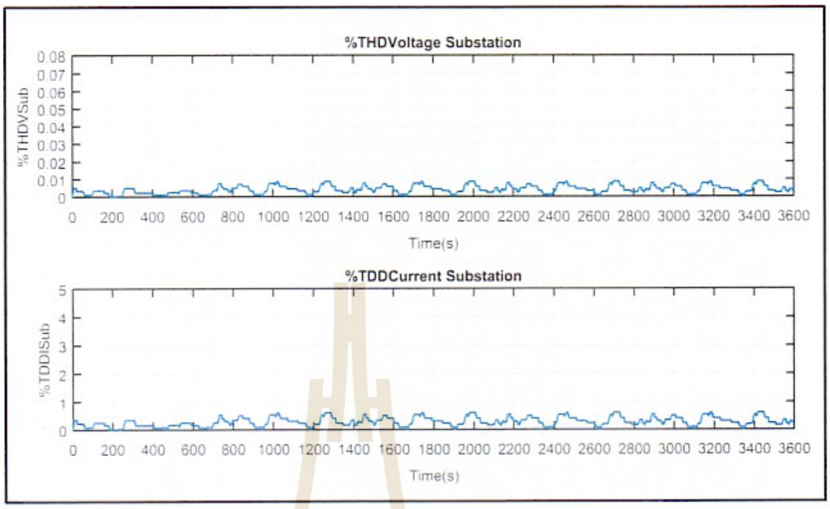


Figure A.37 Total Harmonic Distortion Voltage and Current at substation: C-Type TF=5

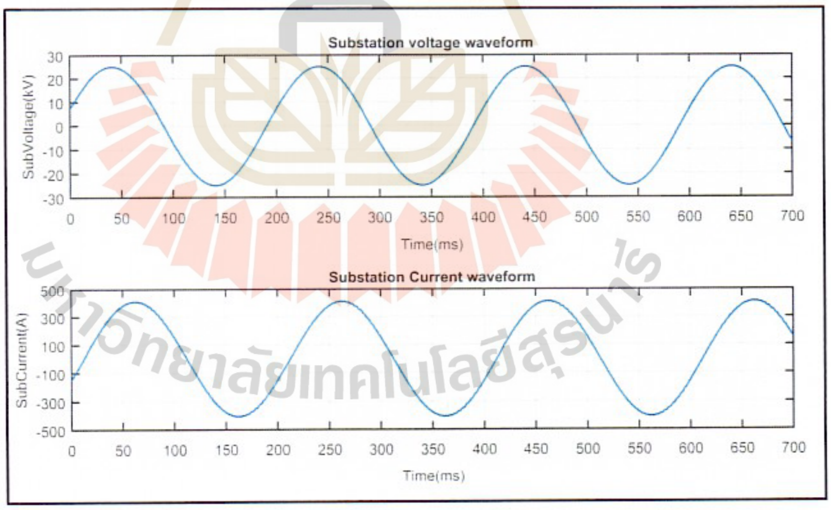


Figure A.38 Harmonic Distortion Voltage and Current at substation wave form: C-Type TF=5

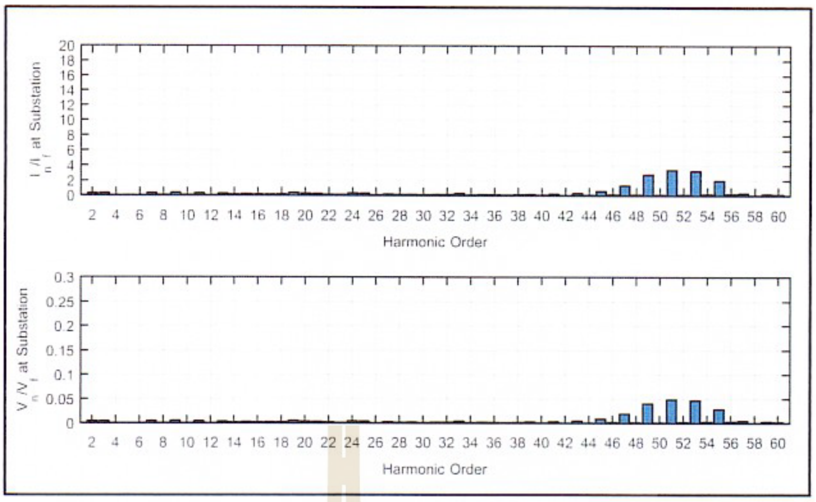


Figure A.39 Harmonics spectrum of Current and Voltage at the Substation: C-Type TF=5

Table A.25 THD Voltage results of installing C-Type filters TF=5 at the substation

Bus voltage V at PCC 25 kV	THD Substation (%) (Simulation)		THD Train (%) (Simulation)		THD (%) IEEE519-2014 Standard
	No Filter	C-Type	No Filter	C-Type	
Minimum	0.00	0.00	0.00	0.00	5.00
Average	2.07	0.004	0.70	0.70	5.00
Maximum	4.48	0.008	7.92	7.92	5.00

Table A.26 TDD current results of installing C-Type filters TF=5 at the substation

Maximum harmonic current distortion in percent of I_L												
Individual harmonic order (odd harmonics) at Substation												
I_{SC}/I_L (100 < 1000)	$3 \le h < 11$		$11 \le h < 17$		$17 \le h < 23$		$23 \le h < 35$		$35 \le h \le 50$		TDD	
	No Filter	C-Type	No Filter	C-Type	No Filter	C-Type	No Filter	C-Type	No Filter	C-Type	No Filter	C-Type
Minimum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Average	1.29	0.03	0.45	0.02	0.32	0.03	0.25	0.03	0.83	0.15	2.07	0.28
Maximum	2.80	0.06	0.97	0.05	0.70	0.05	0.53	0.06	1.79	0.32	4.48	0.61
IEEE514-2014	12.0		5.5		5.0		2.0		1.0		15.0	

- C-Type filters TF=51

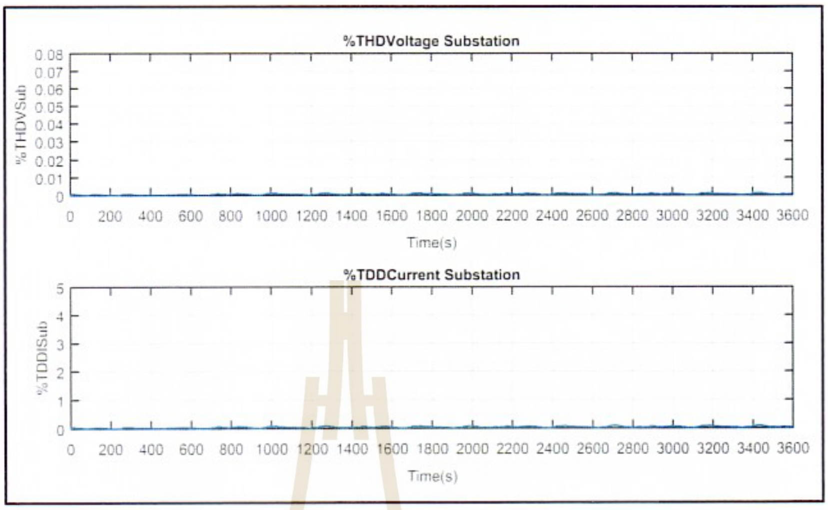


Figure A.40 Total Harmonic Distortion Voltage and Current at substation: C-Type TF=51

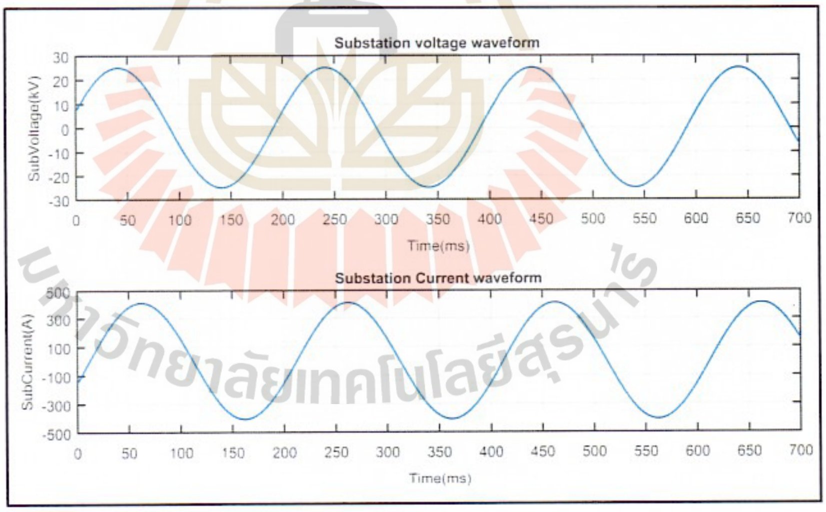


Figure A.41 Harmonic Distortion Voltage and Current at substation wave form: C-Type TF=51

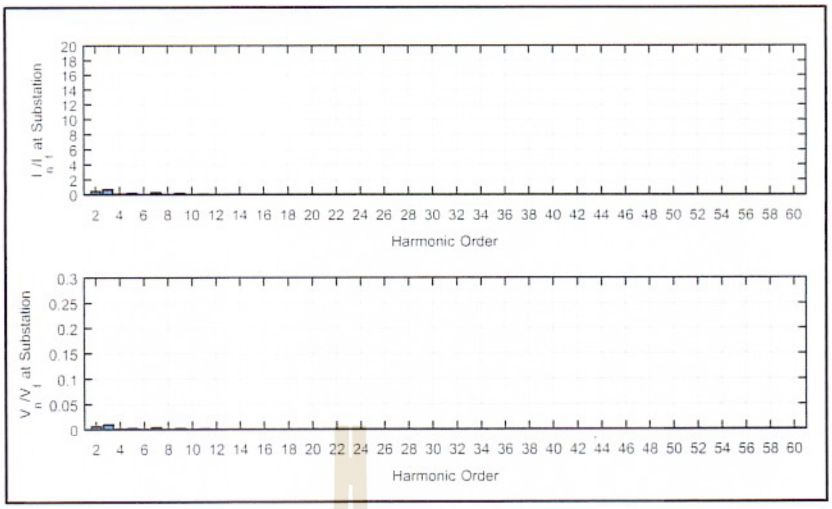


Figure A.42 Harmonics spectrum of Current and Voltage at the Substation: C-Type TF=51

Table A.27 THD Voltage results of installing C-Type filters TF=51 at the substation

Bus voltage V at PCC 25 kV	THD Substation (%) (Simulation)		THD Train (%) (Simulation)		THD (%) IEEE519-2014 Standard
	No Filter	C-Type	No Filter	C-Type	
Minimum	0.00	0.00	0.00	0.00	5.00
Average	0.03	5×10^{-4}	0.70	0.70	5.00
Maximum	0.07	1×10^{-3}	7.92	7.92	5.00

Table A.28 TDD current results of installing C-Type filters TF=51 at the substation

Maximum harmonic current distortion in percent of I_L												
Individual harmonic order (odd harmonics) at Substation												
I_{SC}/I_L (100 < 1000)	$3 \le h < 11$		$11 \le h < 17$		$17 \le h < 23$		$23 \le h < 35$		$35 \le h \le 50$		TDD	
	No Filter	C-Type	No Filter	C-Type	No Filter	C-Type	No Filter	C-Type	No Filter	C-Type	No Filter	C-Type
Minimum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Average	1.29	0.03	0.45	0.003	0.32	0.001	0.25	7×10^{4}	0.83	2×10^{4}	2.07	0.04
Maximum	2.80	0.07	0.97	0.008	0.70	0.003	0.53	1×10^{3}	1.79	5×10^{4}	4.48	0.09
IEEE514-2014	12.0		5.5		5.0		2.0		1.0		15.0	

- C-Type filters TF=53

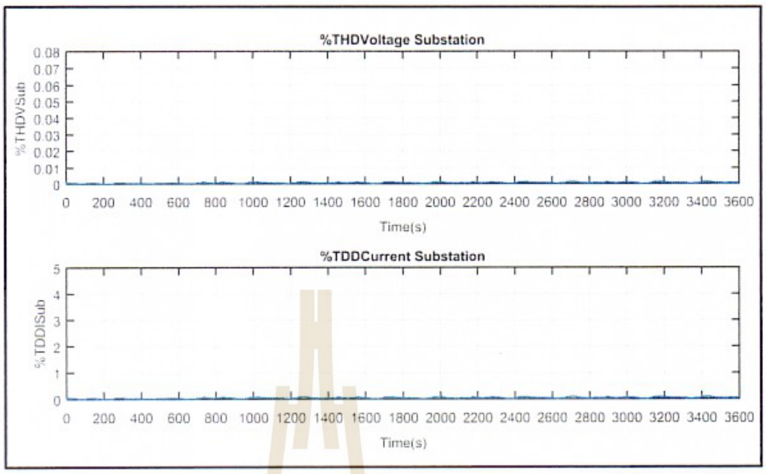


Figure A.43 Total Harmonic Distortion Voltage and Current at substation: C-Type TF=53

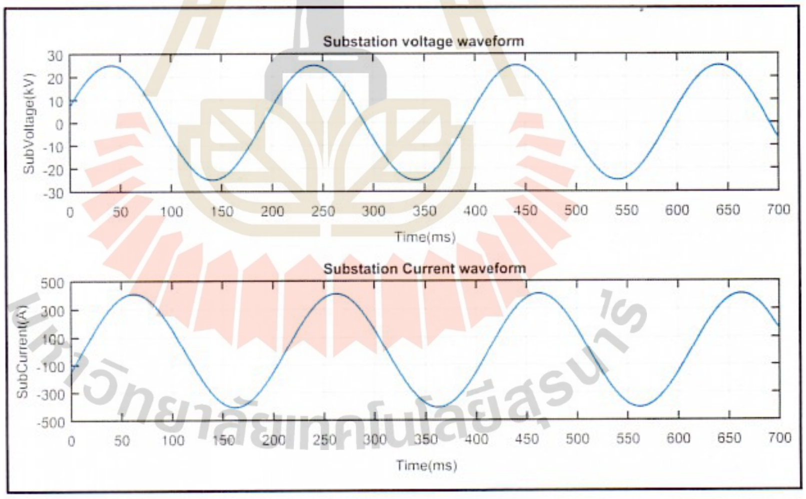


Figure A.44 Harmonic Distortion Voltage and Current at substation wave form: C-Type TF=53

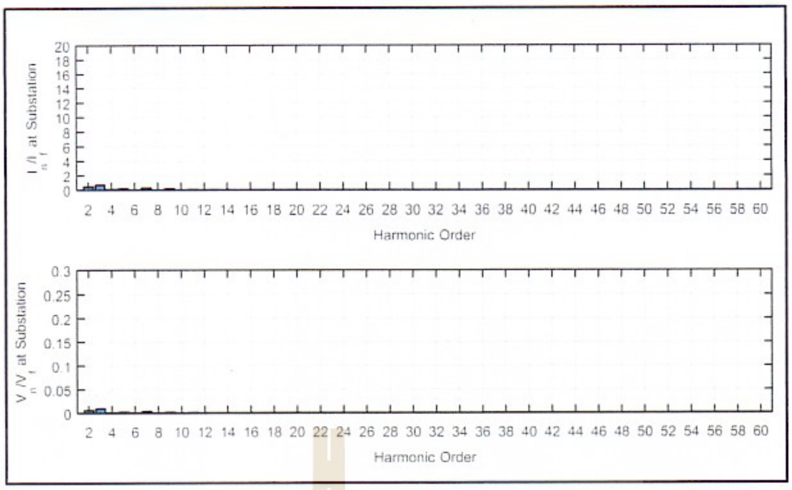


Figure A.45 Harmonics spectrum of Current and Voltage at the Substation: C-Type TF=53

Table A.29 THD Voltage results of installing C-Type filters TF=53 at the substation

Bus voltage V at PCC 25 kV	THD Substation (%) (Simulation)		THD Train (%) (Simulation)		THD (%) IEEE519-2014 Standard
	No Filter	C-Type	No Filter	C-Type	
Minimum	0.00	0.00	0.00	0.00	5.00
Average	2.07	$5x10^{-4}$	0.70	0.70	5.00
Maximum	4.48	$1x10^{-3}$	7.92	7.92	5.00

Table A.30 TDD current results of installing C-Type filters TF=53 at the substation

Maximum harmonic current distortion in percent of I_L												
Individual harmonic order (odd harmonics) at Substation												
I_{SC}/I_L (100 < 1000)	$3 \le h < 11$		$11 \le h < 17$		$17 \le h < 23$		$23 \le h < 35$		$35 \le h \le 50$		TDD	
	No Filter	C-Type	No Filter	C-Type	No Filter	C-Type	No Filter	C-Type	No Filter	C-Type	No Filter	C-Type
Minimum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Average	1.29	0.03	0.45	0.004	0.32	0.002	0.25	$8x10^{4}$	0.83	$3x10^{4}$	2.07	0.04
Maximum	2.80	0.07	0.97	0.008	0.70	0.004	0.53	$2x10^{3}$	1.79	$7x10^{4}$	4.48	0.09
IEEE514-2014	12.0		5.5		5.0		2.0		1.0		15.0	

A.2.2 Harmonic results of installing on-board passive filters.

- Single-Tuned filters TF=3

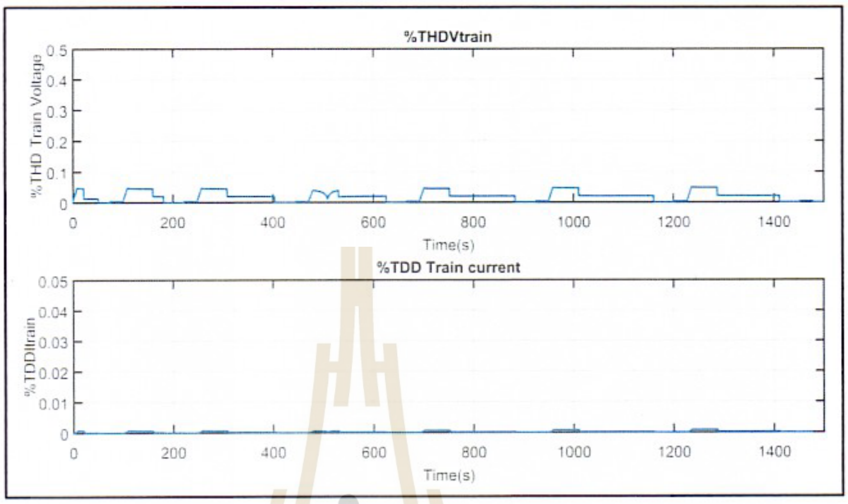


Figure A.46 Total Harmonic Distortion Voltage and Current at train: STF TF=3 on-board

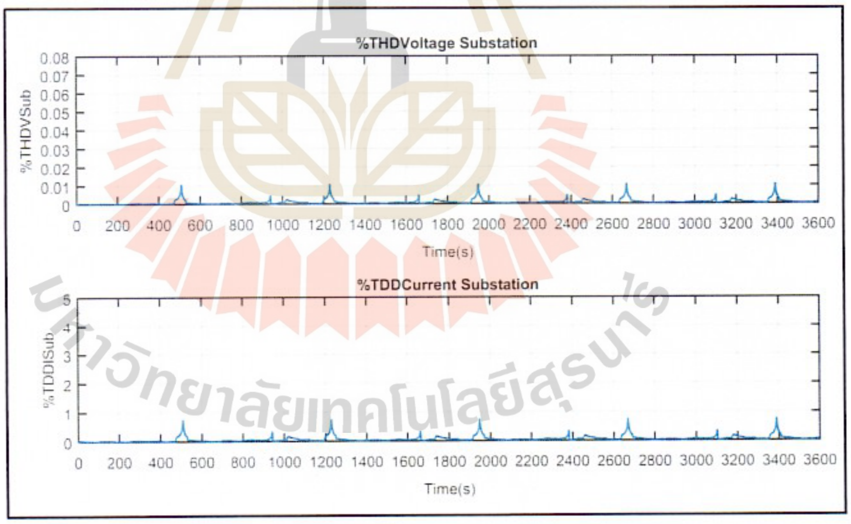


Figure A.47 Total Harmonic Distortion Voltage and Current at substation: STF TF=3 on-board

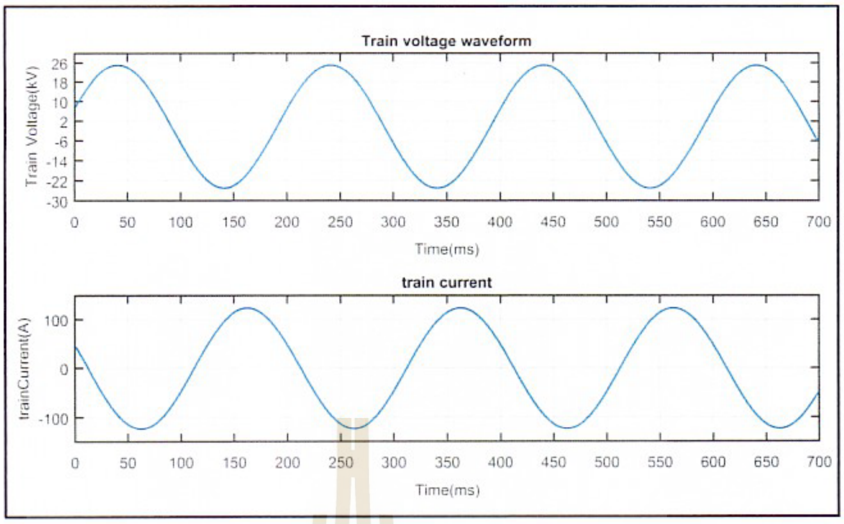


Figure A.48 Harmonic Distortion Voltage and Current at train wave: STF TF=3 on-board

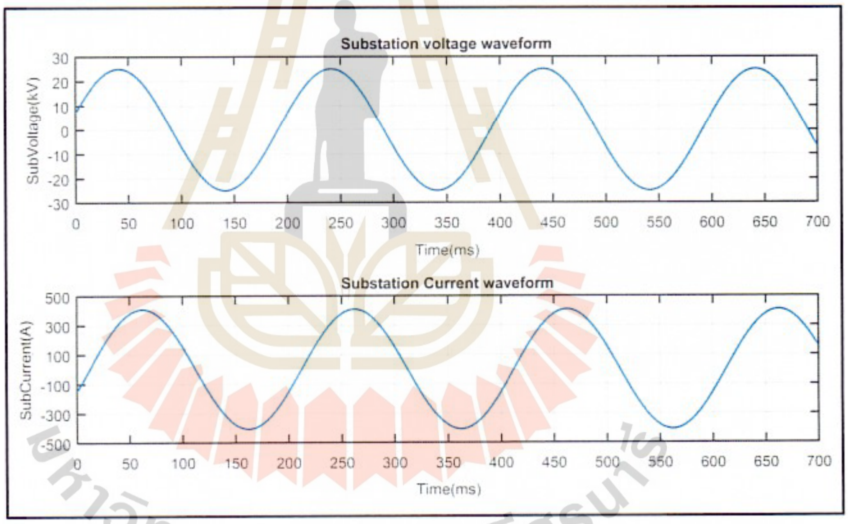


Figure A.49 Harmonic Distortion Voltage and Current at substation wave form: STF TF=3 on-board

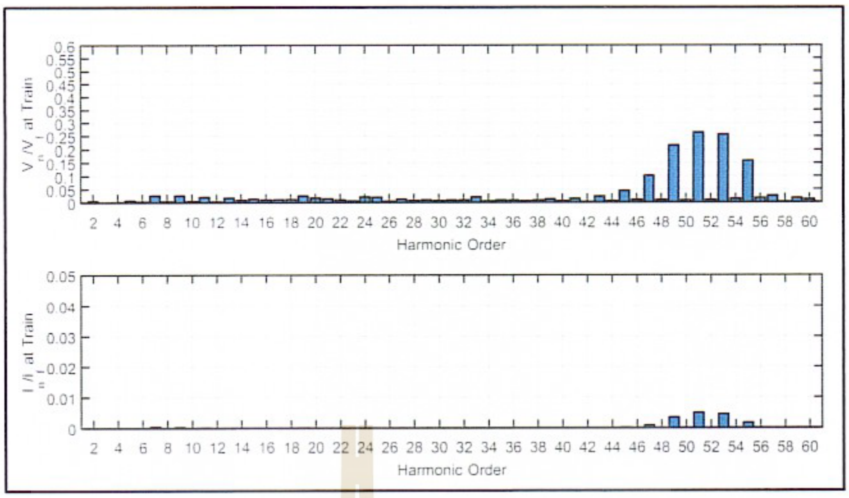


Figure A.50 Harmonics spectrum of Current and Voltage at the train: STF TF=3 on-board

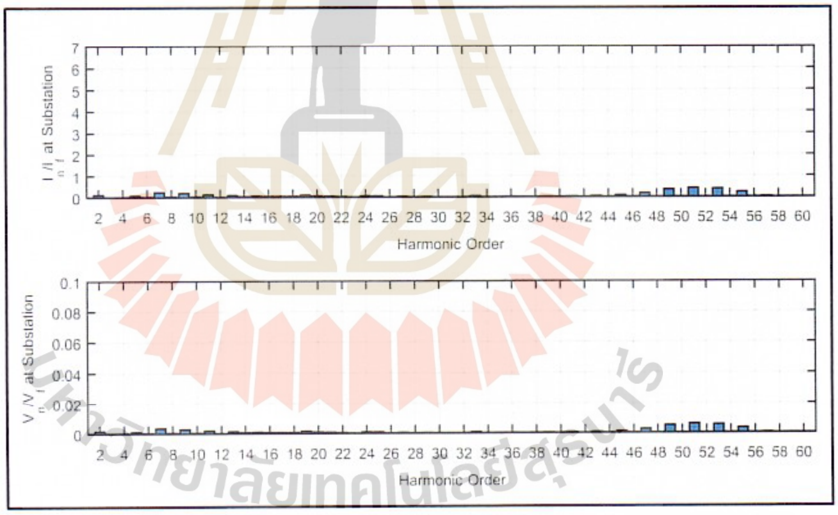


Figure A.51 Harmonics spectrum of Current and Voltage at the Substation: STF TF=3 on-board

Table A.31 THD Voltage results of installing Single-Tuned filters TF=3 on-board

Bus voltage V at PCC 25 kV	THD Substation (%) (Simulation)		THD Train (%) (Simulation)		THD (%) IEEE519-2014 Standard
	No Filter	STF	No Filter	STF	
Minimum	0.00	0.00	0.00	0.00	5.00
Average	0.03	0.00	0.70	0.01	5.00
Maximum	0.07	0.01	7.92	0.05	5.00

