**Harmonics Analysis at Low Voltage (LV) Systems in Universiti Teknologi PETRONAS (UTP)**

by

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Dissertation submitted in partial fulfilment of
the requirement for the
Bachelor of Engineering (Hons)
(Electrical & Electronic)

JANUARY 2017

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CERTIFICATION OF APPROVAL

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Approved by,

______________________________

(Ir. Dr. Mohd Faris Bin Abdullah)

UNIVERSITI TEKNOLOGI PETRONAS

SERI ISKANDAR, PERAK

JANUARY 2017

# CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

HUSNA KHALILAH BINTI MOHD ALA’UYUN

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# ABSTRACT

Harmonics has been part of power quality problem since years ago. Harmonics is stated as the frequency which is a multiple integer of its fundamental frequency of 50 Hz or 60 Hz. There are three groups of harmonic which include positive, negative and zero sequence harmonic. Today, the usage of non-linear loads which contribute in producing a distorted waveform is increasing and it is a serious matter to maintain the quality of voltage and current waveform. This research focused on analysing and identifying the harmonics content at low voltage (LV) system in Universiti Teknologi PETRONAS (UTP). In this research, the levels of harmonics are measured at the point of common coupling (PCC) where the data taken are using the power quality analyser. These data are analysed to identify the sources of harmonics. The level of harmonics that can be accepted are based on the Institute of Electrical and Electronic Engineering (IEEE) Standard 519 where it sets a limit by providing a guideline for the levels of harmonics produced by electric utility or customer. There are a total of 24 main switch boards (MSB) in UTP. Based on the IEEE, the total harmonics distortion voltage measured, all of the 24 MSB are all within 5 %. However, 17 out of 24 of the MSB are not within the TDD limit and only 7 are within the limit. MSB ETS and PC1 are focused on for further analysing of harmonics. The high voltage (HV) side are measured in ETS and it is obtained that the harmonic content of $5^{th}$, $7^{th}$, $11^{th}$, $13^{th}$, $17^{th}$ and $19^{th}$ contributes in high magnitudes of current. Thus, the LV side and the HV side of the MSB ETS are almost the same because the harmonic spectrums that occur in LV side also occur in HV side. At PC1, Blocks 13, 15 and 16 are involved. From the measurement, loads in Blocks 16 which are the electrical discharge machine and the wire cutting machine are the one that contributed to the high harmonics.

# ACKNOWLEDGEMENT

During the two semester of final year, I am able to finish my Final Year Project. Throughout the periods, the project is able to be done from guidance and helps from several individuals that contribute their times.

Primarily, I would like to express my gratitude to my supervisor Ir. Dr. Mohd Faris Bin Abdullah who gave me an opportunity to do this project, which also has helped me in assisting and expert guiding throughout the two semesters. Besides, I am also thankful to technicians Mrs Noralyza, Mr. Zuraimi and Mr Yassin helping for the measurement of harmonics. Without them, I would not be able to finish my project.

Lastly, I would like to thank my dear family and friends for all the encouragement and supports they gave me. I also want to thank to those who have been directly or indirectly helps me during my two semesters of Final Year Project.

# CHAPTER 1

# INTRODUCTION

## 1.1 Background Study

In power system, power quality problem is an unwanted phenomenon such as harmonic, surge, transient etc. Harmonic is distorted current or voltage waveforms causes by short pulses when flow back to the other part of power system. Harmonic in the electrical system is commonly caused by the non-linear load which is generated everywhere in LV system.

There are three groups of harmonic which include positive, negative and zero sequence harmonic. Positive sequence harmonic consist of 1st, 4th, 7th, 10th etc. order of harmonic. These harmonic develop current that rotate in same direction with the fundamental frequency. For negative sequence harmonic, it is the vice versa of the positive sequence where it includes 2nd, 5th, 8th, 11th etc. order of harmonic. There is one more group of harmonic which is zero sequence harmonic. The current does not rotate in any direction and it flows in the neutral wire which leads to additional losses in the power system. Triplen harmonics are known as zero sequence harmonics which are 3rd, 6th, 9th and etc. However, it is rarely to find even numbered harmonic in AC system. This is because even harmonic does not exist if the waveform is symmetry.

Since harmonic may cause malfunction or failure of devices, therefore it is very important to measure and analyse the harmonic content in any system particularly in UTP LV system.

## 1.2 Problem Statement

In 2008, there have been many reported case of equipment damage in UTP suspected due to harmonics. During that time UTP had hired a consultant to do the harmonic study which was to identify the harmonic level in UTP's electrical system. The result of the study showed that the total harmonic distortion for voltage (THDv) for all academic blocks measured were found low and meeting PETRONAS Technical Standard (PTS) and therefore it was not a concern and problem to UTP. Total harmonic distortion for current (THDi) was generally high and mostly exceed IEEE standards. However, despite the high percentage of THDi, the actual current found to be low and it below the cable current carrying capacity. As time goes by, the LV system is also growing and the harmonics level in UTP should be re-measured and re-analysed.

## 1.3 Objectives

i. To measure the harmonic content at LV distribution system in UTP.
ii. To analyse the harmonic content and compare with previous measurement.
iii. To identify the source of harmonic where their voltage and current THD exceed the IEEE 519 Standard limit.

## 1.4 Scope of Study

This study aims to analyse the harmonic content at LV system in UTP where the measurement of the harmonics involve the steady state voltage and current. Thus, through the measurement of the harmonics content, the sources of harmonics are identified based on the limits from IEEE 519-1992 Standard. Besides that, the content of harmonics are analysed based on the data collected from harmonics measurement.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Definition of Power Quality

Power quality covers all of the power system, thus the quality of the electric supply is a serious matter that needs to be overcome. Although there is no definite definition of power quality, it significantly affects the efficiency, security, and reliability of power systems and electric machinery. Power quality has been a concern since many years before. Nowadays, it is more of a concern due to the equipment use is giving impact on poor power quality. Basically, the power quality is conveyed by the quality of voltage and current. Thus, at rated voltage and frequency, sinusoidal waveform is maintained by computing, analysing and improving the bus voltage [1]. The power quality can be described in terms of voltage, current or deviation of frequency which is a problem occurs that affect the end-users equipment. It is stated from Standard IEEE1100 that power quality is “the concept of powering and grounding sensitive electronic equipment in a manner suitable for the equipment” [2], [3], [4].

## 2.2 Problems of Power Quality

In power quality there is bad and good power quality because it depends on the equipment used. Hence, the problems of power quality must be known for the issues to be solved. In power system, there are several phenomena that concern power quality which are disturbances on power frequency, interference on electromagnetic, power system transients, electrostatic discharge, power system harmonic, power factor and grounding and bonding [2], [5]. A frequency variation can results in data loss, program failure, equipment lock-up or complete shutdown. It involves a change in frequency from the fundamental frequency caused by erratic operation of emergency generators or unstable frequency power sources. Radio Frequency Interference (RFI) and Electromagnetic Interference (EMI) cause unwanted effects in the circuits of computer systems. Sources of the problems include motors, relays, motor control devices, broadcast transmissions, microwave radiation, and distant electrical storms. RFI, EMI and other frequency problems can cause equipment to lock-up, and data error or loss [2].

## 2.3 Harmonics Standards

IEEE Standard 519 is “IEEE Recommended Practices and Requirement for Harmonic Control in Electrical Power System”. This standard sets a guideline and limits the harmonic control in designing the power system for linear and non-linear loads. The IEEE Standard 1159 sets that the consumer has the capability to control the harmonic current and the utility also holds the liability in generating a better voltage sine wave [6].

The IEEE Standard 519-1992 limits the level of harmonic at the customer service entrance or point of common coupling (PCC). End user’s current distortion is limited based on the size of load and the power supplier’s voltage distortion based on voltage level. Table 1 shows the limit of harmonics sets by IEEE Standard 519. The total harmonic voltage distortion is only up to 5 % and for individual harmonic voltage is limited to 3 % for 69 kV and below.

IEEE-519 stated the limit sets for current distortion is the ratio between the maximum short circuit current ($I_{Sc}$) at the PCC and maximum demand load current ($I_L$). Table 2 shows the current harmonic limit based on IEEE-519 Standard [7].

*Table 1 Voltage Distortion Limit.*

**Voltage Distortion Limits**

| Bus Voltage at PCC | Individual Voltage Distortion (%) | Total Voltage Distortion THD (%) |
|---|---|---|
| Below 69 kV | 3.0 | 5.0 |
| 69 kV to 161 kV | 1.5 | 2.5 |
| 161 kV and above | 1.0 | 1.5 |
| NOTE: High-voltage systems can have up to 2.0% THD where the cause is an HVDC terminal that will attenuate by the time it is tapped for a user. | | |

*Table 2 Current Distortion Limit.*

| Maximum Harmonic Current Distortion in Percent of $I_L$ | | | | | | |
|---|---|---|---|---|---|---|
| Individual Harmonic Order (Odd Harmonics) | | | | | | |
| $I_{SC}/I_L$ | <11 | $11 \le h < 17$ | $17 \le h < 23$ | $23 \le h < 35$ | $35 \le h$ | TDD |
| <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 |
| Even harmonics are limited to 25% of the odd harmonic limits above. | | | | | | |
| Current distortions that result in a dc offset, e.g. half-wave converters, are not allowed. | | | | | | |
| * All power generation equipment is limited to these values of current distortion, regardless of actual $I_{sc}/I_L$. | | | | | | |

Where

- $I_{sc}$ = maximum short-circuit current at PCC.
- $I_L$ = maximum demand load current (fundamental frequency component) at PCC.
- TDD = Total demand distortion (RSS), harmonic current distortion in % of maximum demand load current (15 or 30 min demand).
- PCC = Point of common coupling.

## 2.4 Definition of Harmonics

Harmonics is one of the problems occur in power quality and defined as the component of periodic sinusoidal wave where the frequency is multiple integer of fundamental frequency of 50 Hz or 60 Hz respectively.

$$f = h\ x\ fundamental\ frequency \tag{1.0}$$

Sinusoidal waveform of harmonics current or voltage is viewed as optimum sinusoids signals which can be expressed as below:

$$v(t) = V\ sin(\omega t) \tag{1.1}$$

$$i(t) = I \sin(\omega t\ \pm\ \emptyset) \tag{1.2}$$

Where $v(t)$ is voltage function and $i(t)$ is current function. The symbol $\omega$ is known as frequency of the waveform, $\omega = 2\pi f$ which is measured in radian per second. If the current leads the voltage, the phase angle, Ø is positive and negative if the voltage leads the current. The non-sinusoidal distorted waveform can be stated as the total sum of harmonics frequencies that is multiple of integer and fundamental frequency [2].

Non-sinusoidal distorted waveform is expressed in Fourier Series where the harmonics frequencies are added forming a harmonic distortion. The Formula of Fourier Series as (1.3) where$C_0$ is the magnitude of the DC component, $C_h$ $and$ $\emptyset_h$is the magnitude and phase angle of the $h$th harmonic component. Distorted waveform only has components of odd harmonics which are 3, 5, 7, etc because the half cycles of positive and negative waveform is identical in shape [1].

$$f(t) = C_0 + \sum_{h=1}^{\infty} C_h \sin(h\omega t + \emptyset_h) \tag{1.3}$$

$$C_0 = \frac{a_0}{2} \tag{1.4}$$

$$C_h = \sqrt{a_h^2 + b_h^2} \tag{1.5}$$

$$\emptyset_h = \tan^{-1}\frac{a_h}{b_h} \tag{1.6}$$

## 2.5 Triplen Harmonics

Triplen harmonics are the odd harmonics which are multiple of third harmonics. Special consideration is given to triplen harmonics because in grounded wye systems the phase current added and flow into the neutral. The flowing of current into the neutral of the systems contributed to two problems that are overloading of the neutral and telephone interference. The overloading of current in neutral leads to failure of devices due to distorted voltage. The third harmonic current flows in neutral of the grounded-wye systems are added up three times resulting in high content of third harmonics [7].

## 2.6 Total Harmonics Distortion

Total harmonic distortion (THD) is used to determine the level of distorted harmonic current and voltage. It is determined in terms of percentage where the value of RMS for the harmonic wave is related to its fundamental frequency [1], [8], [9]. The equation of $THD_V$ and $THD_I$ are defined as follows:

$$V_{rms} = \sqrt{\sum_{h=1}^{\infty} V_h^2} \tag{1.7}$$

$$I_{rms} = \sqrt{\sum_{h=1}^{\infty} I_h^2} \tag{1.8}$$

$$THD_V = \frac{\sqrt{\sum_{h=2}^{\infty} V_h^2}}{V_1} \tag{1.9}$$

$$THD_I = \frac{\sqrt{\sum_{h=2}^{\infty} I_h^2}}{I_1} \tag{2.0}$$

## 2.7 Total Demand Distortion

Total demand distortion (TDD) is define as "the total root sum-square harmonic current distortion, in percent of maximum demand load current" based on IEEE-519. Equation (2.1) shows the formula of TDD where $I_L$ is the maximum demand load current measured at the PCC. High value of THD does not mean it is a threat to power system. TDD is used when the current distortion is high and the magnitude of harmonic current is low to avoid any misleading and difficulty. TDD is referred to the fundamental of the maximum demand load current while THD is based on the fundamental of the sample [9] [7].

$$TDD = \frac{\sqrt{\sum_{h=2}^{\infty} I_h^2}}{I_L} \tag{2.1}$$

## 2.8 Sources of Harmonics

Harmonics is produced from non-linear loads which can come from commercial or industrial loads. Commercial loads are type of nonlinear loads that produce a small harmonic such as fluorescent light and single phase power converter. The harmonic current and the impedance of the circuit can indicate the content of voltage distortion. The non-linear loads in industry have a low power factor where the capacitor banks are used to correct the power factor. Thus, it will draw harmonic currents from the load and might causing a resonant condition.

Power electronic loads with power converter is non-linear harmonic producing loads that include switch mode power supplies (SMPS), fluorescent light and other types of inverter and converter systems. These types of single phase power supply that use single phase full wave rectifiers are usually used in office buildings. Electronic devices that use SMPS such as computers, printers and photocopiers produce harmonics of very high frequency. SMPS is used as converter to convert dc to dc and smoothing the small dc output. The input ac source is regulated to dc voltage and is inverted back to ac by the switcher produce a very high harmonic frequency until it is converted back to dc. This electronic equipment produced a very high triplen harmonic and the neutral is additive where it can cause overloading of neutral conductors [7], [10].

Fluorescent lights are energy saving lights that require ballast. The ballast is required to discharge the current flowing in the tube by producing initial high voltage. The voltage will decrease and current will increase once the discharge has been established [7]. The harmonics content produced is mainly third and fifth harmonics which are odd sequence of harmonics [2]. At the line side, the power factor correction boost rectified the waveform where switching occur at a higher frequency [4], [6].

