POWER QUALITY ANALYSIS BASED ON ROOT MEAN SQUARE AND DISCRETE FOURIER TRANSFORM

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FACULTY OF ENGINEERING
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POWER QUALITY ANALYSIS BASED ON ROOT MEAN SQUARE AND DISCRETE FOURIER TRANSFORM

ABSTRACT

Power Quality (PQ) disturbance is the most significant power issues concern by the customer side due to degradation of the power quality. The root cause of PQ disturbance can be identified by analyzing the characteristics of disturbances. From that, appropriate action can be conducted. The PQ disturbances in the voltage waveform are very difficult to identify using normal human sight. It is also difficult to analyze the PQ disturbance manually because of dealing with the huge sample of data waveform. Besides, the method in sag magnitude determination should be improved to get more relevant result. This project presents two methods for analyzing the PQ disturbance based on Root Mean Square (RMS) and Discrete Fourier Transform (DFT). A new technique is introduced to determine the voltage sag magnitude. This method is applied to the voltage waveform data as provided by the IEEE 1159.2 PQ event working group using MATLAB programming. The proposed method for sag magnitude determination is added by modifying the program of RMS and DFT measurement using Rectangular Approximation technique. For the result, the RMS and DFT method can use to analyze the voltage sag event. Both methods able to analyze the voltage sag detection time, sag duration and sag magnitude. The comparison performance between RMS and DFT method in voltage sag analysis is presented. The analysis result is affected by the sliding window technique and the size of the rectangle in the sag magnitude determination. For future work in this project, the method can be modified to analyze other types of PQ disturbances like swell, transient and harmonics for more practical.

Keywords: Power Quality, PQ Disturbance, voltage sag, RMS, DFT

ANALISA KUALITI KUASA BERDASARKAN PUNCA PURATA KUASA DUA DAN TRANSFORMASI FOURIER DISKRIT

ABSTRAK

Gangguan kualiti kuasa merupakan isu paling ketara oleh pihak pelanggan akibat kemerosotan kualiti tenaga. Punca utama gangguan ini boleh dikenalpasti dengan menganalisa cici-ciri gangguan. Daripada itu, tindakan yang sewajarnya boleh dilaksanakan. Gangguan kualiti kuasa dalam bentuk gelombang voltan amat sukar untuk dikenalpasti menggunakan penglihatan manusia. Ia juga sukar untuk dianalisa secara manual kerana mempunyai sampel yang besar dalam data gelombang. Di samping itu, kaedah menentukan magnitud voltan susut harus diperbaiki untuk mendapatkan hasil yang lebih relevan. Projek ini membentangkan dua kaedah untuk menganalisa gangguan kualiti kuasa berdasarkan kaedah Punca Purata Kuasa Dua (RMS) dan Transformasi Fourier Diskrit (DFT). Satu teknik baru diperkenalkan untuk menentukan magnitud voltan susut. Perbandingan prestasi antara kaedah RMS dan DFT dalam analisis voltan susut dibentangkan. Kaedah analisis ini digunakan untuk data gelombang voltan yang direkodkan seperti yang disediakan oleh IEEE 1159.2 dengan menggunakan pengatucaraan MATLAB. Kaedah yang dicadangkan untuk penentuan magnitud voltan susut adalah dengan mengubah program pengukuran RMS dan DFT menggunakan teknik Penghampiran Segi Empat Tepat. Keputusannya, kaedah RMS dan DFT boleh digunakan untuk menganalisa peristiwa voltan susut. Kedua-dua kaedah ini boleh menganalisa masa pengesan, tempoh masa dan magnitud voltan susut. Keputusan analisis terjejas oleh teknik jendela gelongsor dan saiz segiempat tepat yang digunakan dalam penentuan voltan susut. Untuk kerja di masa hadapan, kaedah ini boleh diubahsuai untuk menaganalisa jenis gangguan kualiti kuasa yang lain seperti peningkatan voltan, voltan sementara dan harmoni untuk lebih praktikal.

Kata kunci: Kualiti Kuasa, Gangguan Kualiti Kuasa, voltan susut, RMS, DFT

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LIST OF SYMBOLS AND ABBREVIATIONS

A_N^{rect}	:	Area of N rectangles
A	:	Area under sag curve
B	:	Larger rectangular area below the threshold
C	:	Number of Cycle
C	:	Sag Area
CBEMA	:	Computer and Business Equipment Manufacturers' Association
DFT	:	Discrete Fourier Transform
f	:	Frequency
h	:	Step size
h	:	Harmonic order
IEC	:	International Electrotechnical Commission
IEEE	:	Institute of Electrical and Electronics Engineers
MATLAB	:	Matrix Laboratory
N	:	Number of Sample
PQ	:	Power Quality
p.u	:	Per-Unit
RMS	:	Root Mean Square
SLG	:	Single Line to Ground Fault
T	:	Period of one-cycle
ts	:	Sampling Time
t_{sag}	:	Sag duration
V_{sag_i}	:	Sag Magnitude

LIST OF APPENDICES

CHAPTER 1: INTRODUCTION

1.1 Overview

Power quality (also known as PQ) deals principally with the variety of supply voltage waveform. The excellent condition of the power supply is an essential factor for the proper operation of the power system network and its load. The quality of power supply is a crucial factor in the development of any country, and this can be accomplished through continuous PQ monitoring system which helps detect, record and prevent PQ disturbance. PQ monitoring is necessary to automatically analyze the PQ disturbance at a particular electrical system network with the specific characteristics and also to predict the future performance of load equipment.

There are various types of PQ disturbance such as voltage sag, swell, momentary interruptions and transients (IEEE 1159:2009). All of these disturbances could degrade the quality of power supply with significant economic effect at the customer side. As a statistical data and survey on the industrial customer in Malaysia conducted by (Muhamad, Mariun et al. 2007), most of the industries observed the losses due to PQ disturbance. From the survey, more than 80% faced losses greater than hundred thousand US Dollar due to each of PQ disturbance. It results in increased cost of the equipment losses, reduced product quality, maintenance, loss of production and many more of hidden damage.

There is a significant issue with the system if the supply voltage conveyed the non-sinusoidal waveform. The PQ disturbance will change the standard sinusoidal to the non-sinusoidal waveform. PQ deals with the highly increased usage of electronic equipment with semiconductor-based technology like a computer, data servers, adjustable speed drive and also the rapid growth of non-conventional energy sources to the grid network contributes new challenges to the PQ environment (Polycarpou, Nouri et al. 2004, Mitter and Sharma 2018).

In brief, the non-sinusoidal waveform either sag or swell can cause sensitive equipment and system shutdowns or malfunction, computer data and memory loss, relay and contactor complete dropout and lighting dimming. All of the effects are dependent on the sensitivity of the equipment performance. Some equipment is sensitive to the voltage magnitude only, magnitude and duration, and also by other PQ characteristics. The sensitivity of the equipment is very important to consider from the impact of PQ variations.

This project aims to analyze the common disturbance automatically in power quality by using an analysis method of Root Mean Square (RMS) and Discrete Fourier Transform (DFT). A new method named Rectangular Approximation technique is introduced to improve voltage sag magnitude. The PQ analysis solution is presented to characterize the voltage sag regarding RMS and DFT method effectively.

1.2 Problem Statement

Power quality is the main issue (Hunter 2001) that covers all from the generation plant to the last customer in the chain of the electricity network. Identification and characterization of PQ disturbance are very important (Venkatesh and Sarma 2010) in order to identify the root cause of power quality problem. It is difficult to analyze the characteristic of the PQ disturbance on the original waveform data using normal vision (Bollen, Gu et al. 2009). In addition, this original waveform does not give details information such as where the event begins, how long the events occur and what the exact magnitude of the event.

There is hardly computational if using manual computation with the huge sample of data (Roscoe, Carter et al. 2011). Therefore, the need for simple, fast and efficient detection and characterization of the voltage variations should be considered in analyzing the voltage waveform signal. Such a requirement may involve sophisticated signal processing techniques that make use of signal decomposition, modeling, parametric estimation, and identification algorithms (Bollen, Gu et al. 2009).

Besides that, the non-rectangular sag waveform is a challenge to determine the magnitude of the voltage sag. This is because most of the voltage sag is not uniformly rectangular in shape. Therefore it cannot simply say that the magnitude of sag is the lowest RMS value (Caicedo, Navarro et al. 2012). To ensure the magnitude is determined correctly, the proper method to quantify the magnitude should be introduced. Hence, the analyzing system on the voltage waveform is crucial to take action against fault condition while enhancing the power quality service.

1.3 Objectives

The purpose of this study is to analyze the common power quality problem by using Root Mean Square (RMS) and Discrete Fourier Transform (DFT) method. The objectives of this analyses are:

1) To analyze the power quality of voltage waveform using RMS and DFT method.
2) To compare the performance of DFT method against RMS in voltage sag analysis.
3) To propose voltage sag magnitude calculation in voltage sag analysis using Rectangular Approximation technique.

1.4 Scope of Work

This project is concerned with conducting the analysis of voltage sag on the test waveform based on RMS and DFT method. The simulation for the analysis will be conducted using MATLAB programming development software.

The project compares both methods with the parameter of sag detection time, sag duration, sag magnitude and also the effect of sliding window size and sliding window technique. Those performances are taken into consideration in the simulation result. The different of the comparison result between both methods will be discussed.

The use of the numerical method is applied to the proposed technique of sag magnitude determination. The proposed technique will solve the challenge in quantifying the voltage sag magnitude of rectangular or any non-rectangular waveform. Hence, the accuracy of sag magnitude of the proposed technique is analyzed.

1.5 Report Outline

The rest of the chapters in this report are organized as follows;

Chapter 2 mainly discussed the literature review including theoretical aspects of power quality analysis, voltage sag characteristics, and voltage sag analysis methods.

Chapter 3 explains the procedures and methodology undertaken for developing a program of voltage sag analysis based on RMS and DFT methods and also proposed method on sag magnitude determination.

Chapter 4 focuses on the simulation result and discussion. The result from the simulation is compared between both methods. The analysis result is presented in both methods and proposed method on sag magnitude determination. The analysis on the effect of one cycle and the half-cycle sliding window and also the impact of the rectangular size to the accuracy of the sag magnitude is presented in this chapter.

Chapter 5 provides the conclusion of the research work and recommendation for future work.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

Power Quality (also known as PQ) is any power issue showed in voltage, current, or frequency deviations that result in failure or malfunction of customer equipment (Dugan, McGranaghan et al. 1996). The term of Power Quality has become a popular and very productive keyword in the power industry since the 1980's. Great power quality can be characterized as a steady supply voltage that stays inside the prescribed limit, steady a.c. frequency close to the rated value, and smooth voltage curve waveform.

2.2 Power Quality Problem

PQ problems include all electric power problems or disturbances in the supply system that prevent end-user equipment from operating properly. Example of voltage, current, or frequency deviations that result in failure of end-user equipment include voltage sag, swell, interruptions, long- and short-duration voltage variations, steady-state harmonics, and inter-harmonics, and transient electromagnetic disturbances. Among power quality problems, voltage sag is the greatest concern for the end user especially industrial customers due to provide available solutions to mitigate the problem.

This statement reinforced by (Mohamed, Shareef et al. 2012) that conducted the survey among industrial customers selected from the utility database in Malaysia, the survey shows voltage sag is the third most frequent disturbance occur in their industries after a short and long interruption. In placing more emphasis, (Kerin, Dermeli et al. 2007) conducted a survey in Slovenia found the similar result where the voltage sag and short interruption have been presented as the most frequent common disturbance in the organization and industrial sites in his country. This issue is presented by (Alves and Ribeiro 1999) with a discussion on the IEEE and IEC power quality related standards, and their applicability to voltage sag evaluation in an industrial or commercial system, utility system, and to equipment.

Another important issue in the power quality problems is to detect and classify types of PQ problems waveform automatically by using an efficient method. To detect, solve and mitigate PQ problems, many utilities perform a variety types of PQ monitoring system for their industrial and customers. PQ problems of voltage supply can be analyzed by performing measurements during operation of the system. The type of power quality problems can be identified by analyzing the measurements waveform using the conventional method like RMS, Peak voltage and DFT.

2.3 Power Quality Analysis

Power Quality analysis able to evaluate electric utility and customer system problems in order to provide mitigation techniques for the system. Both electric utilities and customers of electric power are getting to be progressively concerned about the quality of electric power. The electric utilities will be facing load and revenue losses and dissatisfaction from the customer due to power quality problems. While for the customer of electric power, power quality problems may increase the cost of repairing or replacing new appliances.

One of the reasons for this concerned is because of the load equipment used in the industry now are mostly control by microprocessor and power electronic devices which is very sensitive to the power quality variations. Besides that, the increasing emphasis on overall power system efficiency has resulted in continued growth in the application of devices such as high-efficiency, adjustable-speed motor drives and shunt capacitors for power factor correction to reduce losses. This is resulting in increasing harmonic levels on power systems and has many people concerned about the future impact on system capabilities.

In most cases, power quality is actually being address by the quality of voltage. Technically, power is proportional to the product of voltage and current. It is hard to analyze the quality of this amount in any significant way. The system can only control the quality of voltage compared to the current that might be specific draws by the load. Therefore, the standards in power quality are to maintain the supply voltage within the range.

According to (Bollen, Gu et al. 2009), there are many types of equipment used to capture and characterize PQ variations like PQ monitors, digital fault recorders, digital relays, various power system controllers, and other intelligent electronic devices (IEDs). This claim is proved by many researchers like (Bhuiyan, Khan et al. 2018, Jeevitha and Mabel 2018) and (Thirumala, Prasad et al. 2018) that developed PQ monitoring system with the different proposed method.

(Bollen, Gu et al. 2009) also said that signal processing techniques are used in the recording of PQ variations as well as the analysis of events and conditions. There are difference technique of signal processing that can be found from various researchers like (Kapoor and Saini 2010). Thereby, the conventional method like RMS, Peak voltage and DFT are always used as a benchmark to compare with the potential and performance of their proposed method. All of the proposed method in the attempt of providing better insight into all the features of the conventional method.

2.3.1 Online and Offline Analysis

The online and offline analysis is the basic type of data analysis used in Power Quality. Offline analysis is mainly suitable for system performance evaluation, problem characterization and system diagnosis and maintenance where rapid analysis results are not required. Otherwise, online analyses require the results for rapid analysis in order to determine the immediate action to be taken. This kind of analysis presented by (Johnson and Yadav 2018, Lala, Karmakar et al. 2018) in determining the location of fault from the voltage waveform. Users can take immediate actions upon receiving notifications. Signal processing technique would be used to analyze the voltage and the current waveform. The analysis would reveal the fault location and this information would then be disseminated quickly to the line crew.

2.4 PQ Type Category

The information of PQ type categories and their descriptions are important in order to classify measurement results and to describe electromagnetic phenomena which can cause power quality problems. The IEEE standard 1159-2009 classifies electromagnetic phenomena into the groups shown in Appendix A. From the table, the short duration (RMS) variations will be primarily concerned in the analysis program of this research.