Table A.32 TDD current results of installing Single-Tuned filters TF=3 on-board

Maximum harmonic current distortion in percent of I_L												
Individual harmonic order (odd harmonics) at Substation												
I_{SC}/I_L (100 < 1000)	$3 \le h < 11$		$11 \le h < 17$		$17 \le h < 23$		$23 \le h < 35$		$35 \le h \le 50$		TDD	
	No Filter	STF	No Filter	STF	No Filter	STF	No Filter	STF	No Filter	STF	No Filter	STF
Minimum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Average	1.29	0.02	0.45	0.01	0.32	0.01	0.25	0.01	0.83	0.03	2.07	0.06
Maximum	2.80	0.19	0.97	0.12	0.70	0.10	0.53	0.09	1.79	0.38	4.48	0.75
IEEE514-2014	12.0		5.5		5.0		2.0		1.0		15.0	

- Single-Tuned filters TF=5

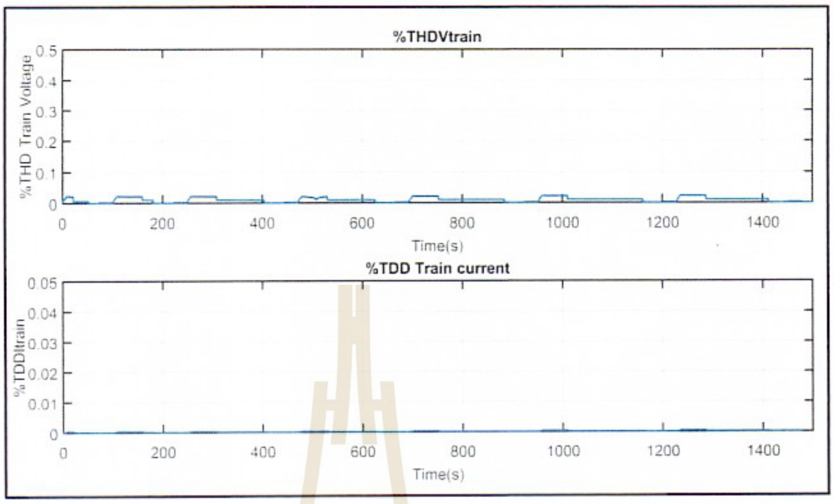


Figure A.52 Total Harmonic Distortion Voltage and Current at train: STF TF=5 on-board

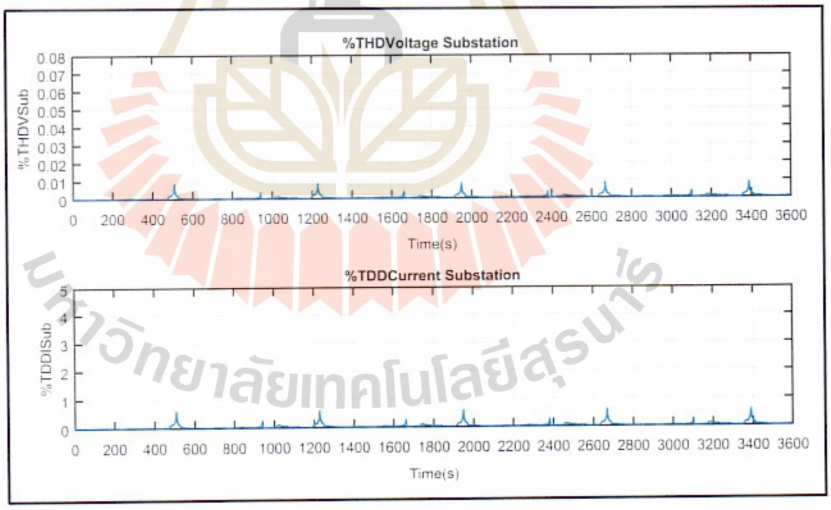


Figure A.53 Total Harmonic Distortion Voltage and Current at substation: STF TF=5 on-board

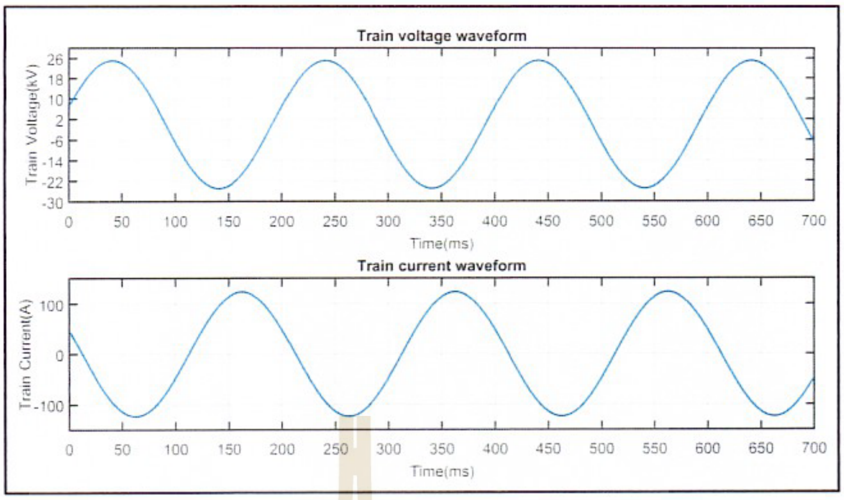


Figure A.54 Harmonic Distortion Voltage and Current at train wave: STF TF=5 on-board

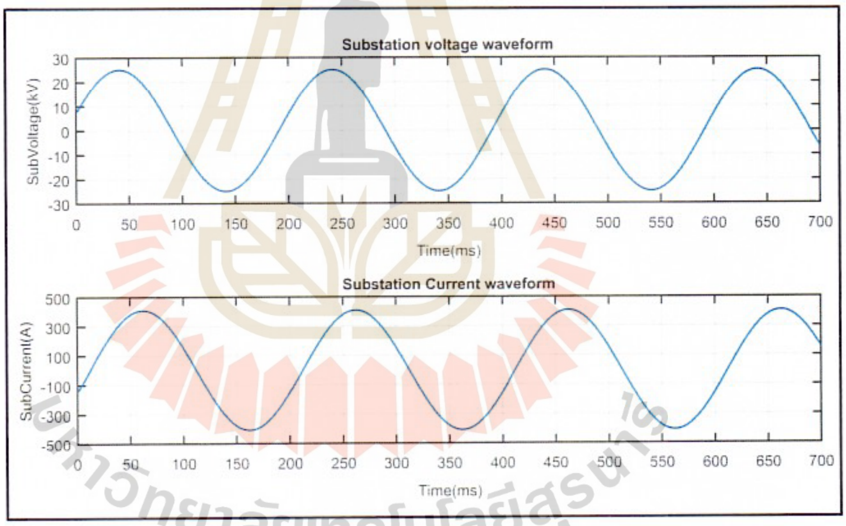


Figure A.55 Harmonic Distortion Voltage and Current at substation wave form: STF TF=5 on-board

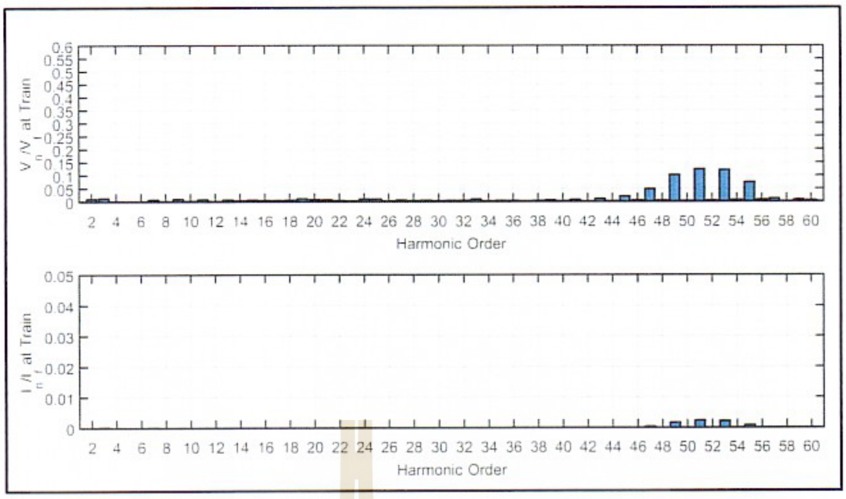


Figure A.56 Harmonics spectrum of Current and Voltage at the train: STF TF=5 on-board

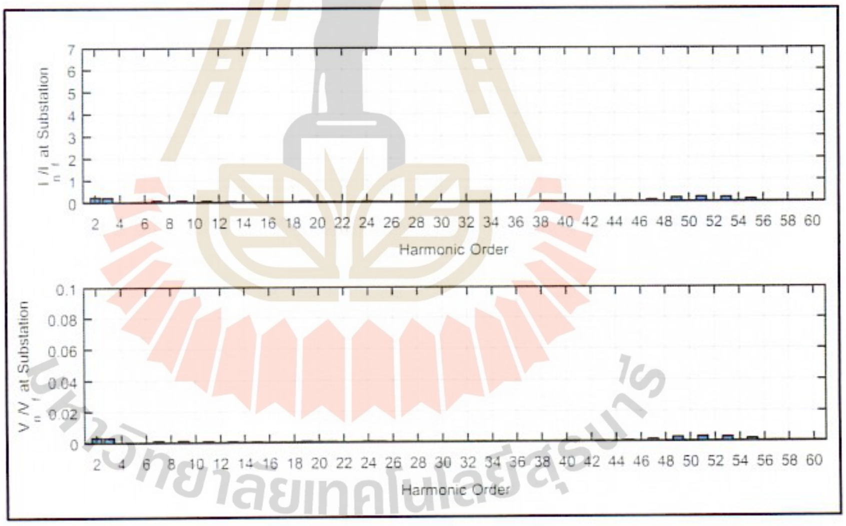


Figure A.57 Harmonics spectrum of Current and Voltage at the Substation: STF TF=5 on-board

Table A.33 THD Voltage results of installing Single-Tuned filters TF=5 on-board

Bus voltage V at PCC 25 kV	THD Substation (%) (Simulation)		THD Train (%) (Simulation)		THD (%) IEEE519-2014 Standard
	No Filter	STF	No Filter	STF	
Minimum	0.00	0.00	0.00	0.00	5.00
Average	0.03	0.00	0.70	0.003	5.00
Maximum	0.07	0.01	7.92	0.02	5.00

Table A.34 TDD current results of installing Single-Tuned filters TF=5 on-board

Maximum harmonic current distortion in percent of I_L												
Individual harmonic order (odd harmonics) at Substation												
I_{SC}/I_L *(100 < 1000)*	$3 \le h < 11$		$11 \le h < 17$		$17 \le h < 23$		$23 \le h < 35$		$35 \le h \le 50$		TDD	
	No Filter	STF	No Filter	STF	No Filter	STF	No Filter	STF	No Filter	STF	No Filter	STF
Minimum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Average	1.29	0.01	0.45	0.01	0.32	0.005	0.25	0.004	0.83	0.02	2.07	0.04
Maximum	2.80	0.13	0.97	0.07	0.70	0.07	0.53	0.07	1.79	0.30	4.48	0.59
IEEE514-2014	12.0		5.5		5.0		2.0		1.0		15.0	

- Single-Tuned filters TF=51

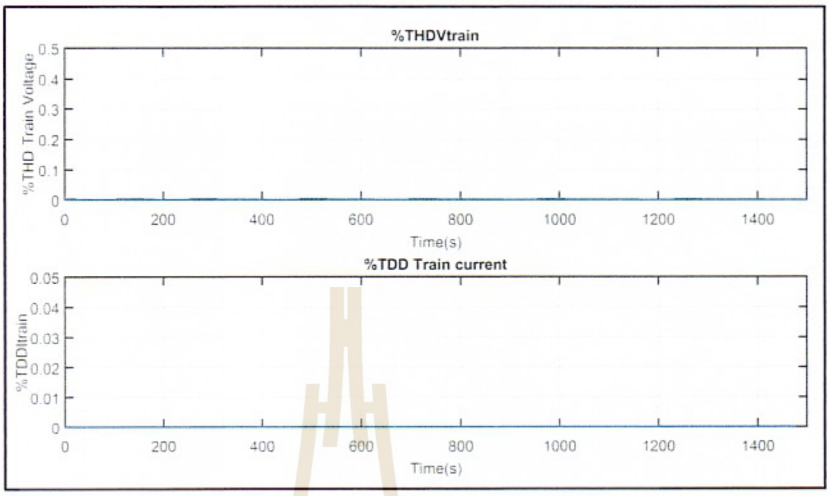


Figure A.58 Total Harmonic Distortion Voltage and Current at train: STF TF=51 on-board

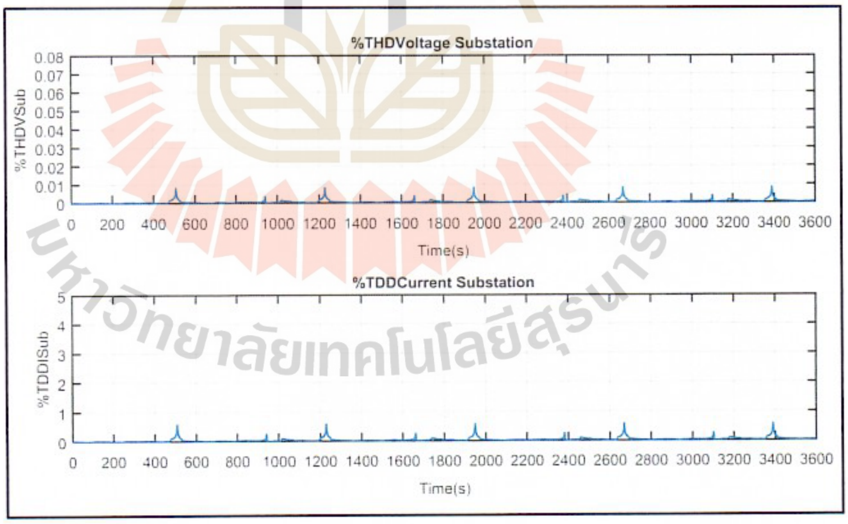


Figure A.59 Total Harmonic Distortion Voltage and Current at substation: STF TF=51 on-board

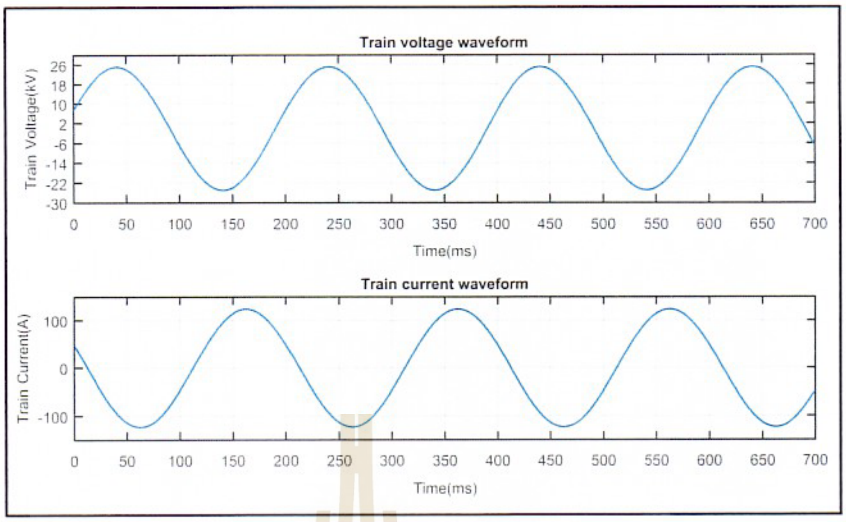


Figure A.60 Harmonic Distortion Voltage and Current at train wave: STF TF=51 on-board

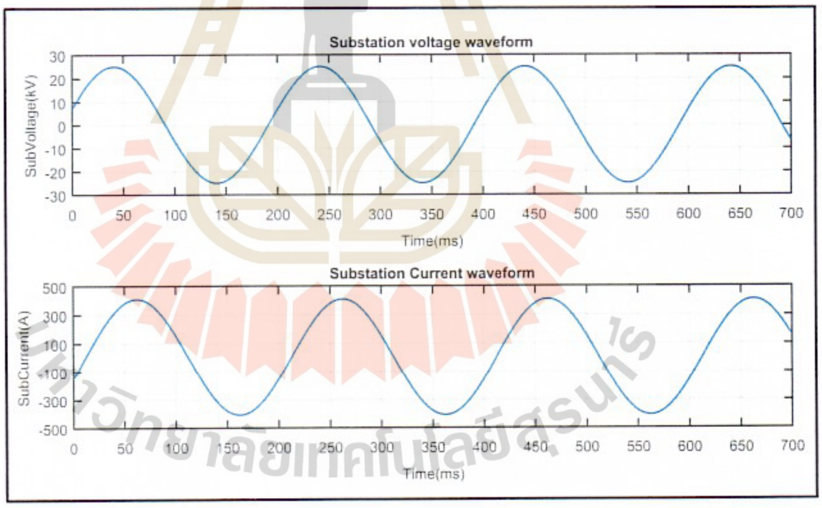


Figure A.61 Harmonic Distortion Voltage and Current at substation wave form: STF TF=51 on-board

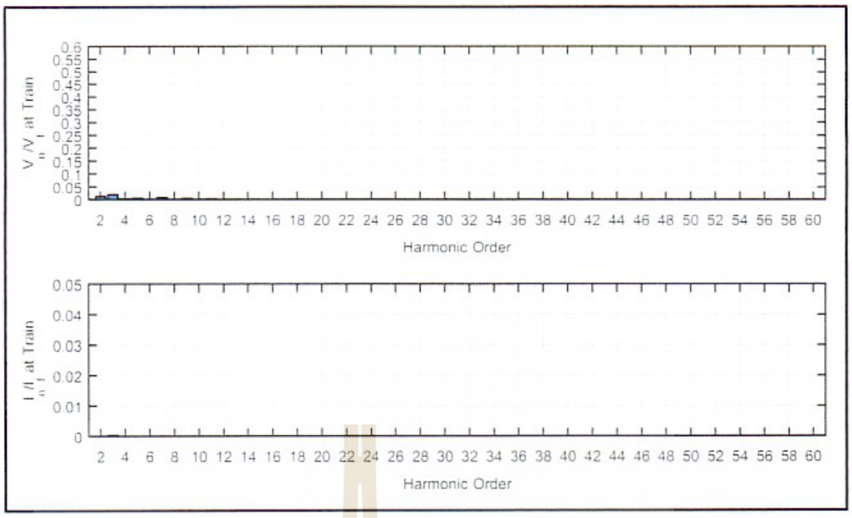


Figure A.62 Harmonics spectrum of Current and Voltage at the train: STF TF=51 on-board

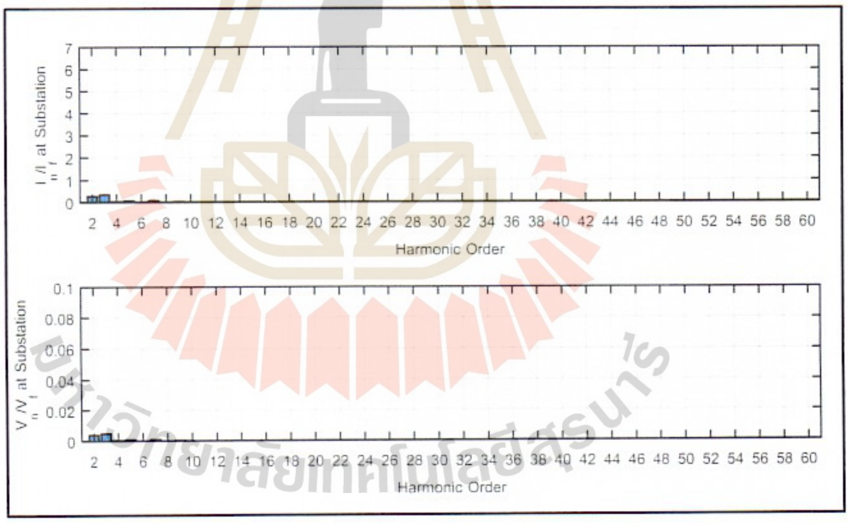


Figure A.63 Harmonics spectrum of Current and Voltage at the Substation: STF TF=51 on-board

Table A.35 THD Voltage results of installing Single-Tuned filters TF=51 on-board

Bus voltage V at PCC 25 kV	THD Substation (%) (Simulation)		THD Train (%) (Simulation)		THD (%) IEEE519-2014 Standard
	No Filter	STF	No Filter	STF	
Minimum	0.00	0.00	0.00	0.00	5.00
Average	0.03	$4x10^{-4}$	0.70	$4x10^{-4}$	5.00
Maximum	0.07	$3x10^{-3}$	7.92	$3x10^{-3}$	5.00

Table A.36 TDD current results of installing Single-Tuned filters TF=51 on-board

Maximum harmonic current distortion in percent of I_L												
Individual harmonic order (odd harmonics) at Substation												
I_{SC}/I_L *(100 < 1000)*	$3 \leq h < 11$		$11 \leq h < 17$		$17 \leq h < 23$		$23 \leq h < 35$		$35 \leq h \leq 50$		TDD	
	No Filter	STF	No Filter	STF	No Filter	STF	No Filter	STF	No Filter	STF	No Filter	STF
Minimum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Average	1.29	0.02	0.45	$1x10^3$	0.32	$3x10^4$	0.25	$1x10^4$	0.83	$3x10^5$	2.07	0.03
Maximum	2.80	0.19	0.97	0.02	0.70	$7x10^3$	0.53	$3x10^3$	1.79	$1x10^3$	4.48	0.24
IEEE514-2014	12.0		5.5		5.0		2.0		1.0		15.0	

- Single-Tuned filters TF=53

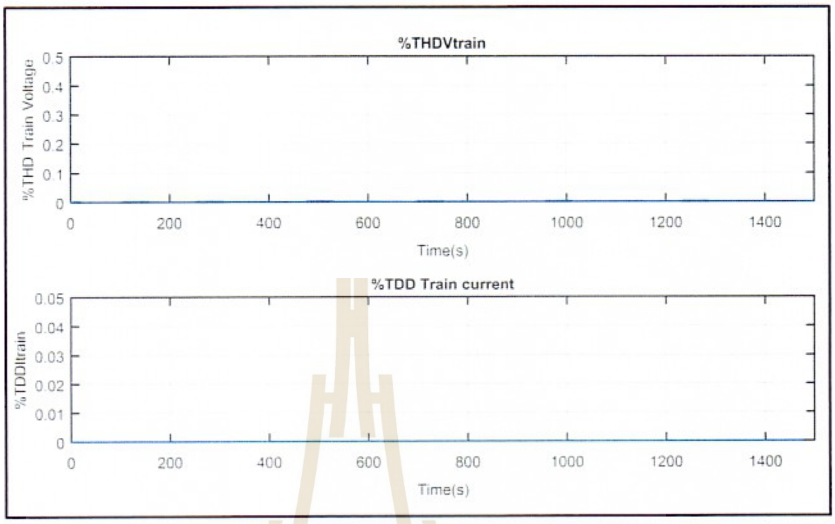


Figure A.64 Total Harmonic Distortion Voltage and Current at train: STF TF=53 on-board

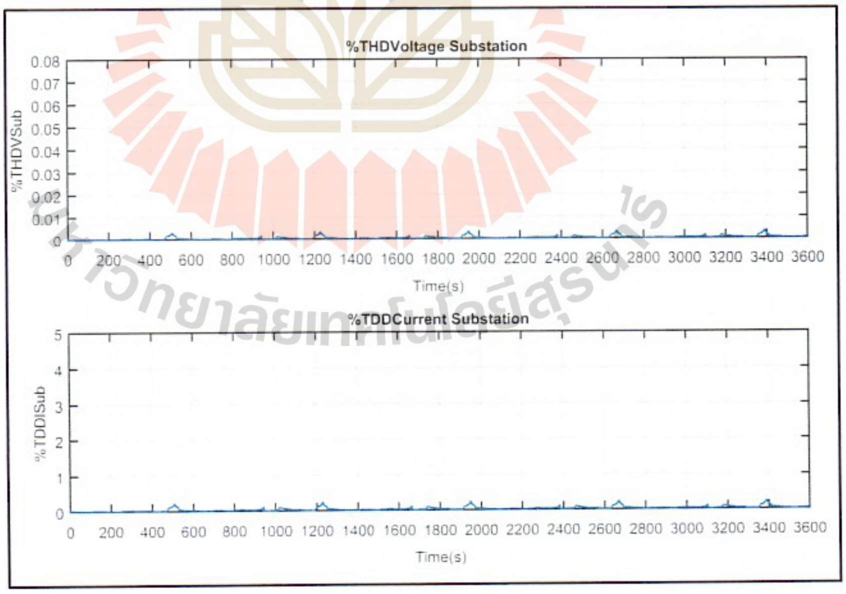


Figure A.65 Total Harmonic Distortion Voltage and Current at substation: STF TF=53 on-board

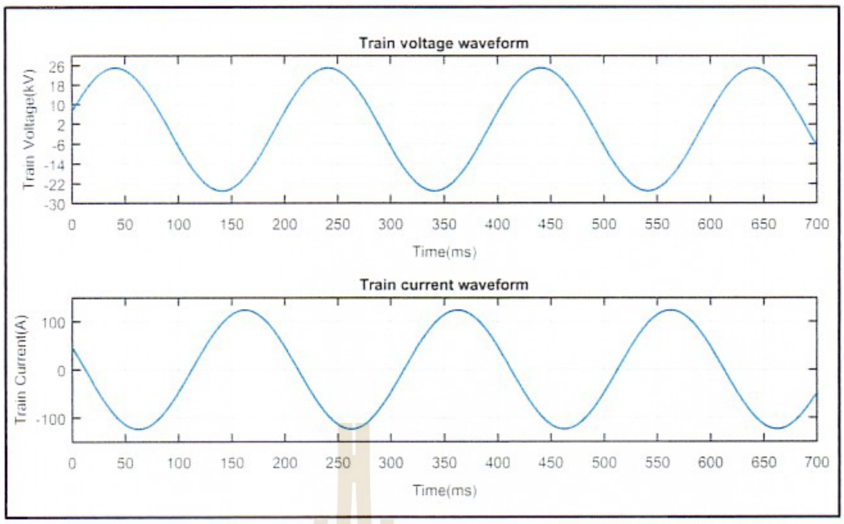


Figure A.66 Harmonic Distortion Voltage and Current at train wave: STF TF=53 on-board