Besides single phase power converter, there is also three phase power converter using a six-pulse rectifier. Equipment such as adjustable speed drives is rectified by the six-pulse rectifier and it produces fifth and seventh harmonic current which are large harmonic current for six pulse rectifier. Twelve-pulse inverter is used to eliminate some of the fifth and seventh harmonic [6].

## 2.9 Effects of Harmonics

Non-linear load is the harmonics sources where it created distorted current waveform that is injected back into the power supply. The distorted waveform can affect the capacitor banks, transformers, motors and the telecommunication system equipment. The affected equipment can suffer from overloading on the neutral, overheating and losses leading to a great harmonic distortion.

Harmonics always occur at the capacitor banks forming a high waveform distortion of voltage. This is due to the resonance condition which involves the capacitor. The RMS current that flows in the capacitor has surpassed the limit of the RMS rated current of the capacitor causing it to overheat and malfunction.

Higher frequencies of harmonic voltages occur on motors can cause losses at the winding. It was found that the fifth harmonic and seventh harmonic occur in the motor. The fluxes of harmonic rotate at a different frequency than the fundamental frequency causing it to induce high frequency currents.

Interference in telecommunication is created due to the flows of harmonic current within the power system. The harmonics current produced are coupled by direct or indirect induction at the communication system. Thus, the current flow caused voltage drop [7], [11].

## 2.10 Mitigation of Harmonics

Harmonics can be controlled and reduced by using two types of filters. These filters are passive filters and active filters. These filters help to improve the power quality by reducing the unwanted harmonics [7].

In passive filters, harmonics can be reduced using the single tuned filters. The single tuned filter is tuned providing low impedance to a certain frequency of harmonic current and cancelling the harmonic current [7]. The low impedance of the filter is present due to the values of the capacitor and inductor chosen to filter out the harmonic frequency. The harmonic frequency circulates between the load and the filter due to the lower impedance of the filter. Thus, the harmonic will divert away from the load and source [2].

Besides passive filter, active filters are also used to mitigate the harmonics frequency. Active filters will cancel the harmonics occur in the non-linear load by generating current that match the harmonic current. Thus, the current is free from harmonics. Active filters can adjust to the changes of harmonics condition in each non-linear load while, passive filters are fixed on one harmonics condition [2].

# CHAPTER 3

# METHODOLOGY

## 3.1 Flow Chart

The main focus of the research is to analyse the harmonics content at LV system in UTP that exceed the IEEE 519 Standard by identifying the sources of the harmonics. The flow chart for the research is shown in Figure 1.

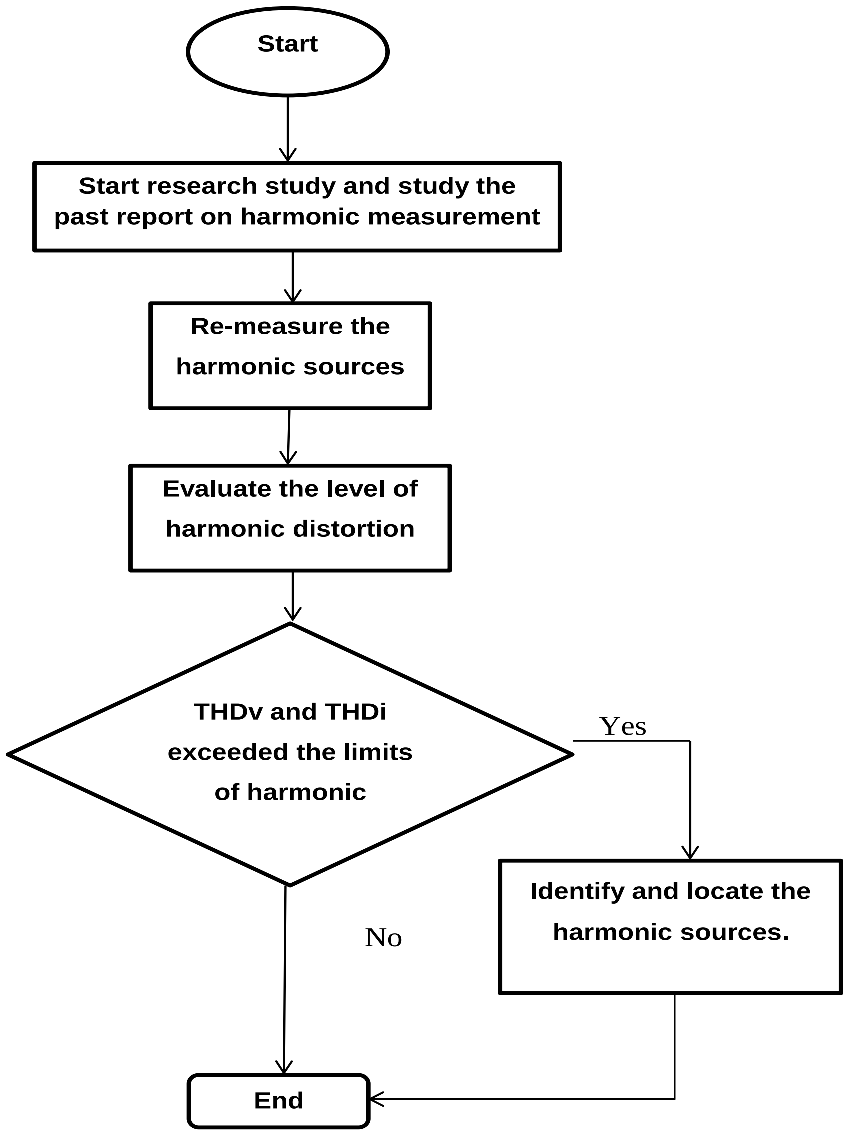


*Figure 1 Flow chart of the study.*

## 3.2 Literature Review

In the first phase, information are gathered and studied to gain more knowledge and understand about the project through books, journals, articles and other research papers. Report from recent case study is also studied before measurement can be done for a better understanding of the research.

Besides that, data from the past research was also studied and analysed to determine which substation in the UTP has exceeded the limits of harmonics based on the IEEE Standard 519-1992. The data is analysed in terms of harmonic content and distortion.

## 3.3 Re-measure the Harmonic Content

The next stage focusses on the measurement of harmonic the PCC. The harmonic will be re-measured so that it can be compared to the past case study. A total of twenty four (24) substations in UTP will be involved. The measurement is taken using the Fluke power quality analyser tool.

## 3.4 Evaluate the content of Harmonics

After the harmonics content has been measured for each substation, the level of harmonic distortion can be compared with the previous record. Measurements are taken again on the substation where the level of harmonic has exceeded the IEEE Standard 519-1992 to narrow down harmonics sources.

## 3.5 Identifying the Sources of Harmonics

This process is to identify the sources of harmonics. The sources of harmonics are identified by determining which substation has exceeded the limits. The substation is further zoomed until the last part to identify where the harmonics come from.

## 3.6 Tools

The tools required to complete the project is stated as below:

- Power Quality Analyser
  Fluke power quality analyser is used to measure the harmonic content and identify the sources of harmonic is shown in Figure 2.

*Figure 2 Fluke Power Quality Analyser.*

## 3.7 Gantt Chart & Key Milestone

### 3.7.1 FYP 1

The Gantt Chart and Key Milestone for FYP1 are shown in Figure 3.

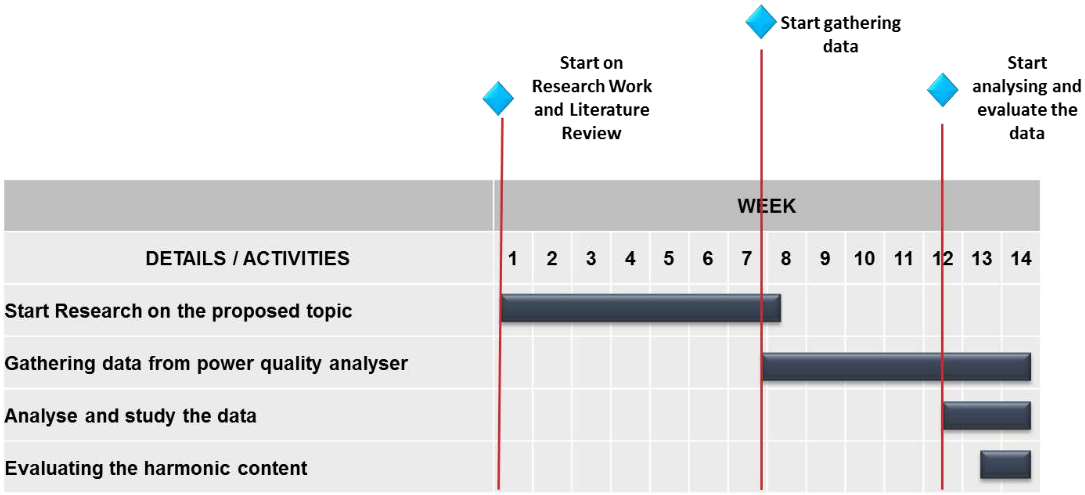


*Figure 3 Gantt Chart & Key Milestone of FYP1.*

### 3.7.2 FYP 2

The Gantt Chart and Key Milestone for FYP2 are shown in Figure 4.

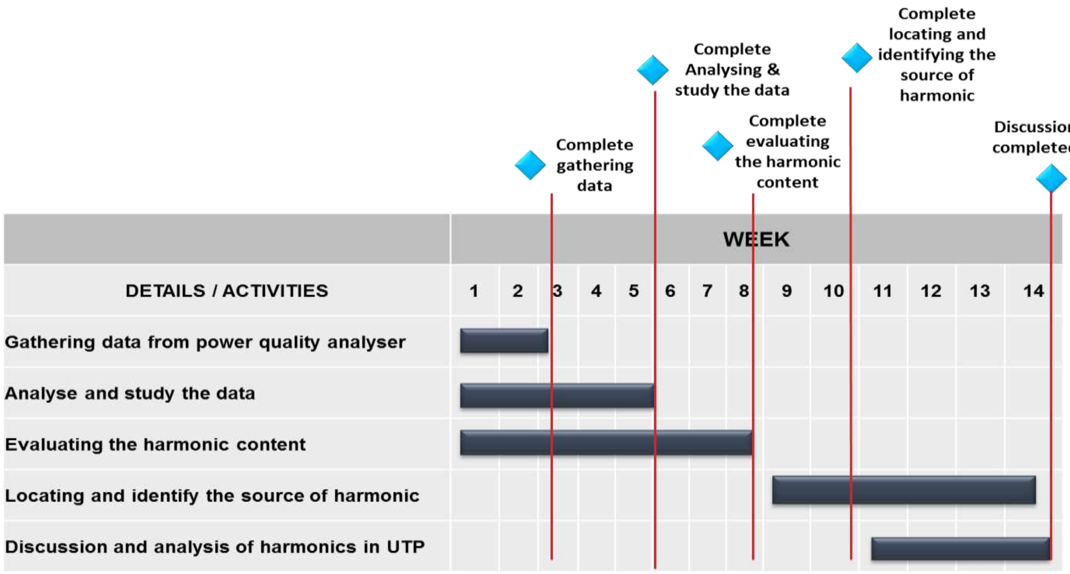


*Figure 4 Gantt Chart & Key Milestone of FYP2.*

# CHAPTER 4

# RESULTS

## 4.1 Total Harmonic Distortion Measured at MSB in UTP

Harmonic measurement at every MSB in UTP was done using the power logger. There are a total of 24 MSB located in UTP as shown by single line diagram in Appendix A. Analysis for THDv and TDD are done from the data collected at each PCC. Table 3 indicated that there are total of 17 MSB exceeded the TDD limit and there are 7 MSB that are within the TDD limit. The THDv in Table 4 shows that all of the MSB are within the THDv limit.

*Table 3 TDD exceed the limit.*

| Total MSB | 24 |
|---|---|
| THDv within limit | 24 |
| THDv exceed within limit | 0 |
| TDD within limit | 7 |
| TDD exceed within limit | 17 |

### 4.1.1 THDv Measured at MSB in UTP

Table 4 shows the THDv measured in UTP LV system. Based on IEEE Standard 519, THDv limit should not exceed 5 %. Results in Table 4 shows the THD of voltage meets the IEEE Standard 519 where it did not exceed the 5 % limits.

*Table 4 THDv measured at PCC.*

| MSB | THDv Red (%) | THDv Yellow (%) | THDv Blue (%) |
|---|---|---|---|
| DS1B | 3.12 | 2.21 | 2.63 |
| MIS | 2.99 | 2.16 | 2.22 |
| 5A | 2.89 | 2.46 | 2.71 |
| DS1A | 2.79 | 2.33 | 2.19 |
| SS2 | 2.7 | 2.62 | 2.75 |
| MB2 | 2.451 | 2.464 | 2.45 |
| PC1 | 2.411 | 2.277 | 2.236 |
| PD2 | 2.26 | 2.24 | 2.19 |
| 5-2 | 2.2 | 2 | 2 |
| PD1 | 2.104 | 1.931 | 1.963 |
| MPH | 2.08 | 2.125 | 2.187 |
| MSB5 | 2.05 | 2.92 | 2.79 |
| DS2 | 2.02 | 2.48 | 2.99 |
| PC2 | 2.012 | 1.906 | 1.934 |
| SS4 | 1.89 | 1.9 | 1.77 |
| 5-1 | 1.7 | 1.7 | 1.6 |
| ETS | 1.6 | 1.6 | 1.6 |
| MB1 | 1.499 | 1.462 | 1.402 |
| MSB 4 | 1.271 | 1.298 | 1.34 |
| MSB 3 | 1.203 | 1.32 | 1.231 |
| 5B2 | 1.135 | 1.098 | 1.102 |
| MSB 1 | 1.15 | 1.12 | 1.18 |
| COMPACT | 1.1 | 1.1 | 1.1 |
| 5B1 | 1.095 | 1.047 | 1.041 |

### 4.1.2 TDD Measured at MSB in UTP

The limits for the THD of current stated in IEEE Standard 519 depends on the ratio of short circuit current to the maximum load current at the point of common coupling which use the TDD as in Appendix B. Table 5 shows the MSB that is within the TDD limits. There are total of 7 MSBs within the TDD limit which are MSB MPH, 3, 4, DS1A, 5A, 5-1, MIS.

*Table 5 TDD within the limit.*

| MSB | Phase | TDD Limit (%) | TDD (%) |
|---|---|---|---|
| MPH | Red | 12 | 3 |
| | Yellow | 12 | 4 |
| | Blue | 12 | 3 |
| | Neutral | 12 | 6 |
| MSB 3 | Red | 12 | 2 |
| | Yellow | 12 | 1 |
| | Blue | 12 | 2 |
| | Neutral | 12 | 11 |
| MSB 4 | Red | 12 | 3 |
| | Yellow | 12 | 3 |
| | Blue | 12 | 3 |
| | Neutral | 12 | 5 |
| DS1A | Red | 12 | 3 |
| | Yellow | 12 | 3 |
| | Blue | 12 | 4 |
| | Neutral | 12 | 11 |
| 5A | Red | 8 | 7 |
| | Yellow | 8 | 8 |
| | Blue | 8 | 8 |
| | Neutral | 8 | 8 |
| 5-1 | Red | 8 | 1 |
| | Yellow | 8 | 1 |
| | Blue | 8 | 2 |
| | Neutral | 8 | 8 |
| MIS | Red | 12 | 11 |
| | Yellow | 12 | 12 |
| | Blue | 12 | 11 |
| | Neutral | 12 | 11 |

Table 6 shows the results of the MSB that exceeded their TDD limits. The highest TDD recorded is at MSB located at ETS where all phase exceed with a high percentage of 289 %, 235 %, 134 %, and 222 % for each red, yellow, blue and neutral phase.

