ANALYSIS OF VOLTAGE SAG SEVERITY CAUSED BY FAULT IN POWER SYSTEM NETWORK

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KUALA LUMPUR

2021

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THESIS SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF POWER SYSTEM ENGINEERING

FACULTY OF ENGINEERING
UNIVERSITY OF MALAYA
KUALA LUMPUR

2021

UNIVERSITY OF MALAYA

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ANALYSIS OF VOLTAGE SAG CAUSED BY FAULT IN POWER SYSTEM NETWORK

ABSTRACT

Power quality issues have become more important to the industry as the impacts created such as plant downtime, production waste, and shorten equipment lifespan are not only caused the financial loss to the industry but also reduce their competitiveness in the market. Besides that, due to the industrial revolution, manufacturing is moving forward to automation, robotics technology, and advance digital technology to have better collaboration, control, and understanding of each operation across all the departments, vendors, products, and people. Therefore, high quality and high-reliability power supply are required in the industry due to the sensitiveness of that electronic equipment especially for the industries such as semiconductor, electronic, computer, and business. As the voltage sag is one of the biggest power quality issues faced by the industry. This study, therefore, aims to analyze the voltage sag severity by a fault in a power system network. An IEEE 14 bus distribution system network will be modeled, and the fault would be applied into the system network and simulated by Power world software. The result of the voltage sag will be recorded and analyzed. Finally, to choose the best location which has the lesser impact of voltage sag when the faults occurred to build a semiconductor manufacturing factory.

Keywords: Power Quality, Power system network, Voltage sag

ANALISIS SEVERITY VOLTAGE SAG DISEBABKAN OLEH FAULT DALAM RANGKAIAN SISTEM KUASA

ABSTRAK

Isu kualiti tenaga menjadi lebih penting bagi industri kerana impak yang dihasilkan seperti downtime kilang, sisa pengeluaran dan memendekkan jangka hayat peralatan bukan sahaja menyebabkan kerugian kewangan kepada industri tetapi juga mengurangkan daya saing mereka di pasaran. Selain itu, kerana revolusi industri, pembuatannya bergerak maju ke automasi, teknologi robotik dan teknologi digital maju untuk memiliki kolaborasi, kontrol dan pemahaman yang lebih baik untuk setiap operasi di semua departemen, vendor, produk, dan orang. Oleh itu, bekalan kuasa berkualiti tinggi dan kebolehpercayaan tinggi diperlukan dalam industri kerana kepekaan peralatan elektronik tersebut terutama untuk industri seperti semikonduktor, elektronik, komputer dan perniagaan. Kerana voltan kendur adalah salah satu masalah kualiti kuasa terbesar yang dihadapi oleh industri. Oleh itu, kajian ini bertujuan untuk menganalisis keterukan sag voltan oleh kesalahan dalam rangkaian sistem kuasa. Rangkaian sistem pengedaran bas IEEE 14 akan dimodelkan, dan kesalahan akan diterapkan ke dalam jaringan sistem dan disimulasikan oleh perisian Power world. Hasil kendur voltan akan direkodkan dan dianalisis. Akhirnya, untuk memilih lokasi terbaik yang mempunyai kesan kendur voltan yang lebih rendah apabila berlaku kesalahan membina kilang pembuatan semikonduktor.

Kata kunci: Kualiti kuasa, Rangkaian sistem kuasa, Voltage sag

ACKNOWLEDGEMENTS

First of all, I am grateful to all those who have contributed and made this project possible.

I would first like to express my most sincere appreciation to my supervisor, Professor IR. Dr. Hazlie Bin Mokhlis, for his generous commitment and dedication towards this project. His exemplary guidance, constant encouragement, and careful monitoring throughout the project are so great that even my most profound gratitude is not enough

Also, I must express my utmost gratitude to my family and friends, for their unconditional support throughout this period. Thank you for your contributions.

Lastly, I want to thank the University of Malaya for lending me the facilities which I required to complete this project. I am fortunate that I have made the decision to pursue my postgraduate program many years back with the University of Malayan, and I have not regretted this decision ever since.

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CHAPTER 1: INTRODUCTION

1.1 Background of Study

Power systems are becoming more significant to modern-day society and industry due to their incredible losses if any of these critical infrastructures fail even for a short moment. The classification of the cost categories that may occur due to power quality issues, presented in Figure 1. The cost categories due to power quality issues refer to process interruption, additional energy losses, equipment damage, lower products quality, lower products quality, lower labour productivity, process slow down, increased defective products, or other indirect costs (Beleiu, Beleiu, Pavel, & Darab, 2018).