2.5 Voltage Sag Measurement

Referring to IEEE standard 1159-2009, voltage sag is defined as a decrease to between 0.1 and 0.9p.u in RMS voltage or current at the power frequency for the duration from 0.5 cycles but less than or equal to one minute (Smith, Hensley et al. 1995). Figure 2.1 shows the voltage sag phenomena in power quality event. The definition specifies that duration and magnitude of RMS voltage are important parameters for characterizing the voltage sag. The parameter of interest in voltage sag analysis could include the detection time of the event, beginning and ending time of the event and the percentage of voltage sag during the event. There are also, other relevant parameters are applied depending on their scope of interest. Therefore, most of the researchers in the field have conducted their research based on these parameters.

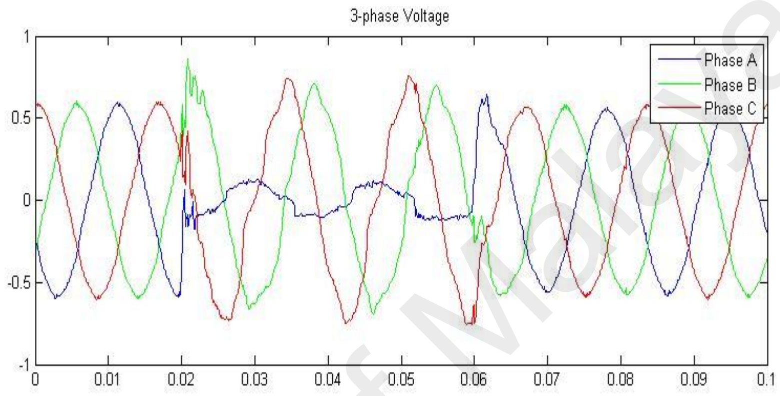


Figure 2.1: Voltage sag waveform

However, the power system fault does not only cause a drop in voltage magnitude but also cause a change in the phase angle of the voltage. For example in (Alkhayyat and Bashi 2018) investigates the effect of voltage sag and variation of phase angle jump to the sensitive load. This is also reinforced by (Espín-Delgado, Camarillo-Peñaranda et al. 2018) that characterized phase angle jump for fault classification. Therefore, this research mainly concerned to the voltage sag magnitude and duration because it is sufficient for characterized voltage sag in the scope of analysis.

2.5.1 Magnitude

The terminology of voltage sag magnitude is an important thing to be considered in order to describe the voltage sag. The magnitude of voltage sag is always present by remaining voltage during the event. As an example of 80 percent sag can refer to the voltage reduced down to 80 percent of the normal value, thus a remaining voltage of 20 percent would be the sag magnitude. Voltage sag magnitude can be determined in many ways. The most common way used to obtain the magnitude of sag is RMS voltage. This claim by (Kamble and Thorat 2012), where the RMS voltage is related to power calculation and can be the most suitable for the characterization of voltage sag even though the voltage sag magnitude can be determined using fundamental voltage (DFT), or peak voltage as long as the input signal is in the sinusoidal form. Figure 2.2 illustrates the typical voltage sag caused by a single line to ground fault. Figure 2.3 illustrates the temporary voltage sag caused by large motor starting. The voltage sags immediately drop to 80 percent and gradually returns to normal in about 3 seconds.

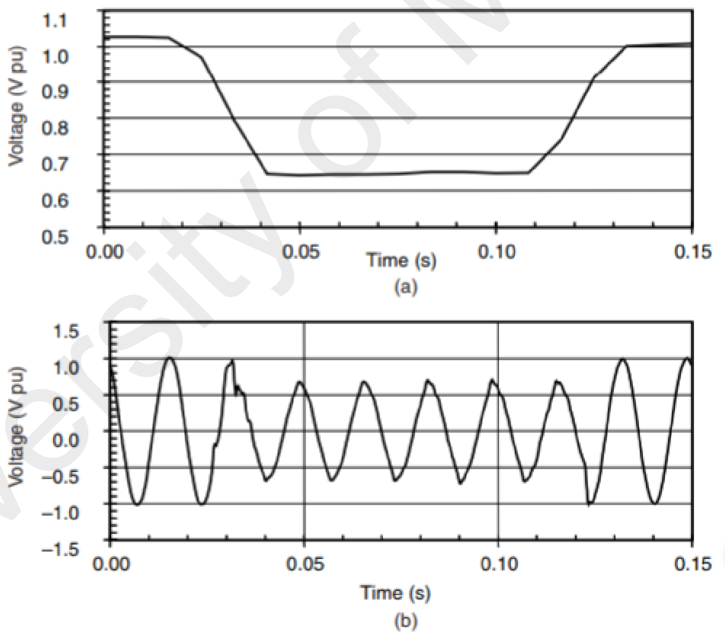


Figure 2.2: Voltage sag caused by SLG fault. (a) RMS variation (b) Voltage waveform for Voltage sag event.

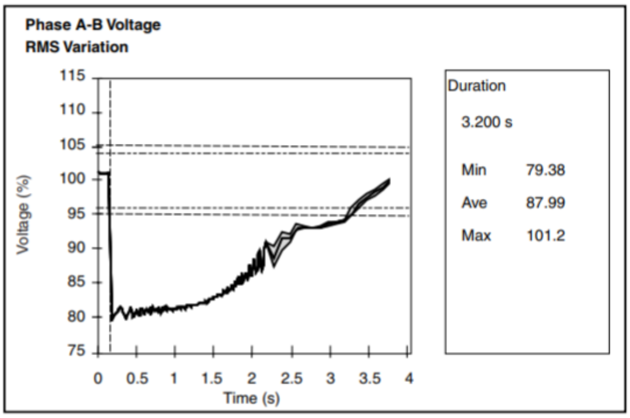


Figure 2.3: Temporary voltage sag caused by motor starting

2.5.2 Duration

Voltage sag duration defines how long voltage sag lasts from the beginning of sag until end of sag. It also can be defined as the length of time needs to recover the sag. In details, voltage sag duration is the amount of time when the magnitude of the voltage is below the threshold (0.9p.u / 90% of the nominal voltage). According to (Bollen and Gu 2006), there are three RMS voltage should be considered in the measurement of sag duration. The time of the voltage sag starts is taken at least one of the RMS voltage drops below the threshold. The time of the voltage sag ends when all the three RMS voltages have recovered above the sag threshold. This is presented graphically by (Mohammadi, Rozbahani et al. 2014) as shown in Figure 2.4.

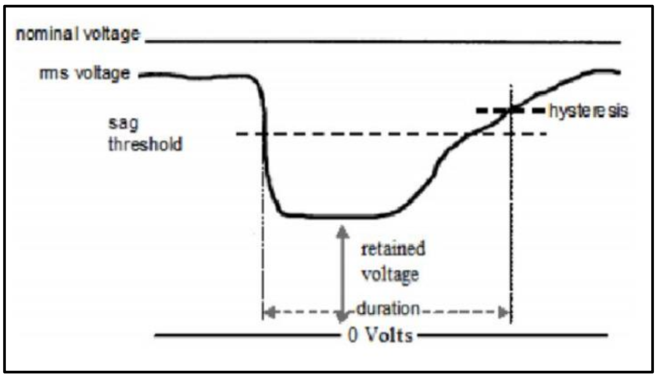


Figure 2.4: Graphical representation of voltage sag duration

2.6 Methods for Analyzing Voltage Sag

In this research, there are two basic methods are interested to study in analyzing the voltage sag event which is Root Mean Square (known as RMS) and Discrete Fourier Transform (known as DFT).

2.6.1 Root Mean Square (RMS)

RMS value calculation is the most common method used in voltage measurement in the power system (Barros and Pérez 2006). From monitoring, voltage waveform is recorded as samples points in the time domain. The magnitude of RMS voltage of a sampled time-domain is calculated using the following formula given by Eq.(2.1):

$$V_{rms}(k) = \sqrt{\frac{1}{N}\sum_{n=1}^{N} v_n^2} \tag{2.1}$$

Where N is the number of samples per cycle, v_n refer to the sample voltage and k is the cycle number. In a practical application, data window is sliding along the time sequence in a specific sample interval. The window length is an integer multiple of one half-cycle. Since the resulting of RMS voltage depends on the sliding window and the window length, there can be a lag or lead from the time voltage actually starts or clear the sag. The voltage magnitude of one cycle window as in Eq.(2.2) and for the half-cycle window as in Eq.(2.3):

$$V_{rms}(kN) = \sqrt{\frac{1}{N}\sum_{n=1}^{i=kN} v_n^2} \tag{2.2}$$

$$V_{rms(1/2)}(k) = \sqrt{\frac{2}{N}\sum_{i=k-(N/2)+1}^{k} v_i^2} \tag{2.3}$$

2.6.2 Discrete Fourier Transform (DFT)

DFT method can be used to characterized voltage sag by using fundamental voltage. Fundamental voltage is a complex quantity obtained by the decomposition of the instantaneous voltage into Fourier components. The fundamental voltage component is extracted normally from a time sequence over a fundamental frequency cycle (Kamble and Thorat 2012). Fourier coefficients in a one-cycle window can be expressed in DFT form as:

$$V_h = \frac{1}{N}\sum_{n=1}^{N} v_n e^{-i\frac{2\pi}{N}(n-1)h} \qquad h=1,2,\ldots N \tag{2.4}$$

Where h is the harmonic component of the signal, N is the number of samples per-cycle, v(n) is the sample voltage in a time domain. This equation can be further extended to calculate the amplitude of the real (Eq.2.5) and imaginary parts (Eq.2.6) of the frequency component.

$$a_h = \frac{2}{N}\sum_{n=1}^{N} v_n \cos\left[\frac{2\pi}{N}(n-1)h\right] \tag{2.5}$$

$$b_h = \frac{2}{N}\sum_{n=1}^{N} v_n \sin\left[\frac{2\pi}{N}(n-1)h\right] \tag{2.6}$$

The magnitude of the signal and the angle of the h harmonic can be calculated as follows:

$$m_h = \sqrt{a_h^2 + b_h^2} \tag{2.7}$$

$$\varphi_h = \tan\left(\frac{b_h}{a_h}\right)^{-1} \tag{2.8}$$

The application of fundamental voltage to estimate voltage sag magnitude and duration was claimed to be accurate for most sag analysis. For the fundamental component, h=1 is obtained as in Eq.(2.9) and Eq.(2.10) separating the real and imaginary parts.

$$a_1 = \frac{2}{N}\sum_{n=1}^{N} v_n \cos\left[\frac{2\pi}{N}(n-1)\right] \tag{2.9}$$

$$b_1 = \frac{2}{N}\sum_{n=1}^{N} v_n \sin\left[\frac{2\pi}{N}(n-1)\right] \tag{2.10}$$

The magnitude and angle of the fundamental component can be calculated as follows:

$$m_1 = \sqrt{a_1^2 + b_1^2} \tag{2.11}$$

$$\varphi_1 = \tan\left(\frac{b_1}{a_1}\right)^{-1} \tag{2.12}$$

CHAPTER 3: METHODOLOGY

3.1 Introduction

In this research, there are two main steps. The first step described the methods to solve the PQ analysis mainly focused on the voltage sag event. The second step described the proposed technique on the voltage sag magnitude determination. Both steps will be carried out using MATLAB software.

The first step will cover two methods of analyzing the voltage sag. The first method is RMS and the second method is DFT. The RMS and DFT method is a computational process that involves mathematical equations to obtain the quantity of the parameters (voltage magnitude and duration) from a large amount of sample data. Both methods will be simulated separately due to allowing easier and faster computation. The simulation result is focusing on the sag detection time and sag ending time to determine sag duration. Those parameters will be analyzed and compared on the performance of RMS and DFT method.

The second step will cover in details the methodology of the proposed technique named as Rectangular Approximation. The proposed technique used to quantify the magnitude of sag based on the numerical integration method. Once the RMS and DFT of the measurement are determined, the proposed Rectangular Approximation technique is applied to obtained voltage sag magnitude. Besides that, the effect of rectangular size used in the approximation technique will be investigated to determine the suitable size that will give a better result of sag magnitude.

Two important aspects that affect the accuracy of the result is considered while computing the sample of data. That are sampling window size (known as a number of the sample) and sampling window technique (sample to sample or half-cycle sliding or one-cycle sliding). For a better understanding of the sampling window size and technique, the effect of varying these parameters will be performed in the simulation and the most suitable size and technique will be determined.

3.2 Programming Development

The purpose of this study is to analyze the voltage sag based on Root Mean Square (RMS) and Discrete Fourier Transform (DFT) method using MATLAB programming software. The programming is developed based on the basic flow chart as shown in Figure 3.1.

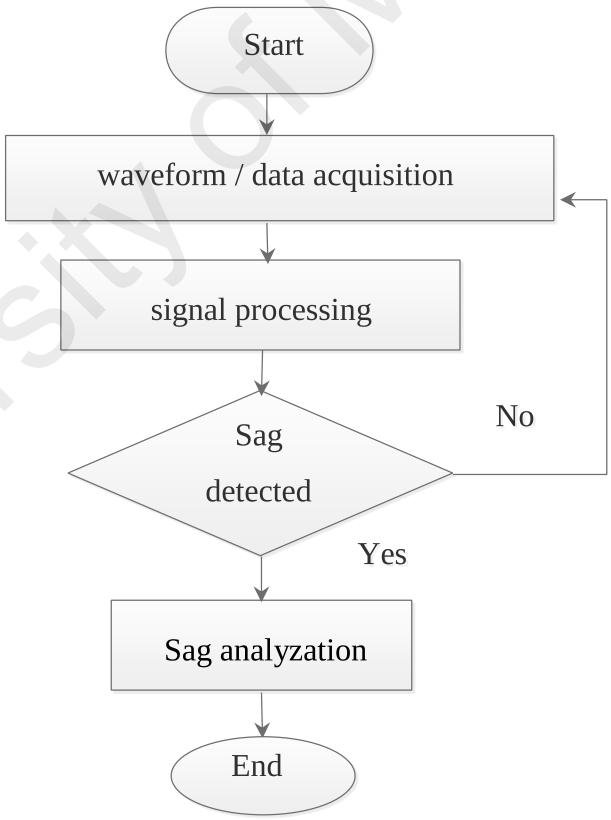


Figure 3.1: Basic flow chart of sag analysis

3.2.1. Voltage sag waveform analysis

The following are the steps taken to analyze the voltage sag in the voltage waveform.

#Step 1: Acquisition of voltage waveform data.

In this research, the voltage waveform data is obtained from the test waveform as provided by the IEEE 1159.2 PQ event working group. In general, for any recorded voltage waveform data can be saved in the Microsoft Excel format as an example shows in the Appendix B. The file should be saved in the MATLAB folder and the spreadsheet data is imported into MATLAB editor using xlsread function.

#Step 2: Identify the basic parameters.

The basic parameters like nominal voltage, frequency, total measured time for the voltage waveform and number of sample data are identified. This parameter will be used in calculating the period of one cycle waveform, sampling time or sampling rate, the total number of cycle involved and number of sample per cycle. The programming flow chart of basic parameter identification shows in Figure 3.2.

#Step 3: Processing of voltage waveform data.

Voltage waveform data in per unit will be processed using Eq.(2.1) for RMS method and Eq.(2.4) until Eq.(2.12) for DFT method. This process will transform the peak-peak voltage magnitude into RMS and DFT voltage waveform. Then, the magnitude of voltage is normalized to the first value of voltage due to allowing a direct comparison of two different scale. All the value obtained will be stored in Vrms and Vrms_norm respectively. The programming flow chart of application RMS and DFT method shows in Figure 3.3 (a) and (b).