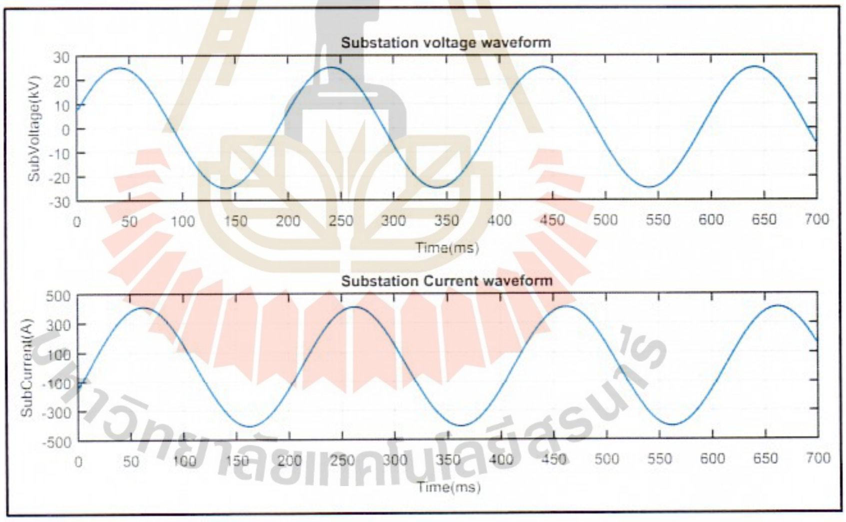


Figure A.67 Harmonic Distortion Voltage and Current at substation wave form: STF TF=53 on-board

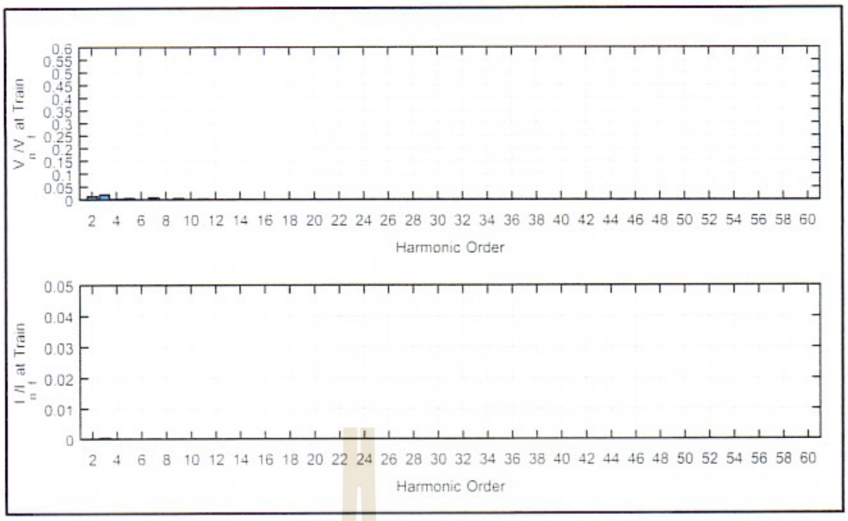


Figure A.68 Harmonics spectrum of Current and Voltage at the train: STF TF=53 on-board

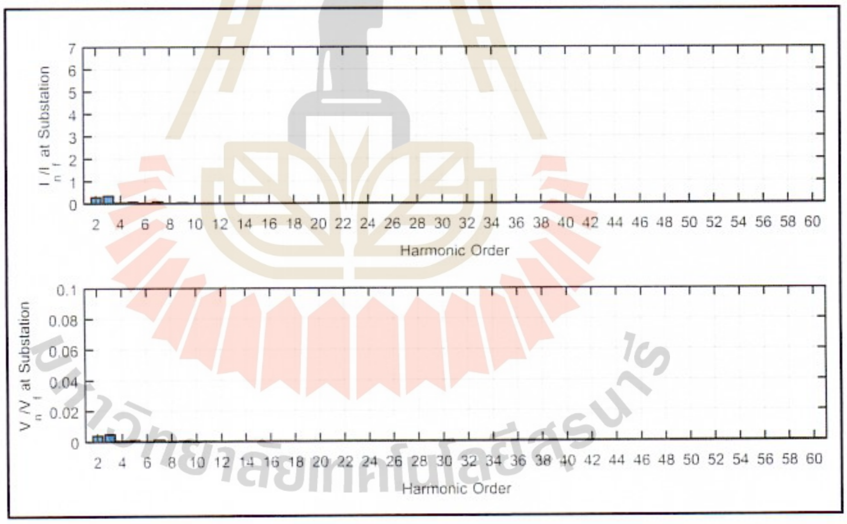


Figure A.69 Harmonics spectrum of Current and Voltage at the Substation: STF TF=53 on-board

Table A.37 THD Voltage results of installing Single-Tuned filters TF=51 on-board

Bus voltage V at PCC 25 kV	THD Substation (%) (Simulation)		THD Train (%) (Simulation)		THD (%) IEEE519-2014 Standard
	No Filter	STF	No Filter	STF	
Minimum	0.00	0.00	0.00	0.00	5.00
Average	2.07	4×10^{-4}	0.70	4×10^{-4}	5.00
Maximum	4.48	3×10^{-3}	7.92	3×10^{-3}	5.00

Table A.38 TDD current results of installing Single-Tuned filters TF=51 on-board

Maximum harmonic current distortion in percent of I_L												
Individual harmonic order (odd harmonics) at Substation												
I_{SC}/I_L (100 < 1000)	$3 \le h < 11$		$11 \le h < 17$		$17 \le h < 23$		$23 \le h < 35$		$35 \le h \le 50$		TDD	
	No Filter	STF	No Filter	STF	No Filter	STF	No Filter	STF	No Filter	STF	No Filter	STF
Minimum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Average	1.29	0.02	0.45	1×10^{3}	0.32	3×10^{4}	0.25	1×10^{4}	0.83	4×10^{5}	2.07	0.03
Maximum	2.80	0.19	0.97	0.02	0.70	7×10^{3}	0.53	3×10^{3}	1.79	1×10^{3}	4.48	0.24
IEEE514-2014	12.0		5.5		5.0		2.0		1.0		15.0	

- Band-Pass filters TF=3

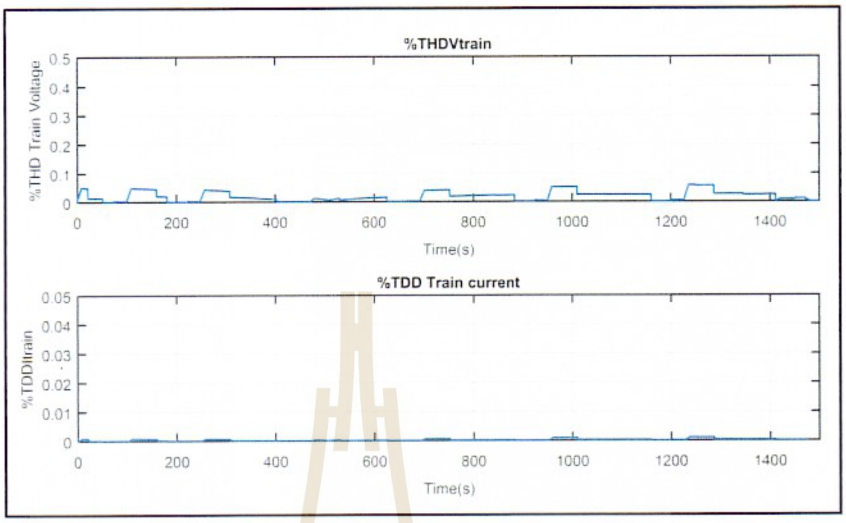


Figure A.70 Total Harmonic Distortion Voltage and Current at train: BP TF=3 on-board

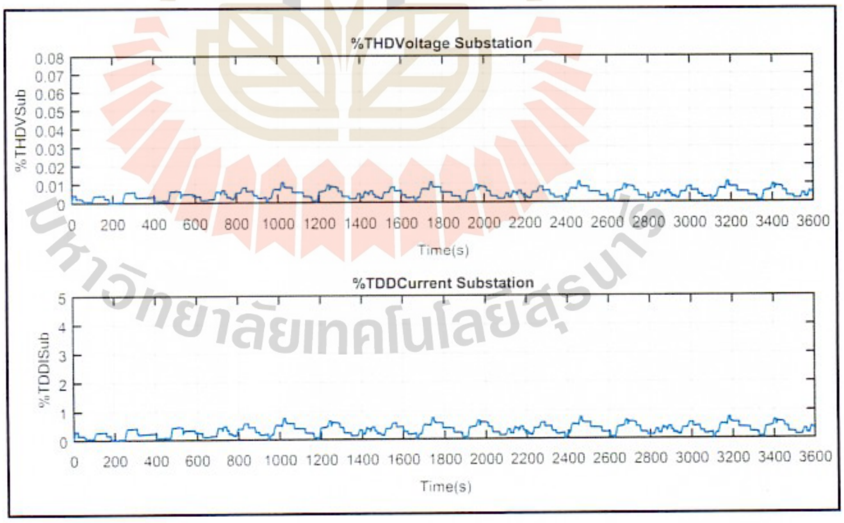


Figure A.71 Total Harmonic Distortion Voltage and Current at substation: BP TF=3 on-board

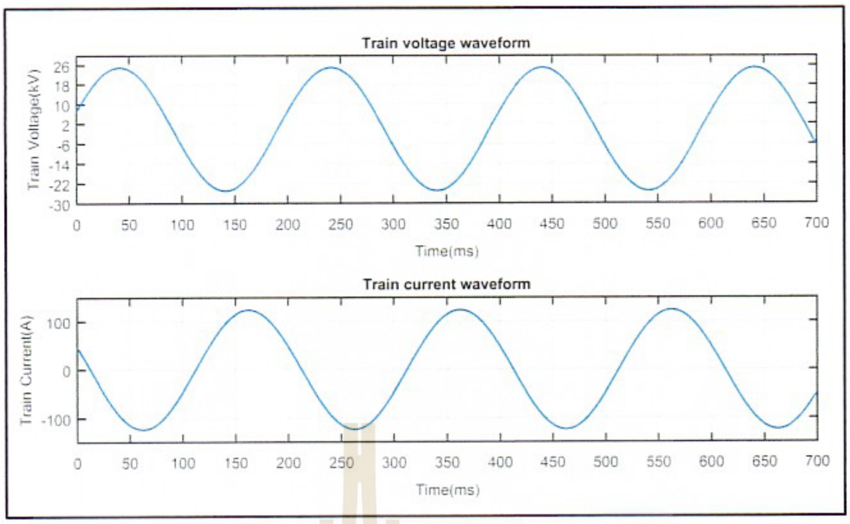


Figure A.72 Harmonic Distortion Voltage and Current at train wave: BP TF=3 on-board

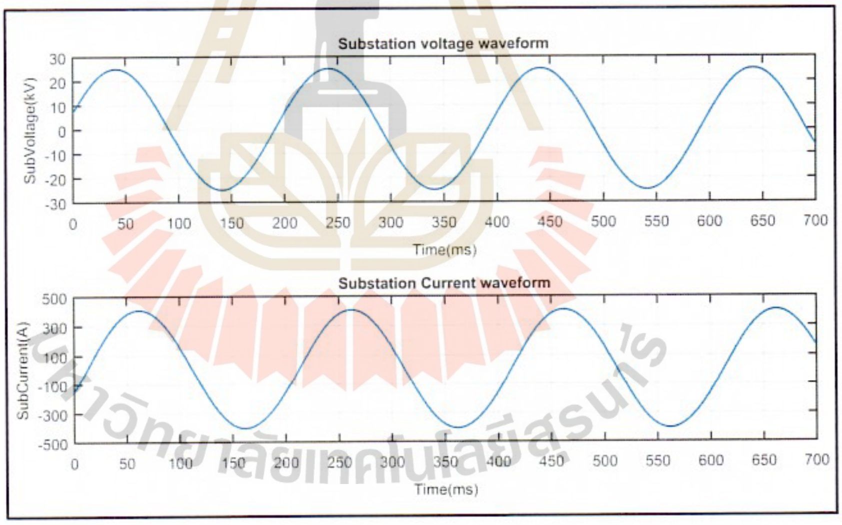


Figure A.73 Harmonic Distortion Voltage and Current at substation wave form: BP TF=3 on-board

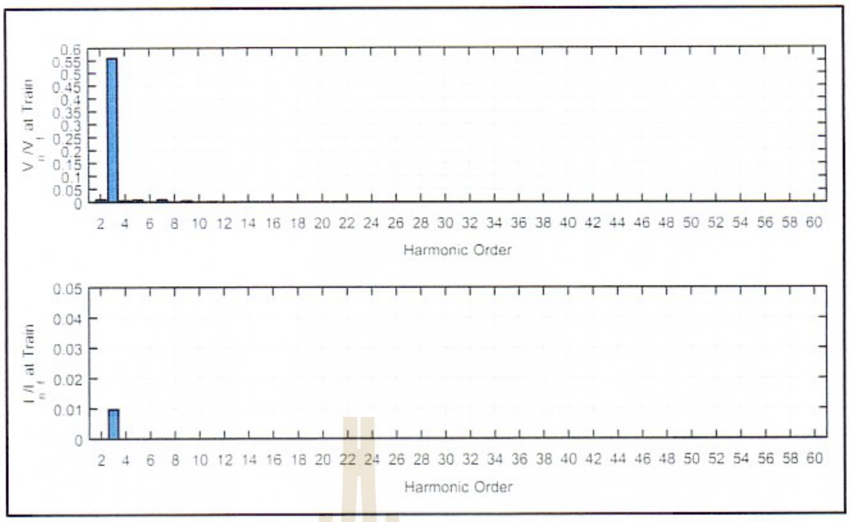


Figure A.74 Harmonics spectrum of Current and Voltage at the train: BP TF=3 on-board

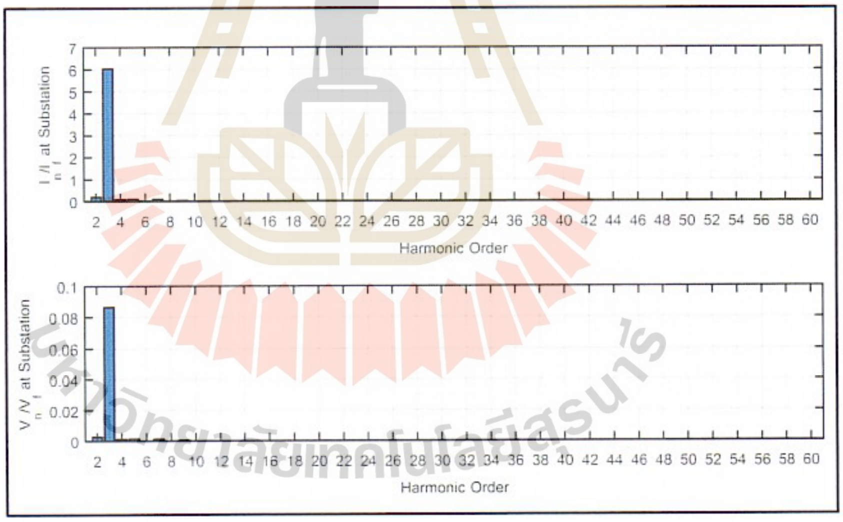


Figure A.75 Harmonics spectrum of Current and Voltage at the Substation: BP TF=3 on-board

Table A. 39 THD Voltage results of installing Band-Pass filters TF=3 on-board

Bus voltage *V* at PCC 25 kV	THD Substation (%) (Simulation)		THD Train (%) (Simulation)		THD (%) IEEE519-2014 Standard
	No Filter	BP	No Filter	BP	
Minimum	0.00	0.00	0.00	0.00	5.00
Average	2.07	$4x10^{-4}$	0.70	$8x10^{-3}$	5.00
Maximum	4.48	$1x10^{-2}$	7.92	0.06	5.00

Table A. 40 TDD current results of installing Band-Pass filters TF=3 on-board

Maximum harmonic current distortion in percent of I_L												
Individual harmonic order (odd harmonics) at Substation												
I_{SC}/I_L (100 < 1000)	$3 \le h < 11$		$11 \le h < 17$		$17 \le h < 23$		$23 \le h < 35$		$35 \le h \le 50$		TDD	
	No Filter	BP	No Filter	BP	No Filter	BP	No Filter	BP	No Filter	BP	No Filter	BP
Minimum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Average	1.29	0.31	0.45	$1x10^{3}$	0.32	$4x10^{4}$	0.25	$1x10^{4}$	0.83	$2x10^{4}$	2.07	0.31
Maximum	2.80	0.76	0.97	0.02	0.70	$8x10^{3}$	0.53	$4x10^{3}$	1.79	$8x10^{3}$	4.48	0.76
IEEE514-2014	12.0		5.5		5.0		2.0		1.0		15.0	

- Band-Pass filters TF=5

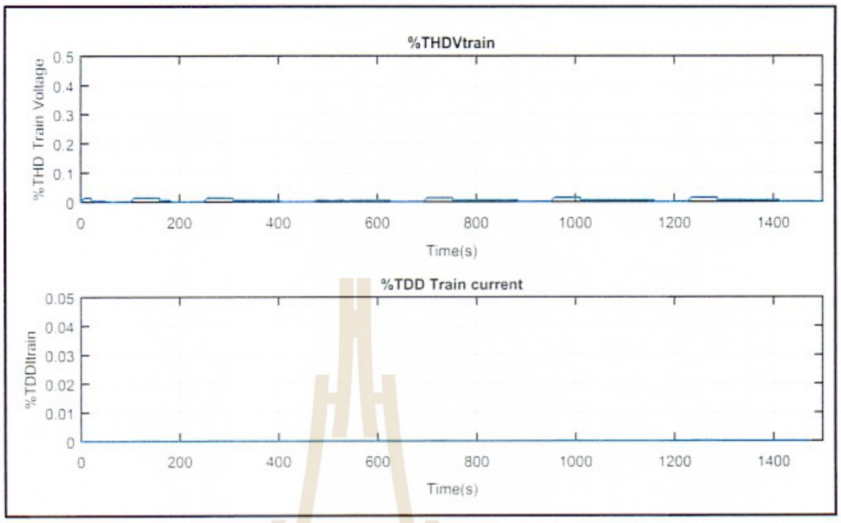


Figure A.76 Total Harmonic Distortion Voltage and Current at train: BP TF=5 on-board

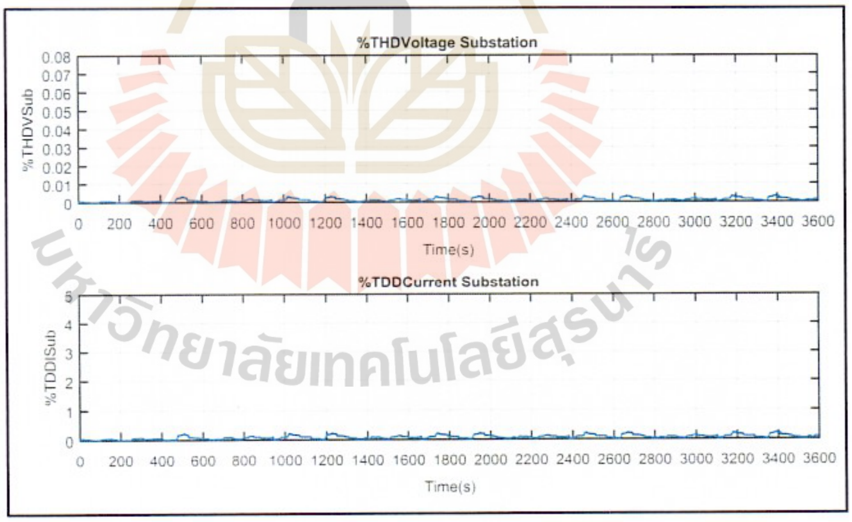


Figure A.77 Total Harmonic Distortion Voltage and Current at substation: BP TF=5 on-board

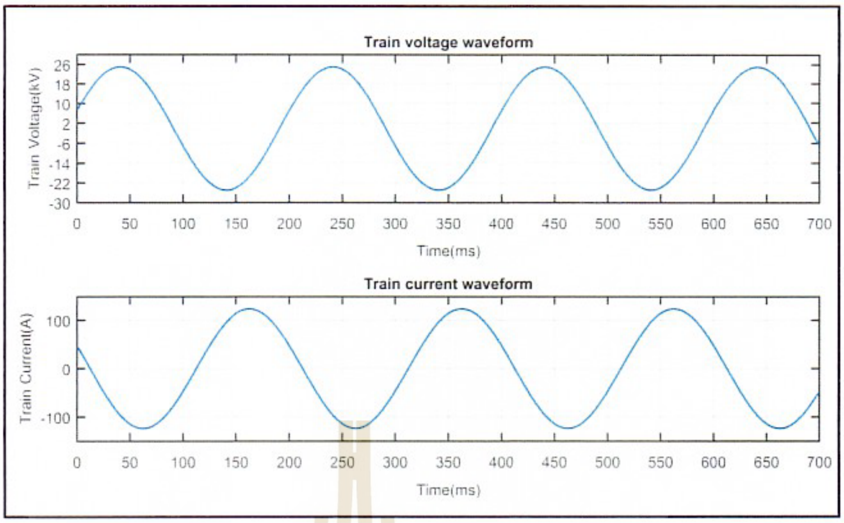


Figure A.78 Harmonic Distortion Voltage and Current at train wave: BP TF=5 on-board

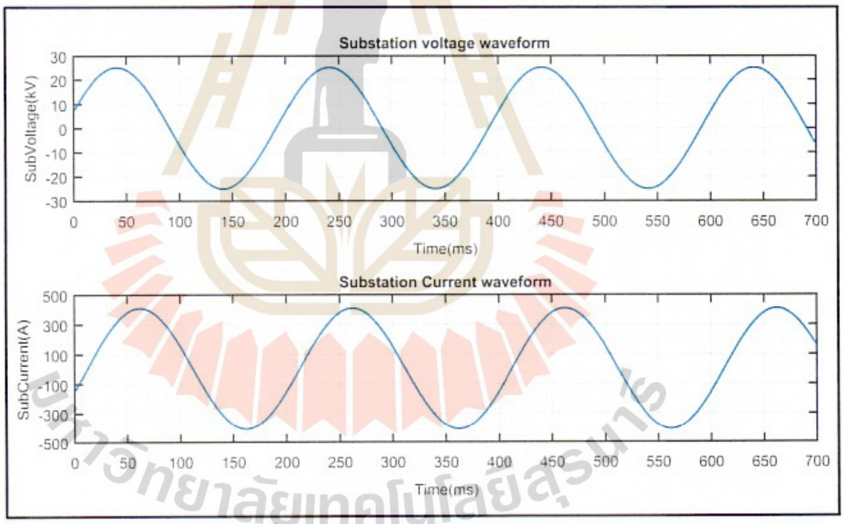


Figure A.79 Harmonic Distortion Voltage and Current at substation wave form: BP TF=5 on-board

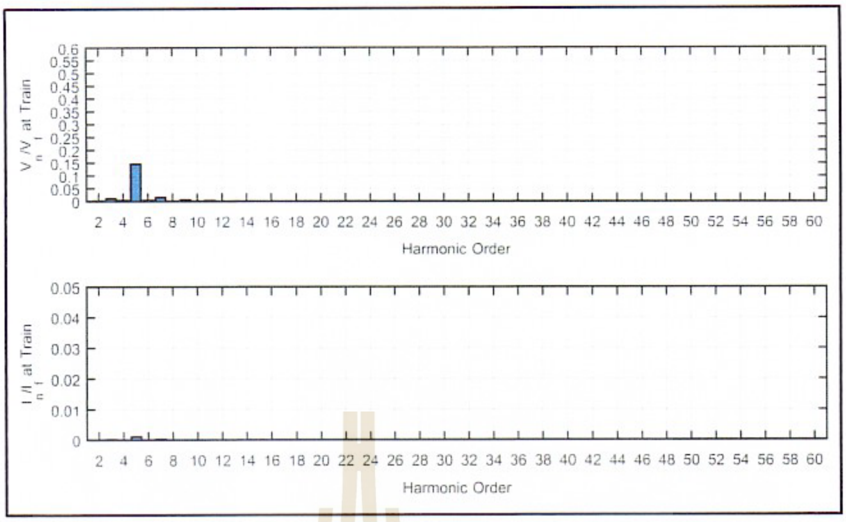


Figure A.80 Harmonics spectrum of Current and Voltage at the train: BP TF=5 on-board

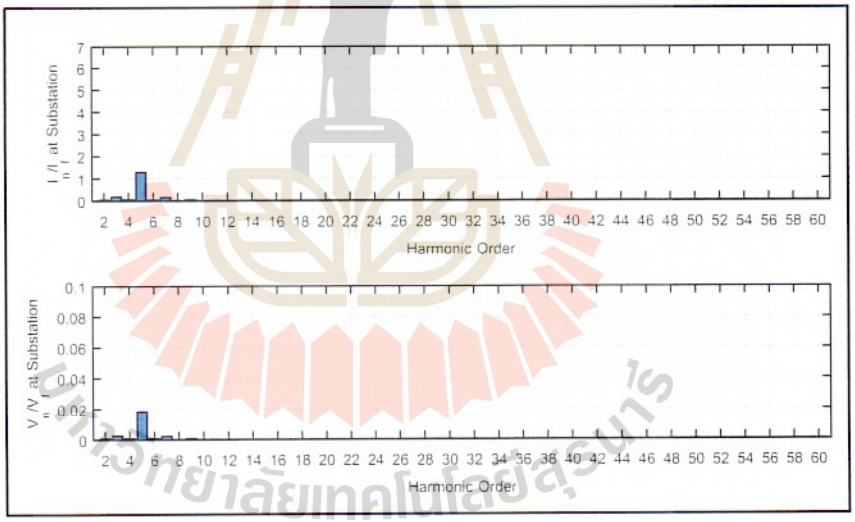


Figure A.81 Harmonics spectrum of Current and Voltage at the Substation: BP TF=5 on-board

Table A.41 THD Voltage results of installing Band-Pass filters TF=5 on-board

Bus voltage *V* at PCC 25 kV	THD Substation (%) (Simulation)		THD Train (%) (Simulation)		THD (%) IEEE519-2014 Standard
	No Filter	BP	No Filter	BP	
Minimum	0.00	0.00	0.00	0.00	5.00
Average	2.07	$1x10^{-3}$	0.70	$2x10^{-3}$	5.00
Maximum	4.48	$3x10^{-3}$	7.92	0.01	5.00