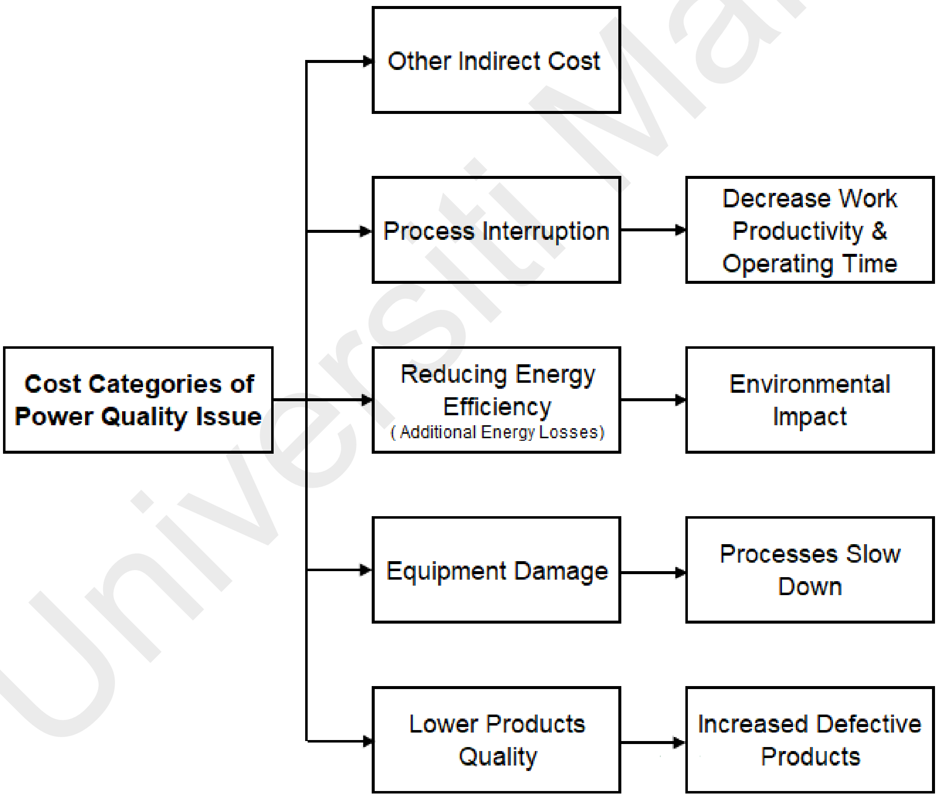

Figure 1.1: Cost categories due to power quality issues

Therefore, the power systems have been consistently improved to increase their quality, reliability, and security.

Additionally, power quality problems can cause heavy financial losses to the industry. For example, a recent study showed the financial losses in Europe due to voltage sag to the industry, and semiconductor industries carried heavy revenue losses compare to others. The figure below showed the financial loss in industries due to voltage sag (Sharma, Rajpurohit & Singh, 2018)

Industries	Cost
Textile	€1000–100,000
Plastics	€2000–50,000
Glass	€10,000–1,000,000
Paper	€30,000–3,000,000
Steel	€50,000–4,000,000
Semiconductor	€75,000–10,000,000

Figure 1.2: Financial loss in industries due to voltage sag

Besides that, Malaysia's University had analyzed the estimated cost due to voltage sag that is violated the IEC 61000-4-34, ITIC, SEMI F47 under 4 regions in Peninsular Malaysia which are Northern Region (Perak, Penang, Kedah, and Perlis), Eastern Region (Kelantan, Terengganu, and Pahang), Central Region (Selangor, Kuala Lumpur, Putrajaya, and Cyberjaya) and Southern Region (Negeri Sembilan, Melaka, and Johor). The voltage sag that violet ITIC estimated incurred the highest financial cost to Malaysia, which totaled RM3,662,988,906.00 among others. Further, the Southern Region had estimated the highest cost due to voltage sag compared to other regions. Table 1.1 showed the total estimated cost due to voltage sag in Malaysia (Salim, Nor, Said & Rahman, 2015).