#Step 4: Detection of voltage sag event.

The normalized voltage magnitude based on RMS and DFT method will be analyzed based on voltage sag characteristic in IEEE standard 1159-2009 in order to detect sag event. The detection of sag magnitude with the corresponding time will be stored in SAG. The programming flow chart of sag detection shows in Figure 3.4.

#Step 5: Determination of sag duration.

The detection time of sag will be identified at the starting time of the first magnitude below the threshold. The ending time will be identified at the last magnitude before recovery. The sag duration can be calculated either using counted number of sag magnitude multiply by the sampling time or subtraction time between start and end of sag. The programming flow chart of sag duration determination shows in Figure 3.4.

#Step 6: Determination of sag magnitude.

The magnitude of sag will be quantified using the proposed technique that will explain in details in Chapter 3.3.

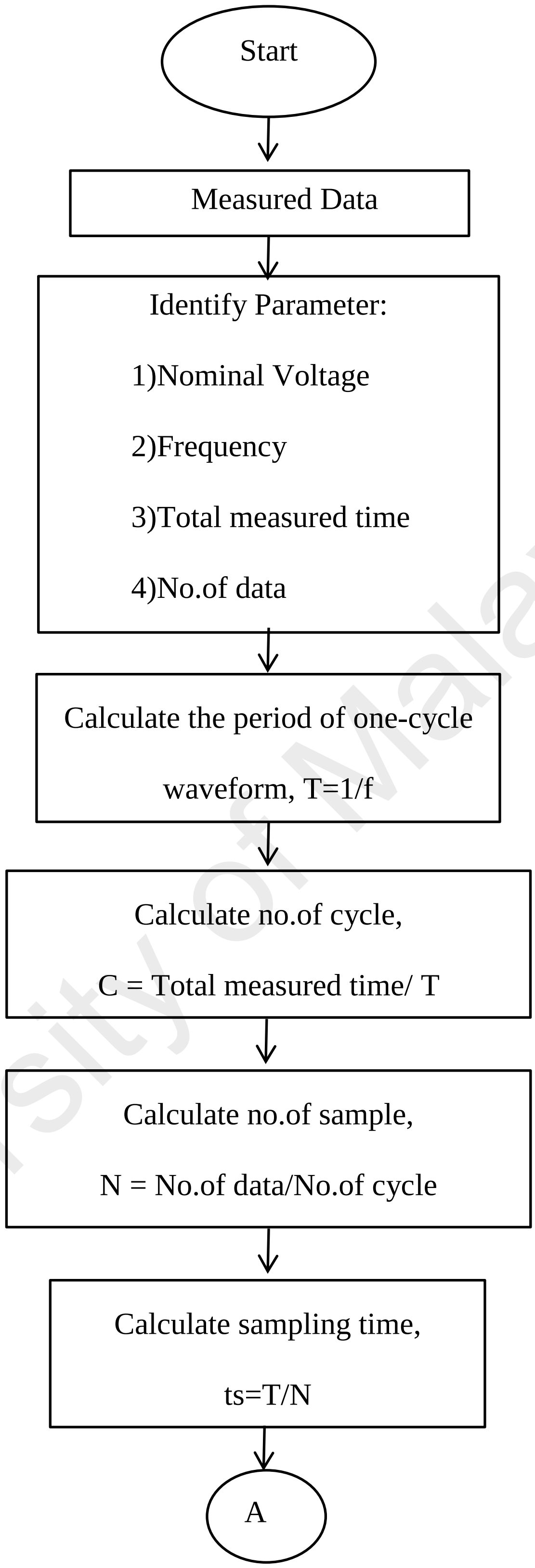
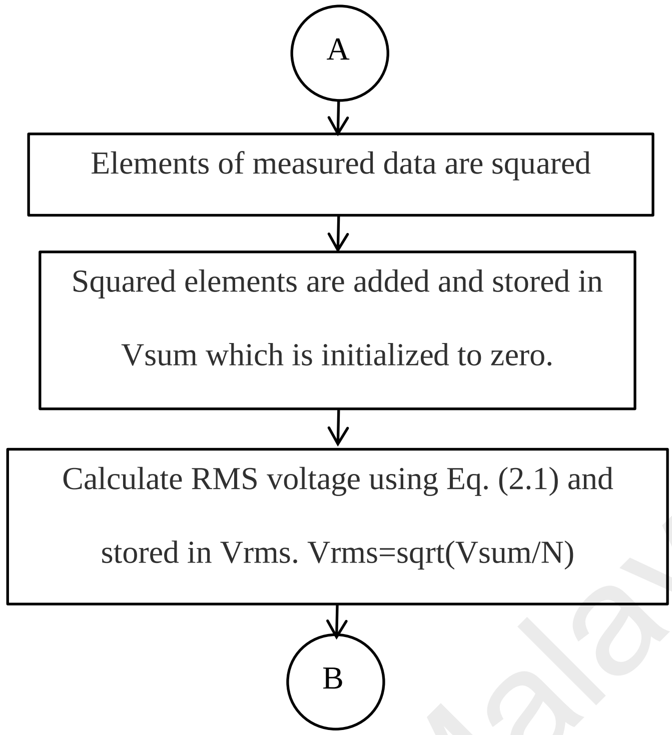
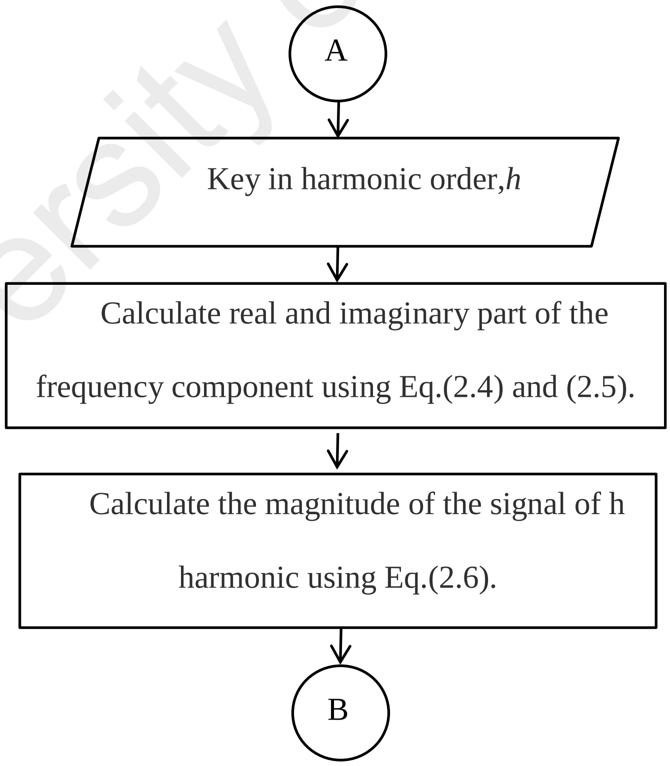


Figure 3.2: Flow chart of the basic parameter identification



(a) RMS method



(b) DFT method.

Figure 3.3: Flow chart of the application (a) RMS method (b) DFT method.

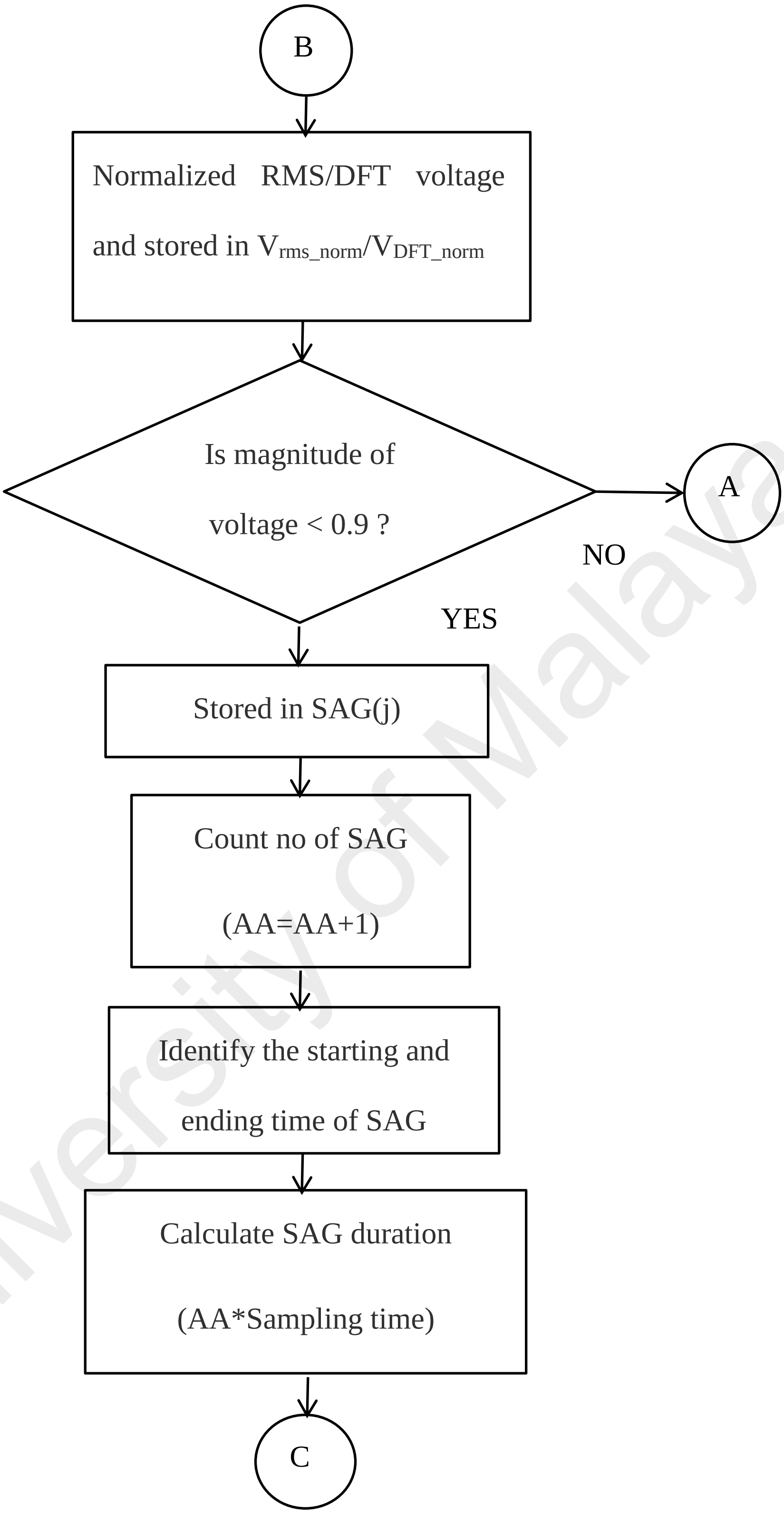


Figure 3.4: Flow chart of the sag duration determination.

3.3 Determination of Sag Magnitude using Rectangular Approximation Technique

The Rectangular Approximation technique is proposed to determine the rectangular or any non-rectangular sag magnitude waveform obtained from the RMS and DFT method.

3.3.1. Rectangular Approximation Technique Based on Numerical Integration

The technique is based on the numerical integration method and also known as numerical quadrature. According to the dictionary, integration means "*to bring together, as parts, into a whole; to unite; to indicate the total amount . . .*" Mathematically, integration is represented by Eq.(3.1):

$$I = \int_{a}^{b} f(x)dx \tag{3.1}$$

Which stands for the integral of the function *f* (*x*) with respect to the independent variable *x*, evaluated between the limits *x* = *a* to *x* = *b*. The function *f* (*x*) in Eq. (3.1) is referred to as the *integrand.* As suggested by the dictionary definition, the "meaning" of Eq.(3.1) is the *total value,* or *summation,* of *f* (*x*) *dx* over the range *x* = *a* to *b*. Figure 3.5 shows the graphical representation of the concept. For functions lying above the x-axis, the integral expressed by Eq.(3.1) corresponds to the area under the curve of *f*(*x*) between the limit x=a to b. The function to be integrated is a tabulated function due to the discrete points obtained from the simulation result where the values of x and *f* (*x*) are given as a time and magnitude of sag. For the discrete data points, the approximation methods must be employed to the integration. The approximation method is applied in terms of Riemann Sums where the area under the curve is divided into a number of rectangle shape by dividing the interval into sub interval with equal-area. Furthermore, the area under the curve is approximately the sum of the rectangular areas. Figure 3.5 shows the graphical representation of the integral. According to (Ostebee and Zorn 1997), there are four methods to divide the rectangles under the curve which is right and left methods, maximum and minimum methods as shown in Figure 3.6.

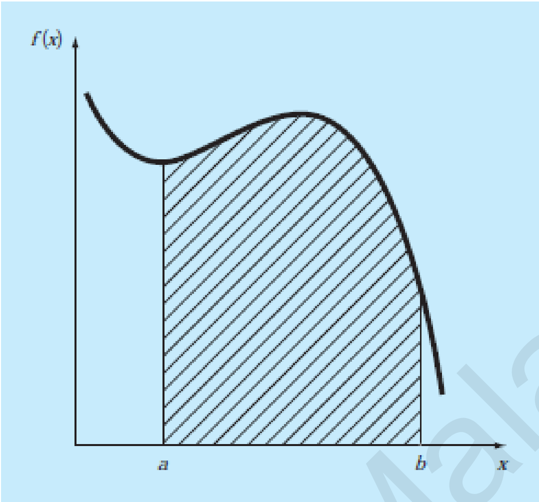


Figure 3.5: Graphical representation of the integral

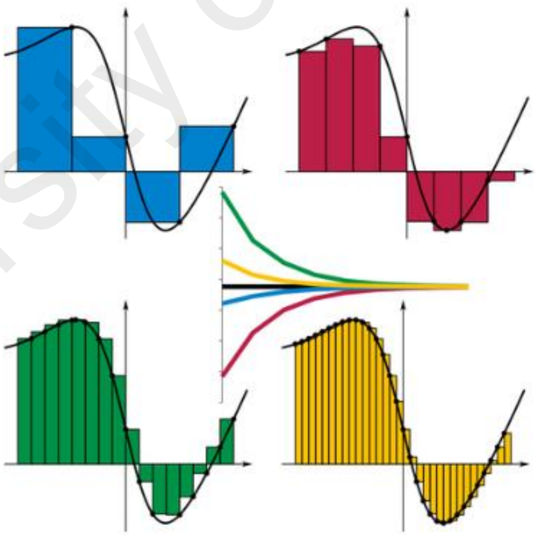


Figure 3.6: Graphical Representation of Riemann Summation Method

3.3.2. Step to Determine Sag Magnitude

The following are the steps taken to determine voltage sag magnitude using the Rectangular Approximation technique.

#Step 1: Determine the rule of rectangular summation.

The rectangular summation rule determines the height and width of the rectangle. The determination is based on left-rule where the left endpoint of each sub-interval is used.

#Step 2: Calculate area under sag curve (A).