Table A.42 TDD current results of installing Band-Pass filters TF=5 on-board

Maximum harmonic current distortion in percent of I_L												
Individual harmonic order (odd harmonics) at Substation												
I_{SC}/I_L *(100 < 1000)*	$3 \le h < 11$		$11 \le h < 17$		$17 \le h < 23$		$23 \le h < 35$		$35 \le h \le 50$		TDD	
	No Filter	BP	No Filter	BP	No Filter	BP	No Filter	BP	No Filter	BP	No Filter	BP
Minimum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Average	1.29	0.08	0.45	$1x10^{3}$	0.32	$4x10^{4}$	0.25	$1x10^{4}$	0.83	$2x10^{4}$	2.07	0.08
Maximum	2.80	0.23	0.97	0.02	0.70	$8x10^{3}$	0.53	$4x10^{3}$	1.79	$8x10^{3}$	4.48	0.24
IEEE514-2014	12.0		5.5		5.0		2.0		1.0		15.0	

- Band-Pass filters TF=51

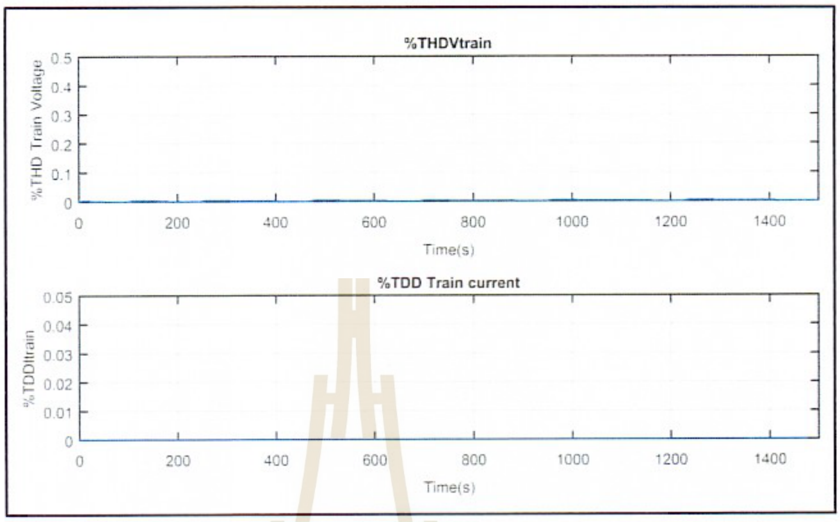


Figure A.82 Total Harmonic Distortion Voltage and Current at train: BP TF=51 on-board

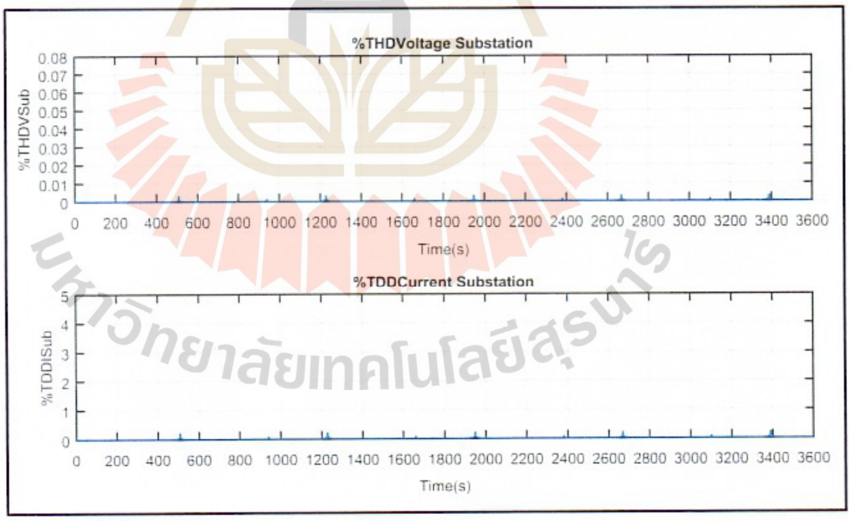


Figure A.83 Total Harmonic Distortion Voltage and Current at substation: BP TF=51 on-board

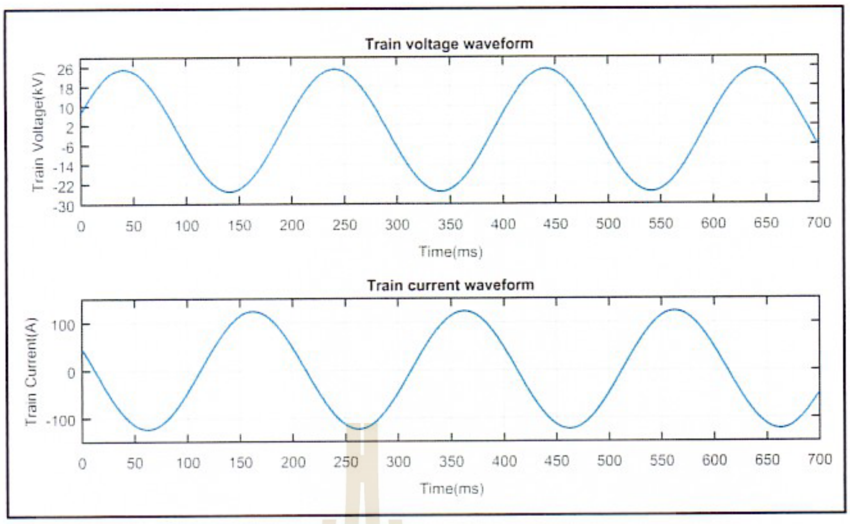


Figure A.84 Harmonic Distortion Voltage and Current at train wave: BP TF=51 on-board

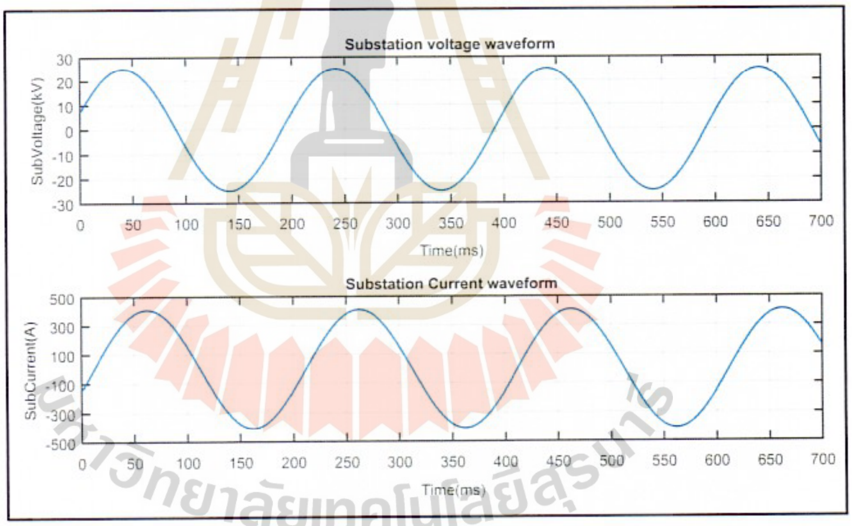


Figure A.85 Harmonic Distortion Voltage and Current at substation wave form: BP TF=51 on-board

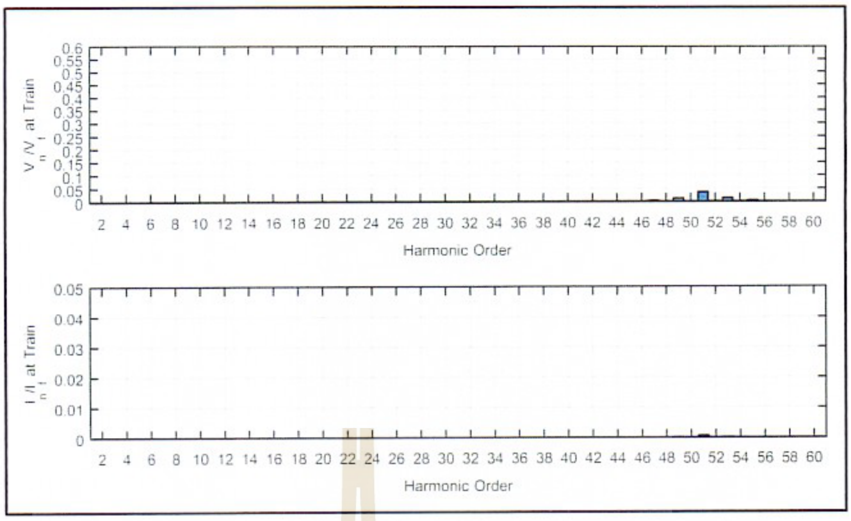


Figure A.86 Harmonics spectrum of Current and Voltage at the train: BP TF=51 on-board

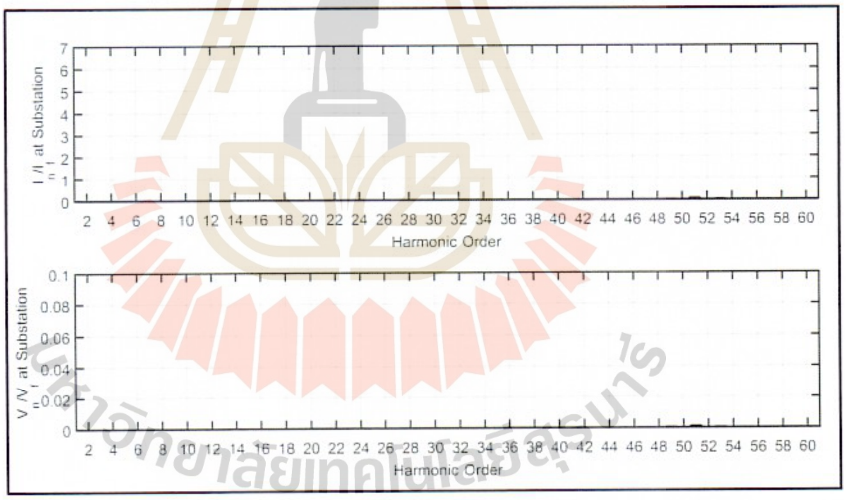


Figure A.87 Harmonics spectrum of Current and Voltage at the Substation: BP TF=51 on-board

Table A.43 THD Voltage results of installing Band-Pass filters TF=51 on-board

Bus voltage V at PCC 25 kV	THD Substation (%) (Simulation)		THD Train (%) (Simulation)		THD (%) IEEE519-2014 Standard
	No Filter	BP	No Filter	BP	
Minimum	0.00	0.00	0.00	0.00	5.00
Average	2.07	$8x10^{-5}$	0.70	$7x10^{-4}$	5.00
Maximum	4.48	$3x10^{-3}$	7.92	$4x10^{-3}$	5.00

Table A.44 TDD current results of installing Band-Pass filters TF=51 on-board

Maximum harmonic current distortion in percent of I_L												
Individual harmonic order (odd harmonics) at Substation												
I_{SC}/I_L (100 < 1000)	$3 \leq h < 11$		$11 \leq h < 17$		$17 \leq h < 23$		$23 \leq h < 35$		$35 \leq h \leq 50$		TDD	
	No Filter	BP	No Filter	BP	No Filter	BP	No Filter	BP	No Filter	BP	No Filter	BP
Minimum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Average	1.29	$1x10^{4}$	0.45	$7x10^{5}$	0.32	$6x10^{5}$	0.25	$6x10^{5}$	0.83	$1x10^{3}$	2.07	0.08
Maximum	2.80	$1x10^{3}$	0.97	$1x10^{3}$	0.70	$1x10^{3}$	0.53	$1x10^{3}$	1.79	$6x10^{2}$	4.48	0.24
IEEE514-2014	12.0		5.5		5.0		2.0		1.0		15.0	

- Band-Pass filters TF=53

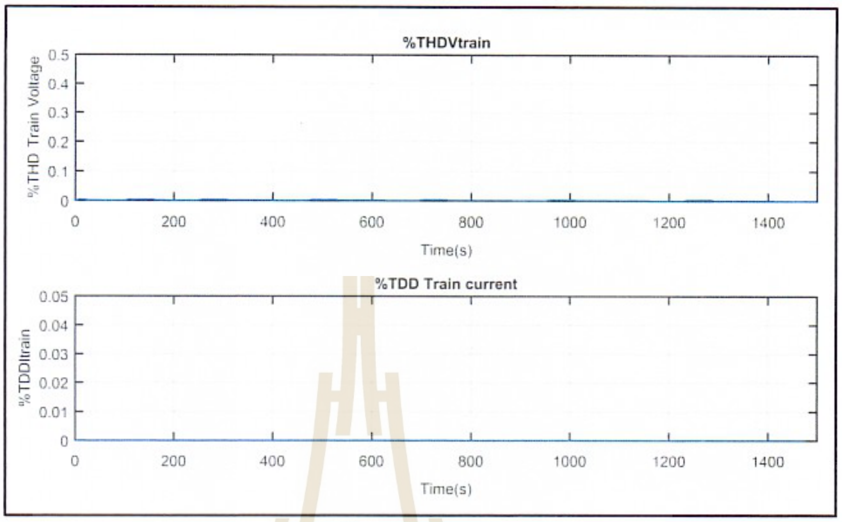


Figure A.88 Total Harmonic Distortion Voltage and Current at train: BP TF=53 on-board

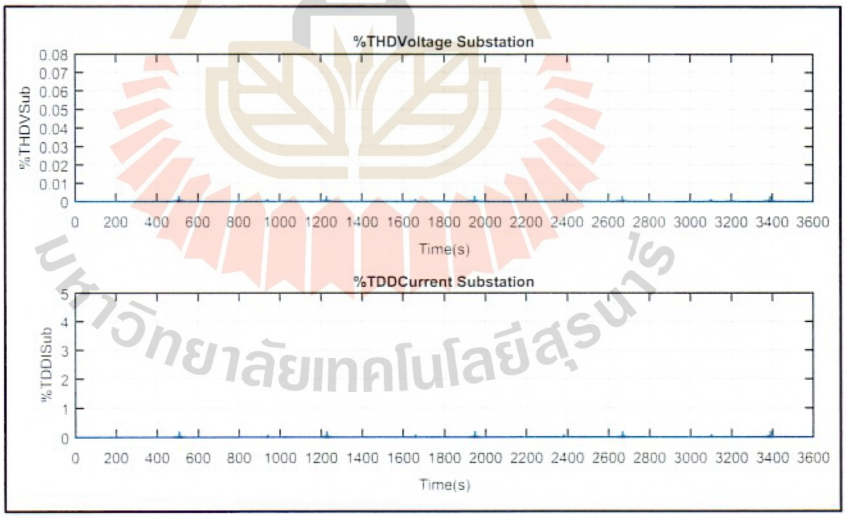


Figure A.89 Total Harmonic Distortion Voltage and Current at substation: BP TF=53 on-board

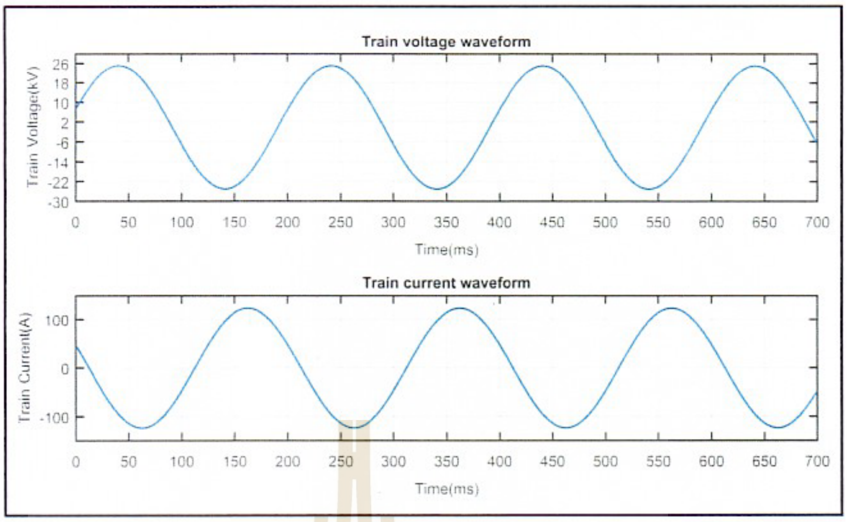


Figure A.90 Harmonic Distortion Voltage and Current at train wave: BP TF=53 on-board

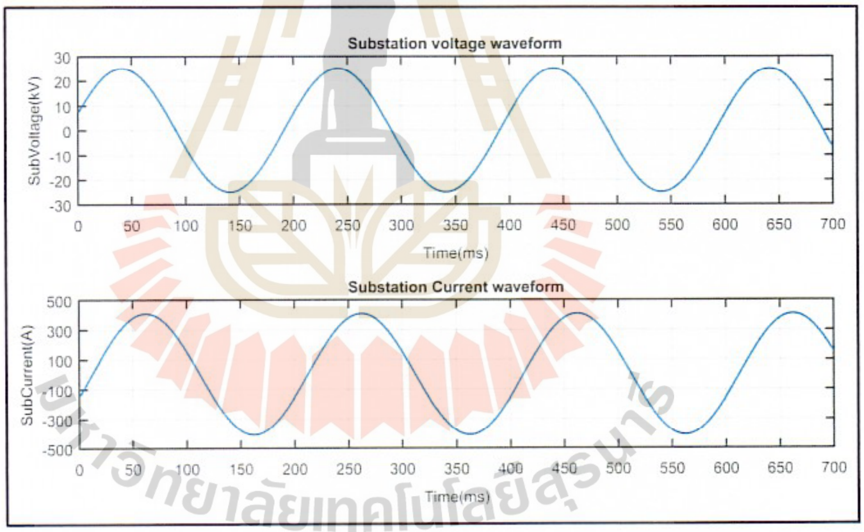


Figure A.91 Harmonic Distortion Voltage and Current at substation wave form: BP TF=53 on-board

Figure A.92 Harmonics spectrum of Current and Voltage at the train: BP TF=53 on-board

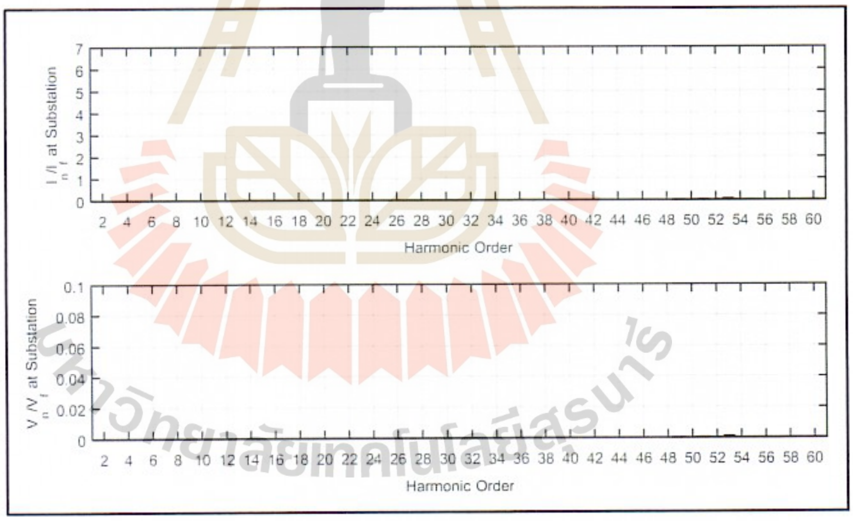


Figure A.93 Harmonics spectrum of Current and Voltage at the Substation: BP TF=53 on-board

Table A.45 THD Voltage results of installing Band-Pass filters TF=53 on-board

Bus voltage V at PCC 25 kV	THD Substation (%) (Simulation)		THD Train (%) (Simulation)		THD (%) IEEE519-2014 Standard
	No Filter	BP	No Filter	BP	
Minimum	0.00	0.00	0.00	0.00	5.00
Average	2.07	$8x10^{-5}$	0.70	$6x10^{-4}$	5.00
Maximum	4.48	$3x10^{-3}$	7.92	$3x10^{-3}$	5.00

Table A.46 TDD current results of installing Band-Pass filters TF=53 on-board

Maximum harmonic current distortion in percent of I_L												
Individual harmonic order (odd harmonics) at <u>Substation</u>												
I_{SC}/I_L *(100 < 1000)*	$3 \leq h < 11$		$11 \leq h < 17$		$17 \leq h < 23$		$23 \leq h < 35$		$35 \leq h \leq 50$		TDD	
	No Filter	BP	No Filter	BP	No Filter	BP	No Filter	BP	No Filter	BP	No Filter	BP
Minimum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Average	1.29	$1x10^4$	0.45	$7x10^5$	0.32	$6x10^5$	0.25	$6x10^5$	0.83	$1x10^3$	2.07	$1x10^3$
Maximum	2.80	$1x10^3$	0.97	$1x10^3$	0.70	$1x10^3$	0.53	$1x10^3$	1.79	$4x10^2$	4.48	0.19
IEEE514-2014	12.0		5.5		5.0		2.0		1.0		15.0	

- High-Pass filters TF= 3

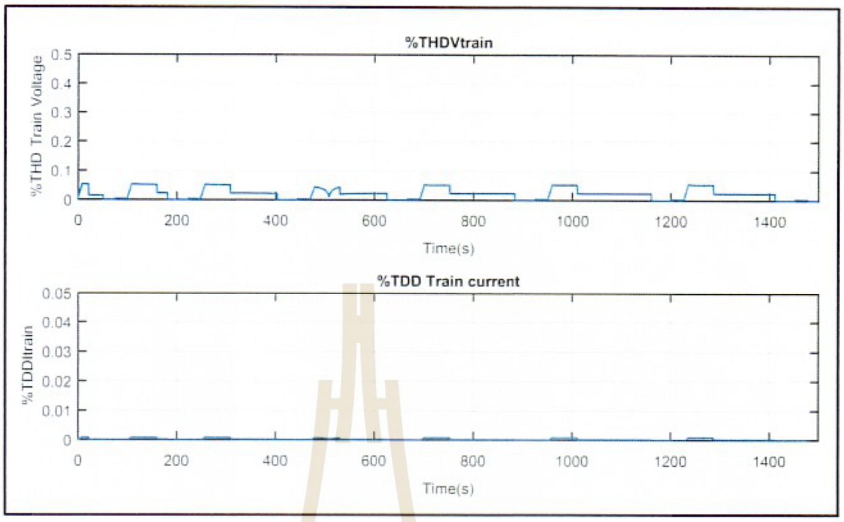


Figure A.94 Total Harmonic Distortion Voltage and Current at train: HP TF=3 on-board

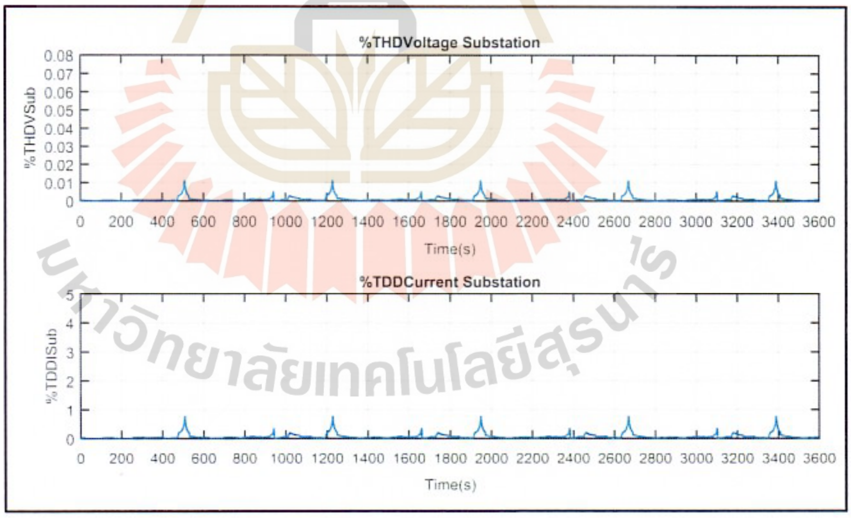


Figure A.95 Total Harmonic Distortion Voltage and Current at substation: HP TF=3 on-board

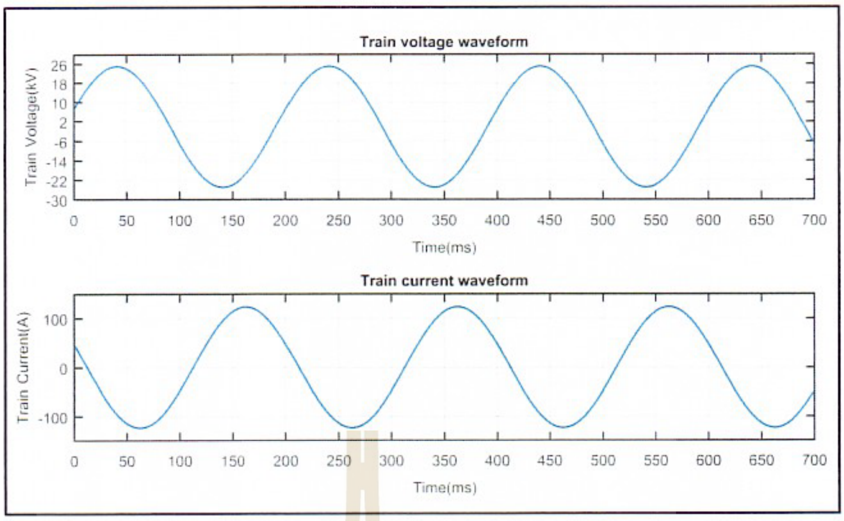


Figure A.96 Harmonic Distortion Voltage and Current at train wave: HP TF=3 on-board

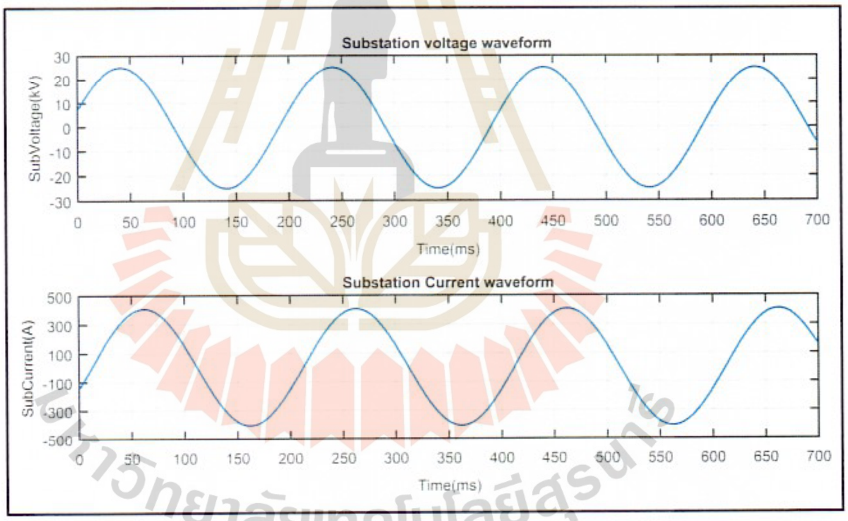


Figure A.97 Harmonic Distortion Voltage and Current at substation wave form: HP TF=3 on-board