Table 1.1: The Total Estimated Cost due to Voltage Sag in Malaysia

Event	Cost of Event				
	Northern Region (RM)	Eastern Region (RM)	Central Region (RM)	Southern Region (RM)	Total
ITIC	661,221,647	619,381,383	1,066,484,474	1,315,901,402	3,662,988,906
SEMI F47	466,744,000	53,413,000	349,700,239	583,844,905	1,453,702,144
IEC	466,744,000	6,597,000	349,700,239	560,744,905	1,383,786,144

The common power quality issues can be categorized into few characteristics such as momentary interruption, temporary interruption, sustain interruption, notch, transient, voltage sag, voltage swell, undervoltage, and overvoltage (Teansri, Pairindra, Uthathip, Bhasaputra, & Pattaraprakorn, 2012). In this study, the primary focus is on voltage sag due to different types of faults.

1.2 Problem Statement

Power quality issues have existed for a long time ago. However, the issues were not the biggest concern for industry; during that time, the operations and processes were mostly controlled by mechanical devices and gearboxes.

With the rapid development of technology, micro-processor, automation, and digital technologies have been introduced into the industry to dramatically increase productivity and reduce the dependency on manpower. Therefore, the various type of equipment or machine controlled by the programmable logic controller, microprocessor and electronic device is being widely used in many industries. Thus, the power quality issue is becoming increasingly significant in the industry as those equipment and machine are sensitive to power quality issues which can lead to machine breakdown, reduction in equipment's lifespan, and incur big losses to industry (Awad, 2012).

One of the frequent types of PQ problems is voltage sags (Anayet, Daut, Indra, Dina & Rajendran, 2008). In a survey reported by Thollot, 68% of power quality problems were due to voltage sag (Salim, Nor, Said & Rahman, 2015)

Voltage sags in power systems commonly occur due to faults. When it happens, voltage magnitude drops below the nominal value that could lead to misoperation or even trip off some of the electronic equipment if not properly solved. Since faults are unavoidable and occur due to natural events such as lightning strikes, equipment aging, and human error, their impacts on voltage sags are required to be studied. In this study, we will analyze the impact of different types of faults on the voltage sag performance for the IEEE 14-Bus system.

1.3 Research Objective

The primary objective of this study is to analyze the voltage sag severity in the power distribution system. The goals of this study can be expressed as shown below.

i. To model an IEEE 14-Bus network using Power World Simulator.
ii. To analyze the impact of different types of fault on the voltage sag performance for the modeled system.
iii. To determine the best location for those industries that require higher power quality such as a factory that has many electronic equipments.

1.4 Scope of Study

In this study, an IEEE 14-Bus network mesh system will be constructed and simulated by using Powerworld software. The single line to ground fault, double line to ground fault, and the three-phase fault would be applied to the network at various locations. The voltage at each bus would be obtained by simulation with Powerworld. The result will be observed and analyzed in this project. Lastly, based on the simulation result, this project will conclude the best location for industries such as semiconductors that are sensitive to voltage sag.

1.5 Report Outline

There are 5 chapters in this study. Chapter 1: Introduction, a brief introduction on power quality issue, objective, and scope of this study. Chapter 2: Literature review, discussion on the power system, topology of power distribution system, type of fault, power quality problem, and studied in voltage sag. Chapter 3: Methodology, detailed description of how the simulation was carried out in this study to obtain the voltage sag from different types of faults. Chapter 4: Results and Discussion, display the simulated output from the POWER WORLD simulator and discussion on the voltage sag severity due to faults. Chapter 5: Conclusion, conclude the result.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

Recent years have shown an increase in the contribution to the body of knowledge about the subject of power quality disturbances in power systems. The increasing emphasis on the subject reflects a growing interest and concern on the power quality issues faced in society (Lamedica, Esposito, Zaninelli, & Prudenzi, 2001). This chapter is to focuses on reviewing power quality issues, specifically voltage sags. As the voltage sags will incur high financial losses in the industry.

2.2 Power Systems in General

Electricity has become a fundamental necessity in our modern society. To ensure our community functions conveniently, electricity must be generated constantly from power infrastructures and generation plants. Hence, electrical power systems are now inseparably woven into the fabric of our civilization.

The electrical power system is a flow of electrical power from the generating station to the end-user. It consists of 3 important components which are generating station, transmission network, and distribution network. The schematic of a typical transmission distribution scheme is shown in figure 2.1 (Bakshi, Bakshi, 2020).