There are 4 MSB where all of the phase exceeded their TDD limit at MSB ETS, 5B2, PC1 and PD1. While for MSB DS2, COMPACT, PC2, MSB5, SS4, MB2, SS2, MSB1, DS1B and, 5-2, the TDD limit only exceeded at neutral phase. For MSB at MB1 the TDD limit exceeded at red and neutral phase and for MSB at 5B1 the TDD limit exceeded at red, yellow and neutral phase. While for MSB PD2, the TDD limit exceeded at the yellow, blue and neutral phase.

*Table 6 TDD exceed the limit.*

| MSB | Phase | TDD Limit (%) | TDD (%) |
|---|---|---|---|
| ETS | Red | 15 | 289 |
| | Yellow | 15 | 235 |
| | Blue | 15 | 134 |
| | Neutral | 15 | 222 |
| 5B2 | Red | 15 | 60 |
| | Yellow | 15 | 58 |
| | Blue | 15 | 79 |
| | Neutral | 15 | 94 |
| PC1 | Red | 15 | 44 |
| | Yellow | 15 | 41 |
| | Blue | 15 | 46 |
| | Neutral | 15 | 48 |
| PD1 | Red | 12 | 17 |
| | Yellow | 12 | 13 |
| | Blue | 12 | 20 |
| | Neutral | 12 | 35 |
| 5B1 | Red | 15 | 31 |
| | Yellow | 15 | 23 |
| | Blue | 15 | 10 |
| | Neutral | 15 | 228 |
| PD2 | Red | 15 | 13 |
| | Yellow | 15 | 25 |
| | Blue | 15 | 17 |
| | Neutral | 15 | 84 |

| | | | |
|---|---|---|---|
| MB1 | Red | 8 | 9 |
| | Yellow | 8 | 8 |
| | Blue | 8 | 8 |
| | Neutral | 8 | 14 |
| DS2 | Red | 12 | 8 |
| | Yellow | 12 | 10 |
| | Blue | 12 | 11 |
| | Neutral | 12 | 39 |
| COMPACT | Red | 15 | 9 |
| | Yellow | 15 | 11 |
| | Blue | 15 | 11 |
| | Neutral | 15 | 63 |
| PC2 | Red | 12 | 4 |
| | Yellow | 12 | 4 |
| | Blue | 12 | 4 |
| | Neutral | 12 | 54 |
| MSB 5 | Red | 12 | 9 |
| | Yellow | 12 | 8 |
| | Blue | 12 | 9 |
| | Neutral | 12 | 50 |
| SS4 | Red | 12 | 10 |
| | Yellow | 12 | 12 |
| | Blue | 12 | 9 |
| | Neutral | 12 | 39 |
| MB2 | Red | 8 | 3 |
| | Yellow | 8 | 3 |
| | Blue | 8 | 3 |
| | Neutral | 8 | 27 |
| SS2 | Red | 12 | 7 |
| | Yellow | 12 | 4 |
| | Blue | 12 | 12 |
| | Neutral | 12 | 24 |
| 5-2 | Red | 8 | 3 |
| | Yellow | 8 | 4 |
| | Blue | 8 | 3 |
| | Neutral | 8 | 24 |
| MSB 1 | Red | 12 | 1 |
| | Yellow | 12 | 3 |
| | Blue | 12 | 1 |
| | Neutral | 12 | 23 |
| DS1B | Red | 12 | 5 |
| | Yellow | 12 | 4 |
| | Blue | 12 | 10 |
| | Neutral | 12 | 16 |

### 4.1.3 Harmonic Spectrum of TDD within limit at each MSB

Figure 5, 6, 7, 8, 9, 10, 11 shows the harmonic spectrum of the MSB within the TDD limit. These 7 MSBs does not need re-measurement since they are within their TDD limits as shown in Table 5.