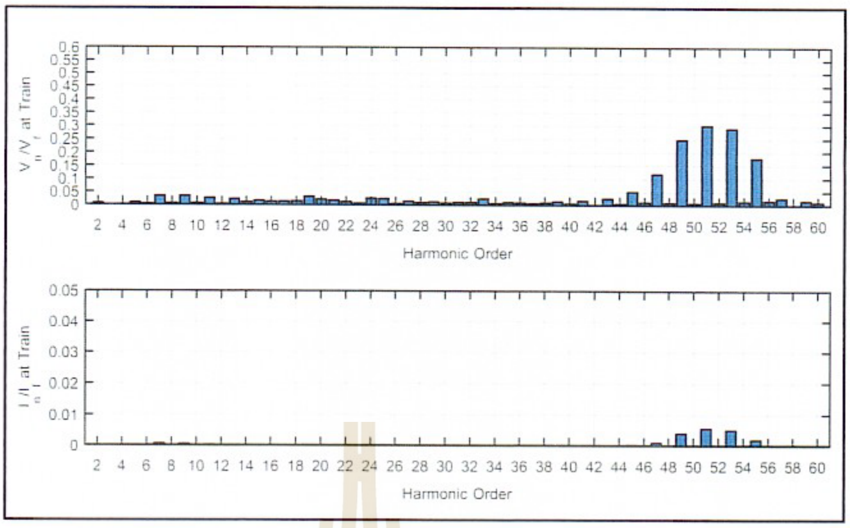


Figure A.98 Harmonics spectrum of Current and Voltage at the train: HP TF=3 on-board

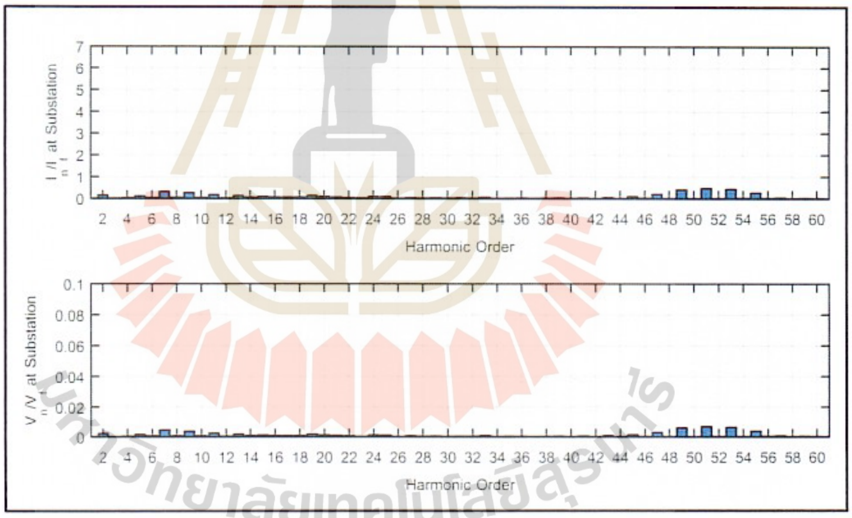


Figure A.99 Harmonics spectrum of Current and Voltage at the Substation: HP TF=3 on-board

Table A. 47 THD Voltage results of installing High-Pass filters TF=3 on-board

Bus voltage V at PCC 25 kV	THD Substation (%) (Simulation)		THD Train (%) (Simulation)		THD (%) IEEE519-2014 Standard
	No Filter	HP	No Filter	HP	
Minimum	0.00	0.00	0.00	0.00	5.00
Average	2.07	9×10^{-4}	0.70	9×10^{-3}	5.00
Maximum	4.48	0.01	7.92	0.06	5.00

Table A. 48 TDD current results of installing High-Pass filters TF=3 on-board

Maximum harmonic current distortion in percent of I_L												
Individual harmonic order (odd harmonics) at Substation												
I_{SC}/I_L (100 < 1000)	$3 \le h < 11$		$11 \le h < 17$		$17 \le h < 23$		$23 \le h < 35$		$35 \le h \le 50$		TDD	
	No Filter	HP	No Filter	HP	No Filter	HP	No Filter	HP	No Filter	HP	No Filter	HP
Minimum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Average	1.29	0.03	0.45	0.02	0.32	0.01	0.25	0.01	0.83	0.03	2.07	0.07
Maximum	2.80	0.22	0.97	0.14	0.70	0.12	0.53	0.1	1.79	0.39	4.48	0.77
IEEE514-2014	12.0		5.5		5.0		2.0		1.0		15.0	

- High-Pass filters TF= 5

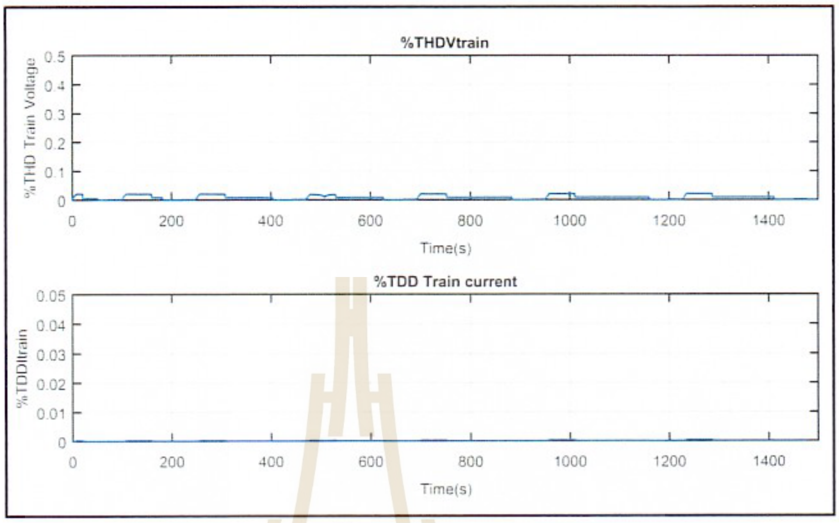


Figure A.100 Total Harmonic Distortion Voltage and Current at train: HP TF=5 on-board

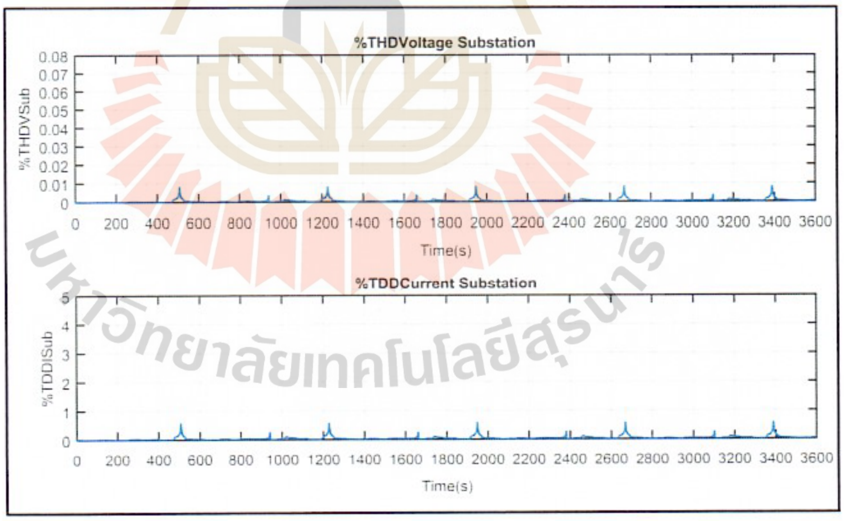


Figure A.101 Total Harmonic Distortion Voltage and Current at substation: HP TF=5 on-board

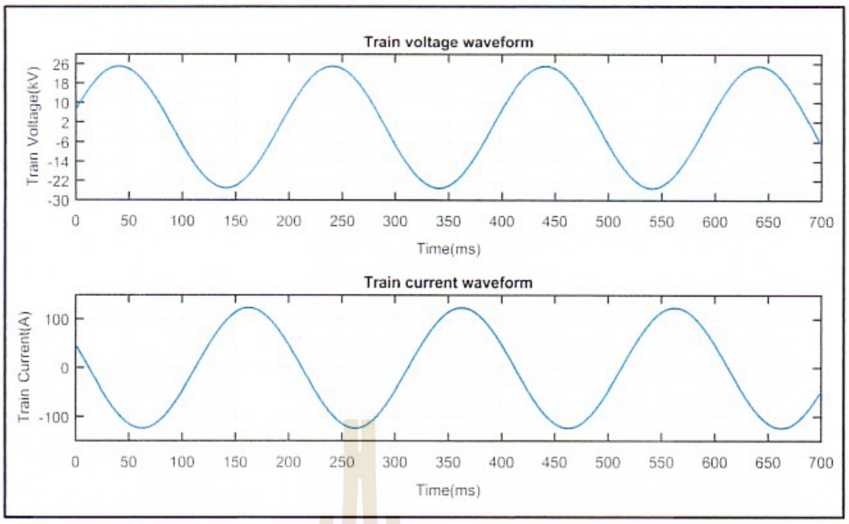


Figure A.102 Harmonic Distortion Voltage and Current at train waveform: HP TF=5 on-board

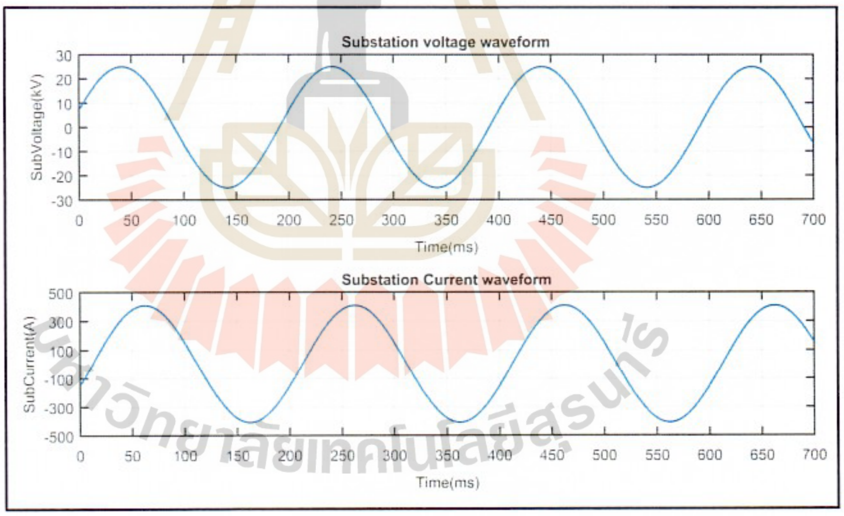


Figure A.103 Harmonic Distortion Voltage and Current at substation waveform: HP TF=5 on-board

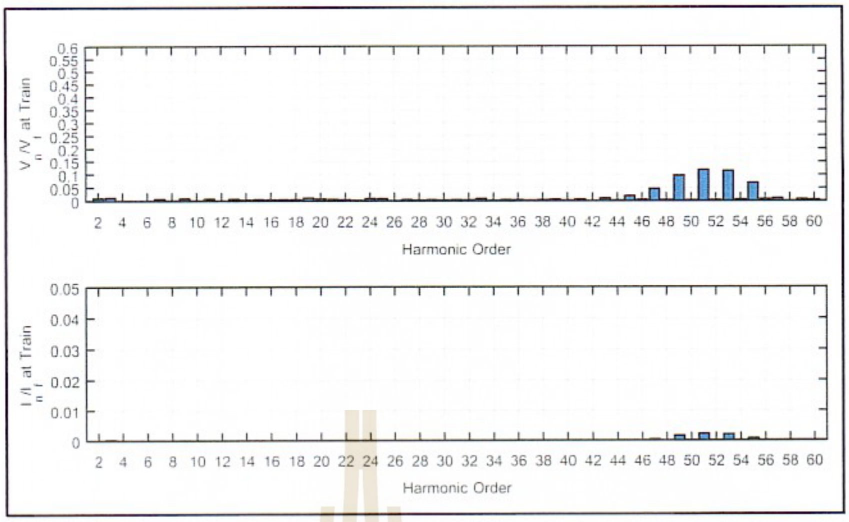


Figure A.104 Harmonics spectrum of Current and Voltage at the train: HP TF=5 on-board

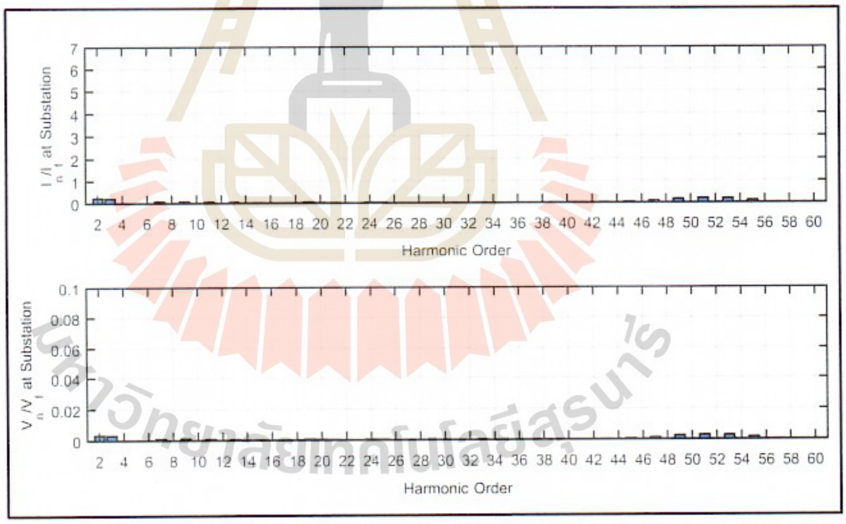


Figure A.105 Harmonics spectrum of Current and Voltage at the Substation: HP TF=5 on-board

Table A.49 THD Voltage results of installing High-Pass filters TF=5 on-board

Bus voltage V at PCC 25 kV	THD Substation (%) (Simulation)		THD Train (%) (Simulation)		THD (%) IEEE519-2014 Standard
	No Filter	HP	No Filter	HP	
Minimum	0.00	0.00	0.00	0.00	5.00
Average	2.07	$5x10^{-4}$	0.70	0.004	5.00
Maximum	4.48	0.009	7.92	0.02	5.00

Table A.50 TDD current results of installing High-Pass filters TF=5 on-board

Maximum harmonic current distortion in percent of I_L												
Individual harmonic order (odd harmonics) at Substation												
I_{SC}/I_L (100 < 1000)	$3 \leq h < 11$		$11 \leq h < 17$		$17 \leq h < 23$		$23 \leq h < 35$		$35 \leq h \leq 50$		TDD	
	No Filter	HP	No Filter	HP	No Filter	HP	No Filter	HP	No Filter	HP	No Filter	HP
Minimum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Average	1.29	0.02	0.45	0.005	0.32	0.005	0.25	0.004	0.83	0.01	2.07	0.04
Maximum	2.80	0.13	0.97	0.07	0.70	0.07	0.53	0.07	1.79	0.29	4.48	0.57
IEEE514-2014	12.0		5.5		5.0		2.0		1.0		15.0	

- High-Pass filters TF= 51

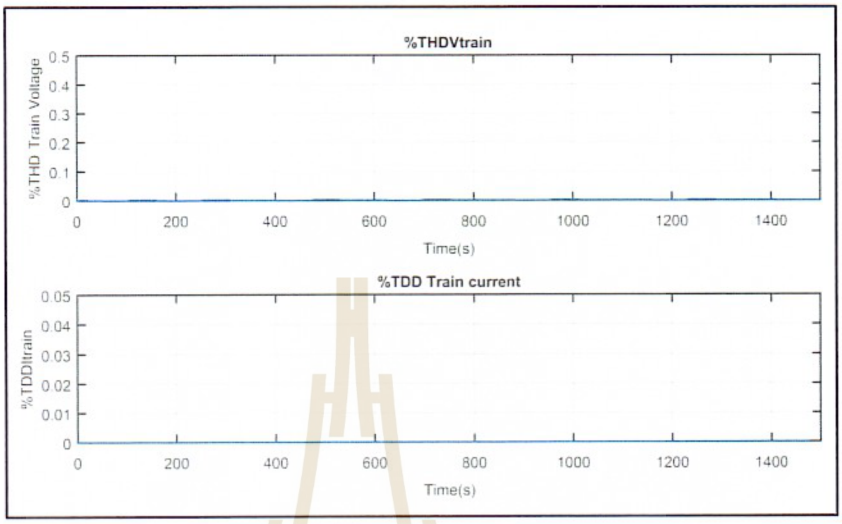


Figure A.106 Total Harmonic Distortion Voltage and Current at train: HP TF=51 on-board

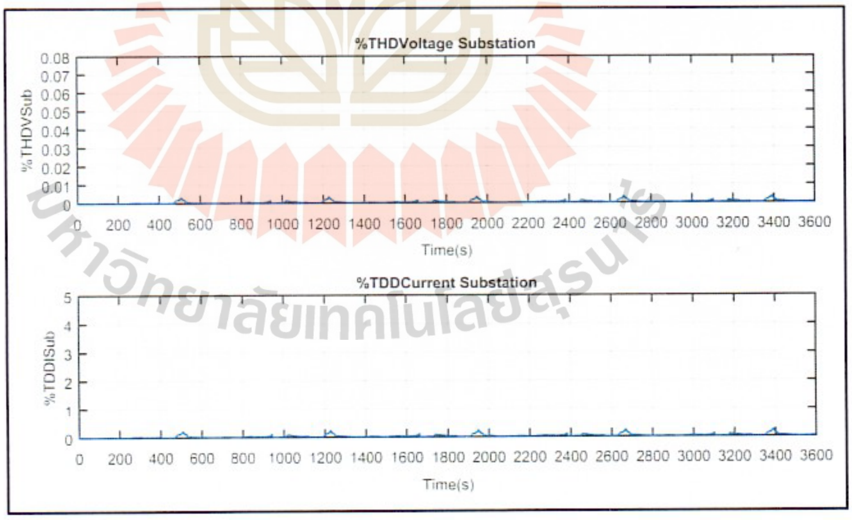


Figure A.107 Total Harmonic Distortion Voltage and Current at substation: HP TF=51 on-board

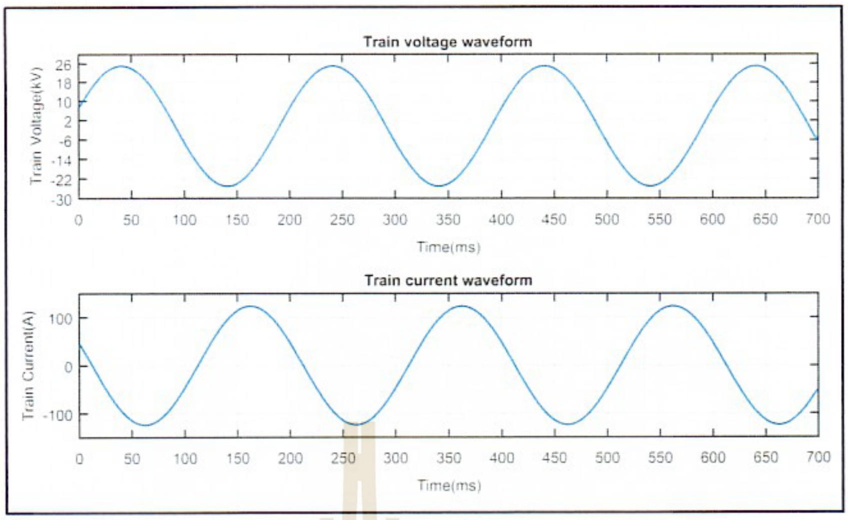


Figure A.108 Harmonic Distortion Voltage and Current at train wave: HP TF=51 on-board

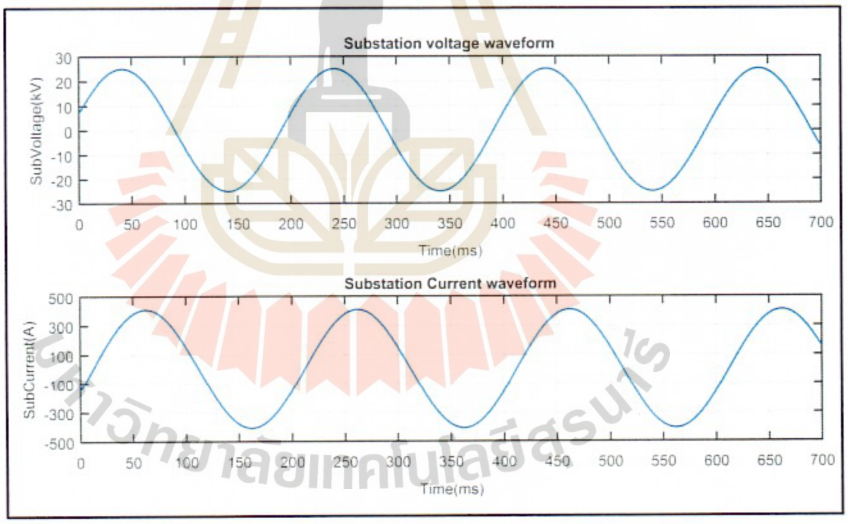


Figure A.109 Harmonic Distortion Voltage and Current at substation wave form: HP TF=51 on-board

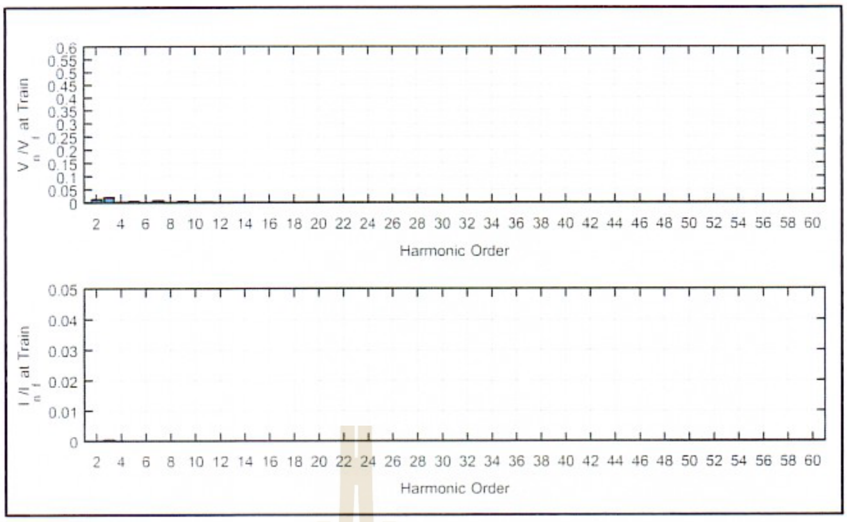


Figure A.110 Harmonics spectrum of Current and Voltage at the train: HP TF=51 on-board

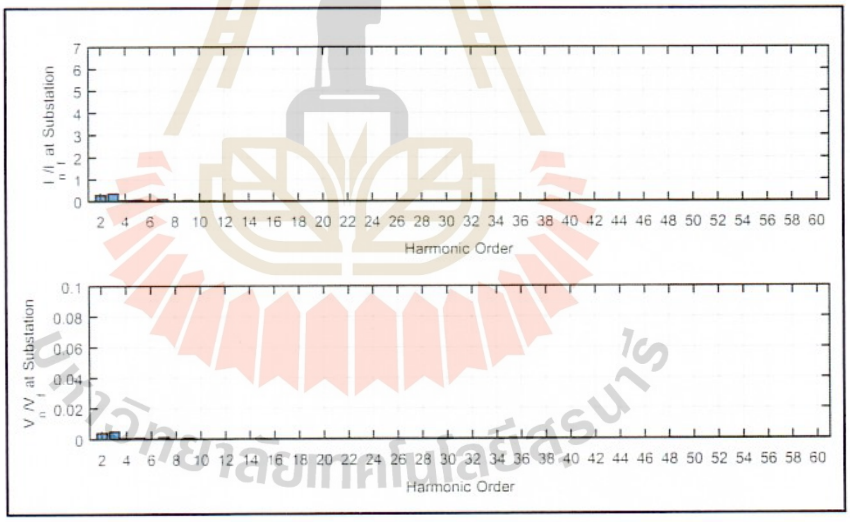


Figure A.111 Harmonics spectrum of Current and Voltage at the Substation: HP TF=51 on-board

Table A. 51 THD Voltage results of installing High-Pass filters TF=51 on-board

Bus voltage V at PCC 25 kV	THD Substation (%) (Simulation)		THD Train (%) (Simulation)		THD (%) IEEE519-2014 Standard
	No Filter	HP	No Filter	HP	
Minimum	0.00	0.00	0.00	0.00	5.00
Average	2.07	4×10^{-4}	0.70	4×10^{-4}	5.00
Maximum	4.48	0.003	7.92	0.003	5.00

Table A.52 TDD current results of installing High-Pass filters TF=51 on-board

Maximum harmonic current distortion in percent of I_L												
Individual harmonic order (odd harmonics) at Substation												
I_{sc}/I_L (100 < 1000)	$3 \le h < 11$		$11 \le h < 17$		$17 \le h < 23$		$23 \le h < 35$		$35 \le h \le 50$		TDD	
	No Filter	HP	No Filter	HP	No Filter	HP	No Filter	HP	No Filter	HP	No Filter	HP
Minimum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Average	1.29	0.02	0.45	0.001	0.32	3×10^{4}	0.25	1×10^{4}	0.83	3×10^{5}	2.07	0.03
Maximum	2.80	0.19	0.97	0.02	0.70	0.007	0.53	0.003	1.79	0.001	4.48	0.24
IEEE514-2014	12.0		5.5		5.0		2.0		1.0		15.0	

- High-Pass filters TF= 53

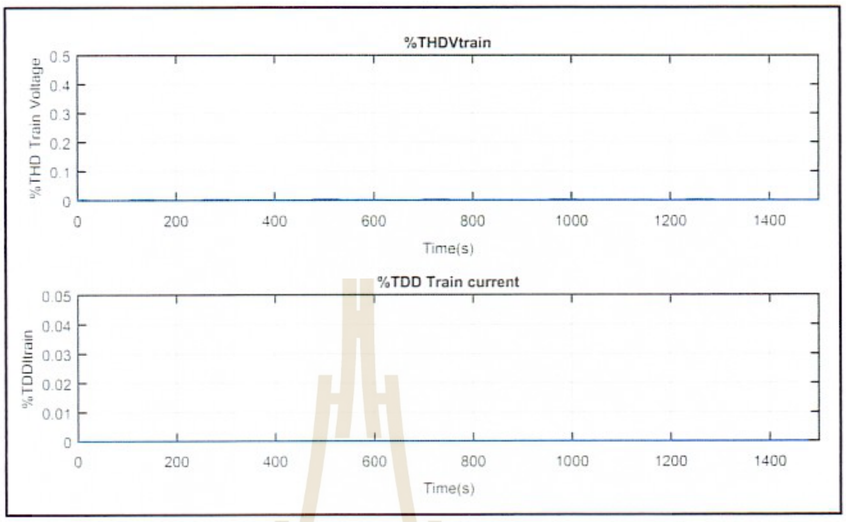


Figure A.112 Total Harmonic Distortion Voltage and Current at train: HP TF=53 on-board