The function of the generating station is to produce electric energy. The voltage generated is around 15 to 25kV (Grigsby, 2012). Conventionally, power generating stations are built a distance away from the city and town. This results in the generated power having to be transmitted from the station over a long distance before it reaches the consumer. It caused the low voltage at the station to be unsuitable for the transmission of energy. Therefore, a step-up transformer is used to increase the voltage and reduce the current. It also helps to reduce the power losses during transmission (Bakshi, Bakshi, 2020).

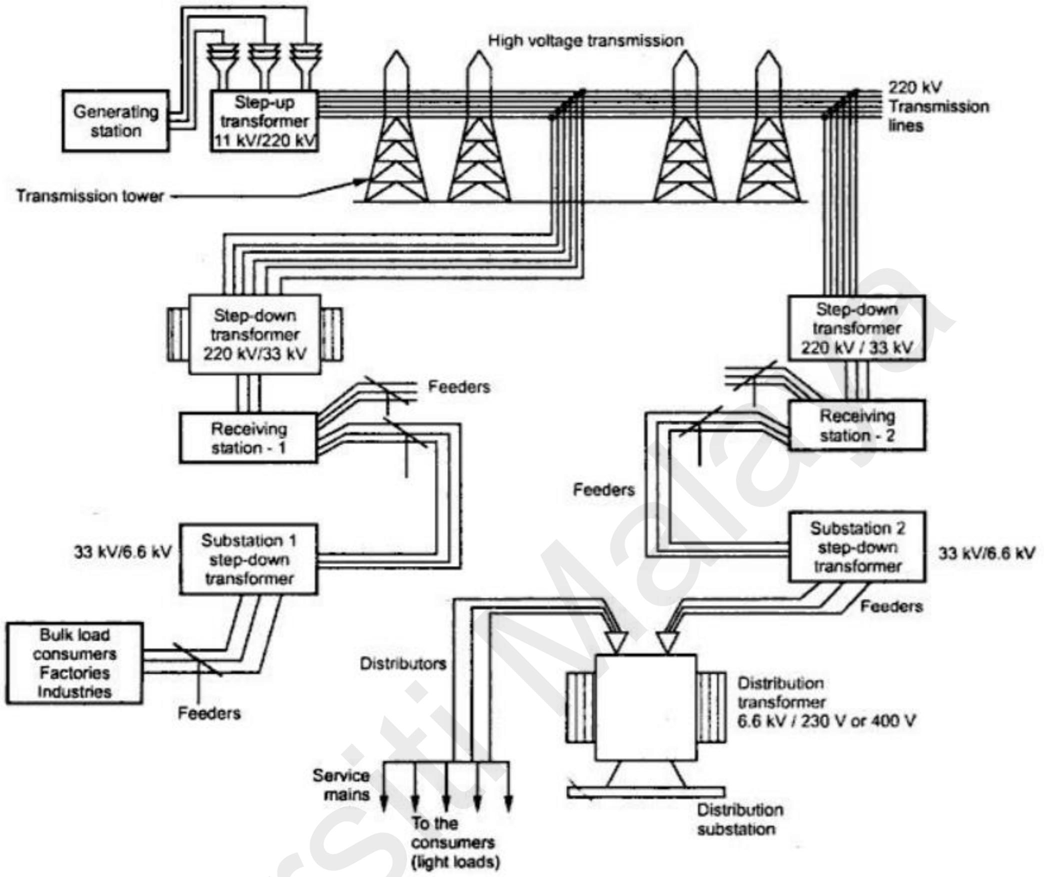

Figure 2.1: Schematic representation of a typical transmission distribution scheme

Then with the help of a transmission network, the power is transmitted at substantial distances. The transmission network may also be categorized as the following

i. Primary Transmission:

Transmits to wholesale power outlets or receiving stations at 132kV, 220kV, and above. It generally uses the overhead transmission line to transmit the electricity.

ii. Secondary Transmission:

Transmits power to a substation at the range of 22 ~ 33kV

Lastly, the substation will step down the voltage level to 11kV, 6.6kV, 400V, or 230V, according to the consumer requirement, and distributed to the end-user (Bakshi, Bakshi, 2020).