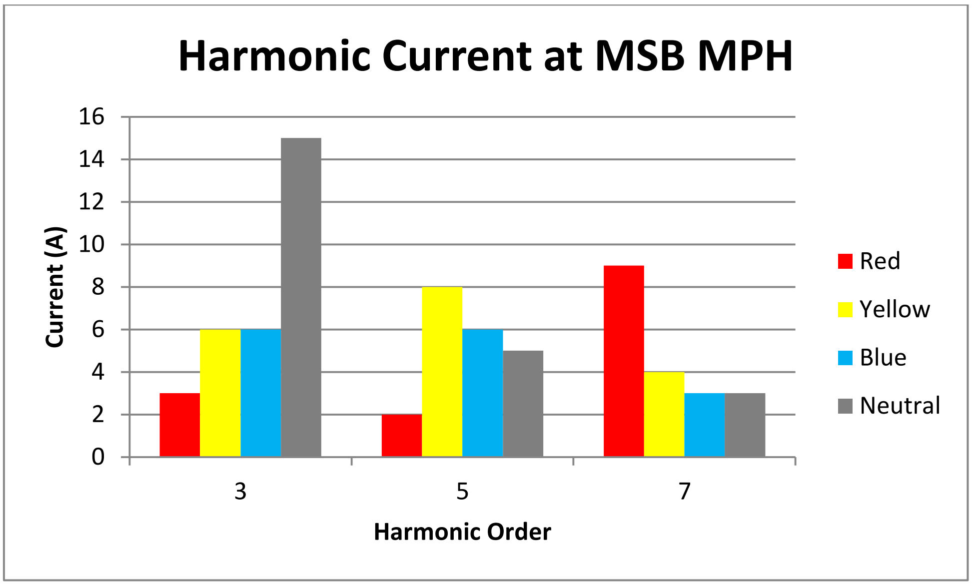


*Figure 5 Current Harmonic Spectrum at MSB MPH.*

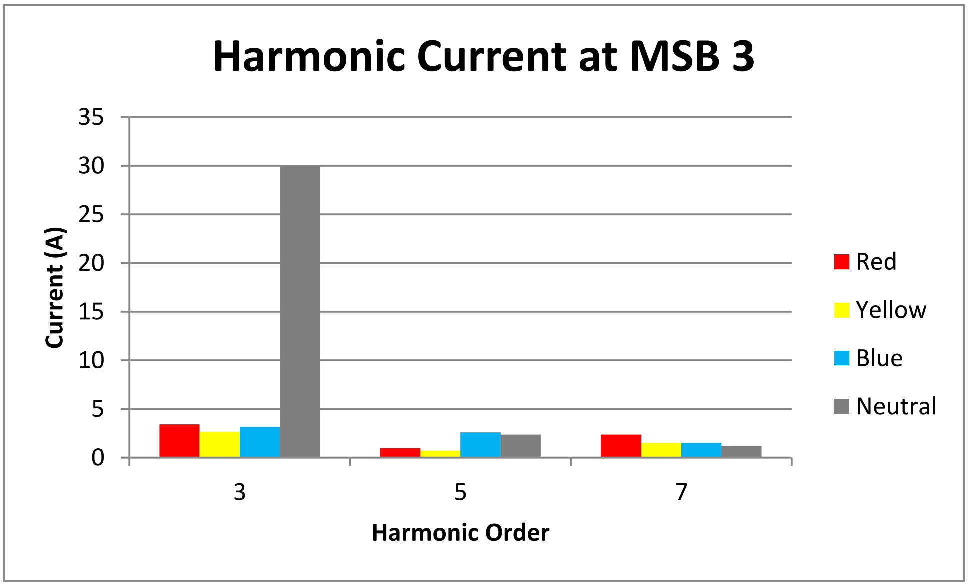


*Figure 6 Current Harmonic Spectrum at MSB 3.*

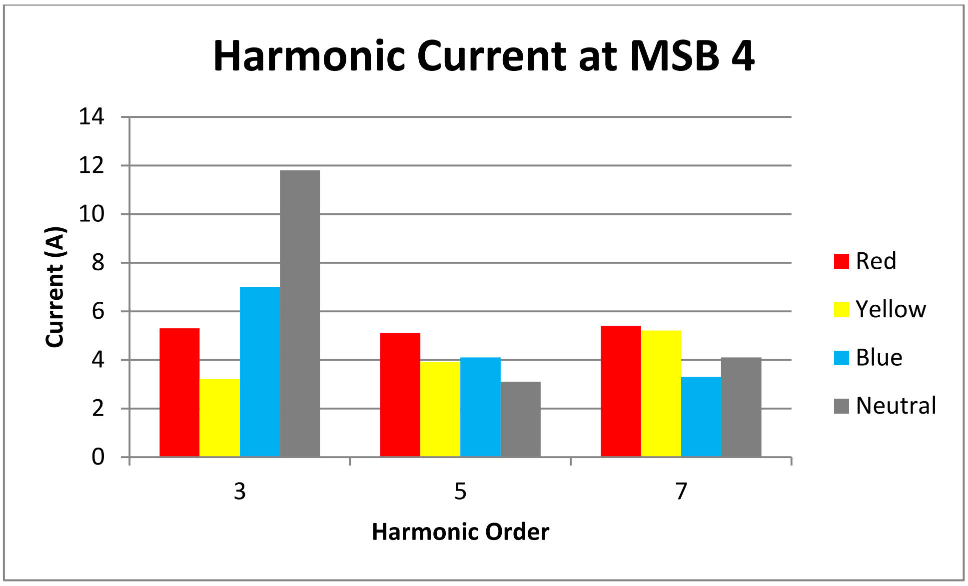


*Figure 7 Current Harmonic Spectrum at MSB 4.*

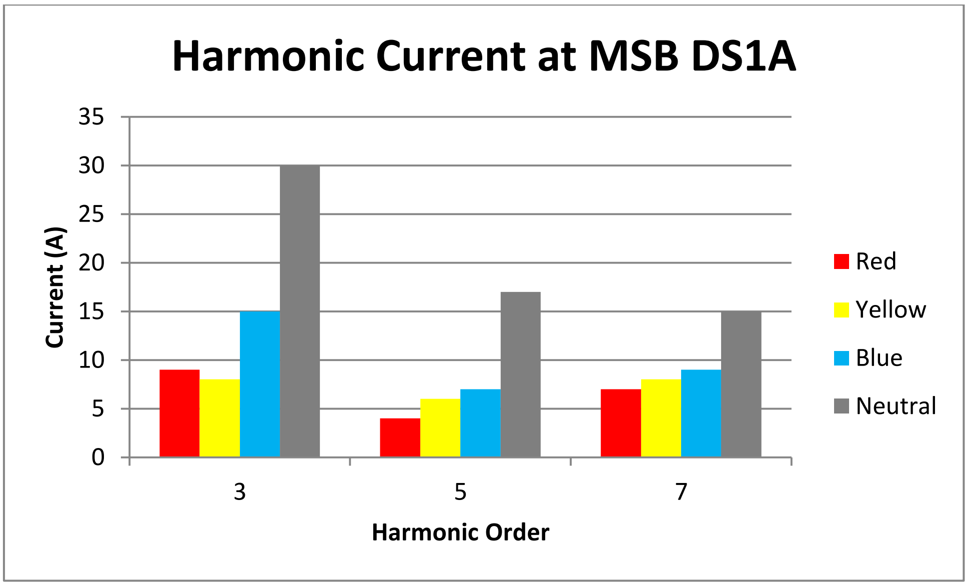


*Figure 8 Current Harmonic Spectrum at MSB DS1A.*

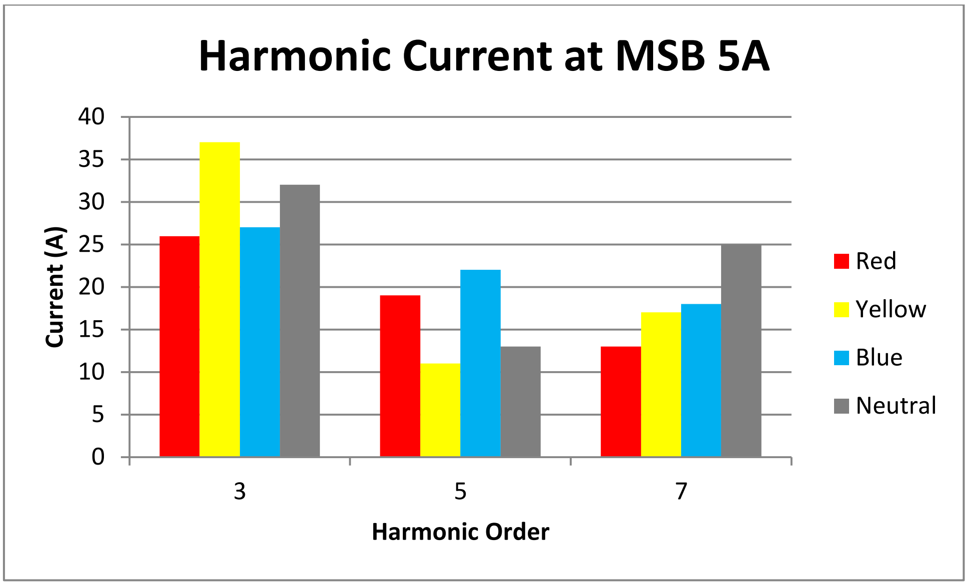


*Figure 9 Current Harmonic Spectrum at MSB 5A.*

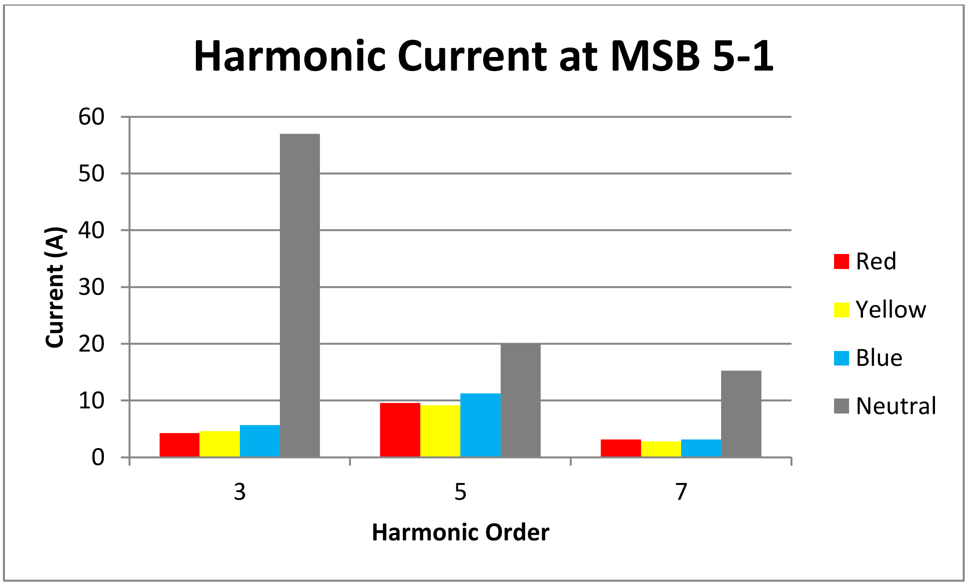


*Figure 10 Current Harmonic Spectrum at MSB 5-1.*

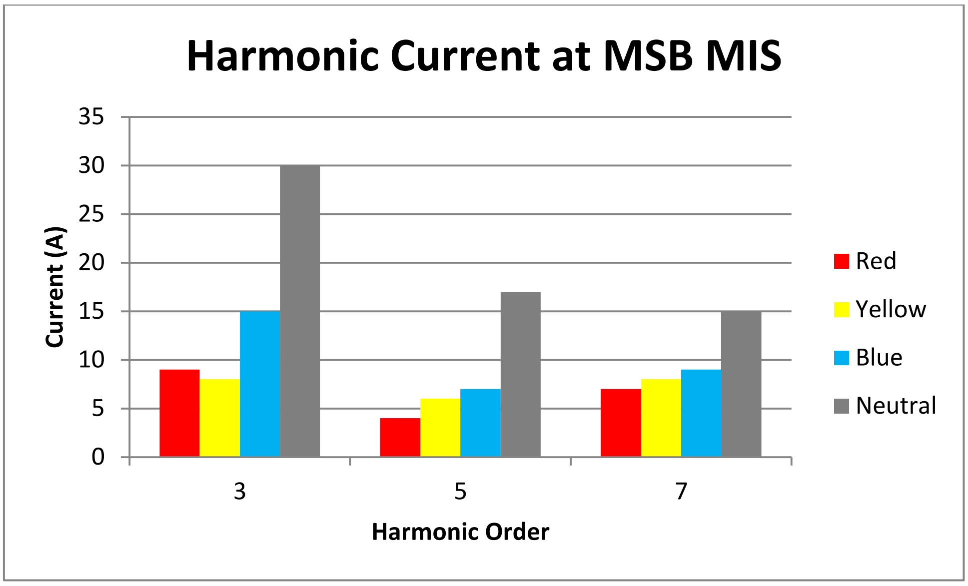


*Figure 11 Current Harmonic Spectrum at MSB MIS.*

### 4.1.4 Harmonic Spectrum of TDD exceed within limit at each MSB

Figure 12 shows the current harmonic spectrum measured at MSB ETS. It is obvious that the 19$^{th}$ harmonic has the highest percentage of phase current.

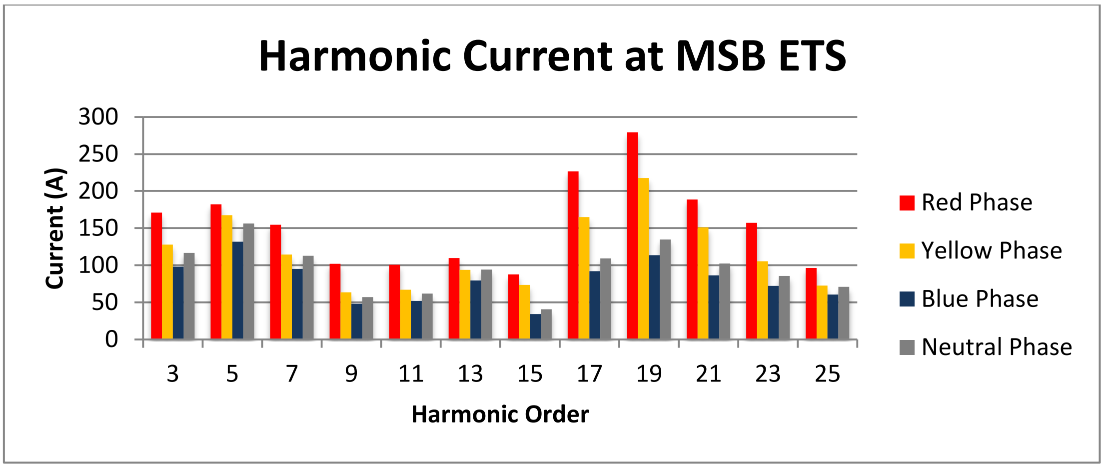


*Figure 12 Current Harmonic Spectrum at MSB ETS.*

Figure 13 shows the current harmonic spectrum at MSB 5B2. The third harmonic current is the highest spectrum among other harmonic order. The neutral phase shows the highest reading followed by the red, blue and yellow phase.

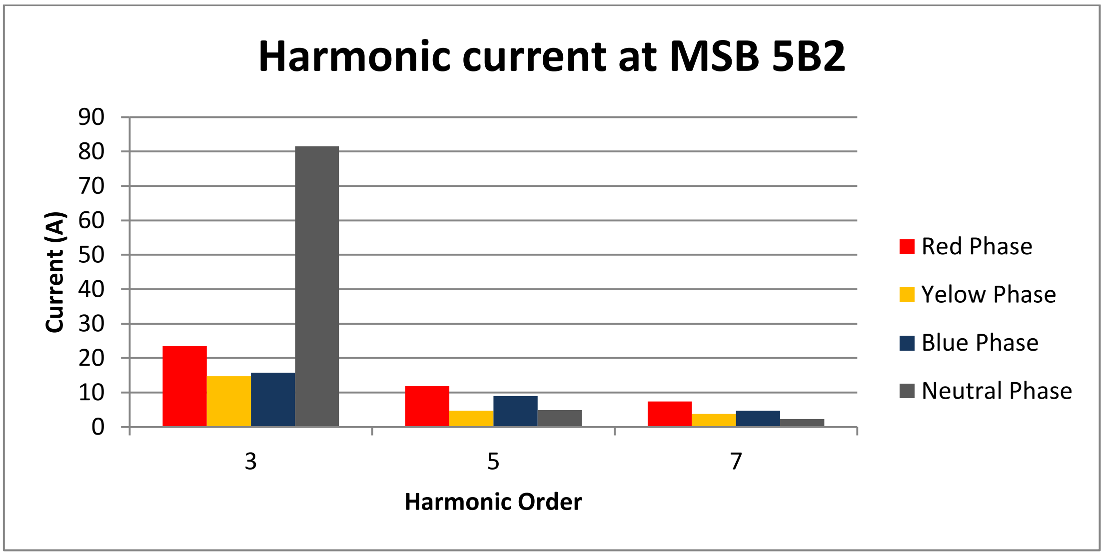


*Figure 13 Current Harmonic Spectrum at MSB 5B2.*

Figure 8 shows the current harmonic spectrum measured at MSB PC1. The fifth harmonic order is the highest for all the three phases except for the neutral phase which is the highest at the 3rd harmonic order.

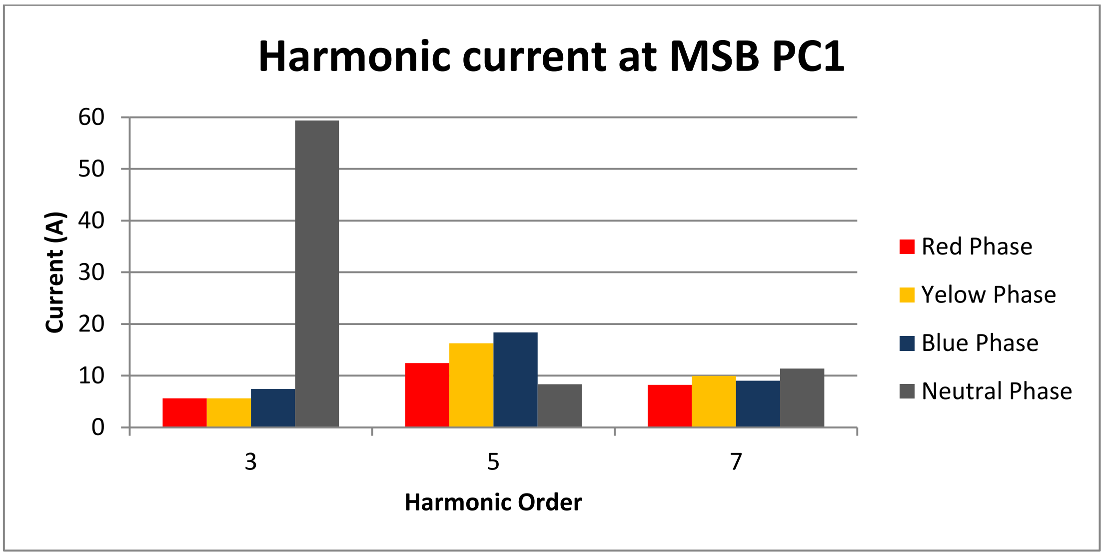


*Figure 14 Current Harmonic Spectrum at MSB PC1.*

Based on the Figure 15, it shows the neutral phase has high harmonic.

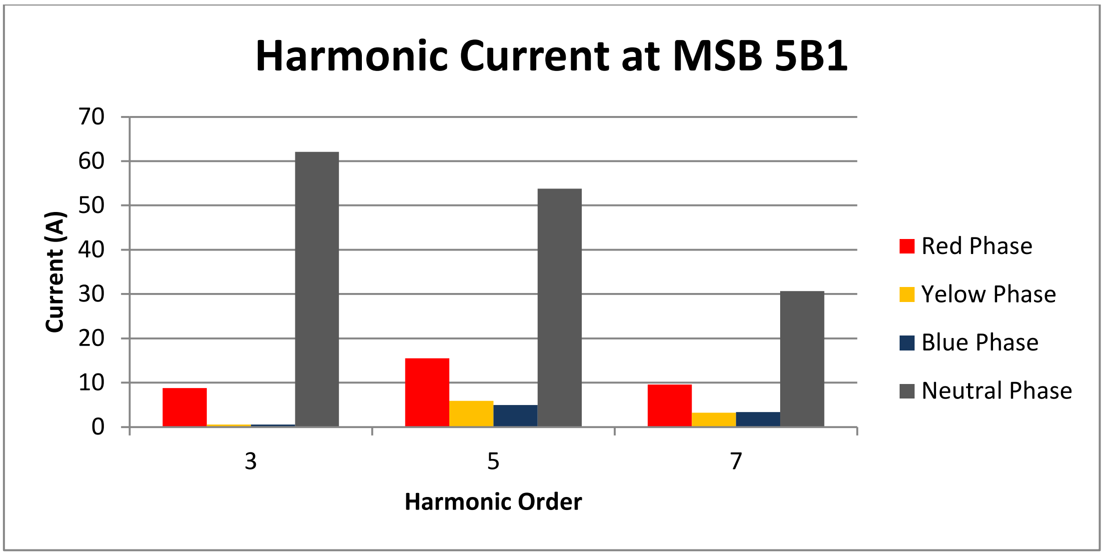


*Figure 15 Current Harmonic Spectrum at MSB 5B1.*

At the MSB PD1, the current spectrum shows that neutral phase for the 3rd harmonics shows high value as in Figure 16.

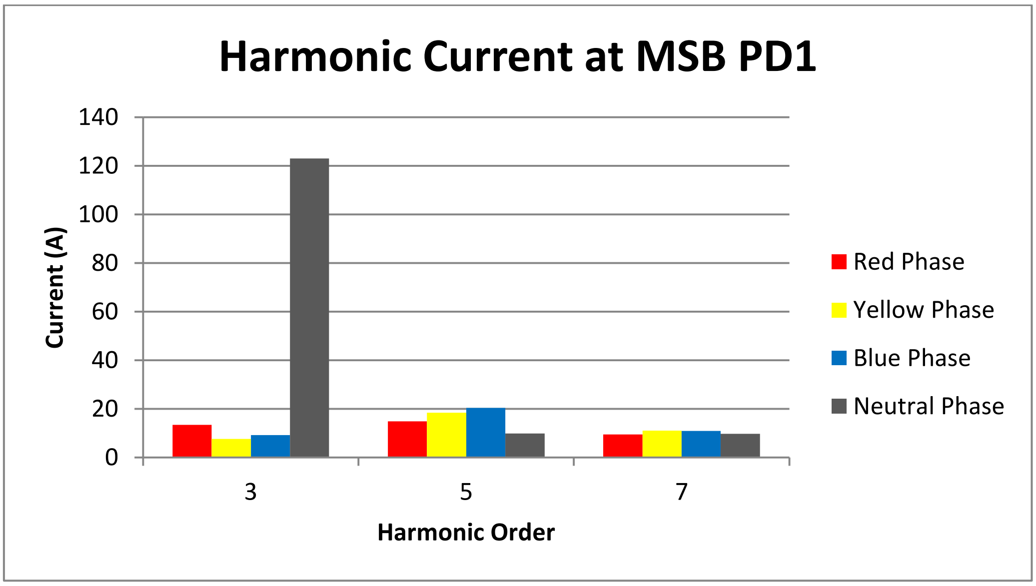


*Figure 16 Current Harmonic Spectrum at MSB PD1.*

Figure 17 shows the current harmonic spectrum measured at MSB PD2. The graph shows that the neutral phase is high at 3rd, 9th and 15th harmonic order which is the triplen harmonic. As for the other three phases, the 3rd and 5th harmonic order are among the highest.

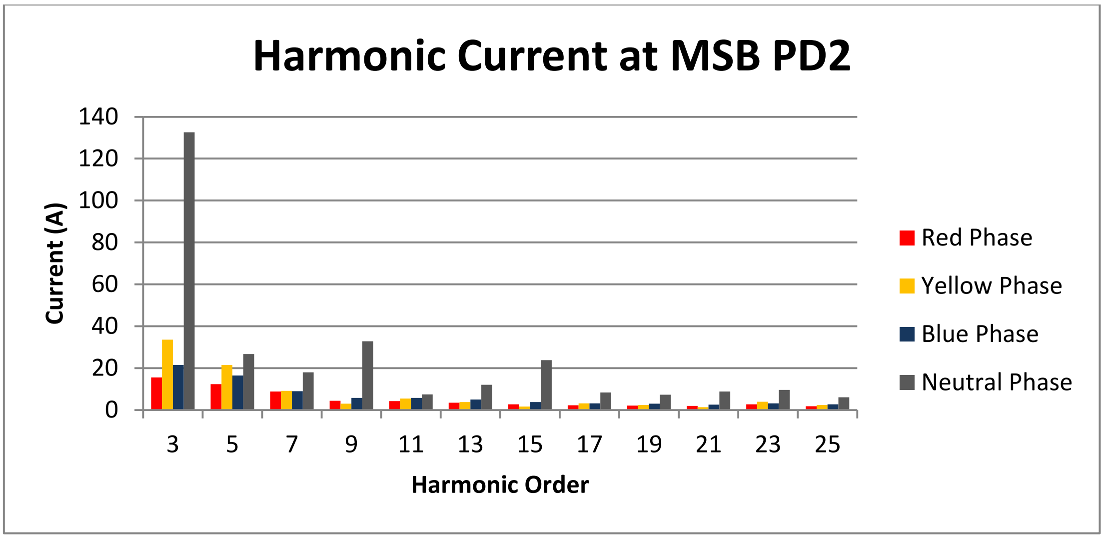


*Figure 17 Current Harmonic Spectrum at MSB PD2.*

Figure 18 shows the result that 3rd harmonics are the most significant at all of the phases which is triplen harmonics that contributes to high harmonics current at neutral phase.