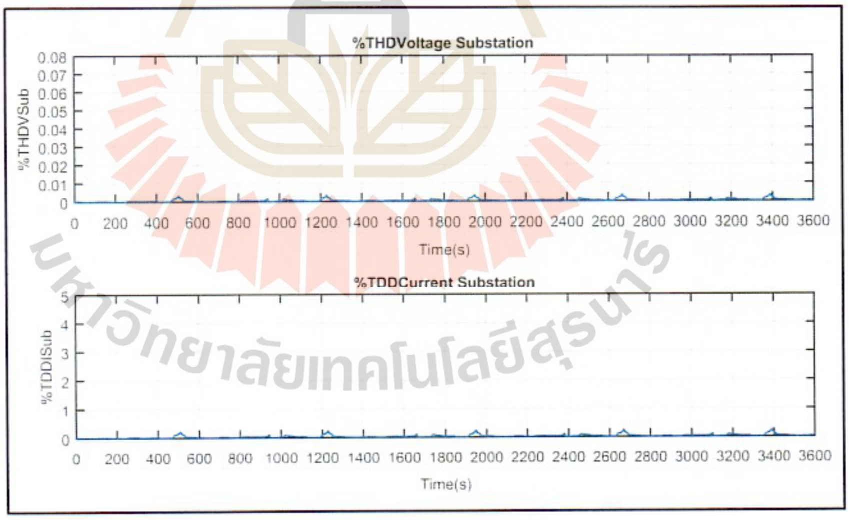


Figure A.113 Total Harmonic Distortion Voltage and Current at substation: HP TF=53 on-board

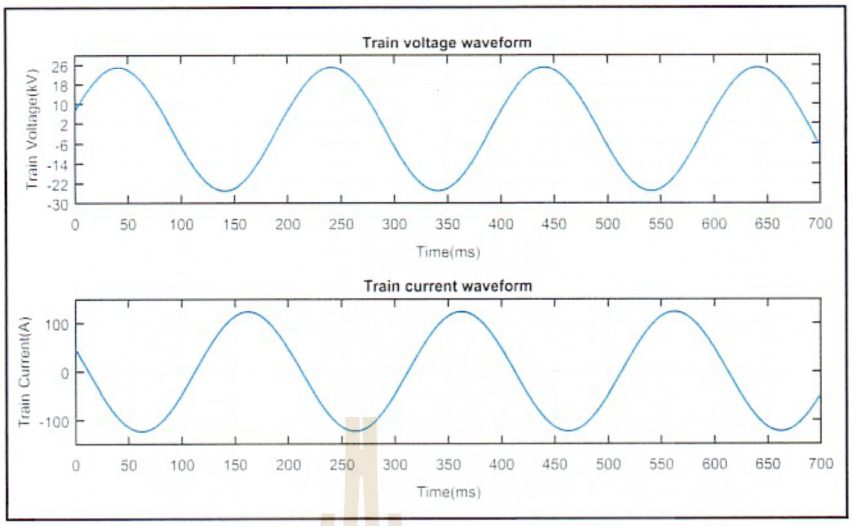


Figure A.114 Harmonic Distortion Voltage and Current at train wave: HP TF=53 on-board

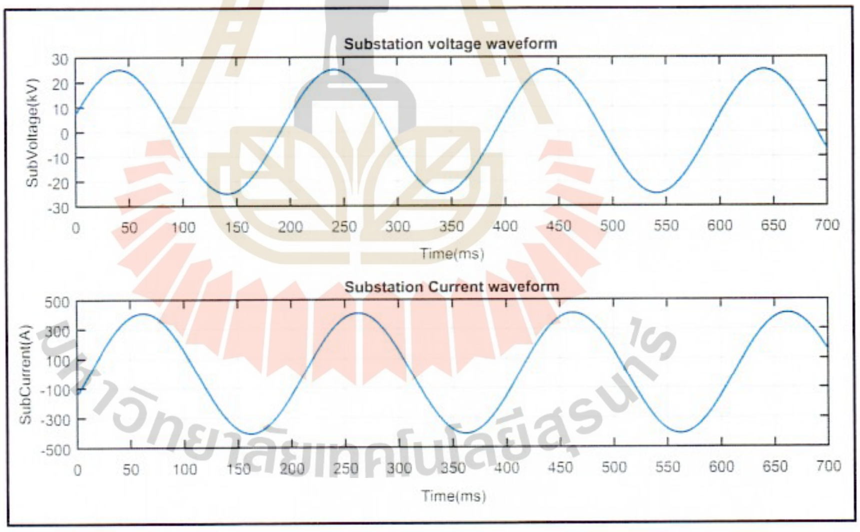


Figure A.115 Harmonic Distortion Voltage and Current at substation wave form: HP TF=53 on-board

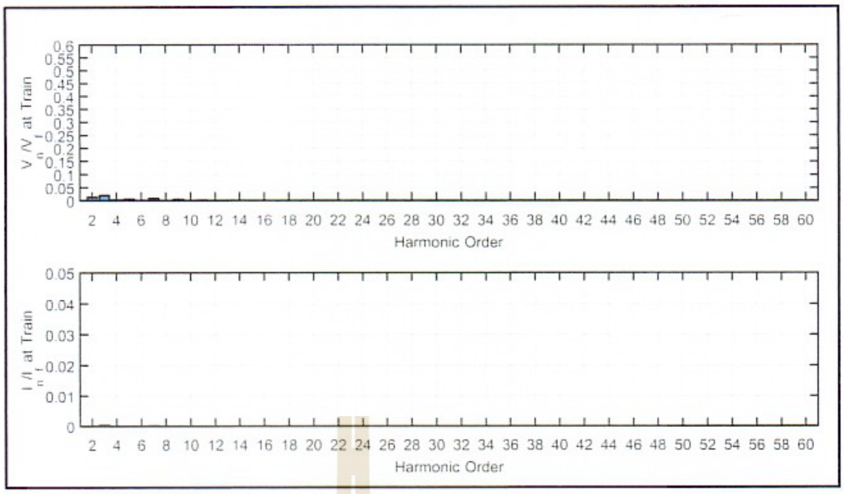


Figure A.116 Harmonics spectrum of Current and Voltage at the train: HP TF=53 on-board

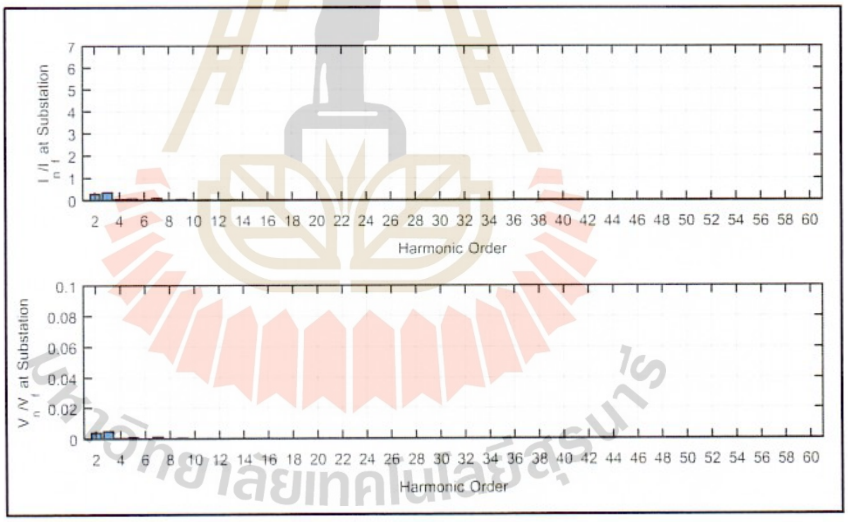


Figure A.117 Harmonics spectrum of Current and Voltage at the Substation: HP TF=53 on-board

Table A.53 THD Voltage results of installing High-Pass filters TF=53 on-board

Bus voltage V at PCC 25 kV	THD Substation (%) (Simulation)		THD Train (%) (Simulation)		THD (%) IEEE519-2014 Standard
	No Filter	HP	No Filter	HP	
Minimum	0.00	0.00	0.00	0.00	5.00
Average	2.07	$4x10^{-4}$	0.70	$4x10^{-4}$	5.00
Maximum	4.48	0.003	7.92	0.003	5.00

Table A.54 TDD current results of installing High-Pass filters TF=53 on-board

Maximum harmonic current distortion in percent of I_L												
Individual harmonic order (odd harmonics) at Substation												
I_{SC}/I_L $(100 < 1000)$	$3 \leq h < 11$		$11 \leq h < 17$		$17 \leq h < 23$		$23 \leq h < 35$		$35 \leq h \leq 50$		TDD	
	No Filter	HP	No Filter	HP	No Filter	HP	No Filter	HP	No Filter	HP	No Filter	HP
Minimum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Average	1.29	0.02	0.45	0.001	0.32	$3x10^{4}$	0.25	$1x10^{4}$	0.83	$4x10^{5}$	2.07	0.03
Maximum	2.80	0.19	0.97	0.02	0.70	0.007	0.53	0.003	1.79	0.001	4.48	0.24
IEEE514-2014	12.0		5.5		5.0		2.0		1.0		15.0	

- C-Type filters TF= 3

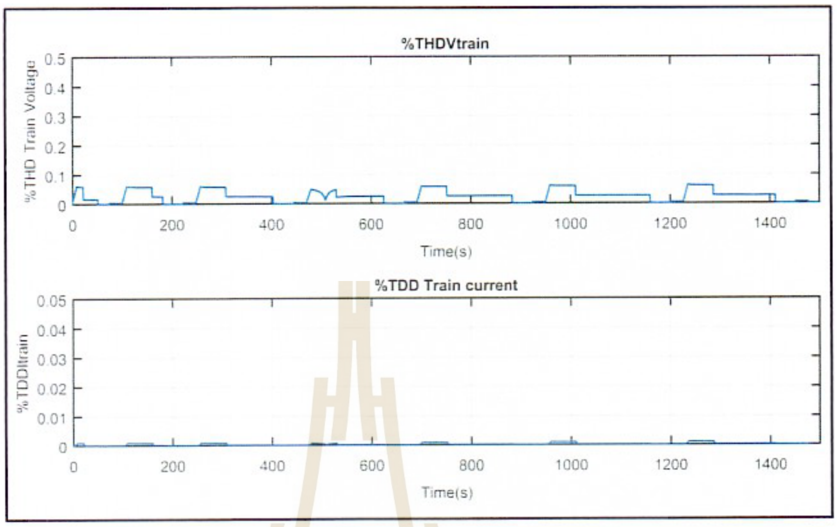


Figure A.118 Total Harmonic Distortion Voltage and Current at train: C-Type TF=3 on-board

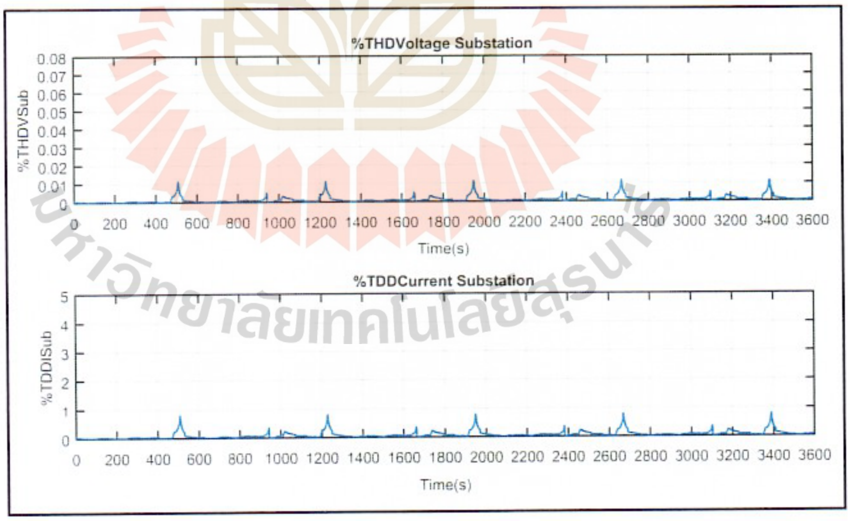


Figure A.119 Total Harmonic Distortion Voltage and Current at substation: C-Type TF=3 on-board

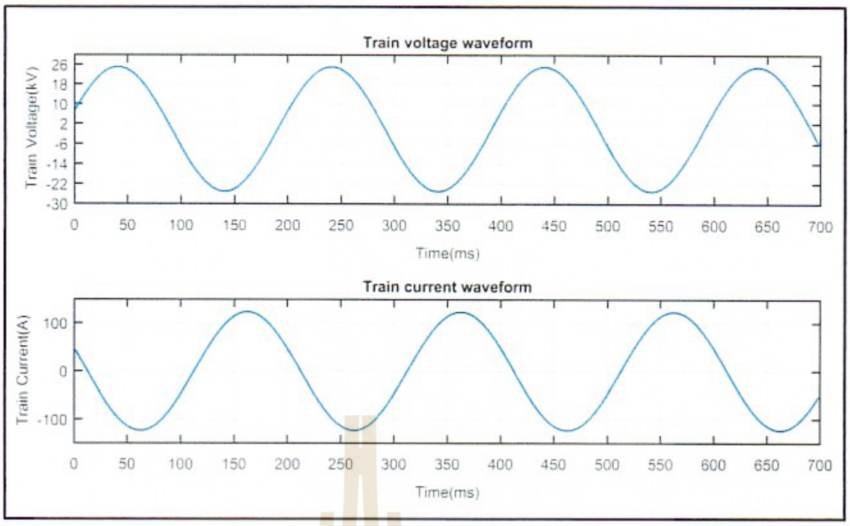


Figure A.120 Harmonic Distortion Voltage and Current at train wave: C-Type TF=3 on-board

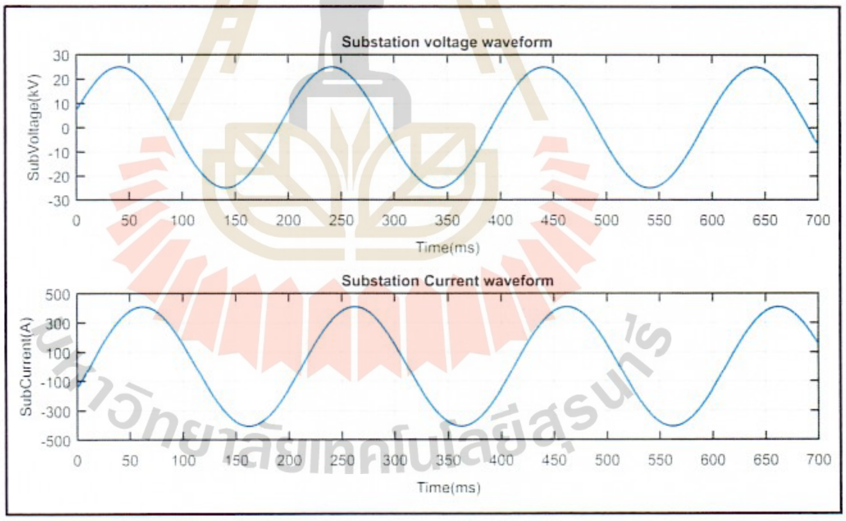


Figure A.121 Harmonic Distortion Voltage and Current at substation wave form: C-Type TF=3 on-board

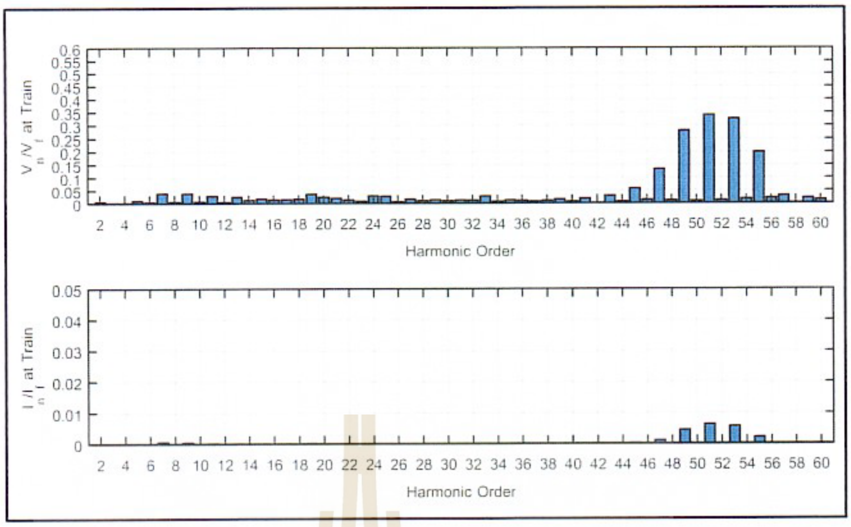


Figure A.122 Harmonics spectrum of Current and Voltage at the train: C-Type TF=3 on-board

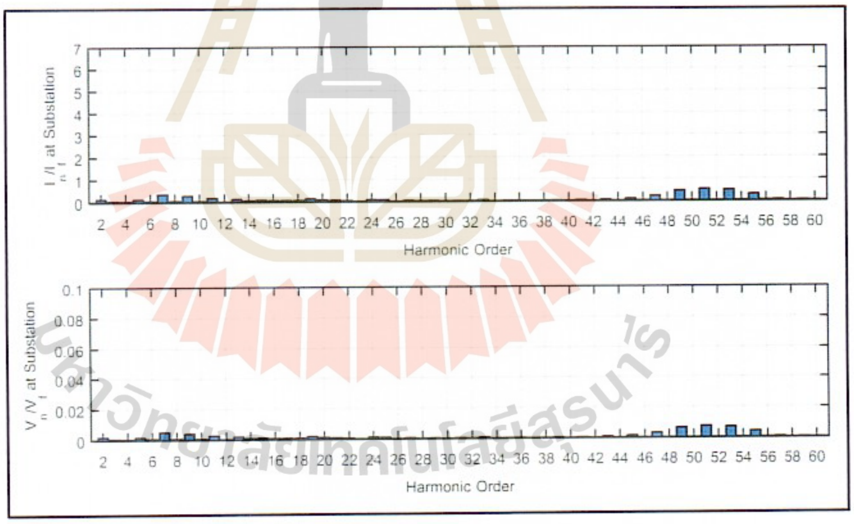


Figure A.123 Harmonics spectrum of Current and Voltage at the Substation: C-Type TF=3 on-board

Table A.55 THD Voltage results of installing C-Type filters TF=3 on-board

Bus voltage V at PCC 25 kV	THD Substation (%) (Simulation)		THD Train (%) (Simulation)		THD (%) IEEE519-2014 Standard
	No Filter	C-Type	No Filter	C-Type	
Minimum	0.00	0.00	0.00	0.00	5.00
Average	2.07	0.001	0.70	0.01	5.00
Maximum	4.48	0.01	7.92	0.06	5.00

Table A.56 TDD current results of installing C-Type filters TF=3 on-board

Maximum harmonic current distortion in percent of I_L												
Individual harmonic order (odd harmonics) at Substation												
I_{SC}/I_L (100 < 1000)	$3 \le h < 11$		$11 \le h < 17$		$17 \le h < 23$		$23 \le h < 35$		$35 \le h \le 50$		TDD	
	No Filter	C-Type	No Filter	C-Type	No Filter	C-Type	No Filter	C-Type	No Filter	C-Type	No Filter	C-Type
Minimum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Average	1.29	0.03	0.45	0.02	0.32	0.01	0.25	0.01	0.83	0.04	2.07	0.07
Maximum	2.80	0.24	0.97	0.15	0.70	0.12	0.53	0.10	1.79	0.40	4.48	0.79
IEEE514-2014	12.0		5.5		5.0		2.0		1.0		15.0	

- C-Type filters TF= 5

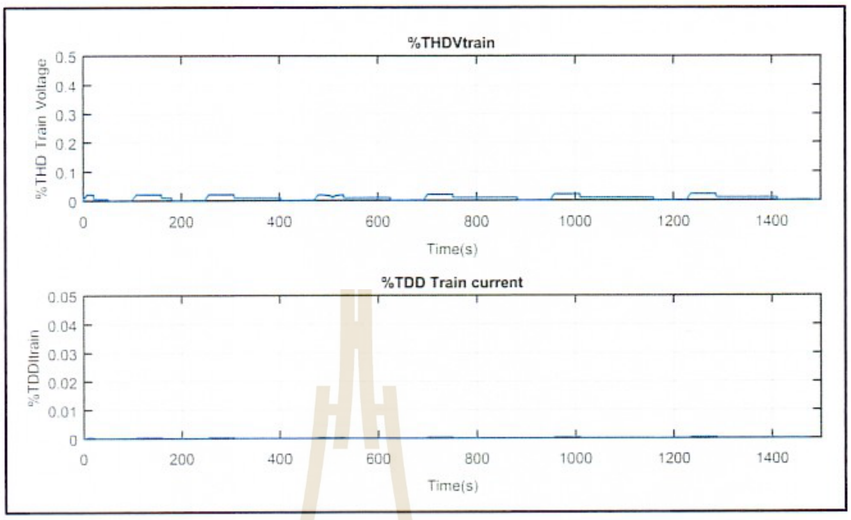


Figure A.124 Total Harmonic Distortion Voltage and Current at train: C-Type TF=5 on-board

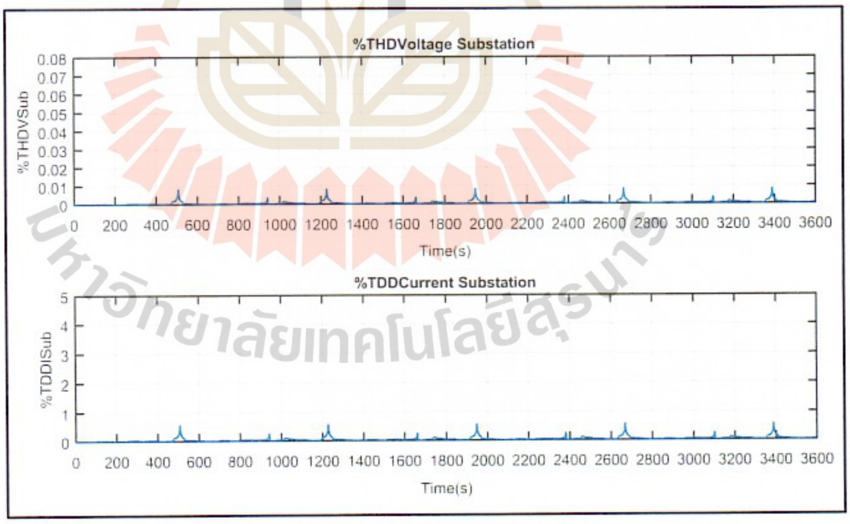


Figure A.125 Total Harmonic Distortion Voltage and Current at substation: C-Type TF=5 on-board

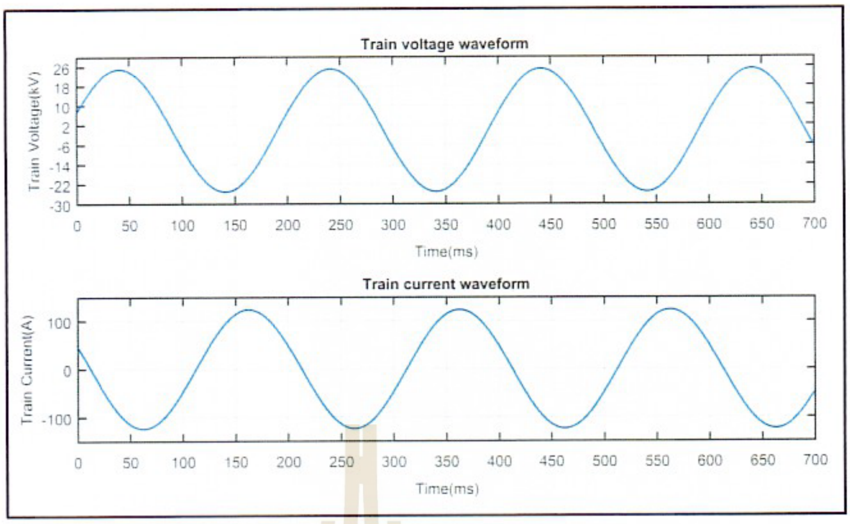


Figure A.126 Harmonic Distortion Voltage and Current at train wave: C-Type TF=5 on-board

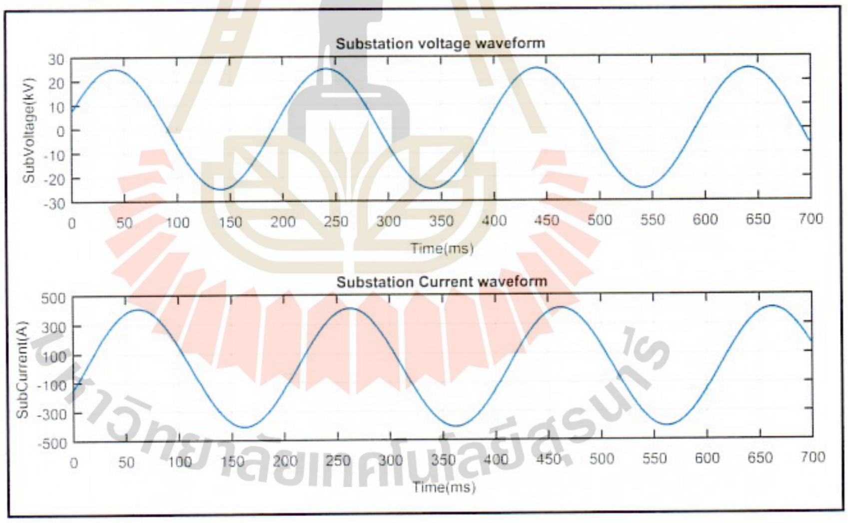


Figure A.127 Harmonic Distortion Voltage and Current at substation wave form: C-Type TF=5 on-board