Figure 3.7 shows the area under the curve is approximated by adding up the rectangular areas with the sampling time as the width and sag magnitude as a height of the rectangle. Doing this by using Eq.(3.2) within sag at starting time and sag at ending time [a,b]. Eq.(3.2) can be written as Eq.(3.3).

$$A_N^{rect} = \sum_{i=a}^{b} V_{sag_i} \times \Delta t \tag{3.2}$$

$$A_N^{rect} = \Delta t \left[V_{sag}(a) + V_{sag}(a + \Delta t) + V_{sag}(a + 2\Delta t) + ... + V_{sag}(b - \Delta t) \right] \tag{3.3}$$

Where A_N^{rect} is an area of N rectangles, V_{sag_i} is a sag magnitude and Δt is a sampling time. This can be represented as a graphical as shown in Figure 3.7.

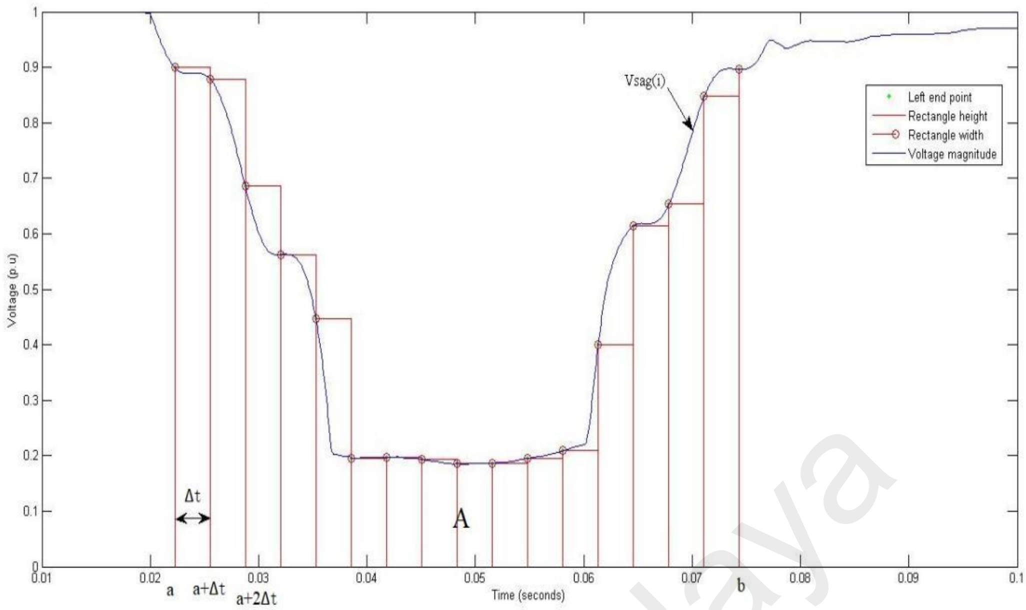


Figure 3.7: Approximation of area under the curve based on the rectangular rule.

#Step 3: Calculate the threshold area (B).

Area noted by B as shown in Figure 3.8 is the larger rectangular area below the threshold. The area is calculated with the height of the rectangle as a threshold value which is 0.9 p.u. and the width is a sag duration. Doing this by using Eq (3.4).

$$A^{rect} = 0.9 \times t_{sag} \tag{3.4}$$

Where A^{rect} is the whole area below the threshold and t_{sag} is a sag duration.

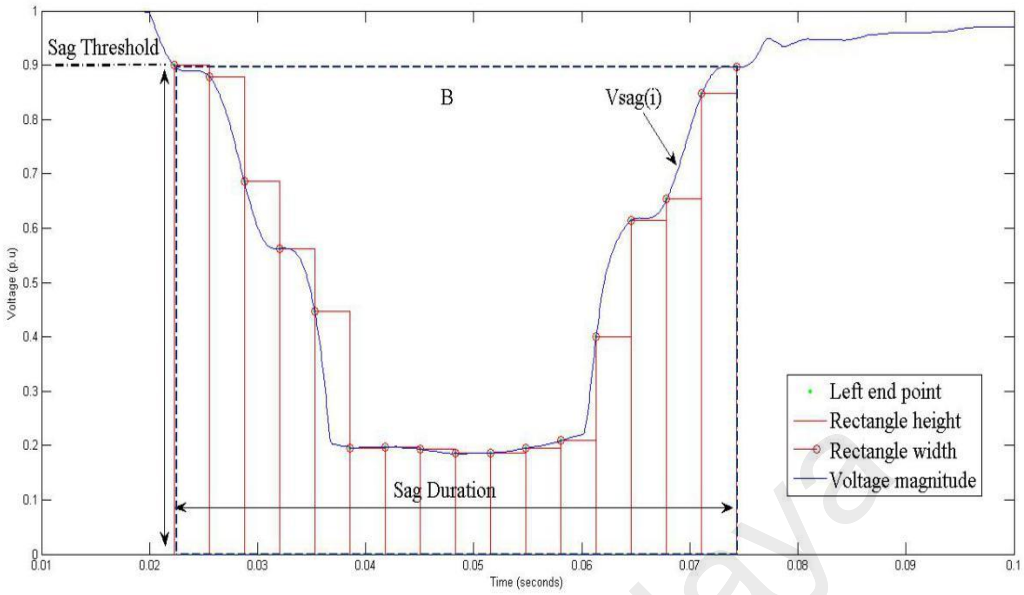


Figure 3.8: Graphical representation of a larger rectangular area.

#Step 4: Determine sag area (C).

The sag area of C as shown in Figure 3.9 is determined by subtracting the cumulative area of N rectangles noted by A from the larger rectangle area below the threshold noted by B. Doing this by using Eq (3.5) where C is a sag area in p.u, B is the area under threshold and A is an area under sag curve.

$$C = B - A \tag{3.5}$$

#Step 5: Convert sag area, C in p.u into voltage.

The conversion is respected to the nominal voltage enter by the user. As an example of 0.4350 p.u converted into a voltage by 230V of nominal voltage, the sag area in p.u is multiply by 230V. Thus, the sag area is equal to 100.05V.

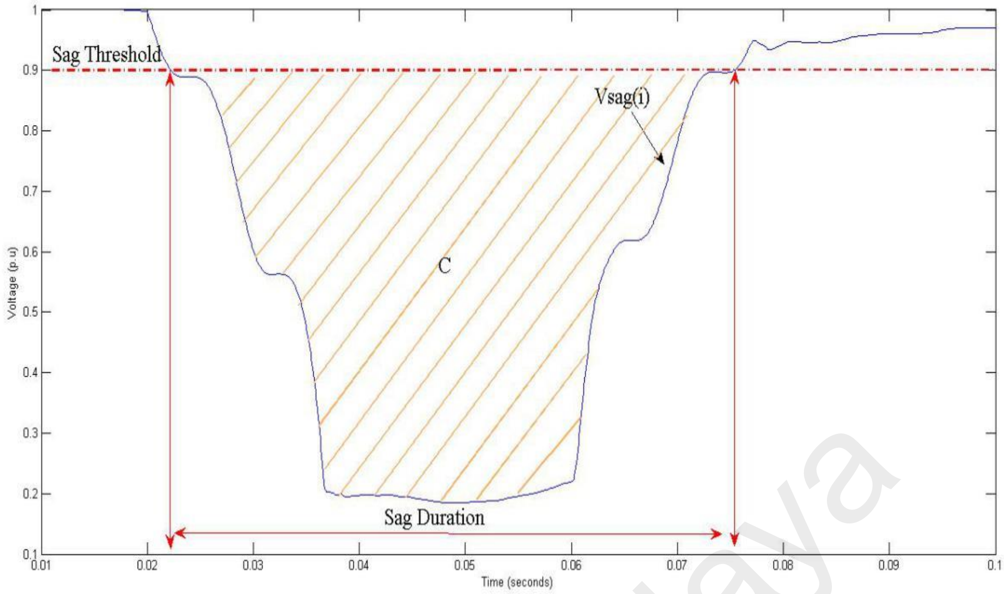


Figure 3.9: Graphical representation of the sag area (C).

#Step 6: Determine sag magnitude in percent.

As mentioned in Chapter 2.5.1, sag magnitude is the remaining of nominal voltage during sag event. The magnitude is determined by subtracting the voltage in sag area from nominal voltage. The result is then convert into percentage. From the example in #step 5, the sag magnitude is equal to 56.5%.

3.3.3. Programming Flow Chart of Sag Magnitude Determination

Figure 3.10 and Figure 3.11 shows the flow chart to develop the programming of sag magnitude determination. The flow chart is continuous from the previous flow chart of sag analysis in Chapter 3.2.1.

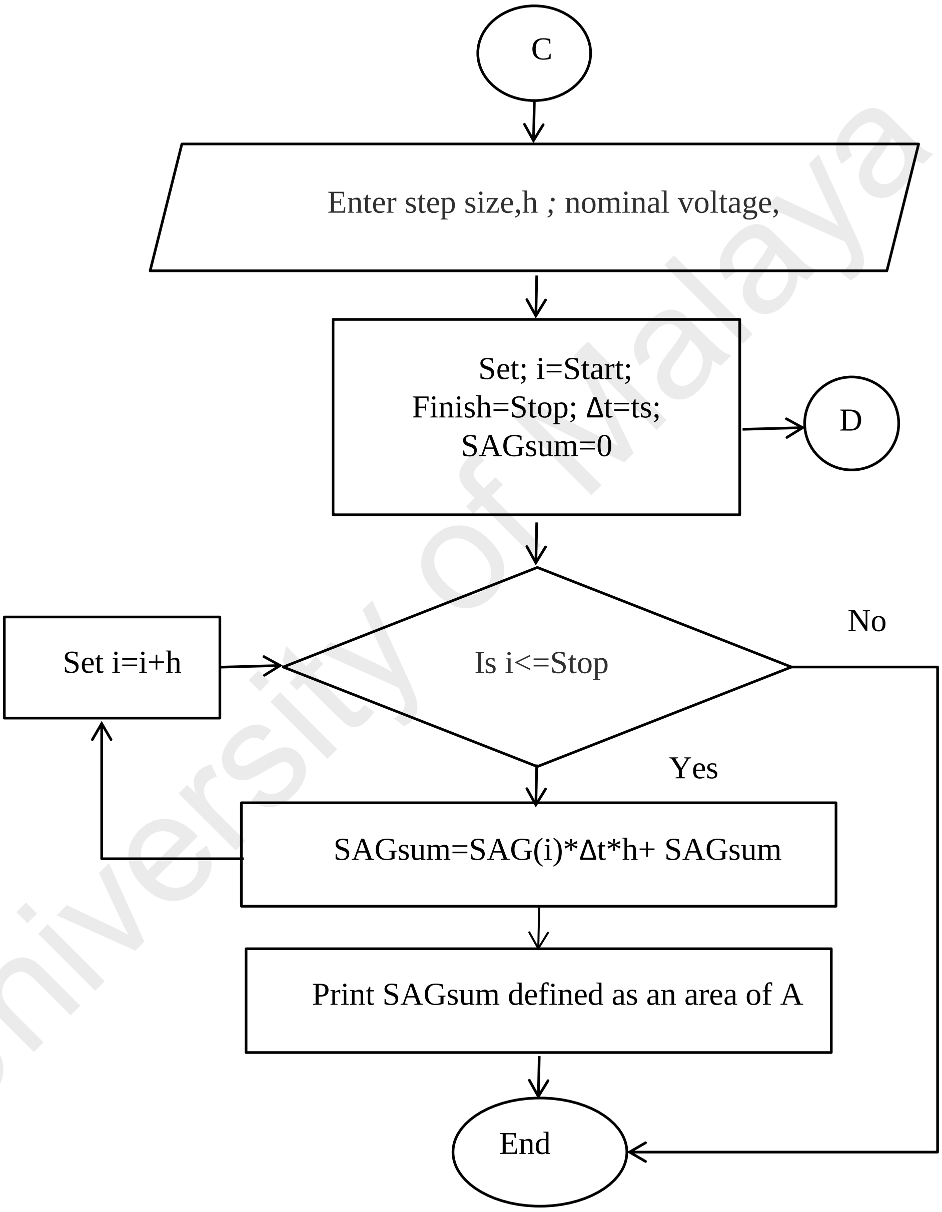


Figure 3.10: Flow chart of under curve area of sag calculation (A).

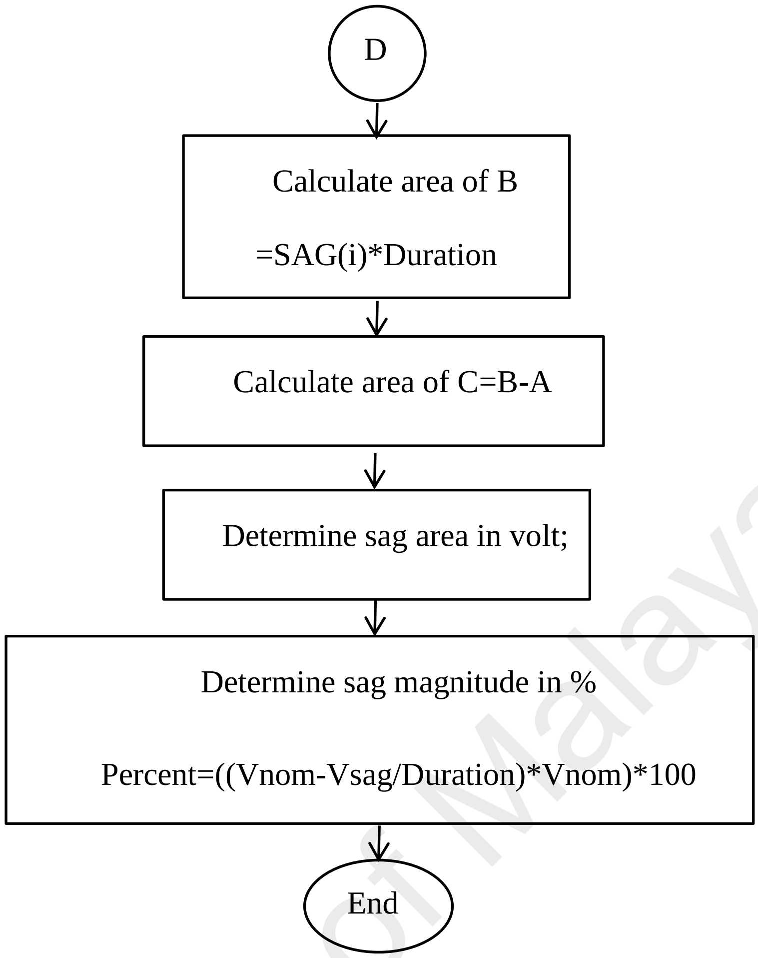


Figure 3.11: Flow chart of sag magnitude determination.

3.4 Summary

The method for analyzing voltage sag in terms of duration and magnitude is described in detail in this chapter. It can be concluded that the RMS and DFT are using different equations in voltage magnitude calculation but using the same way to analyze the voltage waveform. Both methods are useful to detect and analyze the sag events. The next chapter will discuss the result and analysis.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Introduction

This chapter provides the analysis result and discussion for the project. The analysis result for RMS and DFT methods are from the simulation of the programming developed by the MATLAB environment. The voltages magnitude obtained from both methods was analyzed based on the test waveform as provided by the IEEE 1159.2 PQ event working group with the nominal voltage of 250V, 60Hz.

4.2 Voltage Sag Analysis

Voltage sag analysis in this section was obtained based on the characteristics of voltage sag detection time, sag duration, and sag magnitude of the test waveform as shown in Figure 4.1. All the characteristics were analyzed and discussed by comparing RMS and DFT methods.