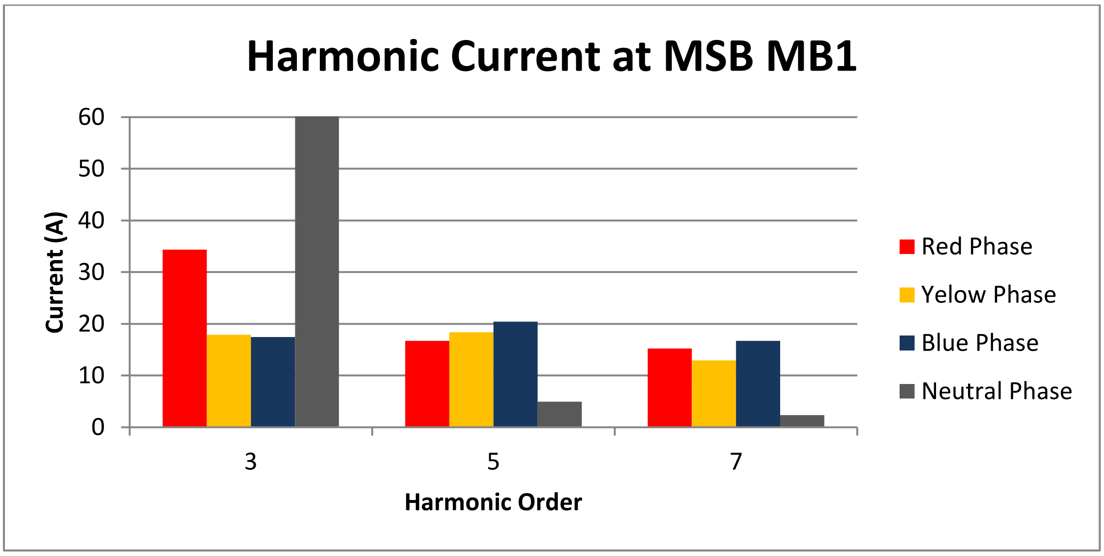


*Figure 18 Current Harmonic Spectrum at MSB PC1.*

Figure 19 shows the current harmonic spectrum measured at the MSB COMPACT. The result stated that 3rd harmonics are the most significant at the neutral phase which can be triplen harmonics that contributes to high harmonics current at neutral phase.

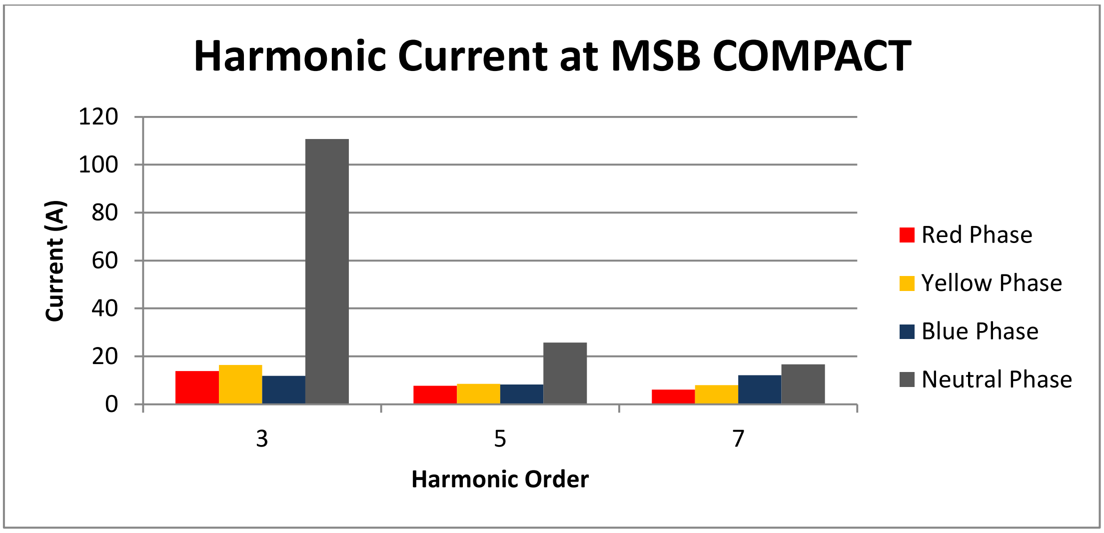


*Figure 19 Current Harmonic Spectrum at MSB 5B2.*

Figure 20 show the neutral phase has high content in 3rd harmonics. Thus, this can be concluded that there are excessive current at the neutral wire.

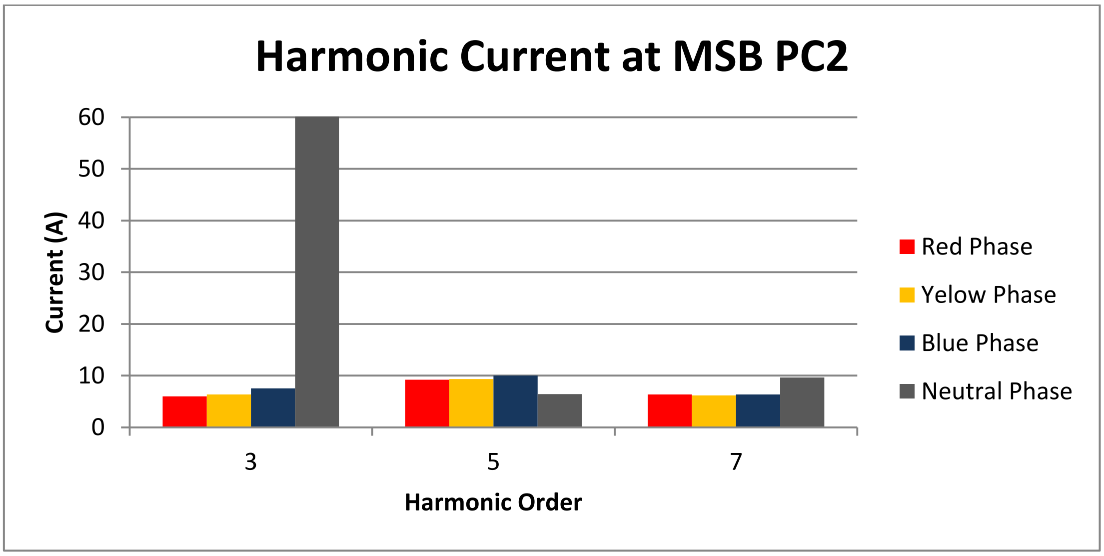


*Figure 20 Current Harmonic Spectrum at MSB PC2.*

Figure 21 shows the current harmonic spectrum measured at the MSB COMPACT. The result below stated that 3rd harmonics are the most significant at the neutral phase which can be triplen harmonics that contributes to high harmonics current at neutral phase.

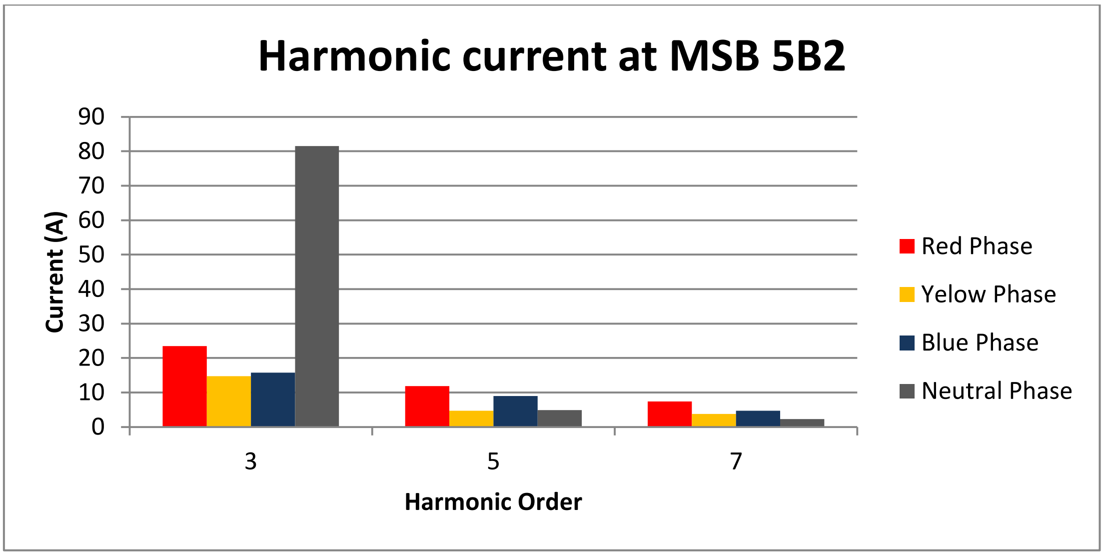


*Figure 21 Current Harmonic Spectrum at MSB 5B2.*

Figure 22 shows the current harmonics spectrum at MSB SS2. It is noted that the neutral phase are the most significant for 3rd harmonics.

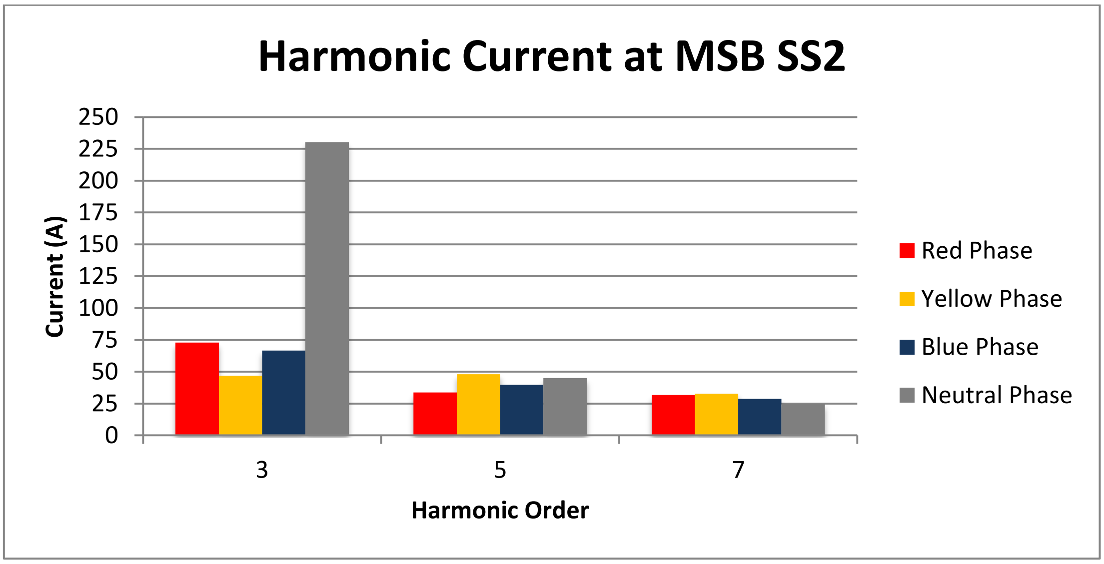


*Figure 22 Current Harmonic Spectrum at MSB SS2.*

Figure 23 shows the current harmonics spectrum at MSB 1. The 3rd and 9th harmonics are highest at the neutral phase. Based on Table 6, it shows that only the harmonics at the neutral phase exceeds the TDD limit.

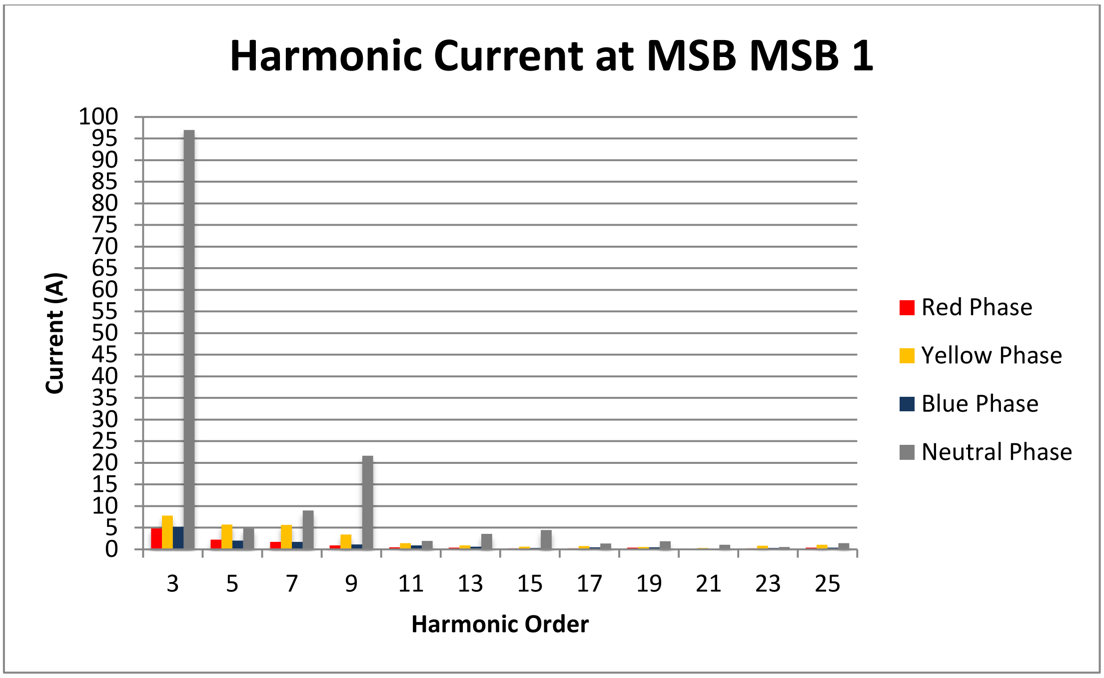


*Figure 23 Current Harmonic Spectrum at MSB 1.*

Figure 24 shows the current spectrum at MSB 5-2. Based on Table 7, only the neutral phase exceeds the TDD limit. The current harmonics in neutral phase is the most significant.