2.3 Distribution Networks

Distribution networks are a system that delivers low-voltage power to the load, by stepping down the stepped-up high-voltage power from the transmission networks connected to it. Therefore, a reliable and stable distribution network is required to successfully deliver the power to the consumer. The network generally consists of a substation, primary feeder, tap changing transformer, and distributor. Depending on the configuration and pattern, distribution networks can be divided primarily into 3 types as follows

i. Radial Network

The radial network is most commonly used in the power distribution system due to its simplicity and low construction cost (Siddiqui, 2011). The network is following a tree-shaped topology, there has one power source in the network for a group of consumers. This is the cheapest and simplest network for an electrical grid, however, if there is any power failure or short circuit, it will affect the entire line power supply (Islam, Prakash, Mamun, Lallu, & Pota,2017). The design of the radial distribution network is shown in figure 2.2 (Siddiqui, 2011)

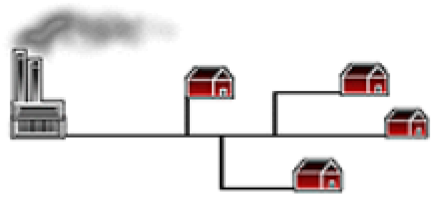

Figure 2.2: The design of radial distribution network

ii. Ring Network

A ring network is also called a loop because the source would loop through all the load in the system and back to sources to form a closed loop. This network is commonly used in residential areas. In the case of fault occurred in a particular line, the fault can be isolated, the network will act as a dynamic radial system and loads fed by either single sources or multiple sources. Therefore, it does not disturb the power supply to the entire network. Lastly, the network is more flexible and reliable than the radial network, but it has a greater cost and higher complexity (Islam, Prakash, Mamun, Lallu, & Pota,2017). The design of the ring /loops distribution network is shown in figure 2.3 (Siddiqui, 2011)

Figure 2.3: The design of ring/loop distribution network

iii. Mesh Network

The structure of the mesh network is similar to the ring network. To provide the backup to reroute the power when the fault happened, it included many redundant lines (Islam, Prakash, Mamun, Lallu, & Pota,2017). In the system, there might be one, two, three, or more different power sources to supply the power to a given customer. Figure 2.4 shows the configuration of the mesh distribution network (Siddiqui, 2011).

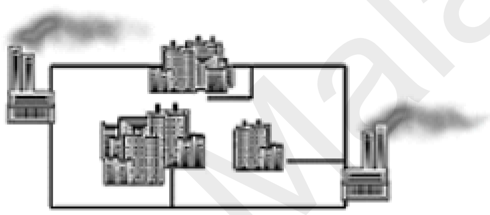

Figure 2.4: The design of mesh distribution network

These three networks have their advantages and disadvantage. Table 2.1 is the comparison between radial, ring, and mesh networks (Prakash, Lallu, Islam, Mamun 2016)

Table 2.1: Comparison between radial, ring, and mesh network.

Description	Network		
	Radial	**Ring**	**Mesh**
Sources	Single	Multiple	Multiple
Stability	Low	High	High
Reliability	Low	Medium	High
Capital Cost	Low	High	low
Maintenance	High	Low	High
Voltage Level	Low	Low	Medium or High
Protection Required	Medium	High	Higher

2.4 Fault in Power System

A fault in a power system is an abnormal condition that interrupts the stability of the system which involves the electrical failure of power system equipment (Almobasher, Habiballah, 2020). Generally, the faults that occur are usually due to insulation failure, flashover, and physical damage due to various reasons such as environmental conditions: lightning, rain, snow, and other conditions (Kumari, Singh, Kumari, Patel, Xalxo, 2016). The fault is an unwanted condition in the power system as it will cause a high flow of current and abnormal voltage and will potentially cause hazards to humans and animals. Additionally, it also will cause damage to equipment, which will further break down the existing whole power system (Almobasher, Habiballah, 2020).

Fault generally can be classified into two types which are short circuit fault and open circuit fault. The short circuit fault is also known as shunt fault. The cause of this fault is due to the sudden overvoltage condition. The open-circuit fault is also called a series fault which is due to the cessation of current flow. Further, the short circuit fault is classified into 2 types which are symmetrical and asymmetrical fault.

2.4.1 Symmetrical Fault

The asymmetrical fault is also called a balanced fault as the three phases are equally affected. Therefore, Symmetrical faults are three-phase balanced fault(L-L-L) and 3 phase balanced to ground fault (L-L-L-G). Three-phase balanced fault (L-L-L) is 3 phases that are short circuits to each other and shown below figure (Chilakala & Rao, 2018).