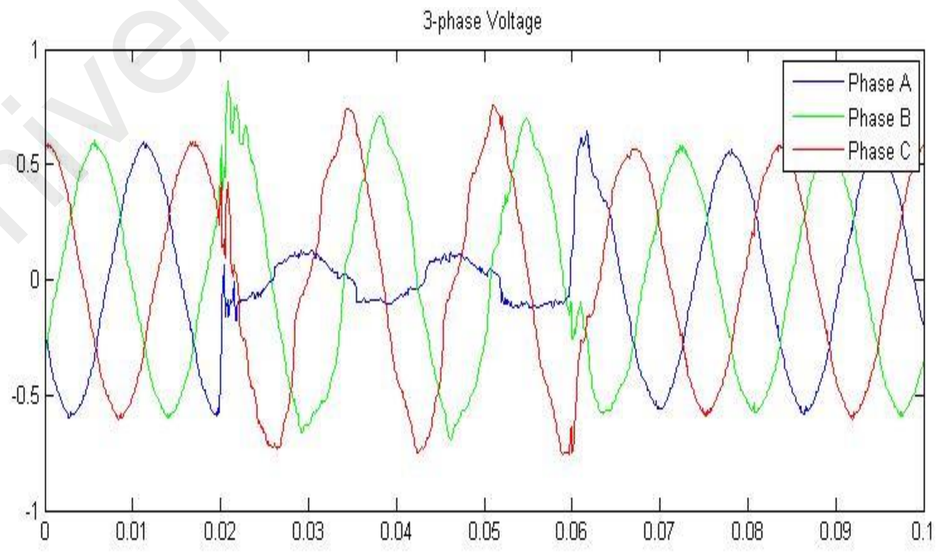


Figure 4.1: Test waveform provided by IEEE 1159.2

4.2.1 Voltage Sag Detection

RMS and DFT voltage with different magnitude levels are generated and represented as a graphical plotted. The voltage amplitude of 1p.u is considered as a normal condition without any events of disturbance. The sampling frequency is 15.4kHz with 256 samples per cycle for supply frequency of 60Hz.

Detection measurement is subject to the speed and accuracy of voltage sag in the signal. Inaccurate of sag detection might cause wrong decision by the mitigation equipment to justify the operation. The sag detection needs to extract the information of the first sag magnitude in terms of time. The location of the first sample of sag was taken as a sag detection. The result of voltage sag detection for RMS and DFT methods have shown in Figure 4.2 and 4.3.

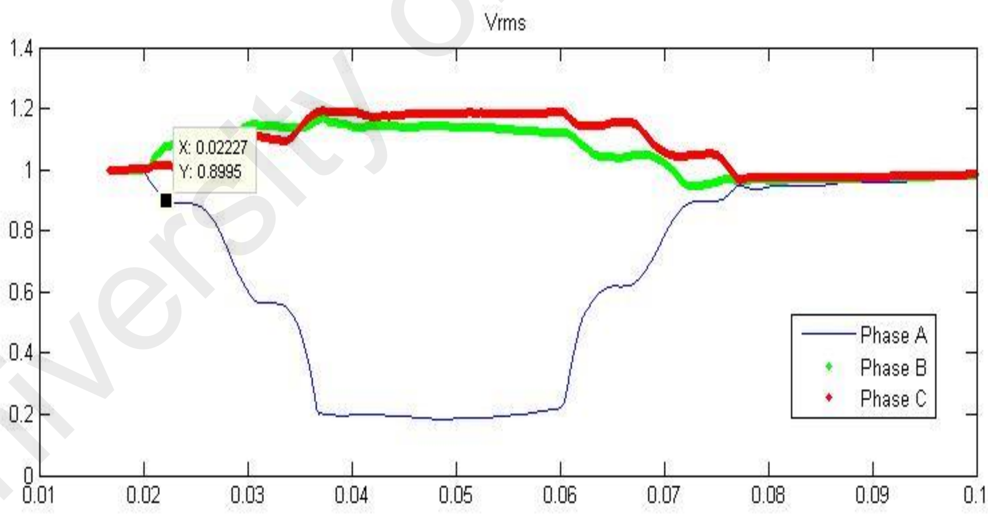


Figure 4.2: Voltage sag detection in terms of One-cycle RMS analysis.

Based on the test waveform in Figure 4.1, voltage sag detection characteristic by the RMS method for one-cycle window length is presented in Figure 4.2. The sag starts detected at time 22.27ms. The time is taken at the RMS voltage start drops below the threshold which is equal to 0.8995p.u.

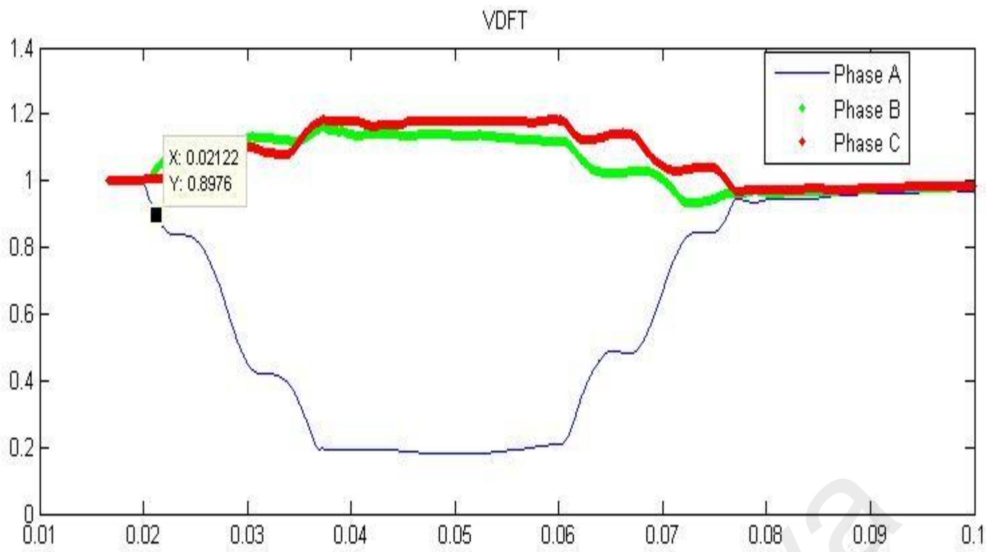


Figure 4.3: Voltage sag detection in terms of One-cycle DFT analysis.

Figure 4.3 shows the voltage sag detection from the fundamental voltage of DFT method. From this method, voltage sag detected for one-cycle window length is 21.22ms with the magnitude of 0.8976p.u which is at the first value of sag magnitude below the threshold.

4.2.2 Voltage Sag Duration

The duration of voltage sag is an important parameter to characterize the voltage sag event. As mentioned in Chapter 2.5, voltage sag is a short duration (0.5 cycles to 1 minute) during the reduction of RMS voltage from 10% to 90% of nominal voltage. Figure 4.4 and Figure 4.5 shows the duration of voltage sag in terms of RMS and DFT analysis.

Figure 4.4 shows the result of voltage sag characteristic in terms of duration by using the RMS method. The maximum duration of the waveform is 100ms and the number of cycles calculated was 6 cycles. The sag duration for one-cycle window length was 53.06ms. The duration was determined by taking the time of sag to start detected (22.27ms) and sag start recovered (75.33ms).

The duration of voltage sag obtained by the one-cycle DFT method was 55.02ms as shown in Figure 4.5. For this case, the starting sag was captured from 21.22ms to 76.24ms and the time needs to recover the voltage sag was 55.02ms.

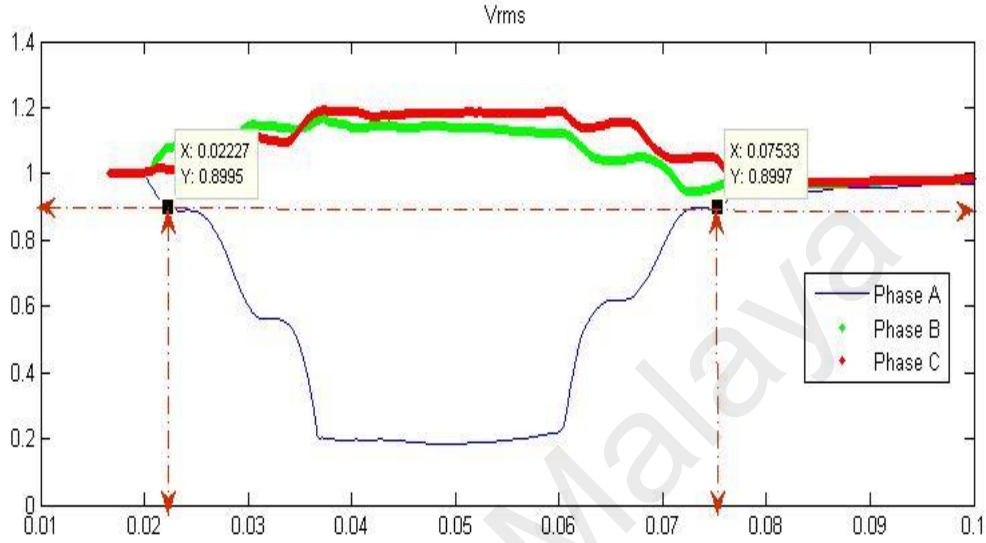


Figure 4.4: Voltage sag duration in terms of the RMS method.

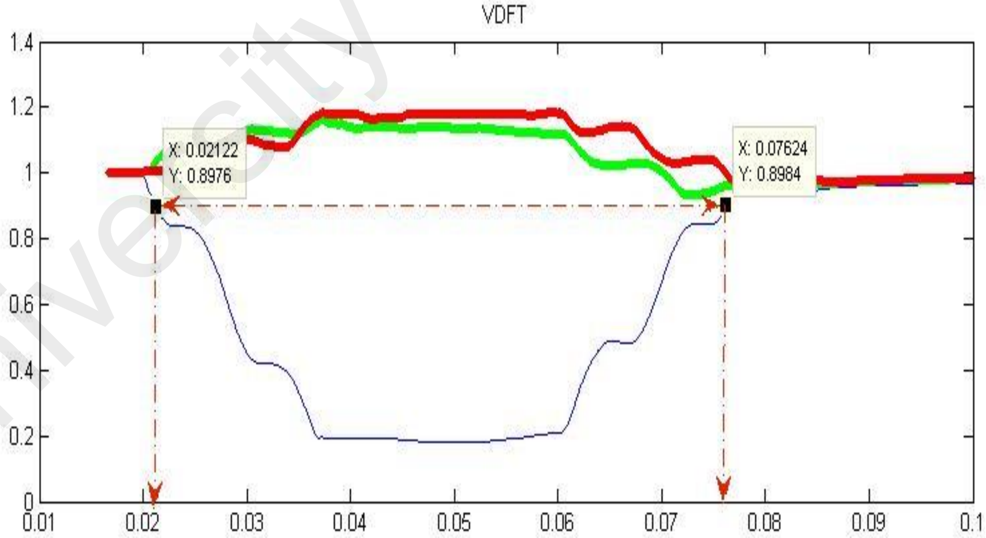


Figure 4.5: Voltage sag duration in terms of the DFT method.

4.2.3 Voltage Sag Magnitude using Rectangular Approximation Technique.

The single-phase voltage sag waveform in Figure 4.6 is analyzed based on RMS and DFT methods, and the results presented in Figure 4.7. The dotted red line indicated the RMS voltage while the blue line plotted the voltage obtained by the DFT method. The Rectangular Approximation technique applied to the voltage sag in Figure 4.7 and the effect illustrated in Figure 4.8 and Figure 4.9. Thus, the sag magnitude was quantified based on the procedures as explained in Chapter 3.3.2 by using the smallest step size (h=1) used as a multiplier to the rectangular width.

The total area of rectangles noted by A (refer to Figure 3.7) was quantified based on the left-rule summation method, and the amount is 0.4642p.u. The area indicated by B and C (refer to Figure 3.8 and Figure 3.9) were 0.9p.u and 0.4358p.u. The remaining voltage was 0.4358p.u and respected to the nominal voltage is equal to 108.95V or in percentage is 56.49%. This 56.49% of sag meaning that voltage was reduced down to 43.51% of the nominal value.

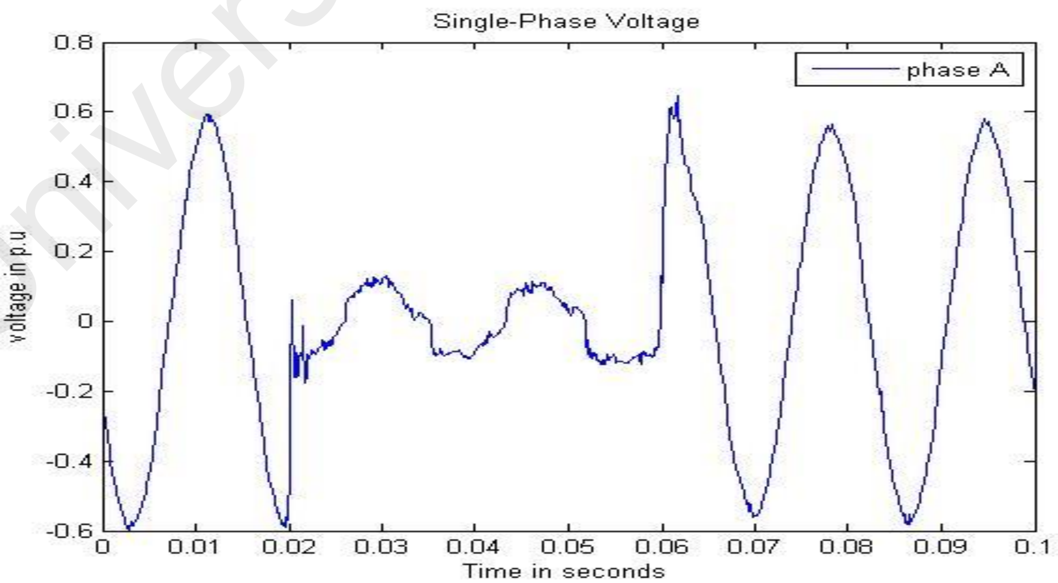


Figure 4.6: Single-phase voltage sag waveform.

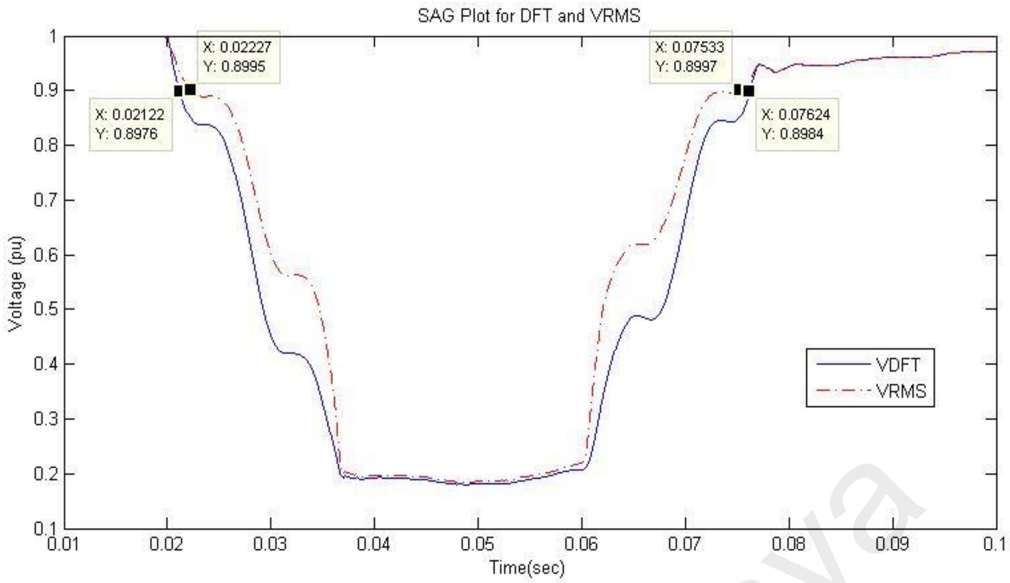


Figure 4.7: Single-phase voltage sag in terms of RMS and DFT.