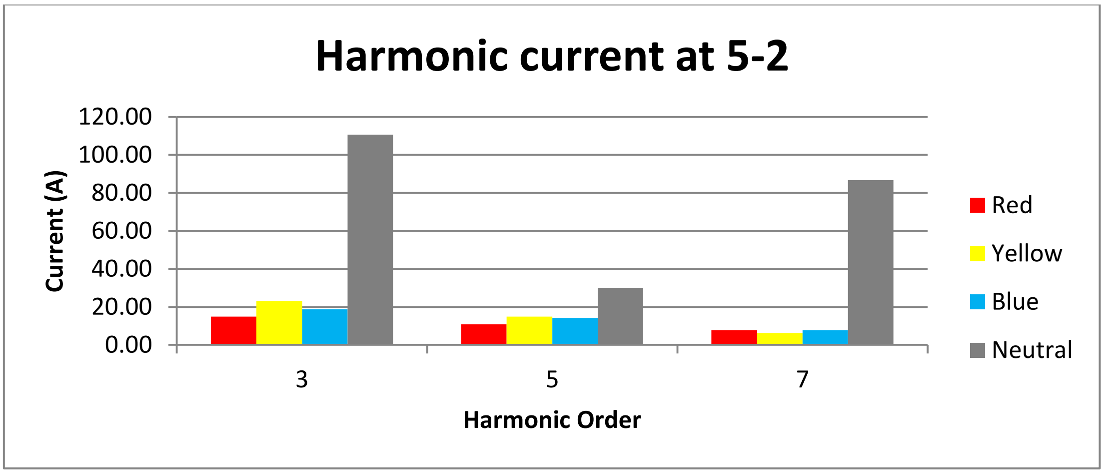


*Figure 24 Current Harmonic Spectrum at MSB 5-2.*

## 4.2 Harmonics Measurement at HV side of MSB ETS

Table 7, shows the data for phase red, yellow and blue taken at the HV side of MSB ETS. The harmonics are measured at the HV side of the ETS is to compare with the LV side of the ETS since MSB ETS only feeds to motor pump. Thus, harmonics are measured at the LV side to determine whether the harmonics from the HV side went to the LV side.

*Table 7 TDD percentage at HV side of MSB ETS.*

| Block | Phase | TDD Limit (%) | TDD (%) |
|---|---|---|---|
| ETS | Red | 5 | 155.10 |
| | Yellow | 5 | 184.02 |
| | Blue | 5 | 160.41 |

Figure 25 shows the harmonics spectrum of the HV side of the ETS for phase red, yellow, blue. The graph illustrated that the harmonic spectrum for the $5^{th}$, $7^{th}$, $11^{th}$, $13^{th}$, $17^{th}$ and $19^{th}$ harmonics are among the highest reading. This can be due to the VFD at the LV side or the motor pump at MSB ETS. Thus, this shows that the comparison between the LV side and the HV side of the MSB ETS is almost the same because the harmonic spectrums that occur in LV side also occur in HV side. The only differences is that the there are no triplen harmonics transmitted to HV side due to the delta configuration that trapping the triplen harmonics.

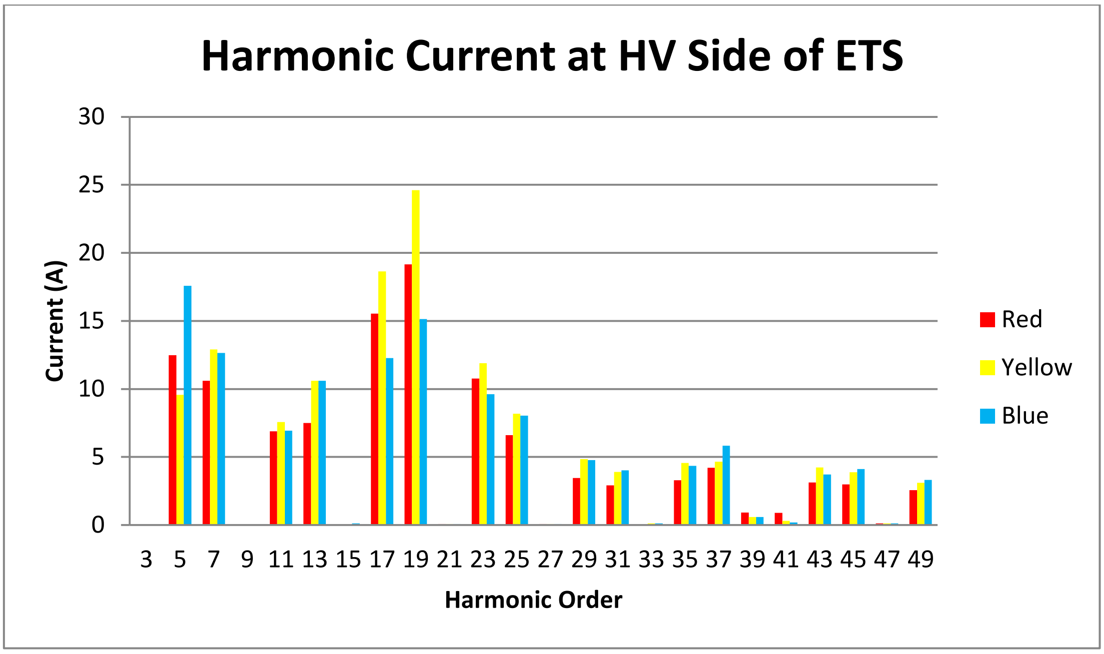


*Figure 25 Current Harmonic Spectrum at HV side of MSB ETS.*

### 4.3 Locating Harmonics Sources at MSB PC1

Among the 17 MSB that had exceed the TDD percentage, MSB PC1 is focussed on as it is among the highest TDD percentage. The measurements of harmonics are taken at three blocks which are Block 13 that have two incoming, Block 15 and Block 16. The schematic diagram for block 13 is illustrated as in Figure 26. TDD Calculation for Block 13, 15 and 16 is shown in Appendix C.

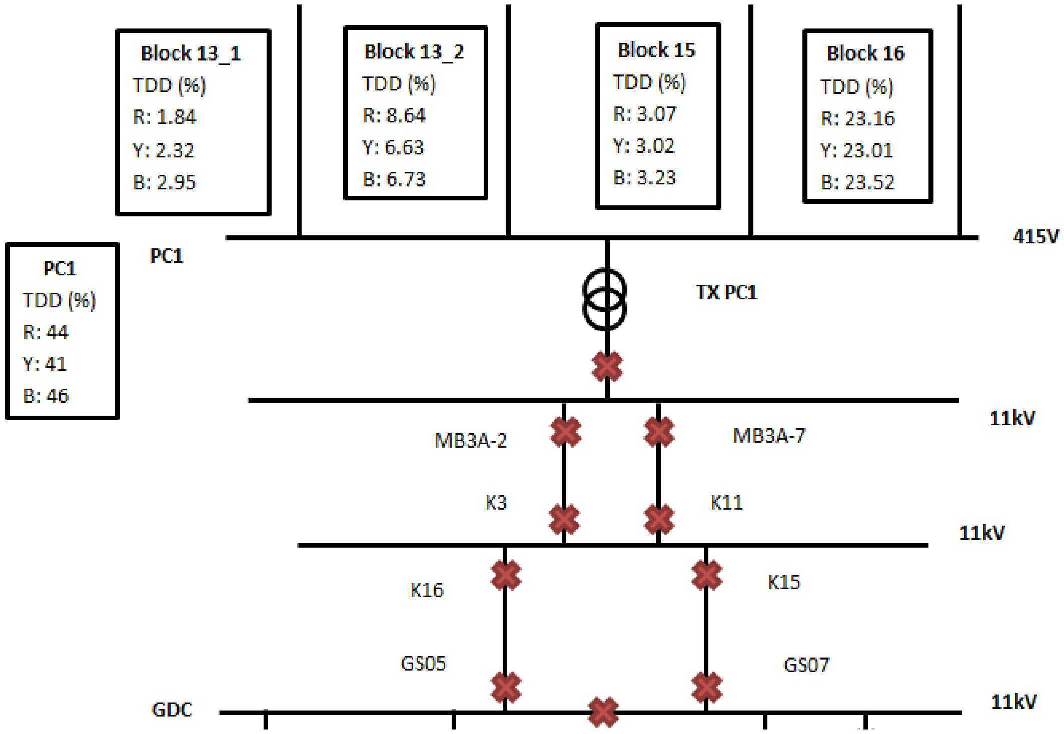


*Figure 26 Schematic Diagram of MSB PC1.*

The data for the TDD percentage for the three blocks outgoing from MSB PC1 is shown in Table 8 below. The TDD percentage showed at block 16 shows that it exceeds the TDD limit of 15 %. Thus, the source of harmonics can be identified coming from Block 16.

*Table 8 TDD percentage at Block 13, 15 and 16.*

| Block | Phase | TDD Limit (%) | TDD (%) |
|---|---|---|---|
| 13_1 | Red | 15 | 1.84 |
| | Yellow | 15 | 2.32 |
| | Blue | 15 | 2.95 |
| | Neutral | 15 | 0.08 |
| 13_2 | Red | 15 | 8.64 |
| | Yellow | 15 | 6.63 |
| | Blue | 15 | 6.73 |
| | Neutral | 15 | 0.04 |
| 15 | Red | 15 | 3.07 |
| | Yellow | 15 | 3.02 |
| | Blue | 15 | 3.23 |
| | Neutral | 15 | 2.52 |

| | | | |
|---|---|---|---|
| 16 | Red | 15 | 23.16 |
| | Yellow | 15 | 23.01 |
| | Blue | 15 | 23.52 |
| | Neutral | 15 | 2.79 |

Two data logger are left at the PCC of Block 13 since there are two incoming and one data logger is left at Block 15 and 16. Measurement of the harmonic current at the block 13, 15 and 16 are taken and logged for a week. Figure 27, 28 and 29 show the bar graph for phase red, yellow and blue where the TDD percentage is within the limit.

Whereby, Figure 30 shows the graph for phase red, yellow and blue taken at Block 16. As stated in Table 8, the TDD percentage for block 16 has exceeded the TDD limits.