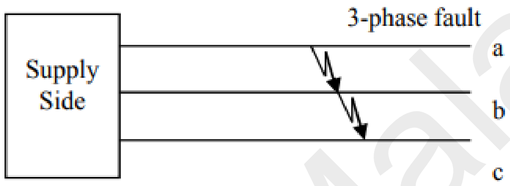

Figure 2.5: Balanced three-phase fault (L-L-L)

Three phases balanced to ground fault(L-L-L-G) is 3 phases and ground are short circuit to each other and shown in below figure (Chilakala & Rao, 2018).

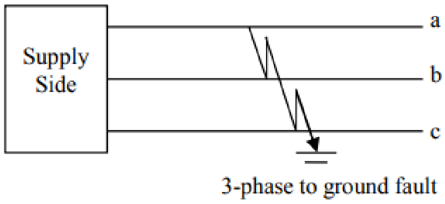

Figure 2.6: Balanced three-phase to ground fault (L-L-L-G)

The symmetrical fault is the most severe fault that can occur; however, it is a rare occurrence (Kumari, Singh, Kumari, Patel, Xalxo, 2016).

2.4.2 Asymmetrical Fault

The asymmetrical fault is unbalanced. It occurred when one or two phases short circuit with the ground. There is a single line to ground fault (L-G), double line to ground fault (L-L-G), and line to line fault (L-L). The single line fault (L-G) occurs when one phase short circuits with the ground. This fault is the most common type of fault (Kumari, Singh, Kumari, Patel, Xalxo, 2016). Figure 2.7 show the diagram of single line to ground fault (L-G)

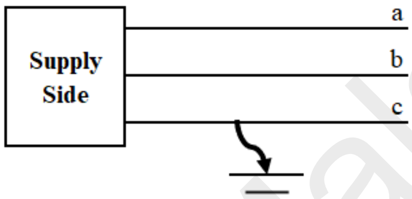

Figure 2.7: Single line to ground fault (L-G)

Double line to ground fault (L-L-G) occurs when 2 phases are short circuits together with the ground (Kumari, Singh, Kumari, Patel, Xalxo, 2016). Figure 2.8 show the diagram of double line to ground fault (L-L-G)

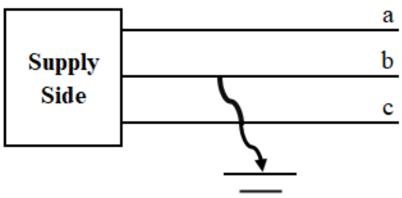

Figure 2.8: Double line to ground fault (L-L-G)

The line to line fault (L-L) is when one phase touches another phase (Kumari, Singh, Kumari, Patel, Xalxo, 2016). Figure 2.9 show the diagram of line to line fault (L-L)

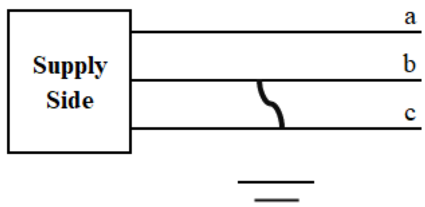

Figure 2.9: Line to line fault (L-L)

2.5 Definition of Power Quality

According to IEEE Standard.1100-1999, "Power Quality" is defined as "The concept of powering and grounding electronic equipment in a manner that is suitable to the operation of that equipment in a manner that is suitable to the operation of that equipment and compatible with premise wiring system and other connected equipment". Additionally, In IEC, the term "Power Quality" is defined as "Set of parameters defining the properties of power quality as delivered to a user in normal operating conditions in term of continuity of supply and characteristics of voltage (symmetry, frequency, magnitude, waveform) (Ise, Hayashi & Tsuji, 2000). In summary from the definitions, the power quality can be categorized into 3 segments which are voltage stability, continuity of supplying power, and voltage waveform (Ise, Hayashi & Tsuji, 2000).

2.6 Common Power Quality Problem

Power quality problems can be generally divided into 6 categories which are voltage fluctuation (flicker), harmonic distortion, power frequency variation, under or over voltage, transients, and voltage sag (Awad, 2012).