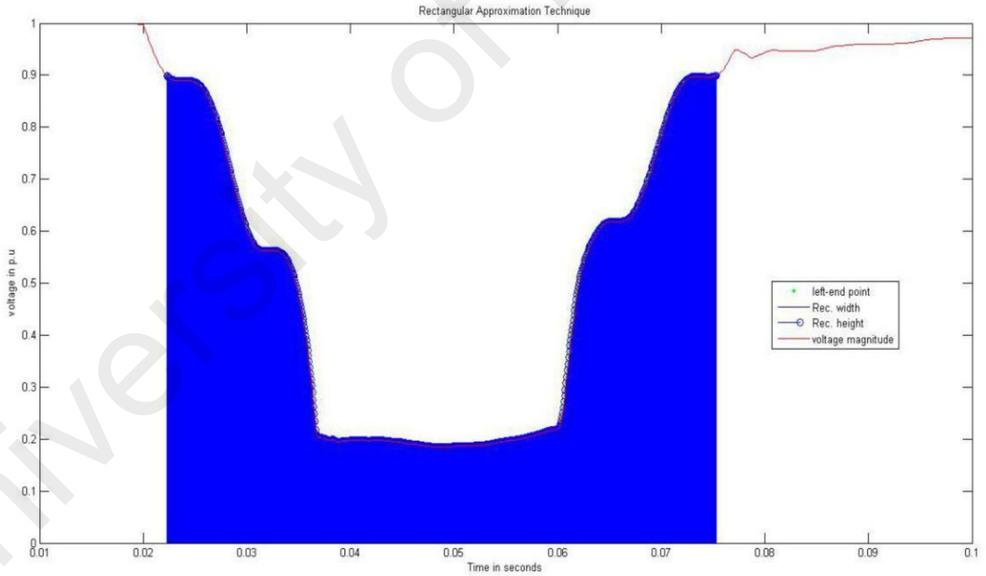


Figure 4.8: Application of the Rectangular Approximation Technique (h=1) to the RMS voltage.

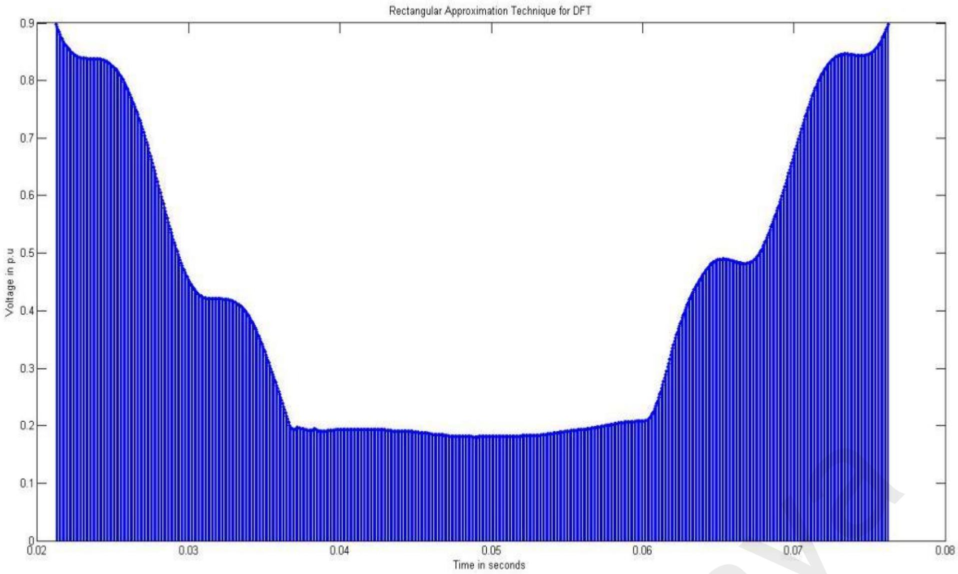


Figure 4.9: Application of the Rectangular Approximation Technique (h=1) to the fundamental voltage of DFT.

Figure 4.9 shows the Rectangular Approximation Technique applied to the fundamental voltage of DFT with the similar way as RMS. The comparison results for each area were shown in Table 4.1.

Table 4.1: Sag magnitude by RMS and DFT methods.

Method	A (p.u)	B (p.u)	C (p.u)=B-A	Sag Magnitude (%)
RMS	0.4642	0.9	0.4358	56.49
DFT	0.4164	0.9	0.4836	51.95

Table 4.1 shows the magnitude for each region A, B, C and voltage sag magnitude in percent. The voltage sag magnitude was determined by subtracting the value of C from 1.0p.u, and the result converted into a percentage.

In the usual application, the sag magnitude is taken from the lowest RMS value during a voltage sag (Caicedo, Navarro et al. 2012) but the new method proposed by this project considers all the RMS voltage during the event. Hence, the resultant sag magnitude determined from the proposed technique can be applied to the CBEMA curve for voltage sag assessment. To further understand the accuracy of sag magnitude quantified by the proposed method, the effect of rectangular size is investigated in Chapter 4.5.

4.2.4 Comparison Performance of RMS and DFT Method

The result from the MATLAB program shows the comparison between the RMS and DFT analysis as shown in Figure 4.10 and Table 4.2. The comparison is made in terms of sag detection, sag duration and sag magnitude.

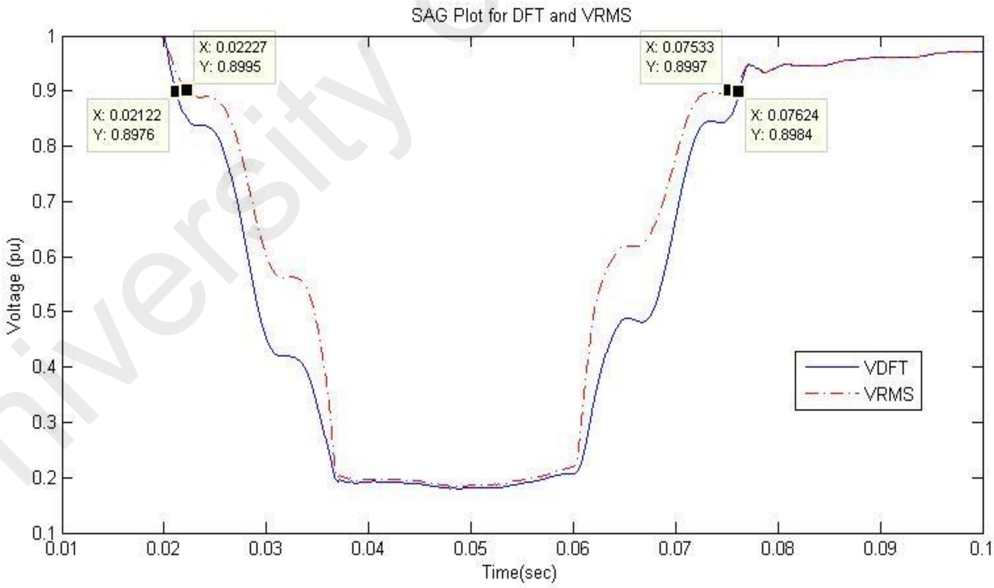


Figure 4.10: Magnitude of voltage sag in terms of RMS and DFT method.

Figure 4.10 shows the DFT method also can detect the voltage sag like the RMS method. The waveform obtained is quite similar but slightly difference in voltage magnitude. There only have a little bit different about 3 to 8 percent in all parameters as shown in Table 4.2.

Table 4.2 shows the sag detection time, sag duration, sag magnitude and also the deviation for each parameter analyzed as regards the RMS and DFT method. The DFT detects the sag at 21.2ms and the RMS at 22.3ms. The result in a difference in sag detection time of 1.1ms. Its means that DFT detect sag faster than RMS method.

Table 4.2: Comparison of voltage sag characteristic between RMS and DFT

Sag characteristic	RMS	DFT	Deviation
Detection (ms)	22.3	21.2	1.1
Duration (ms)	53	55	2
Max. of voltage sag (p.u)	0.8997	0.8984	0.0013
Min of voltage sag (p.u)	0.1849	0.1802	0.0047
Magnitude (%)	56.49	51.95	4.54

The simulation result for sag duration shows the difference in 2ms between both methods which is 55ms for DFT and 53ms for RMS. It shows that, the sag duration obtained from DFT method takes longer time to recover the voltage sag.

The voltage sag magnitude is presented by remaining voltage during the event. Table 4.2 showed the remaining voltage from DFT method is lower which is 51.95% compare to 56.49% for RMS method. The difference in sag magnitude between the two methods is 4.54%. This is due to the longer duration of sag occurred in the DFT method.

There is a significant different when comparing the sag magnitude quantified by the Rectangular Approximation technique with the minimum voltage of sag magnitude obtained by RMS and DFT method.

4.3 Voltage Sag Analysis on Different Test Waveform

Voltage sag analysis in this section was obtained to show the developed analysis program can be applied to any voltage waveform. The analysis is done based on the voltage waveform in the IEEE 1159.2 PQ event working group but using two different test waveform as presented in Chapter 4.2. The voltage waveform is analyzed based on the procedure in Chapter 3. All the characteristics as given in Chapter 4.2 is analyzed on the test waveform 1 and 2 as shown in Figure 4.11 and Figure 4.15.

4.3.1 Test Waveform 1

The following figures and table are the analysis result for the test waveform 1. Figure 4.11 is the voltage sag waveform occur on phase C, and the transform results for RMS and DFT voltage magnitude measurement are plotted in the graph as shown in Figure 4.12. Figure 4.13 and 4.14 is the application of sag magnitude calculation using the proposed technique in voltage sag analysis. As referring to Table 4.3, the analysis result shows that the DFT method detects the sag faster and the duration of sag is longer than RMS method with 0.45ms and 0.88ms deviation. By referring to the percentage of voltage sag magnitude, the DFT method gives a less remaining voltage of nominal compared to the RMS method. From the analysis of the test waveform 1, the result revealed the same finding of the performance for DFT and RMS method as presented in Chapter 4.2.

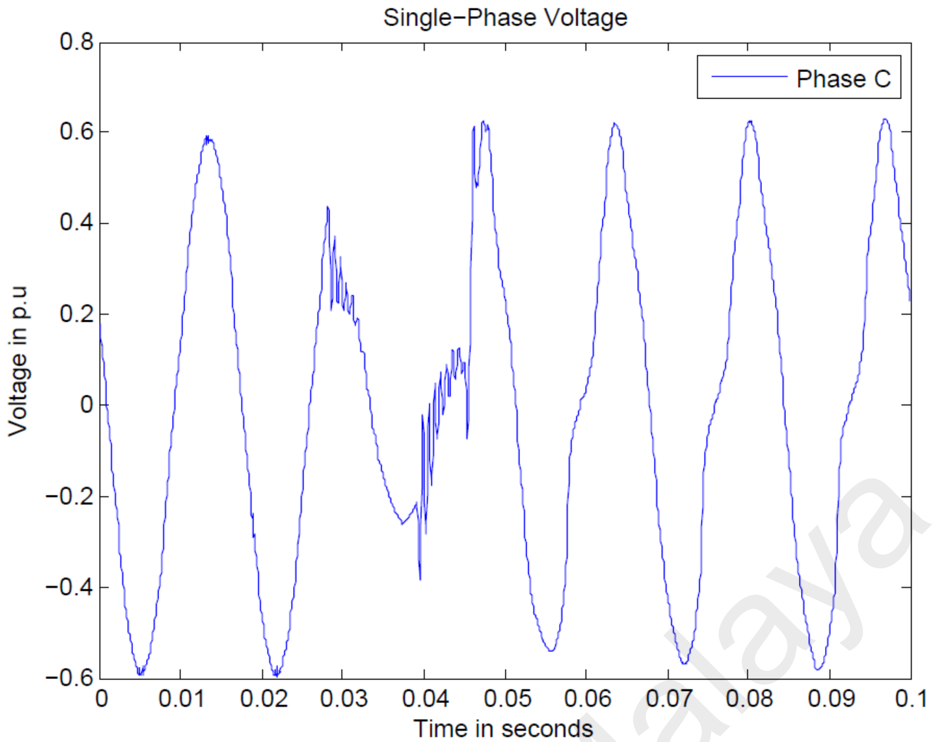


Figure 4.11: Single-phase voltage sag on test waveform 1.

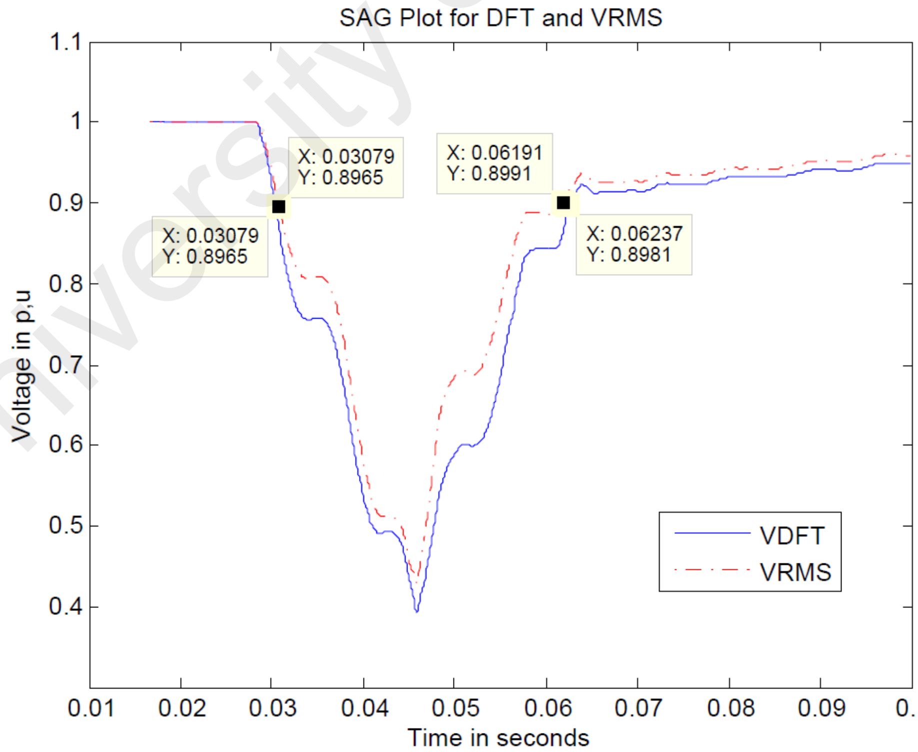


Figure 4.12: Voltage sag in terms of RMS and DFT method for test waveform 1.