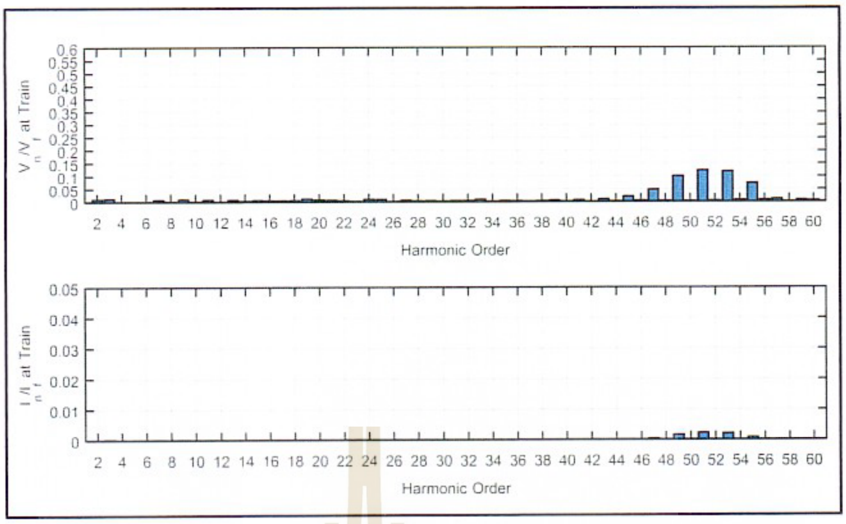


Figure A.128 Harmonics spectrum of Current and Voltage at the train: C-Type TF=5 on-board

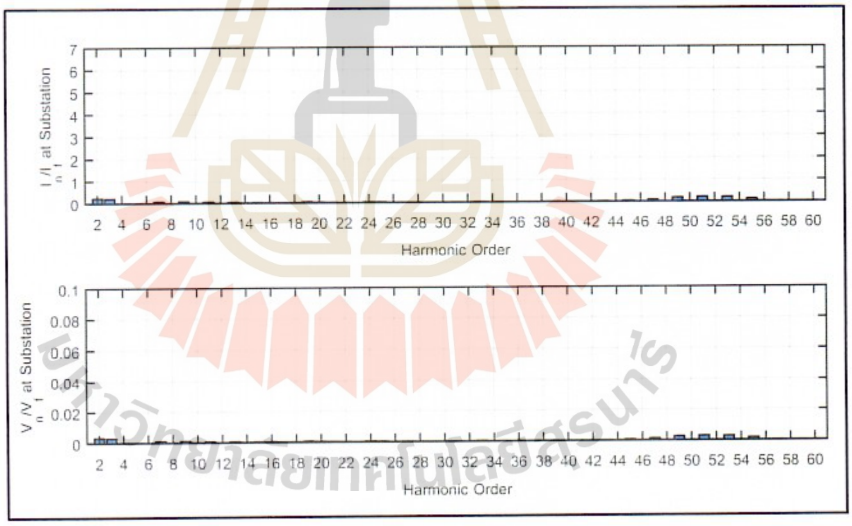


Figure A.129 Harmonics spectrum of Current and Voltage at the Substation: C-Type TF=5 on-board

Table A.57 THD Voltage results of installing C-Type filters TF=5 on-board

Bus voltage V at PCC 25 kV	THD Substation (%) (Simulation)		THD Train (%) (Simulation)		THD (%) IEEE519-2014 Standard
	No Filter	C-Type	No Filter	C-Type	
Minimum	0.00	0.00	0.00	0.00	5.00
Average	2.07	$5x10^{-4}$	0.70	$3x10^{-3}$	5.00
Maximum	4.48	$8x10^{-3}$	7.92	0.02	5.00

Table A.58 TDD current results of installing C-Type filters TF=5 on-board

Maximum harmonic current distortion in percent of I_L												
Individual harmonic order (odd harmonics) at Substation												
I_{SC}/I_L *(100 < 1000)*	$3 \le h < 11$		$11 \le h < 17$		$17 \le h < 23$		$23 \le h < 35$		$35 \le h \le 50$		TDD	
	No Filter	C-Type	No Filter	C-Type	No Filter	C-Type	No Filter	C-Type	No Filter	C-Type	No Filter	C-Type
Minimum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Average	1.29	0.01	0.45	0.006	0.32	0.005	0.25	0.004	0.83	0.02	2.07	0.04
Maximum	2.80	0.12	0.97	0.07	0.70	0.07	0.53	0.07	1.79	0.29	4.48	0.58
IEEE514-2014	12.0		5.5		5.0		2.0		1.0		15.0	

- C-Type filters TF= 51

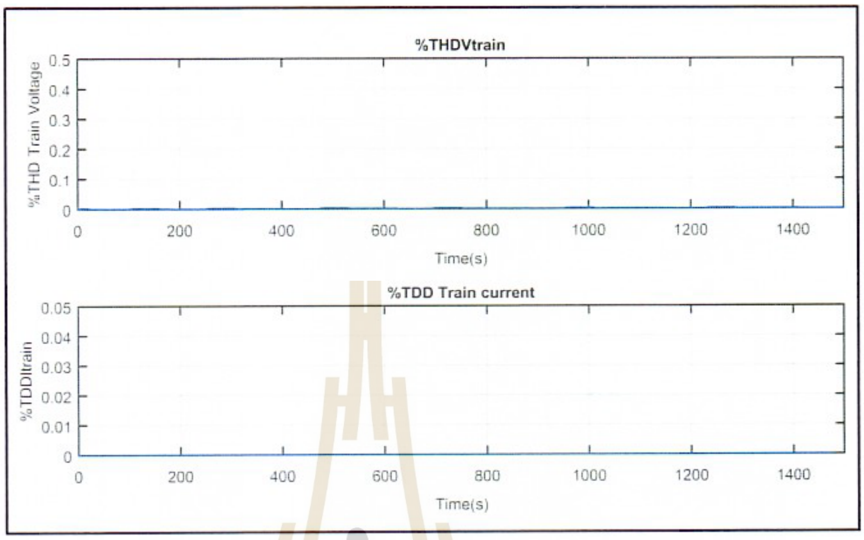


Figure A.130 Total Harmonic Distortion Voltage and Current at train: C-Type TF=51 on-board

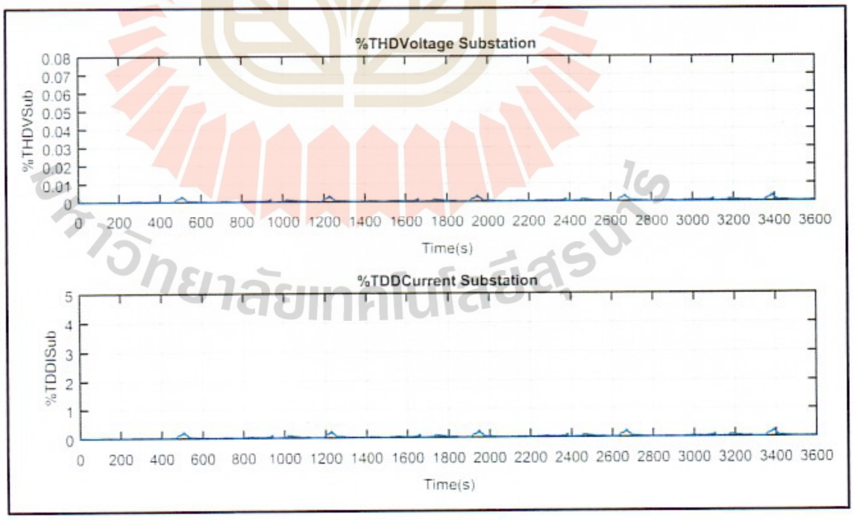


Figure A.131 Total Harmonic Distortion Voltage and Current at substation: C-Type TF=51 on-board

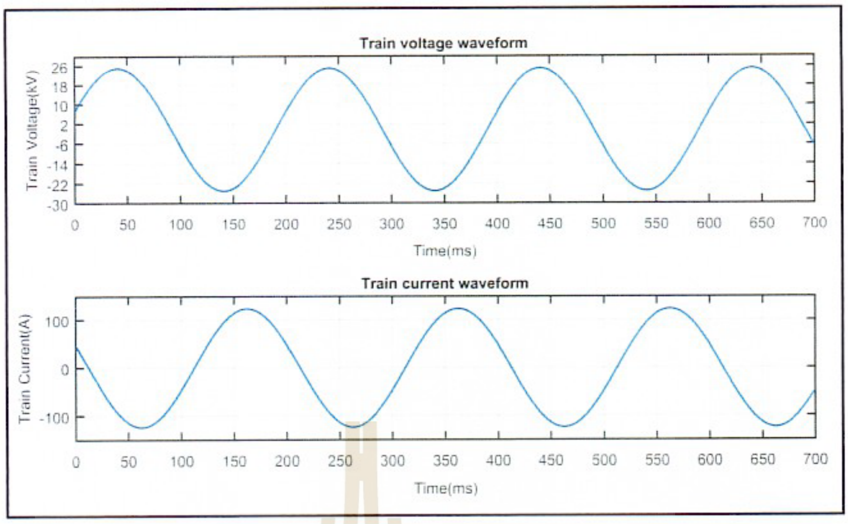


Figure A.132 Harmonic Distortion Voltage and Current at train wave: C-Type TF=51 on-board

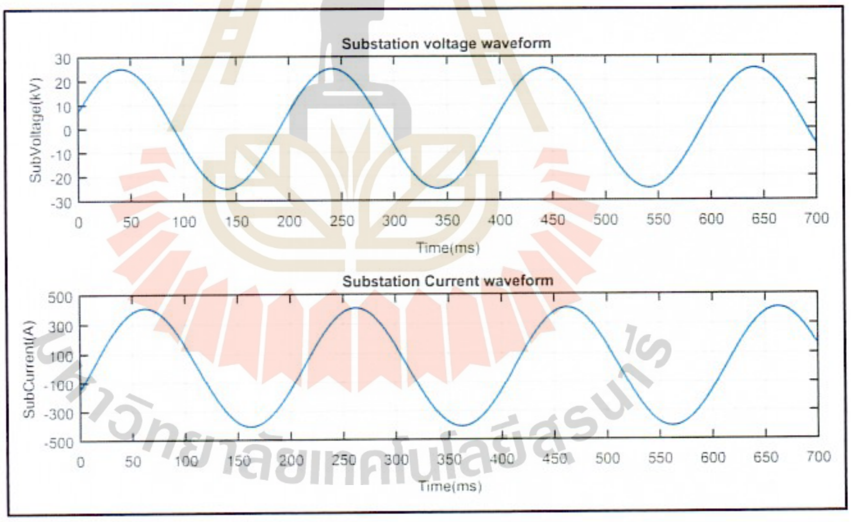


Figure A.133 Harmonic Distortion Voltage and Current at substation wave form: C-Type TF=51 on-board

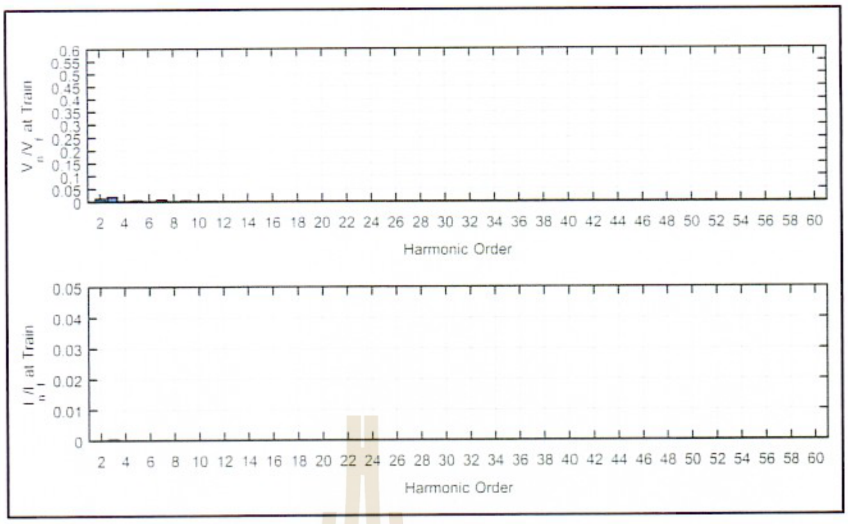


Figure A.134 Harmonics spectrum of Current and Voltage at the train: C-Type TF=51 on-board

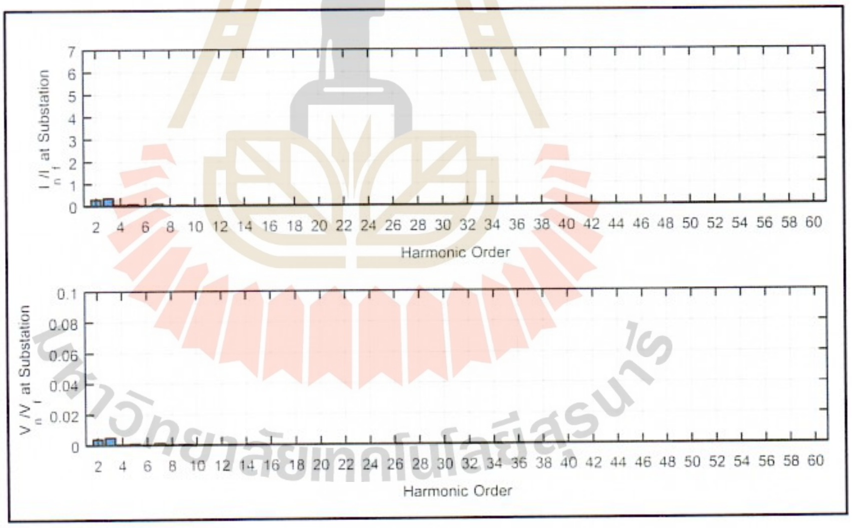


Figure A.135 Harmonics spectrum of Current and Voltage at the Substation: C-Type TF=51 on-board

Table A.59 THD Voltage results of installing C-Type filters TF=51 on-board

Bus voltage V at PCC 25 kV	THD Substation (%) (Simulation)		THD Train (%) (Simulation)		THD (%) IEEE519-2014 Standard
	No Filter	C-Type	No Filter	C-Type	
Minimum	0.00	0.00	0.00	0.00	5.00
Average	2.07	$4x10^{-4}$	0.70	$4x10^{-4}$	5.00
Maximum	4.48	$3x10^{-3}$	7.92	$3x10^{-3}$	5.00

Table A.60 TDD current results of installing C-Type filters TF=51 on-board

Maximum harmonic current distortion in percent of I_L												
Individual harmonic order (odd harmonics) at Substation												
I_{SC}/I_L *(100 < 1000)*	$3 \le h < 11$		$11 \le h < 17$		$17 \le h < 23$		$23 \le h < 35$		$35 \le h \le 50$		TDD	
	No Filter	C-Type	No Filter	C-Type	No Filter	C-Type	No Filter	C-Type	No Filter	C-Type	No Filter	C-Type
Minimum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Average	1.29	0.02	0.45	0.001	0.32	$3x10^4$	0.25	$1x10^4$	0.83	$3x10^5$	2.07	0.03
Maximum	2.80	0.19	0.97	0.02	0.70	$7x10^3$	0.53	$3x10^3$	1.79	$1x10^3$	4.48	0.24
IEEE514-2014	12.0		5.5		5.0		2.0		1.0		15.0	

- C-Type filters TF= 53

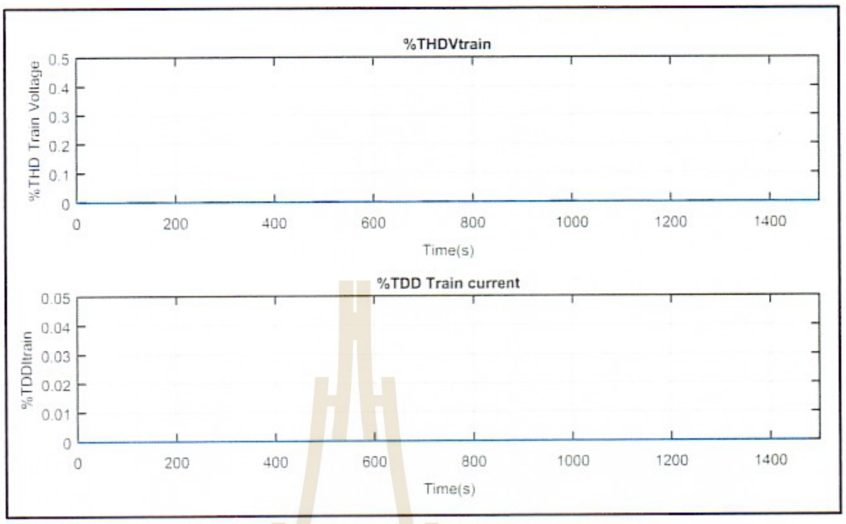


Figure A.136 Total Harmonic Distortion Voltage and Current at train: C-Type TF=53 on-board

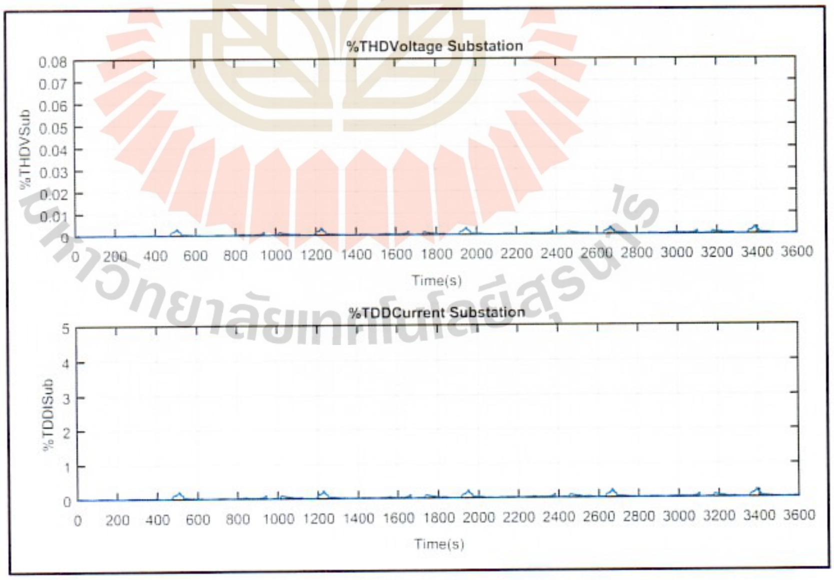


Figure A.137 Total Harmonic Distortion Voltage and Current at substation: C-Type TF=53 on-board

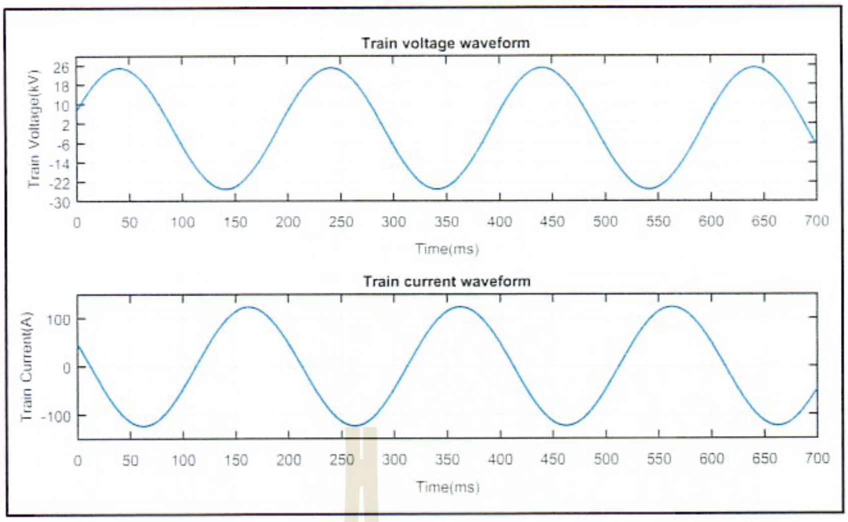


Figure A.138 Harmonic Distortion Voltage and Current at train wave: C-Type TF=53 on-board

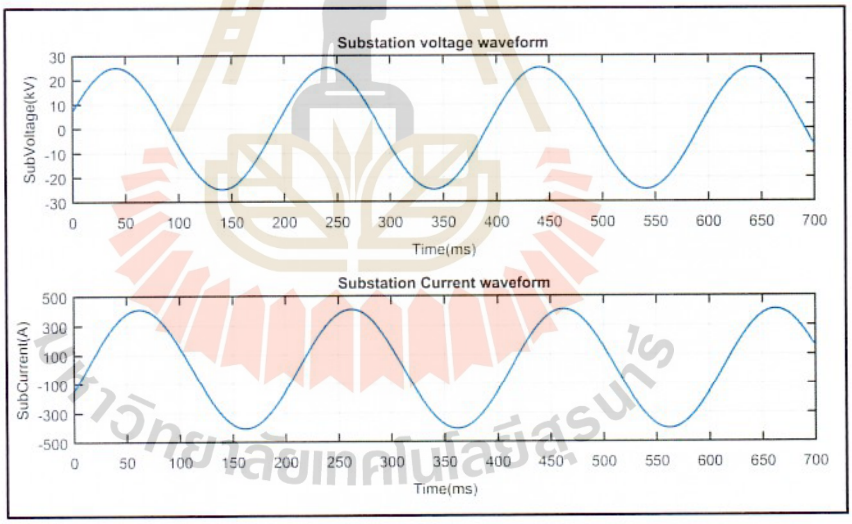


Figure A.139 Harmonic Distortion Voltage and Current at substation wave form: C-Type TF=53 on-board

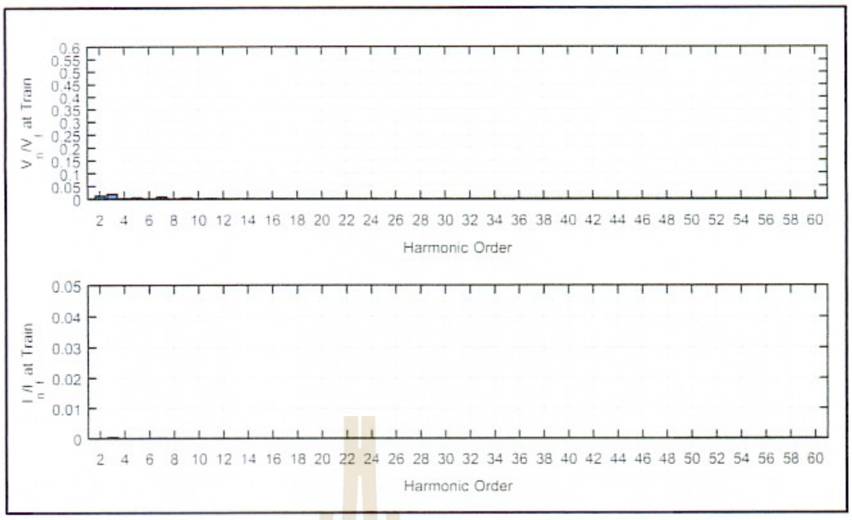


Figure A.140 Harmonics spectrum of Current and Voltage at the train: C-Type TF=53 on-board

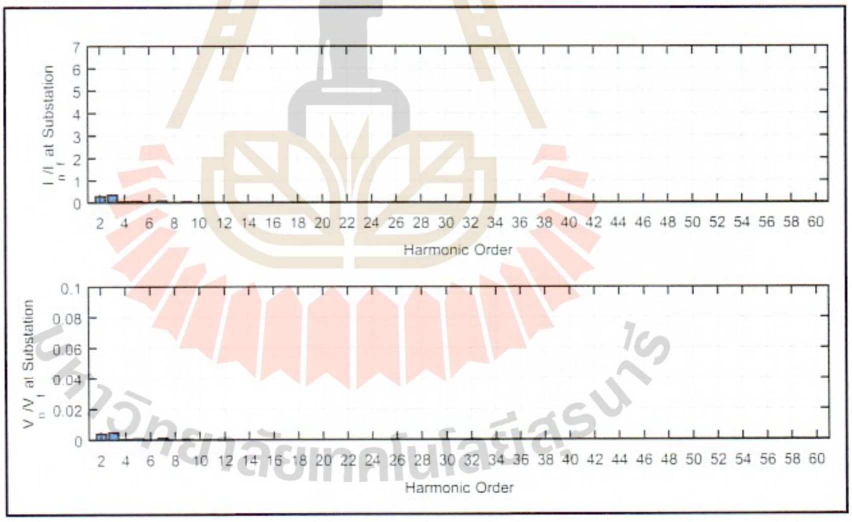


Figure A.141 Harmonics spectrum of Current and Voltage at the Substation: C-Type TF=53 on-board

Table A.61 THD Voltage results of installing C-Type filters TF=53 on-board

Bus voltage *V* at PCC 25 kV	THD Substation (%) (Simulation)		THD Train (%) (Simulation)		THD (%) IEEE519-2014 Standard
	No Filter	C-Type	No Filter	C-Type	
Minimum	0.00	0.00	0.00	0.00	5.00
Average	2.07	$4x10^{-4}$	0.70	$4x10^{-4}$	5.00
Maximum	4.48	$3x10^{-3}$	7.92	$3x10^{-3}$	5.00

Table A.62 TDD current results of installing C-Type filters TF=53 on-board

Maximum harmonic current distortion in percent of I_L												
Individual harmonic order (odd harmonics) at <u>Substation</u>												
I_{sc}/I_L *(100 < 1000)*	$3 \le h < 11$		$11 \le h < 17$		$17 \le h < 23$		$23 \le h < 35$		$35 \le h \le 50$		TDD	
	No Filter	C-Type	No Filter	C-Type	No Filter	C-Type	No Filter	C-Type	No Filter	C-Type	No Filter	C-Type
Minimum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Average	1.29	0.02	0.45	0.001	0.32	$3x10^4$	0.25	$1x10^4$	0.83	$3x10^5$	2.07	0.03
Maximum	2.80	0.19	0.97	0.02	0.70	$7x10^3$	0.53	$3x10^3$	1.79	$1x10^3$	4.48	0.24
IEEE514-2014	12.0		5.5		5.0		2.0		1.0		15.0	

A.3 Part 2 the results of the case study input voltage harmonics of the four-quadrant

A.2.3 Harmonic results of installing C-Type passive filters at Substation.