2.6.1 Voltage Fluctuation (Flicker)

Flicker is the distortion of voltage variations ranging between 0.9 to 1.1 pu (Johnson & Hassan, 2016). The problem is generally due to the switching of pulsating load, welding equipment, and arc furnaces. It will cause visible changes in the brightening of the screen and lack of luminous bulbs (Shanmugasundaram & Sunikumar, 2020)

2.6.2 Harmonic Distortion

Harmonic distortion is non-sinusoidal waves of current or current distortion caused by a high value of frequency. It results in tripping of thermal protection, on linear load and electromagnetic interference (Shanmugasundaram & Sunikumar, 2020). The problem is commonly caused by nonlinear electric loads such as rectifier, inverter, variable drive, arc furnace, voltage controller, and frequency controller (Johnson & Hassan, 2016)

2.6.3 Power Frequency Variation

Power frequency variation is when the frequency variation is more or less than 5% from the acceptable standard nominal value (usually 50 or 60kHz) (Johnson & Hassan, 2016). It results in generator failure, high demand, and a decrease in turbine speed. (Shanmugasundaram & Sunikumar, 2020).

2.6.4 Under or Over Voltage

Undervoltage is when the nominal voltage is less than 0.9pu for more than one minute. The causes commonly are switching on of large load, and circuit loading.

Overvoltage is when the nominal voltage is more than 1.1 pu for more than one minute. The causes generally are switching off large load, wrong operation in tap setting of transformer and insufficient voltage control (Johnson & Hassan, 2016).

2.6.5 Voltage Sag

Voltage sags are a common power quality issue in the power distribution system (Deshmukh, Dewani & Gawande, 2013). According to IEEE Standard 1159-1995, voltage sag is defined as a decrease to between 0.1 and 0.9 p.u. in root mean square(rms) voltage at power frequency for a duration of 0.5 cycles to 1 min (Heine & Lehtonen, 2003). The voltage sags are commonly due to switching operation associated with a temporary disconnection of supply, starting of motor load or flow of fault current, and lightning strikes. The voltage sag can lead to a stoppage of production, failure of equipment which incurred high costs to the industry (Kamble & Thorat, 2014). Additionally, voltage sag can be characterized in terms of the following parameters:

i. Voltage Sag Magnitude

Generally, the rms voltage is used to obtain the voltage sag magnitude. However, there are other alternative ways to determine voltage sag magnitudes such as fundamental rms voltage and peak voltage. The voltage sag magnitude is known as the residual voltage or remaining voltage of the power system when a fault occurs.

The magnitude of voltage sag can be affected by the type and the resistance of the fault, the distance to the fault, and the configuration of the system (Kamble & Thorat, 2014).

For a distribution system operated in a radial network, the voltage sag magnitude can be calculated by using the voltage divider model which is shown in figure 2.10.

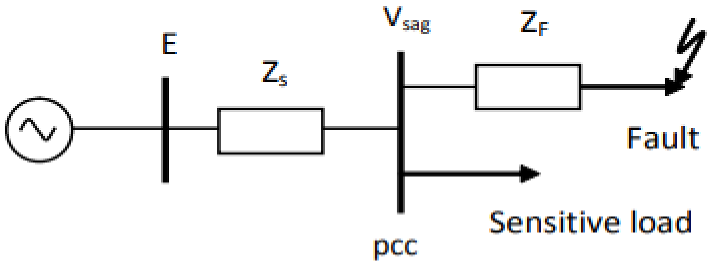

Figure 2.10: Voltage Divider Model

In the voltage divider model, it requires the point of common coupling (pcc) between the load and fault to be found. The load current during and before fault is neglected. The calculation of voltage sag can be found in the equation below (Kamble & Thorat, 2012).

$$V_{sag} = \frac{Z_F}{Z_S + Z_F} E \tag{2.1}$$

Where Z_S is the source impedance at the point of common coupling (PCC), Z_F is the impedance between the pcc and the fault.

The assumption is made, the pre-event voltage, E is exactly 1 pu, thus E=1. Therefore, the equation is simplified as below (Kamble & Thorat, 2012)

$$V_{sag} = \frac{Z_F}{Z_S + Z_F} \tag{2.2}$$

If the value of Z_F is smaller, then the V_{sag} would be smaller.