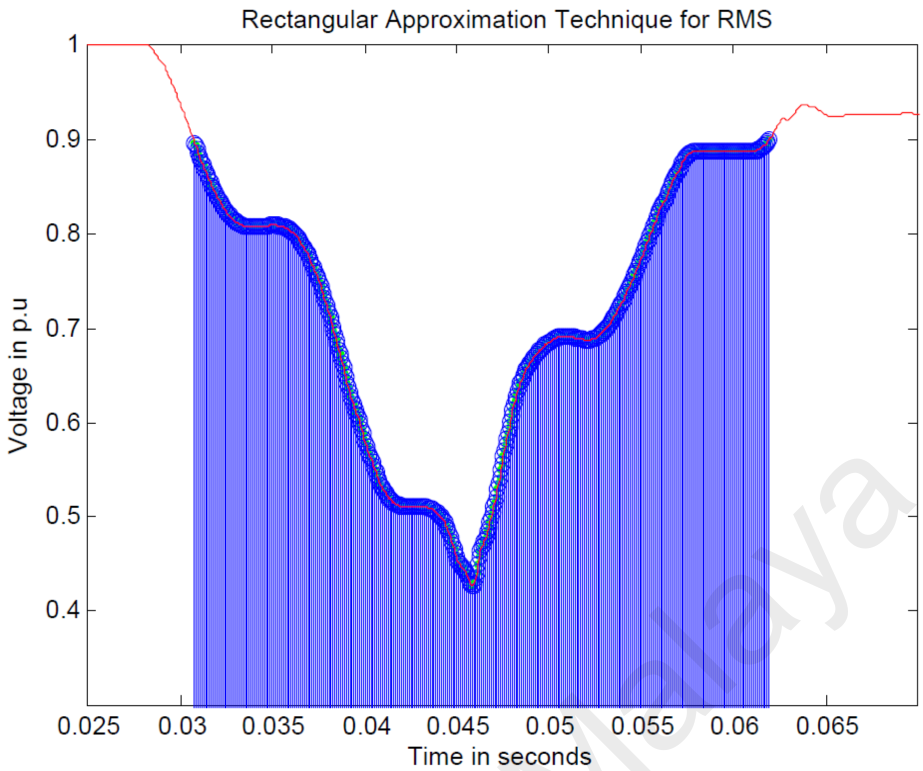


Figure 4.13: Rectangular Approximation Technique (h=1) apply to the RMS voltage on test waveform 1.

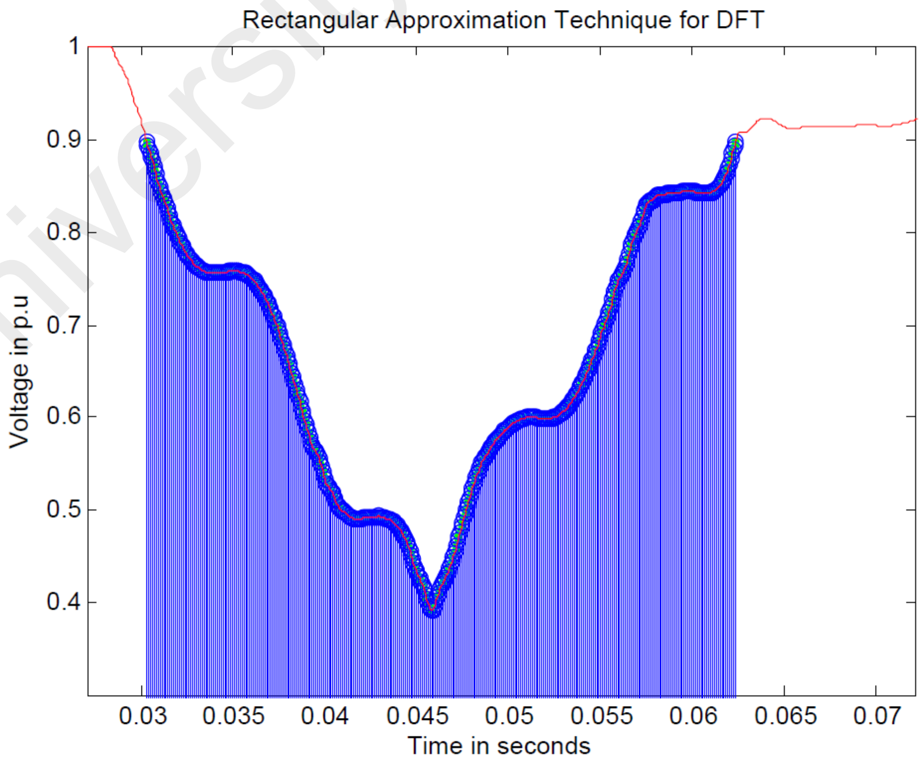


Figure 4.14: Rectangular Approximation Technique (h=1) apply to the DFT voltage on test waveform 1.

Table 4.3: Comparison of voltage sag characteristic between RMS and DFT for test waveform 1.

Sag characteristic	RMS	DFT	Deviation
Detection (ms)	30.79	30.34	0.45
Duration (ms)	31.12	32.00	0.88
Max. of voltage sag (p.u)	0.8991	0.8981	0.001
Min of voltage sag (p.u)	0.4272	0.3921	0.0351
Magnitude (%)	81.21	76.06	5.15

4.3.2 Test Waveform 2

Other analysis of voltage sag is tested on the test waveform 2 as shown in Figure 4.15. The analysis results for voltage waveform are summarized into Table 4.4. By referring to the table, the result revealed the same findings of the performance for DFT and RMS method as presented in Chapter 4.2 and test waveform 1 as well. The DFT method detects the sag faster, longer in sag duration and gives a less remaining voltage of nominal compared to the RMS method.

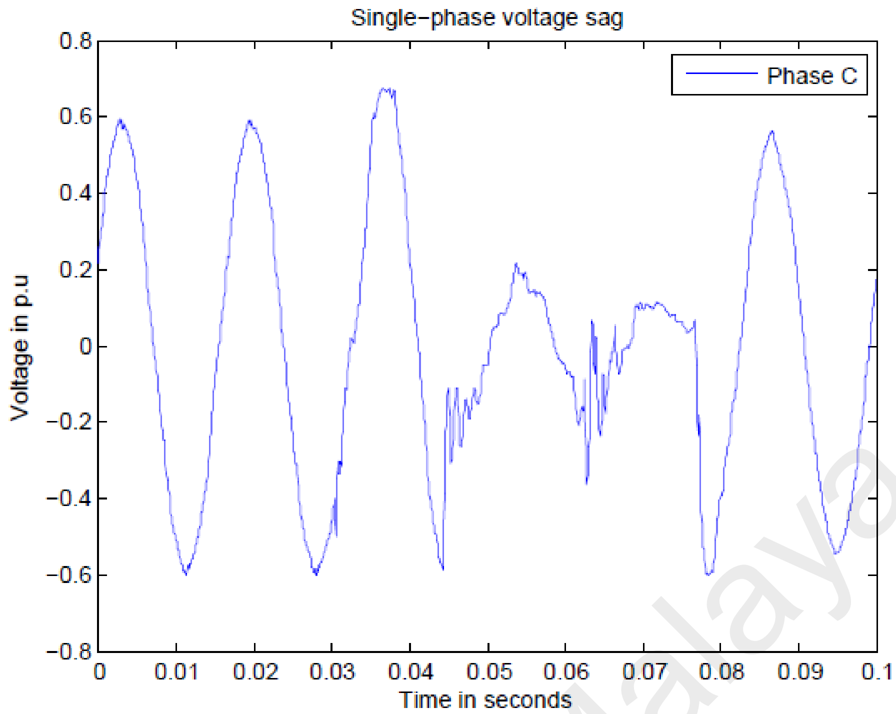


Figure 4.15: Single-phase voltage sag on test waveform 2

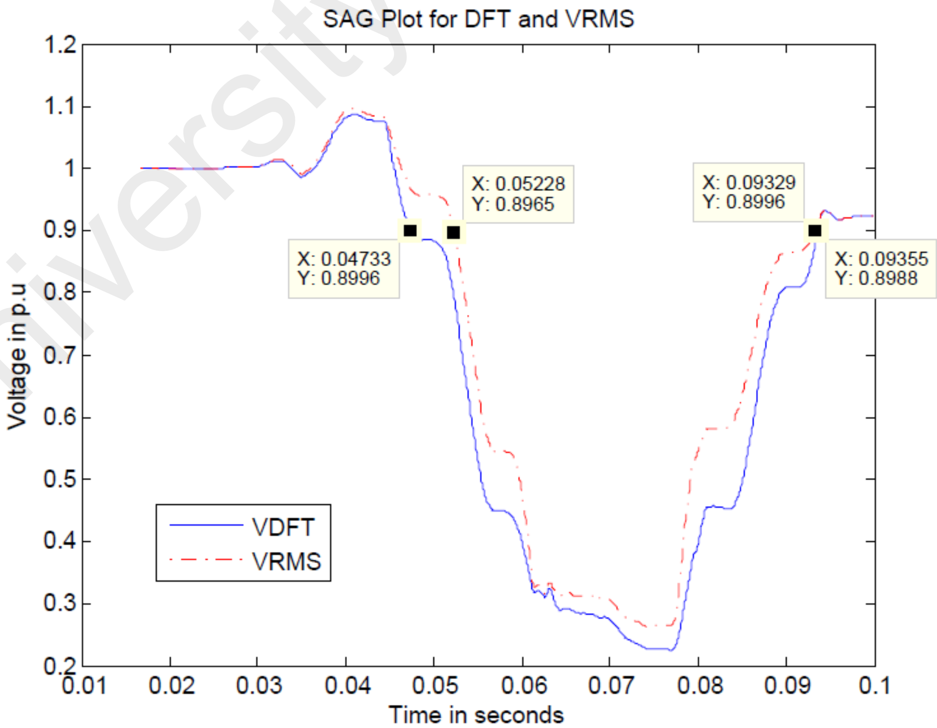


Figure 4.16: Voltage sag in terms of RMS and DFT method for test waveform 2.

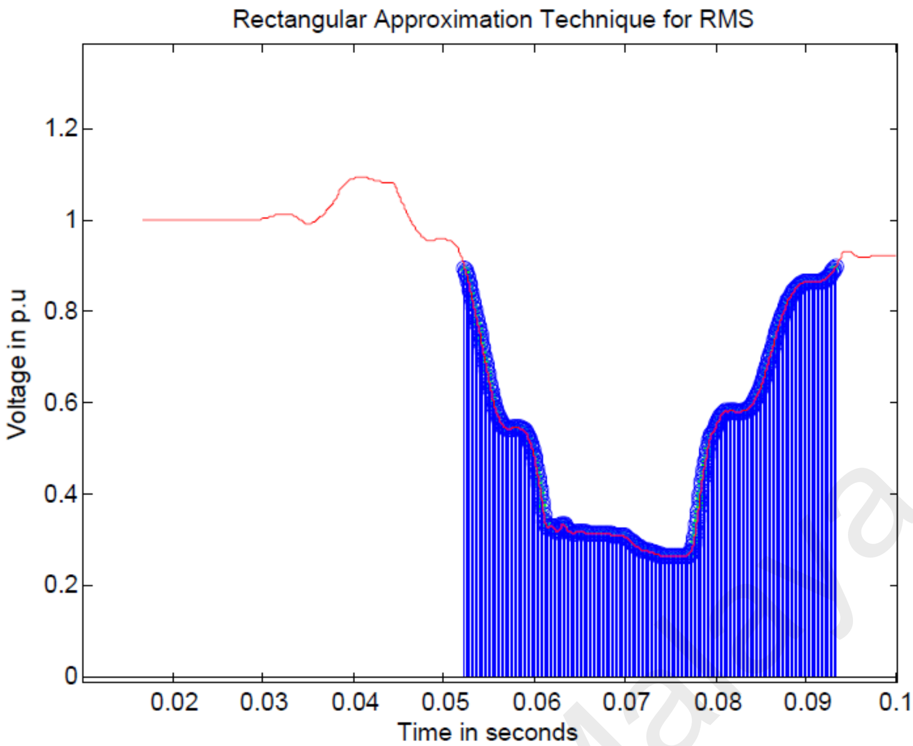


Figure 4.17: Rectangular Approximation Technique (h=1) apply to the RMS voltage on test waveform 2.

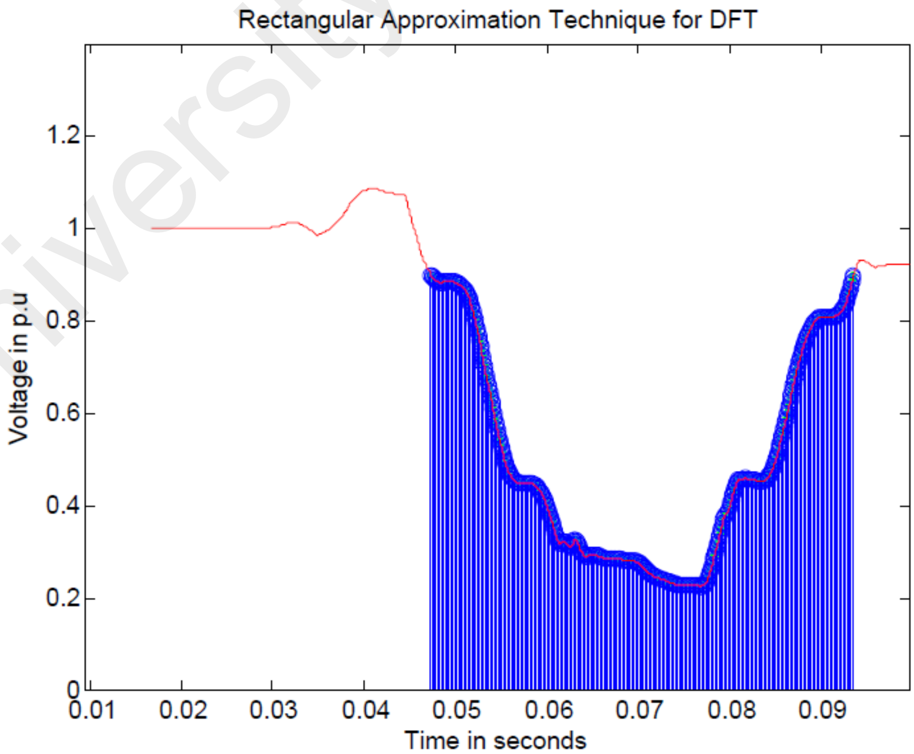


Figure 4.18: Rectangular Approximation Technique (h=1) apply to the DFT voltage on test waveform 2.

Table 4.4: Comparison of voltage sag characteristic between RMS and DFT for test waveform 2.