- C-Type filters TF= 53

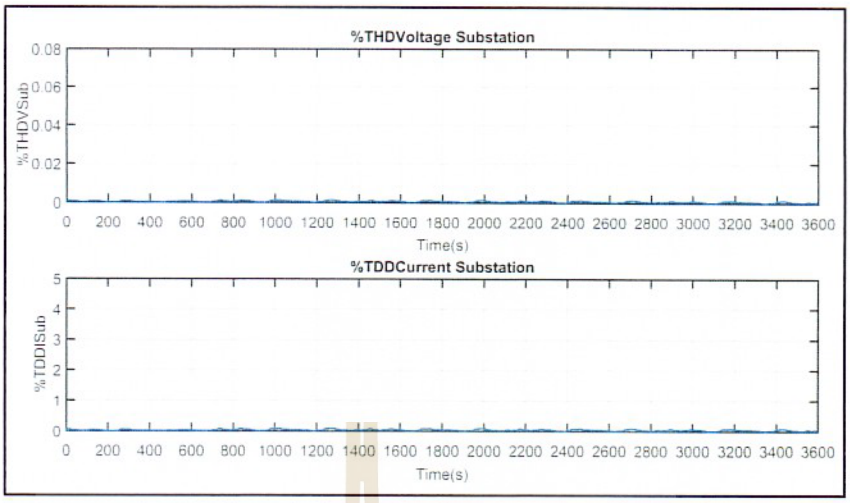


Figure A.142 Total Harmonic Distortion Voltage and Current at Train of the four-quadrant converter: C-Type TF=53 at Substation

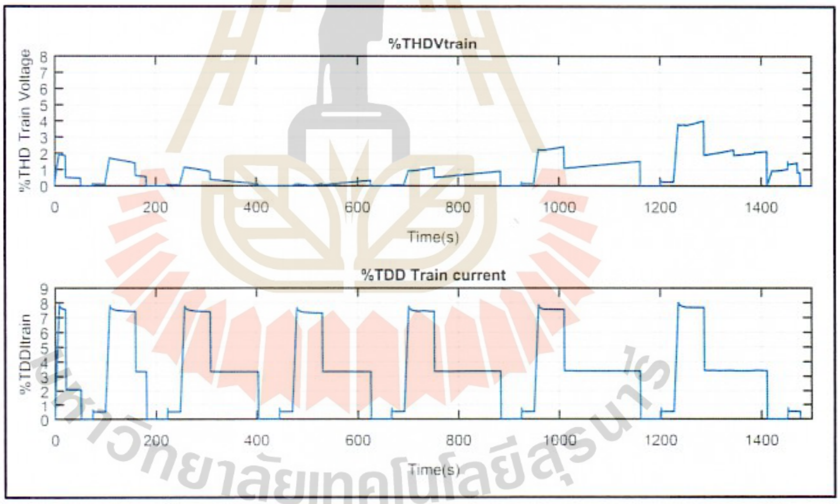


Figure A.143 Total Harmonic Distortion Voltage and Current at substation of the four-quadrant converter: C-Type TF=53 at Substation

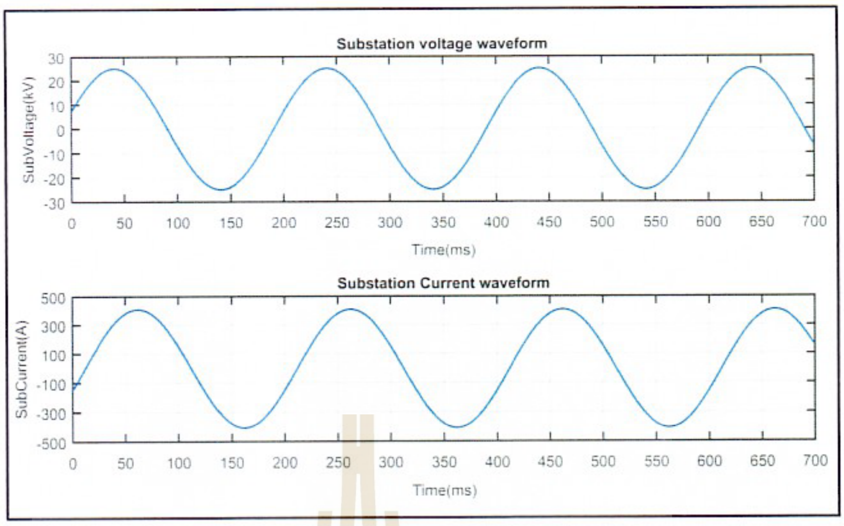


Figure A.144 Harmonic Distortion Voltage and Current at train wave of the four-quadrant converter: C-Type TF=53 at Substation

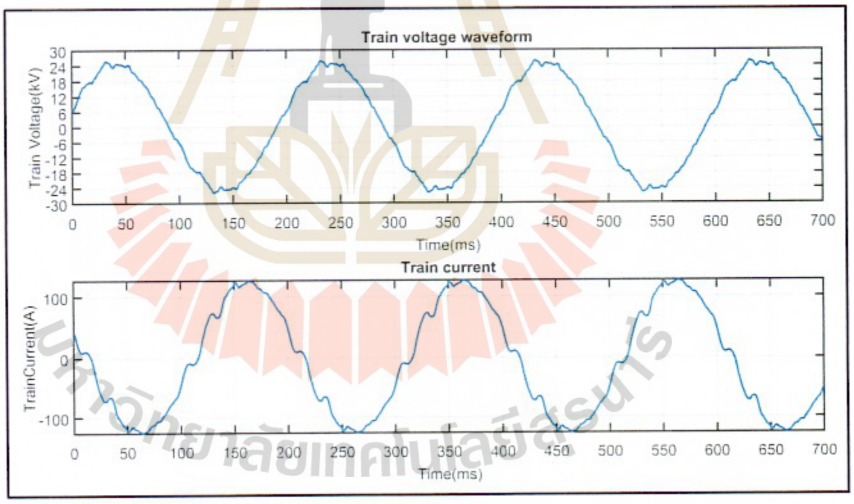


Figure A.145 Harmonic Distortion Voltage and Current at substation wave form of the four-quadrant converter: C-Type TF=53 at Substation

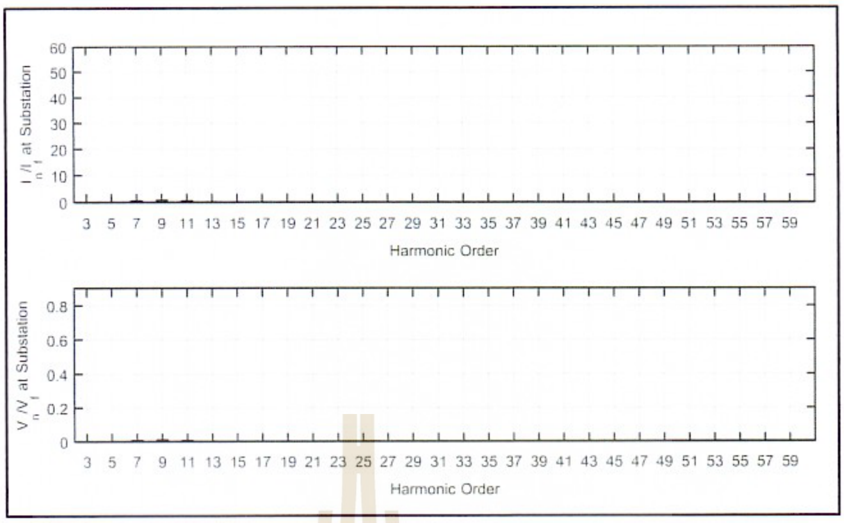


Figure A.146 Harmonics spectrum of Current and Voltage at the train of the four-quadrant converter: C-Type TF=53 at Substation

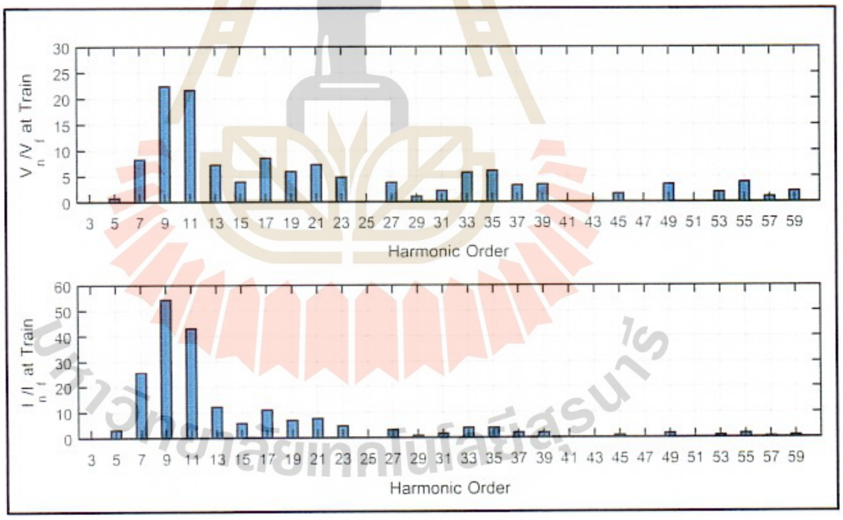


Figure A.147 Harmonics spectrum of Current and Voltage at the Substation of the four-quadrant converter: C-Type TF=53 at Substation

Table A. 63 THD Voltage results of installing C-Type filters TF=53 on-board

Bus voltage *V* at PCC 25 kV	THD Substation (%) (Simulation)		THD Train (%) (Simulation)		THD (%) IEEE519-2014 Standard
	No Filter	C-Type	No Filter	C-Type	
Minimum	0.00	0.00	0.00	0.00	5.00
Average	0.05	$6x10^{-4}$	0.37	0.35	5.00
Maximum	0.11	$2x10^{-3}$	4.12	4.02	5.00

Table A. 64 TDD current results of installing C-Type filters TF=53 on-board

Maximum harmonic current distortion in percent of I_L												
Individual harmonic order (odd harmonics) at Substation												
I_{SC}/I_L (100 < 1000)	$3 \le h < 11$		$11 \le h < 17$		$17 \le h < 23$		$23 \le h < 35$		$35 \le h \le 50$		TDD	
	No Filter	C-Type	No Filter	C-Type	No Filter	C-Type	No Filter	C-Type	No Filter	C-Type	No Filter	C-Type
Minimum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Average	3.56	0.04	2.23	0.02	0.75	$4x10^{3}$	0.38	$1x10^{3}$	0.24	$4x10^{4}$	3.71	0.04
Maximum	7.69	0.09	4.82	0.04	1.62	$8x10^{3}$	0.81	$2x10^{3}$	0.51	$8x10^{4}$	8.03	0.09
IEEE514-2014	12.0		5.5		5.0		2.0		1.0		15.0	

A.2.4 Harmonic results of installing on-board C-Type passive filters.

- C-Type filters TF= 53

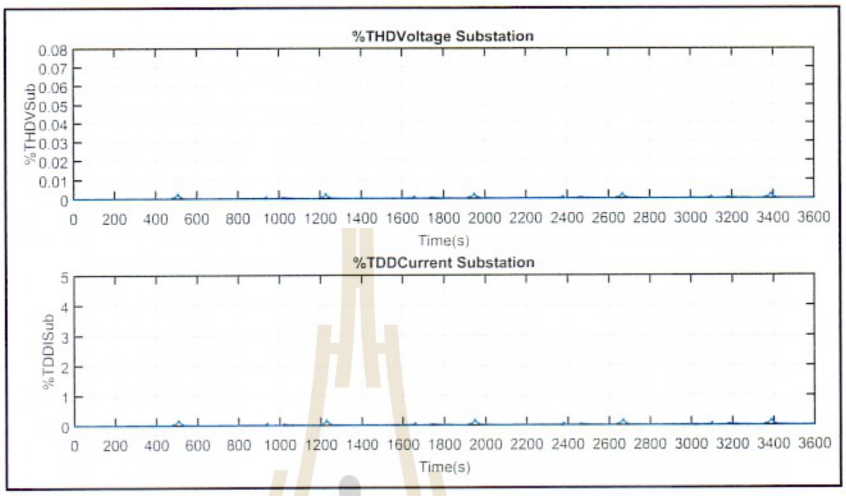


Figure A.148 Total Harmonic Distortion Voltage and Current at Train of the four-quadrant converter: C-Type TF=53 On-board

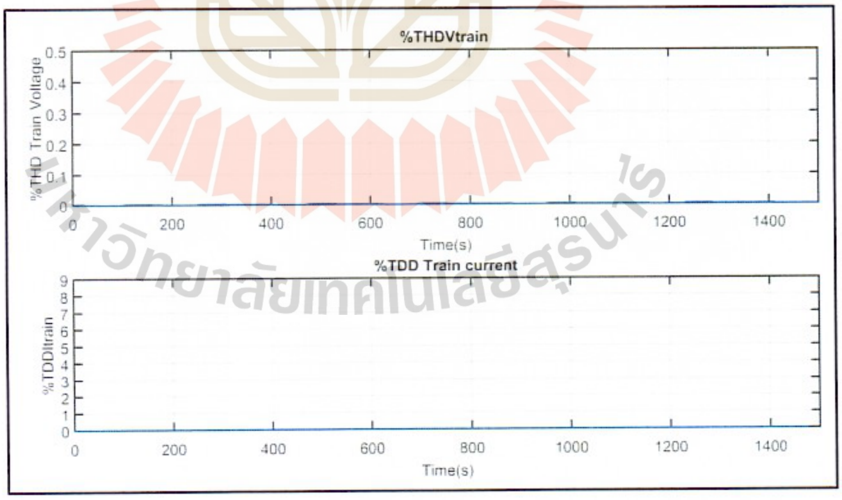


Figure A.149 Total Harmonic Distortion Voltage and Current at substation of the four-quadrant converter: C-Type TF=53 On-board

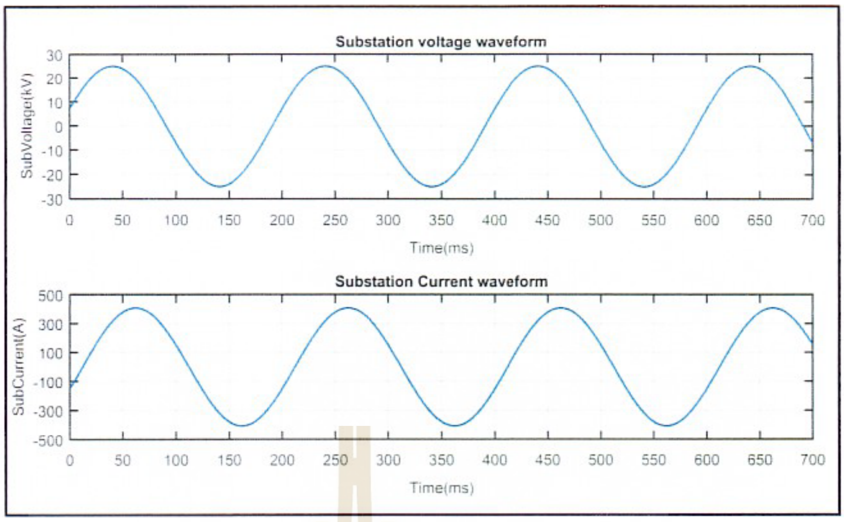


Figure A.150 Harmonic Distortion Voltage and Current at train wave of the four-quadrant converter: C-Type TF=53 On-board

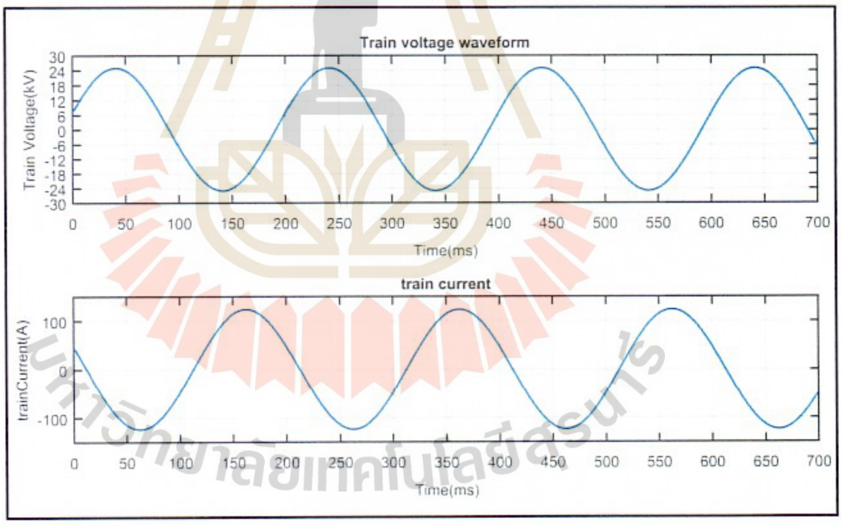


Figure A.151 Harmonic Distortion Voltage and Current at substation wave form of the four-quadrant converter: C-Type TF=53 On-board

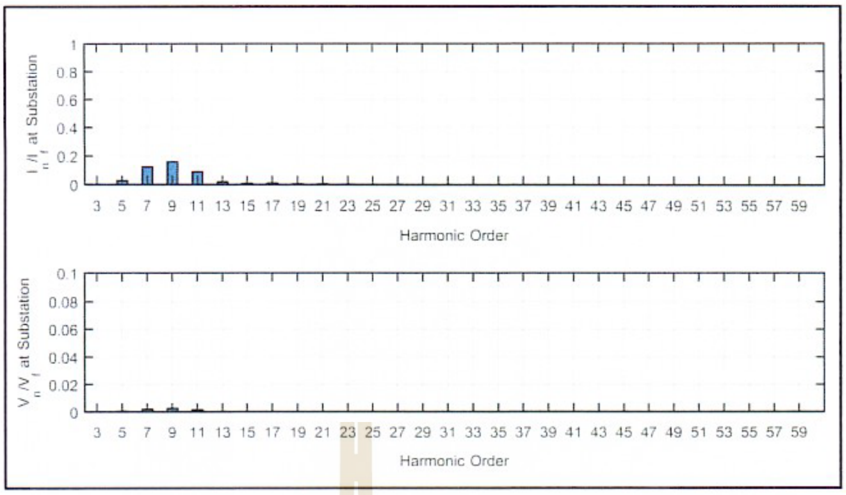


Figure A.152 Harmonics spectrum of Current and Voltage at the train of the four-quadrant converter: C-Type TF=53 On-board

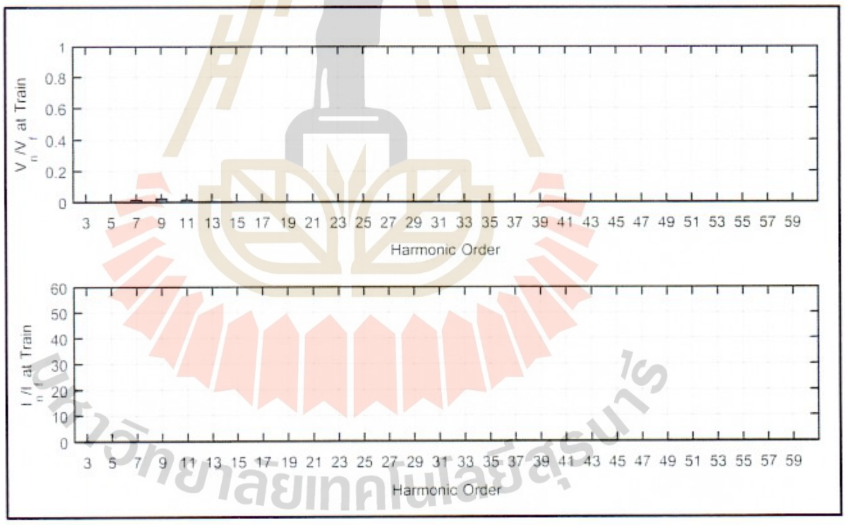


Figure A.153 Harmonics spectrum of Current and Voltage at the Substation of the four-quadrant converter: C-Type TF=53 On-board

Table A.65 THD Voltage results of installing C-Type filters TF=53 on-board

Bus voltage *V* at PCC 25 kV	THD Substation (%) (Simulation)		THD Train (%) (Simulation)		THD (%) IEEE519-2014 Standard
	No Filter	C-Type	No Filter	C-Type	
Minimum	0.00	0.00	0.00	0.00	5.00
Average	0.05	$2x10^{-4}$	0.37	$4x10^{-4}$	5.00
Maximum	0.11	$1x10^{-3}$	4.12	$2x10^{-3}$	5.00

Table A.66 TDD current results of installing C-Type filters TF=53 on-board

Maximum harmonic current distortion in percent of I_L												
Individual harmonic order (odd harmonics) at Substation												
I_{SC}/I_L (100 < 1000)	$3 \le h < 11$		$11 \le h < 17$		$17 \le h < 23$		$23 \le h < 35$		$35 \le h \le 50$		TDD	
	No Filter	C-Type	No Filter	C-Type	No Filter	C-Type	No Filter	C-Type	No Filter	C-Type	No Filter	C-Type
Minimum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Average	3.56	0.01	2.23	$7x10^{3}$	0.75	$9x10^{4}$	0.38	$2x10^{4}$	0.24	$5x10^{5}$	3.71	0.04
Maximum	7.69	0.19	4.82	0.09	1.62	0.02	0.81	$5x10^{3}$	0.51	$2x10^{3}$	8.03	0.09
IEEE514-2014	12.0		5.5		5.0		2.0		1.0		15.0	

APPENDIX B

List of Publications

Available online at www.sciencedirect.com
ScienceDirect
ELSEVIER
Energy Reports 8 (2022) 1116–1124
ENERGY REPORTS
www.elsevier.com/locate/egyr

2022 The 4th International Conference on Clean Energy and Electrical Systems (CEES 2022), 2–4 April 2022, Tokyo, Japan

Harmonic mitigation of AC electric railway power feeding system by using single-tuned passive filters

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Abstract

Harmonic is an important factor affecting the quality of the power transmission system. caused by non-linear loads and power conversion devices. In this research, several train simulation samples of the city line Airport Rail Link (ARL) electric train were used to simulate the effects of harmonics on the power electric substation (ESS) by calculating the Total Harmonic Distortion of voltage (THDv) and current (THDi). Then compared with IEEE519-2014 standards to indicate the quality of power found that THDi 35th–50th exceeds the standard. In addition, the comparison of the harmonic reduction effect of the sample train from the single tuned passive filter designs of 3rd, 5th, 7th, and 11th showed that the 11th filter was able to keep the THD within the standard.

Peer-review under responsibility of the scientific committee of the 4th International Conference on Clean Energy and Electrical Systems, CEES, 2022.

Keywords: Harmonic; Total Harmonic Distortion; Characteristic harmonics; Harmonic model; Railway system; Single tuned passive filter

1. Introduction

The railway has made significant progress in terms of speed, technology, and energy management in recent years, but there are still significant issues with power quality resulting from nonlinear loads and the power-electronic energy conversion of the electric railway system, which affects the overall power quality of the electric train system.

This research use, The City line Airport Rail Link (ARL) as a case study [1], the ARL railway line in Thailand uses 1 × 25 kV, 50 Hz ESS. Suvarnabhumi Airport is connected to Bangkok's center via ARL. It began by understanding the multi-train movement, the railway power feeding system, and the energy computation of running train consumption [2]. Learning about the occurrence, effects of harmonics [3], analysis of the transmission of harmonics through electric power transmission systems including types of harmonics [4]. In-depth information on electric powertrains and methods for reducing or eliminating harmonics occurring in power transmission systems [5]

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Peer-review under responsibility of the scientific committee of the 4th International Conference on Clean Energy and Electrical Systems, CEES, 2022.

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Study of Harmonic and Simulation of an AC Electric Railway System

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***Abstract*— A harmonic problem is a concern in railway systems because it impacts on performances of railway traction and power quality of the utility supply grid. The harmonic distortion is mainly caused by power electronic equipment onboard electric trains which consuming a huge amount of power due to its powering mode of operations. This paper studies characteristics of harmonic distortion in AC single-phase railway. Total harmonic distortion (THD) is observed when short circuit current (SCC) at electrical substation (ESS) is variant. Referring to the standard GB/T 14549-93, voltage harmonic distortion of the ESS are exhibited and the reported in accordance with the short circuit level of the substation. From which satisfactory results it shows that the short circuit level of the substation should not be less than 350 A in order to meet the minimum requirement of the GB/T 14549-3 standard.**

Keywords—Harmonic, Total harmonic distortion, Characteristic Harmonics, Harmonic model, Railway system

I. INTRODUCTION

The railway in present has been great advances in the development of speed, technology and energy management, but there are still significant problems with the power quality from the power-electronic energy conversion of the electric railway system such as caused by diode rectifiers, voltage source converters (VSC), electric traction motors and electrical equipment onboard, etc. These can create harmonic distortion, affecting the power quality of the electric railway system as a whole. Therefore, analyzing power qualities of electric railways is important in order to improve and fix these issues.

In order to manage the power quality problem, it first started from learning the train movement, the railway power feeding system, and energy calculation of running train consumption described in [1], [2]. Study of the causes and suppression of the harmonic distortion [3], harmonic characterization, harmonic effects [4] and the harmonic analysis in the power transmission system of the electric railway is showed in [5]. In addition, a method for calculating harmonic contents in the energy transmission system [6] and for Calculating the total harmonic distortion (THD) in the electric system [7] are presented. After the total harmonic distortion is successfully calculated, its values can be compared with those of the minimum standard requirement appeared in the GB/T 14549-93 [8]. Unless the calculated THD is not met the requirement, further studies to reduce or suppression harmonic distortion [9] - [12], for example, the use of a passive filter solution to reduce harmonic distortion will be conducted in a future work.

In this report, only the harmonic characterization in an electric railway power system is studied in such a way that modelling of a railway power feeding system is formulated. By varying the short circuit current at 25-kV busbar side of an electrical feeder substation [13] is to investigate the characteristics of the total harmonic distortion occurring in the railway power system, e.g. voltage at substation terminal busbar, voltage at a train location, current injection from the power substation and current drawn by a running train. Total harmonic distortion of voltage (THDV) is comparing with those values given in the GB/T 14549-93 standard requirement.

In this report, data of CRH380A, China HST is used for test, These include parameters of the power feeding system, traction vehicle data and measured harmonic spectra [7].

II. AC RAILWAY SYSTEM AND METHODOLOGY

A. AC Railway Single-Phase Power Supply System

Considering an electrical power supply system of AC single-phase railways provides electric power to the railway from the power network by establishing a single-phase traction transformer substation. Regardless to the transformer connection, the electrical power is distributed to the overhead contact system. A railway vehicle is running on running rail that is laid beneath the earth surface as shown in Fig. 1.

In order to limit the short circuit current at the same voltage level. Method is to increase the inductive reactance at the ESS. The first is increase inductance by adding rectors, the second is removing part of the circuit from the fault path by current limiters. In this paper present 8 level of short circuit current to simulation.

BIOGRAPHY

Mr. Kongtun Kritsanasuwan was born on December 26, 1997, in Muang District. Nakhon Ratchasima Province Graduated with a Bachelor of Engineering degree (Electrical Engineering) from Suranaree University of Technology Nakhon Ratchasima Province in 2020 and entered a master's degree in engineering (Electrical Engineering) at Suranaree University of Technology. Has research experience on railway electrification, power system analysis, and power quality in electrified railway.