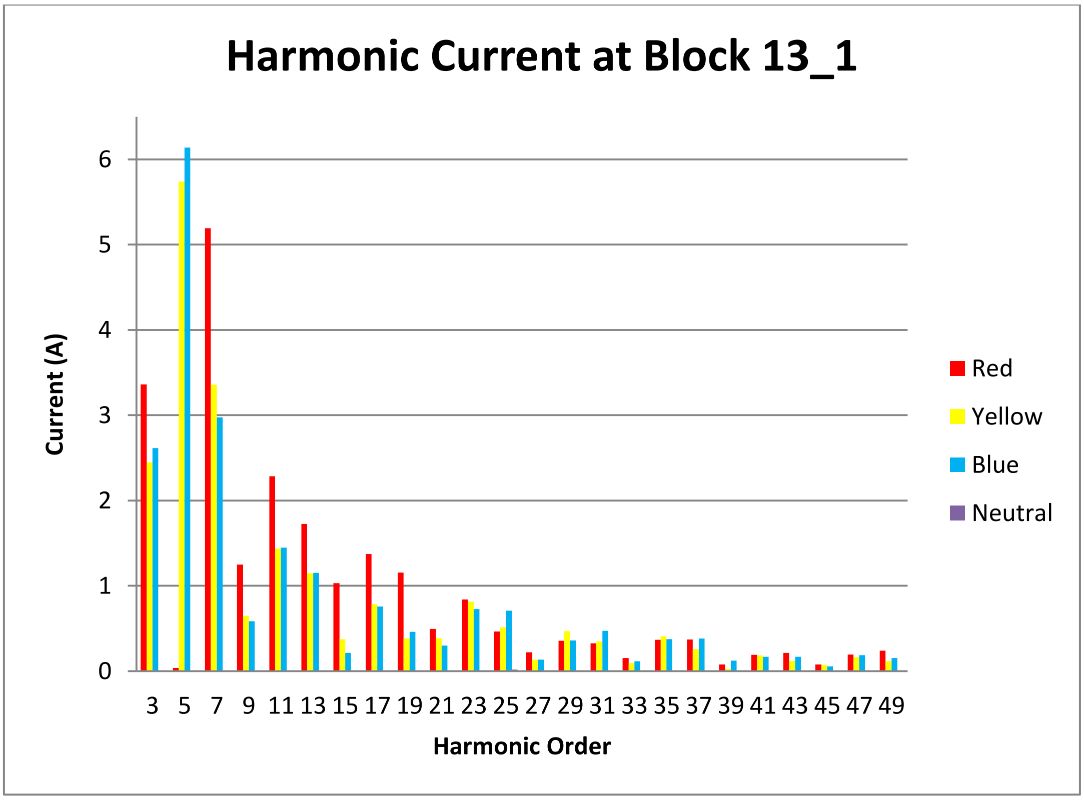


*Figure 27 Current Harmonic Spectrum at Block 13_1.*

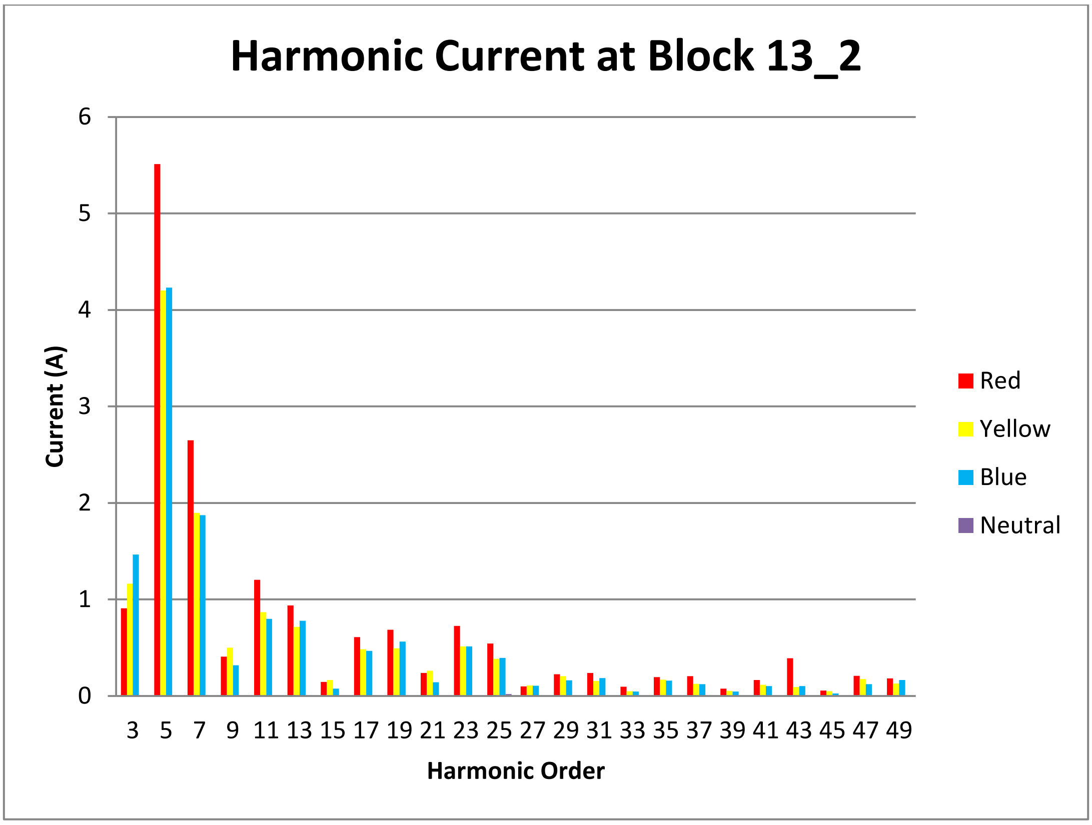


*Figure 28 Current Harmonic Spectrum at Block 13_2.*

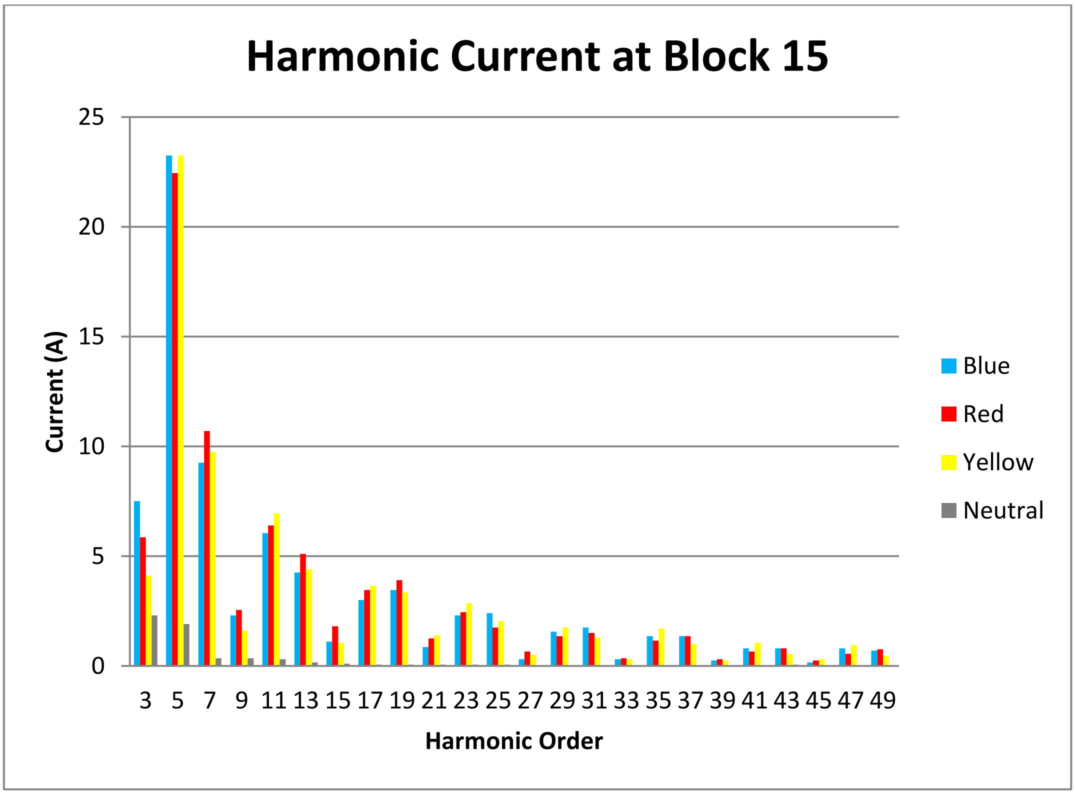


*Figure 29 Current Harmonic Spectrum at Block 15.*

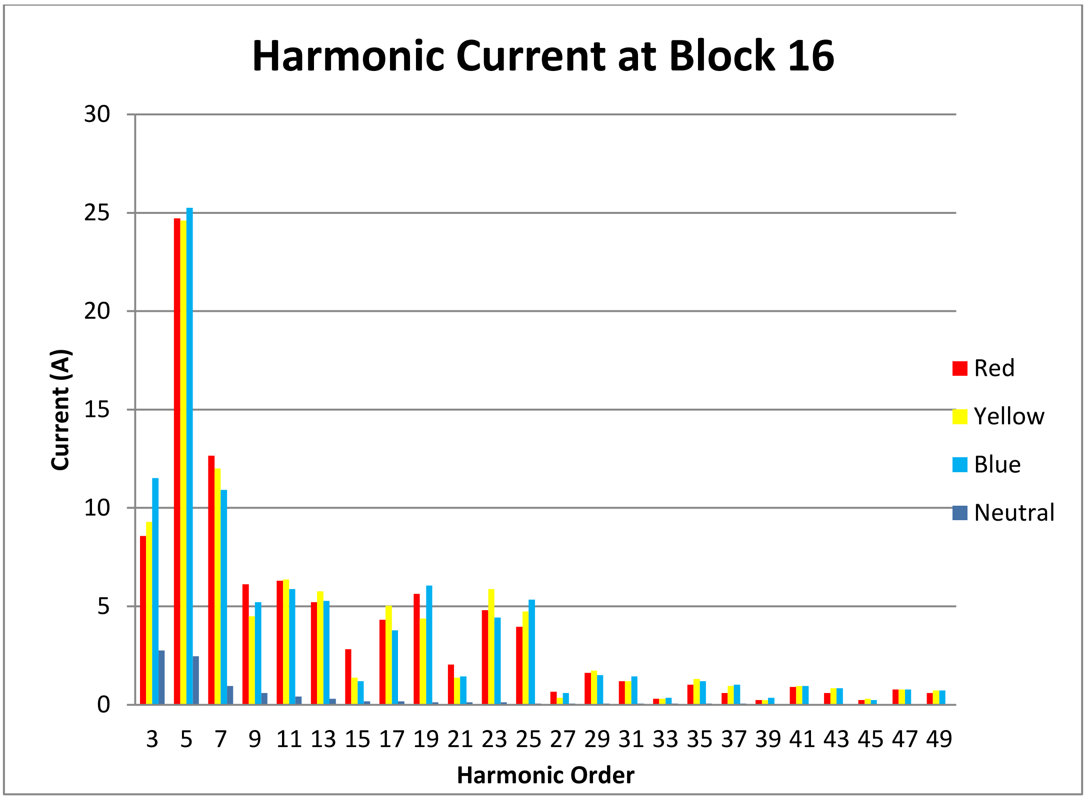


*Figure 30 Current Harmonic Spectrum at Block 16.*

### 4.4 Locating Harmonics Sources at Block 16

Table 9 shows the TDD limits for loads that highly contribute to the harmonics at Block 16. The two loads are known as the electrical discharge machine (EDM) and wire electrical discharge machine (WEDM). Both EDM and WEDM are used to manufacture shape of any desired objects by using electrical discharges. Thus, with the use of high electricity to produce charges to cut the objects, it is shown in Figure 31 and 32 that 5$^{th}$ harmonics are the highest harmonics followed by 7$^{th}$ and 3$^{rd}$ harmonics.

*Table 9 TDD percentage at EDM & WEDM.*

| Loads | Phase | TDD Limit (%) | TDD (%) |
|---|---|---|---|
| EDM | Red | 15 | 20.50 |
| | Yellow | 15 | 23.00 |
| | Blue | 15 | 27.00 |
| | Neutral | 15 | 14.00 |
| WEDM | Red | 15 | 17.60 |
| | Yellow | 15 | 21.20 |
| | Blue | 15 | 19.50 |
| | Neutral | 15 | 13.00 |

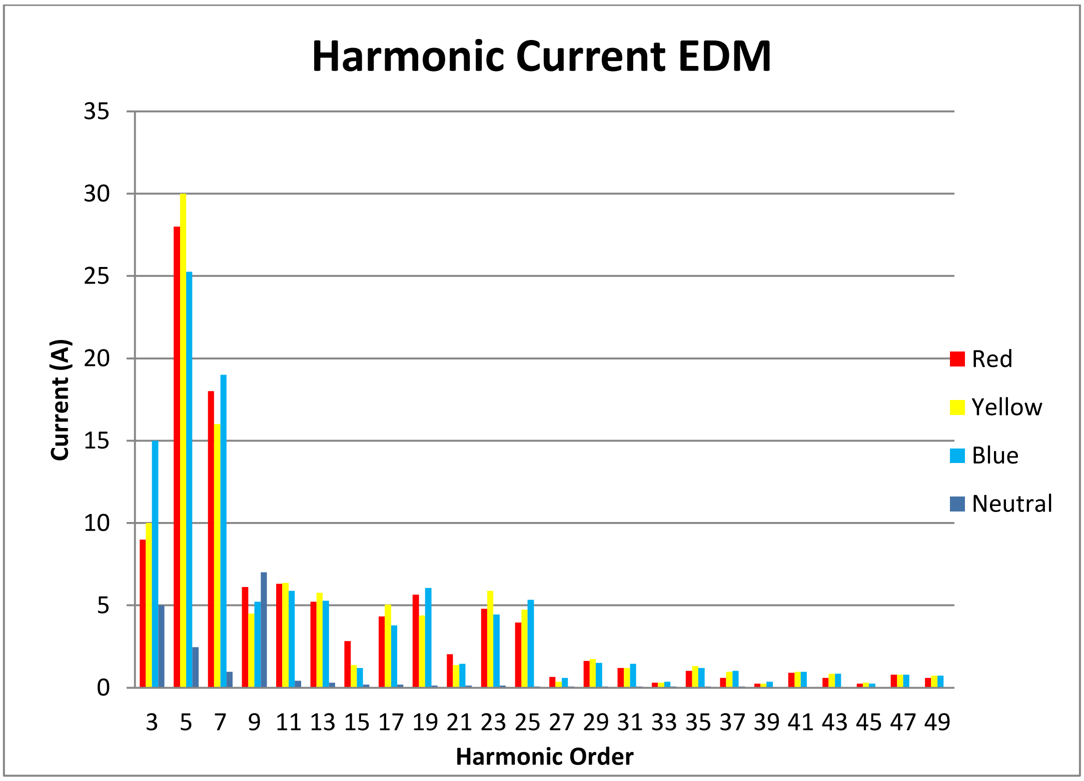


*Figure 31 Current Harmonic Spectrum at EDM.*

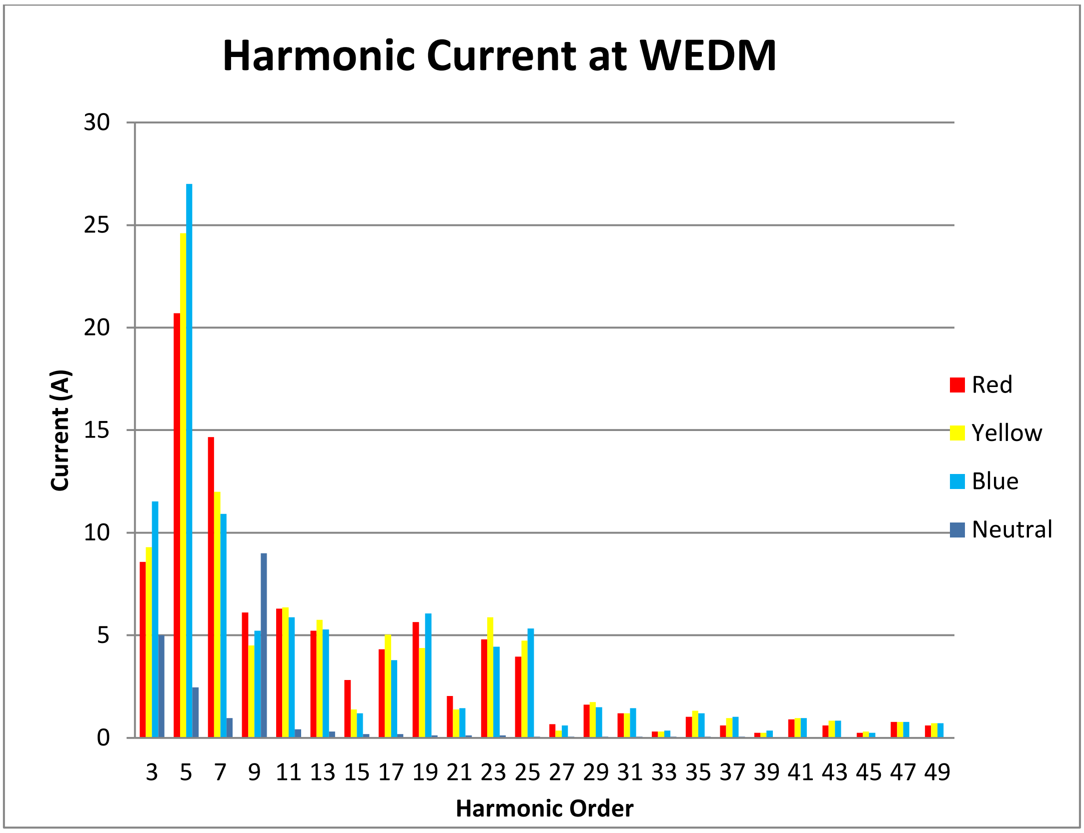


*Figure 32 Current Harmonic Spectrum at WEDM.*

## 4.5 Comparison with previous report from Group Technology Solution (GTS)

GTS has done the harmonic measurement at UTP 6 new academic block (2, 3, 5, 13, 17 and 22). Based on Appendix D, all of the THDv are within the IEEE Standard 519. The THDv measured at all of the 24 MSB also are within the limit. It can be concluded that the THDv measured at each of the 24 MSB and the measurement done by GTS are still within the limit.

Appendix E shows that the TDD measured by GTS exceeds the limits of IEEE Standard 519 as shown in Appendix F. Among all 6 blocks previously measured by GTS, Block 13 is also the only block that has been measured. Harmonics data in Table 8 shows that it is within the TDD limit. Thus, this can be concluded that the measurement done by GTS at and the latest measurement of harmonics at Block 13 is still within the TDD limits.

# CHAPTER 5

# CONCLUSION

## 5.1 Conclusion

The comparison of THDv between the latest measurement and the previous measurement done by GTS is within the limit stated by IEEE Standard 519. While the TDD for both measurements did exceed the limit but the distorted current is still within the cable current carrying capacity of 410A as in Appendix E. Most of the current spectrums where the TDD exceeds the limits at neutral phase are triplen harmonics type.

For MSB ETS, the harmonics are compared between the LV side and HV side to know whether the harmonics from the HV side went to the LV side or vice versa. The data shows that the harmonics content that occur in LV side and HV side are about the same. The only difference is that the triplen harmonics does not occur at the HV side due to the delta configuration that trapped the triplen harmonics. The harmonic content of $5^{th}$, $7^{th}$, $11^{th}$, $13^{th}$, $17^{th}$ and $19^{th}$ contributes in high magnitudes of current.