Sag characteristic	RMS	DFT	Deviation
Detection (ms)	52.28	47.33	4.95
Duration (ms)	41.00	46.20	5.2
Max. of voltage sag (p.u)	0.8996	0.8996	0
Min of voltage sag (p.u)	0.2636	0.2245	0.0391
Magnitude (%)	61.64	59.00	2.64

4.4 Windowing Analysis in the Measurement

The effect of Sliding window size and technique were investigated based on RMS measurement as shown in Figure 4.19. The calculation of RMS voltage magnitude for the half-cycle and one-cycle sliding window is similar but using a different number of samples. The number of samples is depended to the length of the window and have to change during simulation. In this research, the number of samples for one-cycle sliding window size is 256 samples per cycle, and 128 samples per cycle for half-cycle were used in the investigation.

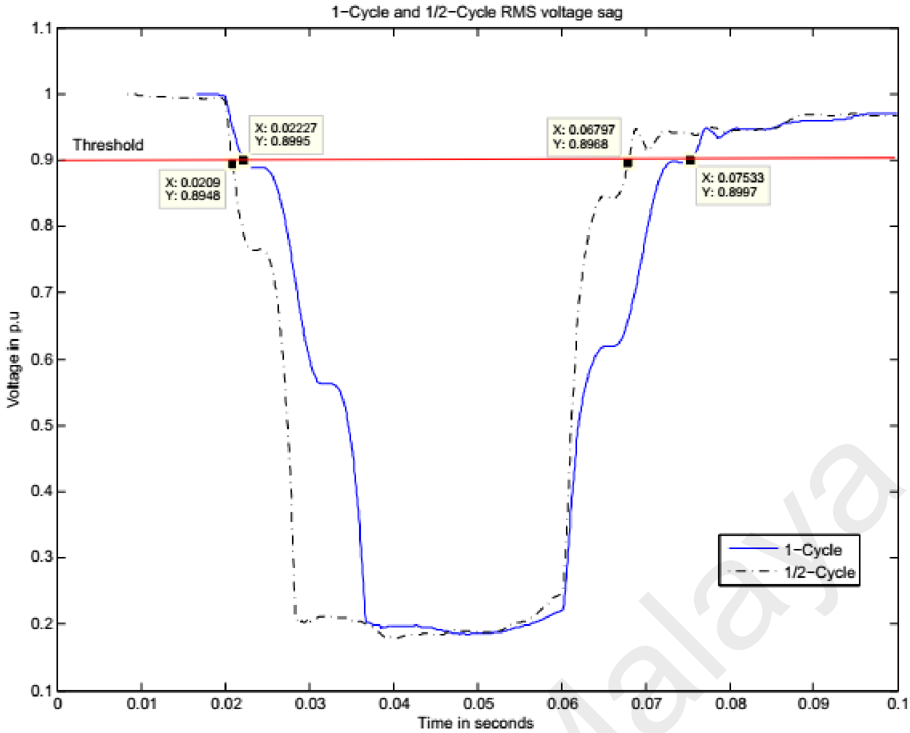


Figure 4.19: Plot of One-cycle and half-cycle sliding window RMS voltage

The performance results of one-cycle and half-cycle windowing technique can be observed in Figure 4.19. The one-cycle shows slow in time detection and also slow in rising time to recover. This is because the moving window retains to complete 256 samples for every single cycle require longer time compared to half-cycle only need 128 samples of historical data in calculation.

Based on the waveform, the number of sag samples detected in one-cycle is 816 samples and 724 samples for half-cycle out of 1536 samples of data. In terms of sag detection, one-cycle start detect the voltage sag at sample 22.7ms and completed the sag at 75.33ms. Meanwhile, for the half-cycle sag start at 20.9ms and finish at 67.97ms. The sag duration for one-cycle is 53ms and 47ms for half-cycle.

For the sag magnitude, the result shows that one cycle sliding window have greater sag magnitude compare to half-cycle sliding window. It is mean, the half-cycle produces less amount of the remaining voltage which is 118V (47.29% from 250V) and 141.25V (56.5% of 250V) produced by the one-cycle sliding window. The comparison results are given in the Table 4.5.

Table 4.5: Simulation result for One-Cycle and Half-Cycle Sliding Window.

Sag characteristic	1-Cycle	1/2-Cycle	Deviation
No.of sag sample	816	724	92
Detection (ms)	22.7	20.9	1.8
Duration (ms)	53	47	6
Magnitude (%)	56.5	47.29	9.21

The half-cycle of the sliding window method is much faster in sag detection and sag recovering but having the greatest of voltage sag. However, the one-cycle sliding shows the voltage sag magnitude increase by means increasing the remaining voltage of nominal with longer recovery time.

All this advantages and disadvantages for RMS measurement are useful for application in voltage sag analysis. Otherwise, the half-cycle sliding window are not suitable to be practiced in DFT measurement due to the oscillated waveform occurred.

4.5 Rectangles Size Analysis in the Sag Magnitude Measurement

Basically, the rectangle size is an area determined by the width and height. The area is given by multiplying the width times the height. For this application, the area of the rectangles is encompassed by the sag magnitude which is on y-axis and sampling time on the x-axis graph where the RMS and DFT voltages are plotted. The rectangle area determination has a great impact on the voltage sag magnitude as the width (sampling time) and height (voltage sag magnitude) of the rectangle are dependent variables of voltage sag magnitude.

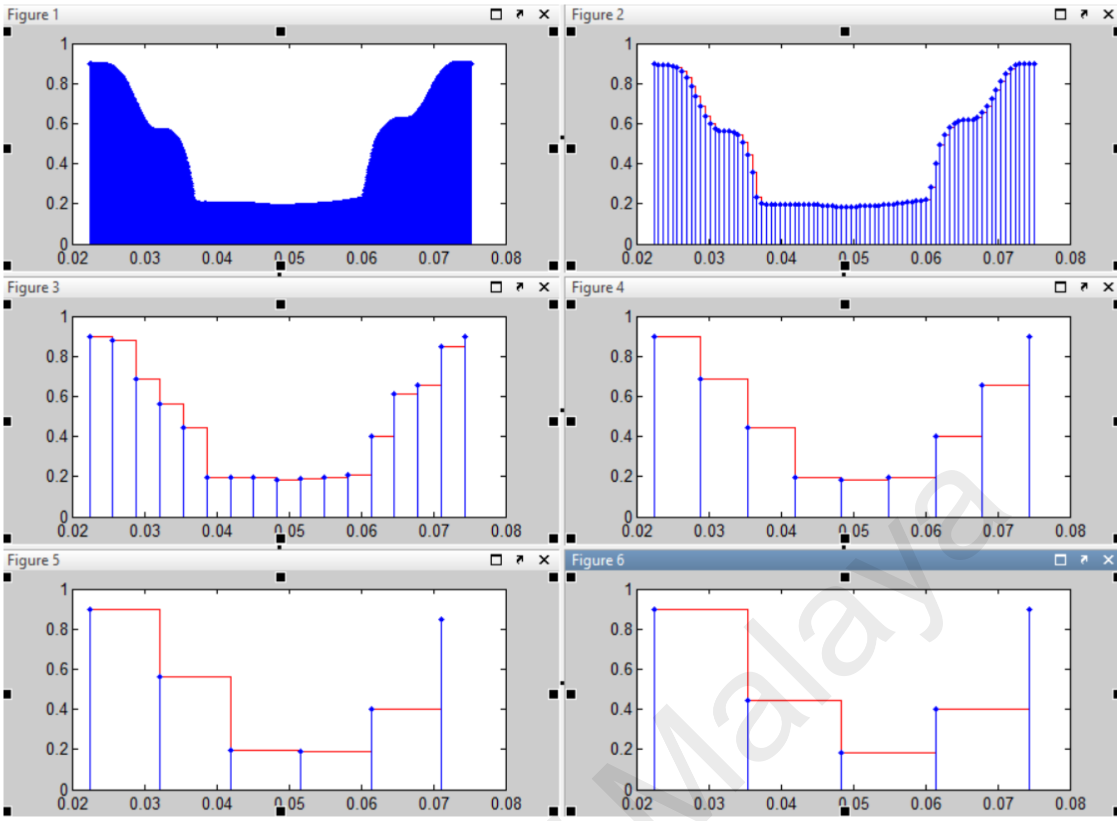
The simulation of the rectangles area has been done by using different step size as shown in Figure 4.20 (a) and 4.20 (b) in order to determine the most suitable area of a rectangle. The step size will be used as the multiplier of the sampling time on the x-axis, then the sag magnitude on the y-axis will also change accordingly.

Table 4.6: Rectangular approximation analysis based on rectangles size (RMS).

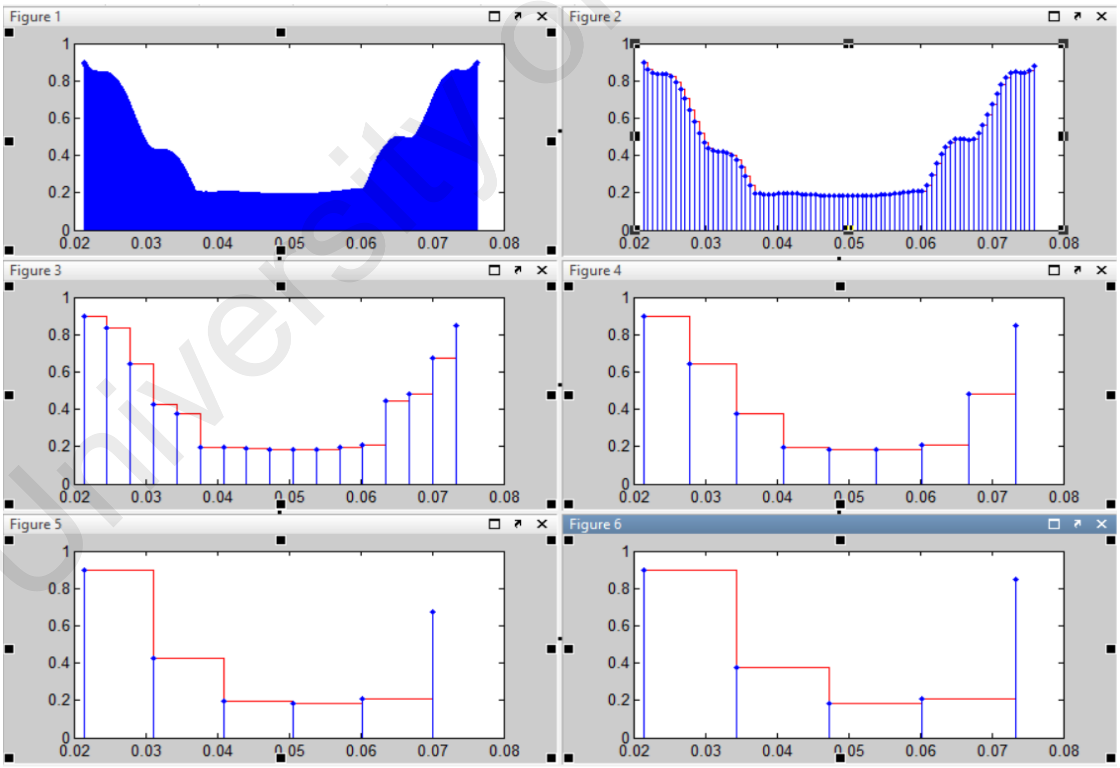
Method / Parameter	RMS					
Step Size,h	1	10	50	100	150	200
No.of Rectangle	815	82	16	8	5	4
Sag Magnitude (Volt)	108.76	107.64	98.55	85.24	82.76	51.67
Nominal Voltage (%)	56.50	56.94	60.58	65.91	66.90	79.33

Table 4.7: Rectangular approximation analysis based on rectangles size (DFT).

Method / Parameter	DFT					
Step Size,h	1	10	50	100	150	200
No.of Rectangle	846	85	16	8	5	4
Sag Magnitude (Volt)	120.13	119.07	118.73	105.77	110.11	75.96
Nominal Voltage (%)	51.95	52.37	52.51	57.69	55.96	69.62



(a)



(b)

Figure 4.20: Analysis based on different step size,*h* for (a) RMS (b) DFT.

(Fig.1,h=1;Fig.2,h=10;Fig.3,h=50;Fig.4,h=100;Fig.5,h=150;Fig.6,h=200)

The finding of the simulation result in the table 4.6 and table 4.7 shows that the smallest step size gives more relevant to the voltage sag magnitude. Furthermore, the number of the rectangle used also increased with respect to the area below the sag curve. The increasing of the step size would increase the area of a rectangle and result in weakness approximation of sag magnitude due to cover the area that should not be considered as an area under the sag curve. This is one of the disadvantages when using a larger step size even it gives simple and easy computation.

4.6 Summary

All the analysis result with the discussion as regards the scopes and the objectives of the project were presented in this chapter. Most of the result was analyzed from the graphical representation of voltage magnitude and summarized into the table. The result of voltage sag characteristics, effect of windowing technique and rectangle size were analyzed and discussed by comparing both methods.

CHAPTER 5: CONCLUSION AND RECOMMENDATION

5.1. Conclusion

Since the PQ disturbance is the most significant concern by the end users of the power system network, the PQ analysis has been developed rapidly due to improving power system performance by conducting the appropriate actions against disturbances. The analysis system has to monitor huge samples of waveform data, and it must accurately analyze the characteristics using the suitable method.

For that reason, the PQ analysis based on RMS and DFT method has been developed in this project. The voltage sag has been automatically analyzed by simulating the developed program with mainly examined the voltage sag characteristics regarding of sag detection, sag duration, and sag magnitude. These characteristics have been compared to show the differences between the DFT and RMS performance. From the analysis, the comparative result reveal that the DFT method shows faster in sag detection, lower in sag magnitude and longer time in sag duration compare to RMS method.

From the result, both methods have an advantage in terms of calculation which is fast and straightforward. However, these methods have a drawback of sliding window dependency. As to investigate the disadvantage, the sampling size has been simulated between one-cycle and half-cycle sliding window. The findings of the simulation result conclude that the method of sliding window was affected to the RMS and DFT measurement by an average of 6% different. As the smaller size of the sliding window used, the RMS and DFT measurement are less relevant. Therefore, it is seen that the one-cycle sliding window is applicable and suitable to apply on RMS and DFT methods in this project.

The Rectangular Approximation technique has been presented in the voltage sag magnitude determination. As the new method proposed, the calculation of voltage sag magnitude has been improved by decreasing the voltage sag magnitude with an average of 30% as compared to the voltage sag determination without using the Rectangular Approximation technique. This improvement is due to the consideration of the area below and above the sag curve rather than taking the lowest sag magnitude as reviewed in Chapter 2. It can be concluded that the Rectangular Approximation technique has shown the ability to quantify the voltage sag magnitude by using the smallest size of rectangle that gives more relevant to the voltage sag magnitude.

As a conclusion from all above, the characteristics of single-phase voltage sag can be accurately analyzed by using one-cycle sliding of the RMS method with the additional proposed method of sag magnitude determination.

5.2. Recommendation

The power quality analysis developed in this project is limited to the single-phase of voltage sag. For future work, the coding can be modified to analyze simultaneously either three-phase or single-phase for other types of PQ disturbances like swell, transient and harmonics. Thus, it can be more practical to be applied.

From the result, the phase angle information from DFT analysis is ignored due to unrelated with the scopes of the project. Therefore, it can be use in the future analysis for example in characterized the phase-angle jump associated in voltage sag as review in Chapter 2.5.

In addition, the PQ analysis developed can be implemented into real cases for example in the motor starting application by integrates the system into experimental setup. In practices, it looks more reliable due to prove the proposed method is applicable to apply in power system network.

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