MSB PC1 is focussed on to identify the load that causes the high harmonics to occur. For MSB PC1, it feeds on three blocks which are block 13, 15 and 16 that have two incoming. All the data obtained during the measurement of harmonics of all the three blocks stated that block 16 is the only one that exceeds the TDD limits. It can be concluded that the loads from the block 16 are the one that contributes to the high harmonics to occur for MSB PC1.

At Block 16, it is known that there are two loads that contribute to harmonics which are EDM and WEDM. These two loads use high discharge power for the machine to conducts their process. Thus, it can be concluded that WEDM and EDM are the one that produce harmonics at MSB PC1.

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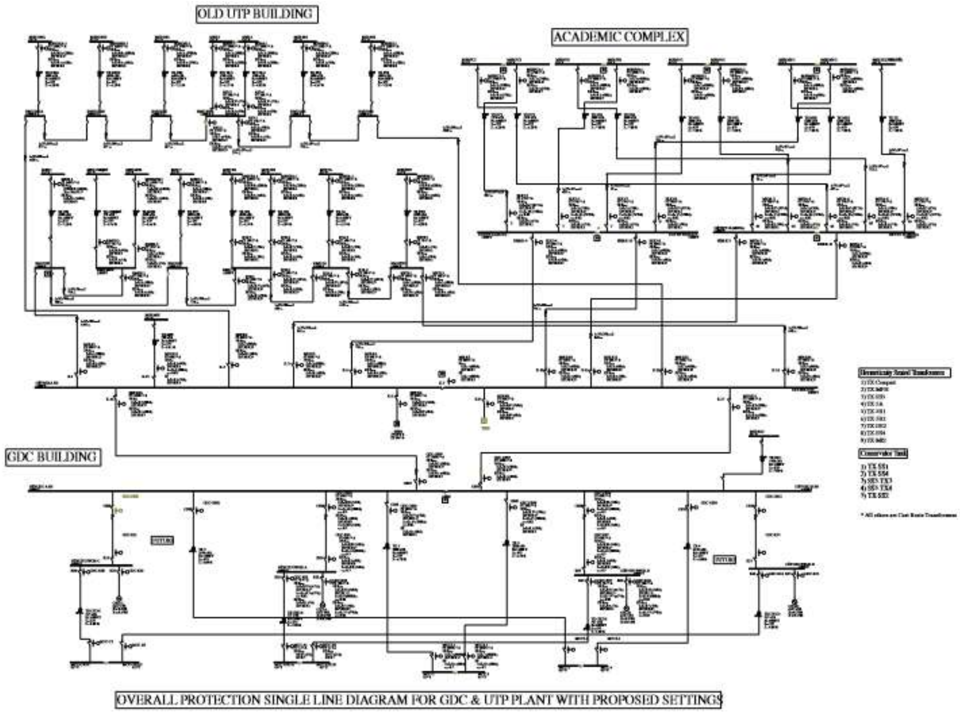
[11] Associated Power Technologies, “Total Harmonic Distortion and effects in Electrical Power Systems,” *Apt*, no. Figure 1, pp. 1–4, 2011.

# APPENDIX

## APPENDIX A: Single Line Diagram of MSB in UTP



## APPENDIX B: TDD limit for all of 24 MSB

| MSB | Maximum Demand, W | Maximum load (I_Load), A | Ratio (I_sc/I_load) | TDD Limit (%) |
|---|---|---|---|---|
| PC1 | 109200 | 179 | 140 | 15 |
| PC2 | 229200 | 375 | 67 | 12 |
| PD1 | 310900 | 509 | 49 | 8 |
| MPH | 205067 | 336 | 74 | 12 |
| MB1 | 546000 | 894 | 28 | 8 |
| MB2 | 372300 | 609 | 41 | 8 |
| MSB3 | 191100 | 313 | 80 | 12 |
| MSB4 | 188100 | 308 | 81 | 12 |
| 5B1 | 45493 | 74 | 336 | 15 |
| 5B2 | 29867 | 49 | 511 | 15 |
| DS1A | 309000 | 506 | 49 | 5 |
| DS1B | 244440 | 400 | 62 | 12 |
| DS2 | 179800 | 294 | 85 | 12 |
| SS4 | 198000 | 324 | 77 | 12 |
| SS2 | 254700 | 417 | 60 | 12 |
| MSB 1 | 306750 | 502 | 50 | 12 |
| COMPACT | 127800 | 209 | 120 | 15 |
| MSB 5 | 345333 | 565 | 44 | 8 |
| 5A | 358500 | 587 | 43 | 8 |
| ETS | 72130 | 118 | 212 | 8 |
| 5-1 | 563150 | 922 | 27 | 15 |
| 5-2 | 561600 | 919 | 27 | 8 |
| MIS | 207200 | 339 | 74 | 12 |
| PD2 | 116350 | 190 | 131 | 15 |

## APPENDIX C: TDD Calculation for Block 13, 15 and 16

| BLOCK 13_ | THDi (%) | 3 | 5 | 7 | 9 | 11 | 13 | 15 | 17 | 19 | 21 | 23 | 25 | 27 | 29 | 31 | 33 | 35 | 37 | 39 | 41 | 43 | 45 | 47 | 49 | TDD Limit | TDD (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Red | | 3.36 | 0.036 | 5.194 | 1.248 | 2.286 | 1.727 | 1.032 | 1.373 | 1.156 | 0.493 | 0.839 | 0.466 | 0.219 | 0.355 | 0.327 | 0.155 | 0.368 | 0.37 | 0.079 | 0.189 | 0.213 | 0.078 | 0.194 | 0.238 | 15 | 1.84 |
| Yellow | | 2.445 | 5.74 | 3.358 | 0.647 | 1.435 | 1.148 | 0.376 | 0.785 | 0.364 | 0.387 | 0.813 | 0.515 | 0.134 | 0.463 | 0.348 | 0.093 | 0.409 | 0.257 | 0.024 | 0.184 | 0.118 | 0.07 | 0.165 | 0.116 | 15 | 2.32 |
| Blue | | 2.615 | 6.138 | 2.974 | 0.584 | 1.449 | 1.152 | 0.214 | 0.757 | 0.46 | 0.3 | 0.726 | 0.71 | 0.135 | 0.361 | 0.473 | 0.115 | 0.376 | 0.383 | 0.122 | 0.169 | 0.17 | 0.057 | 0.187 | 0.154 | 15 | 2.95 |
| Neutral | | 0.008 | 0.007 | 0.007 | 0.006 | 0.005 | 0.005 | 0.004 | 0.004 | 0.004 | 0.003 | 0.002 | 0.02 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0 | 15 | 0.08 |

| BLOCK 13_ | THDi (%) | 3rd (A) | 5th (A) | 7th (A) | 9 | 11 | 13 | 15 | 17 | 19 | 21 | 23 | 25 | 27 | 29 | 31 | 33 | 35 | 37 | 39 | 41 | 43 | 45 | 47 | 49 | TDD Limit (%) | TDD (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Red | | 0.908 | 5.513 | 2.65 | 0.409 | 1.205 | 0.939 | 0.147 | 0.611 | 0.687 | 0.238 | 0.727 | 0.543 | 0.1 | 0.224 | 0.238 | 0.097 | 0.197 | 0.206 | 0.076 | 0.166 | 0.39 | 0.057 | 0.21 | 0.183 | 15 | 8.64 |
| Yellow | | 1.164 | 4.201 | 1.896 | 0.5 | 0.868 | 0.717 | 0.167 | 0.484 | 0.493 | 0.262 | 0.515 | 0.383 | 0.11 | 0.206 | 0.157 | 0.049 | 0.169 | 0.125 | 0.052 | 0.117 | 0.094 | 0.048 | 0.177 | 0.13 | 15 | 6.63 |
| Blue | | 1.466 | 4.231 | 1.875 | 0.318 | 0.739 | 0.778 | 0.075 | 0.466 | 0.564 | 0.142 | 0.514 | 0.395 | 0.106 | 0.162 | 0.186 | 0.047 | 0.159 | 0.123 | 0.045 | 0.104 | 0.102 | 0.028 | 0.124 | 0.1667 | 15 | 6.73 |
| Neutral | | 0.008 | 0.007 | 0.007 | 0.006 | 0.005 | 0.005 | 0.004 | 0.004 | 0.004 | 0.003 | 0.002 | 0.02 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0 | 15 | 0.04 |

| BLOCK 15 | THDi (%) | 3rd (A) | 5th (A) | 7th (A) | 9 | 11 | 13 | 15 | 17 | 19 | 21 | 23 | 25 | 27 | 29 | 31 | 33 | 35 | 37 | 39 | 41 | 43 | 45 | 47 | 49 | TDD Limit (%) | TDD (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Red | | 5.85 | 22.45 | 10.7 | 2.55 | 6.4 | 5.1 | 1.8 | 3.45 | 3.9 | 1.25 | 2.45 | 1.75 | 0.65 | 1.35 | 1.5 | 0.35 | 1.15 | 1.35 | 0.3 | 0.65 | 0.8 | 0.25 | 0.55 | 0.75 | 15 | 3.07 |
| Yellow | | 4.1 | 23.25 | 9.75 | 1.6 | 6.95 | 4.4 | 1.05 | 3.65 | 3.35 | 1.4 | 2.85 | 2.04 | 0.5 | 1.75 | 1.3 | 0.3 | 1.7 | 1 | 0.25 | 1.05 | 0.55 | 0.3 | 0.95 | 0.45 | 15 | 3.02 |
| Blue | | 7.5 | 23.25 | 9.25 | 2.3 | 6.05 | 4.25 | 1.1 | 3 | 3.45 | 0.85 | 2.3 | 2.4 | 0.3 | 1.55 | 1.75 | 0.3 | 1.35 | 1.35 | 0.25 | 0.8 | 0.8 | 0.15 | 0.8 | 0.7 | 15 | 3.23 |
| Neutral | | 2.3 | 1.9 | 0.35 | 0.35 | 0.3 | 0.15 | 0.1 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.05 | 0 | 0 | 0 | 15 | 2.52 |

| BLOCK 16 | THDi (%) | 3rd (A) | 5th (A) | 7th (A) | 9 | 11 | 13 | 15 | 17 | 19 | 21 | 23 | 25 | 27 | 29 | 31 | 33 | 35 | 37 | 39 | 41 | 43 | 45 | 47 | 49 | TDD Limit (%) | TDD (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Red | | 8.58 | 24.72 | 12.66 | 6.12 | 6.3 | 5.22 | 2.82 | 4.32 | 5.64 | 2.04 | 4.8 | 3.96 | 0.66 | 1.62 | 1.2 | 0.3 | 1.02 | 0.6 | 0.24 | 0.9 | 0.6 | 0.24 | 0.78 | 0.6 | 15 | 23.16 |
| Yellow | | 9.3 | 24.6 | 12 | 4.5 | 6.36 | 5.76 | 1.38 | 5.04 | 4.38 | 1.38 | 5.88 | 4.74 | 0.36 | 1.74 | 1.2 | 0.3 | 1.32 | 0.96 | 0.24 | 0.96 | 0.84 | 0.3 | 0.78 | 0.72 | 15 | 23.01 |
| Blue | | 11.52 | 25.26 | 10.92 | 5.22 | 5.88 | 5.28 | 1.2 | 3.78 | 6.06 | 1.44 | 4.44 | 5.34 | 0.6 | 1.5 | 1.44 | 0.36 | 1.2 | 1.02 | 0.36 | 0.96 | 0.84 | 0.24 | 0.78 | 0.72 | 15 | 23.52 |
| Neutral | | 2.76 | 2.46 | 0.96 | 0.6 | 0.42 | 0.3 | 0.18 | 0.18 | 0.12 | 0.12 | 0.12 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0 | 0 | 0 | 0 | 0 | 0 | 15 | 2.79 |

| ETS (HV) | THDi (%) | 3rd (A) | 5th (A) | 7th (A) | 9 | 11 | 13 | 15 | 17 | 19 | 21 | 23 | 25 | 27 | 29 | 31 | 33 | 35 | 37 | 39 | 41 | 43 | 45 | 47 | 49 | TDD Limit (%) | TDD (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Red | | 0.01 | 12.49 | 10.59 | 0.01 | 6.89 | 7.51 | 0.02 | 15.54 | 13.16 | 0.06 | 10.77 | 6.61 | 0.06 | 3.46 | 2.91 | 0.02 | 3.29 | 4.2 | 0.92 | 0.9 | 3.13 | 2.98 | 0.12 | 2.57 | 5 | 155.10 |
| Yellow | | 0.02 | 9.56 | 12.9 | 0.01 | 7.56 | 10.6 | 0.02 | 18.63 | 24.6 | 0.06 | 11.89 | 8.17 | 0.06 | 4.85 | 3.91 | 0.12 | 4.55 | 4.65 | 0.6 | 0.3 | 4.24 | 3.87 | 0.12 | 3.1 | 5 | 184.02 |
| Blue | | 0.01 | 17.59 | 12.65 | 0.01 | 6.94 | 10.59 | 0.12 | 12.27 | 15.14 | 0.06 | 9.62 | 8.04 | 0.06 | 4.77 | 4.02 | 0.12 | 4.34 | 5.84 | 0.6 | 0.2 | 3.72 | 4.12 | 0.12 | 3.31 | 5 | 160.41 |

## APPENDIX D: THDv Measurement by GTS

| Block | THDv Red (%) | THDv Yellow (%) | THDv Blue (%) |
|---|---|---|---|
| 22 | 4.4 | 4.4 | 4.4 |
| 5 | 1.2 | 1.2 | 1.2 |
| 2 | 1.8 | 2 | 2 |
| 3 | 2 | 2 | 2 |
| 13 | 1.8 | 1.8 | 1.8 |
| 17 | 1.6 | 1.6 | 1.6 |

## APPENDIX E: TDD Measurement by GTS

| Block | TDDi Red (%) | TDD Yellow (%) | TDD Blue (%) |
|---|---|---|---|
| 22 | 30 | 40 | 300 |
| 5 | 3 | 3 | 45 |
| 2 | 28 | 90 | 350 |
| 3 | 5 | 3 | 150 |
| 13 | 30 | 20 | 120 |
| 17 | 35 | 30 | 100 |

## APPENDIX F: TDD limit by GTS

| Block | Maximum Demand, kW | Maximum load (I_Load), A | Ratio (I_sc/I_load) | TDD Limit (%) | Current (Red) | Current (Blue) | Current (Neutral) |
|---|---|---|---|---|---|---|---|
| 22 | 312600 | 511.64 | 49 | 8 | 18A | 18A | 50A |
| 5 | 788600 | 1290.71 | 19 | 5 | 6A | 5A | 11A |
| 2 | 447000 | 731.61 | 34 | 8 | 20A | 25A | 80A |
| 3 | 770600 | 1261.25 | 20 | 5 | 18A | 20A | 10A |
| 13 | 270000 | 441.91 | 57 | 12 | 8A | 6A | 10A |
| 17 | 487410 | 797.75 | 31 | 8 | 24A | 26A | 14A |