ii. Voltage Sag Duration

The duration of voltage sag is the amount of time when the voltage magnitude is below 90% of the nominal voltage magnitude. Therefore, the duration of voltage sag is based on the fault clearing time (Kamble & Thorat, 2014)

iii. Phase angle jump

To obtain the phase angle jump in the voltage sag, the Z_S, and Z_F should be in complex quantities which denote as $\overline{Z_S}$ and Z_F .Therefore, the voltage sag magnitude is

$$\bar{V}\text{sag}= \frac{\bar{Z}_F}{\bar{Z}_S+\bar{Z}_F} \tag{2.3}$$

Let $\bar{Z}_S = R_S + JX_S$ and $\bar{Z}_F = R_F + JX_F$. The argument of $\bar{V}sag$, thus the phase-angle jump in the voltage is given by the following expression

$$\Delta\varphi = \arg(\bar{V}sag) = \tan^{-1}\left(\frac{X_F}{R_F}\right) - \tan^{-1}\left(\frac{X_S+X_F}{R_S+R_F}\right) \tag{2.4}$$

If $\frac{X_S}{R_S} = \frac{X_F}{R_F}$, the equation 2.4 becomes zero which means there is no phase-angle jump. The phase-angle jump will thus be present if $\frac{X}{R}$ ratio of the feeder and the source is not similar (Goswami & Gupta, 2008)

2.7 Regulating Standard on Power Quality

International Electrotechnical Commission, IEC, and Institute of Electrical and Electronics Engineers, IEEE are the most recognized professional standard organization which provide minimum requirements, technical practices and give a recommendation of technical issue related to electrical and electronic. The table below shown the IEEE and IEC standard on specific power quality issues (Johnson & Hassan, 2016).

Table 2.2: IEEE and IEC standards on specific power quality issues.

Power Quality Issue	Appropriate Standards
Voltage sag/swell	IEC 61000-4-11, IEC 61000-43, IEEE P1564
Flickers	IEC 61000-2-2, IEEE P 1453
Harmonic	IEC SC 77 A, IEEE 1346, IEEE SA-519-2014

2.8 Studies on Voltage Sags

Voltage sag in power system is one of most concern power quality issues happened in the network as it caused high financial and economic losses. Therefore, lots of analysis and study-related voltage sag are published.

A recent paper conducted an analysis of voltage sag profile for single line to ground fault based on static impedance load model. The TNB 132/11 distribution network with a single line to ground fault that occurs in a network is used to estimate the voltage sag. This paper showed the impact of fault impedance and distance to voltage sag. The lower fault impedance will create a lower voltage sag value due to the principle of Ohm's Law. Additionally, it also proved that the further the node to the faulty node, the higher the voltage sag value it will get. This is because when voltage sag occurs, the current will increase as voltage become smaller. Lastly, the paper proved that the impedance-based method has a satisfactory accuracy in estimating the voltage sag value in the distribution network (Awalin, Mokhlis, Albatsh, Ismail & Alhamrouni, 2016).

Additionally, a paper published in the year 2008, also mentioned that type of fault and the location of the fault can affect the characteristic of voltage sag in power systems. It showed that if the fault occurs in the power system is a symmetrical fault, the voltage sag will be symmetrical (balance) as well. Furthers, it also proved that the location that is nearer to the fault location has a lower value in voltage sag (Patne, Thakre, 2008).

Furthermore, a paper analyzed the impact of voltage sag due to single line to ground fault, 3 phase fault, and line to line fault on induction motor performance. It proved that voltage sag due to 3 phase fault has the biggest impact on the induction motor performance compared to other types of fault. It caused higher peak current and higher variation of the speed and torque (Hardi, Daut, Nisja, Chan & Dahlan, 2013).

Additionally, another study also mentioned that the voltage sags are generally caused by faults in the transmission and distribution system. The common cause of the power system fault is due to weather conditions, contamination of insulators, accidents due to construction and transportation activities, and animal contact. The study also agreed that the three-phase fault can cause more severe voltage sag compared to other faults (Aung, Milanovic & Guptal, 2004).

Besides, a study was conducted to investigate the impact of voltage sag on the power of grid connected wind power plants. The impacts of voltage sag included the breakdown of sensitive machines, system halt, loss of data, fail functions, and complete system shutdown (Kadandani & Maiwada, 2015).

Voltage sag is the most serious issue in terms of power quality problem. However, many studies have been carried out to resolve or mitigate the problem. A study has proven that the DC voltage source can be used to mitigate voltage sag in a low voltage 3 phase distribution system. The DC voltage source is a dynamic voltage restorer (DVR) which incorporates a PV array module (Kaur & Brar, 2015).

Furthermore, voltage sag can be compensated by a distribution static compensator (DSTATCOM). A study has proven that a distribution static compensator (DSTATCOM) which employing with sliding mode control (SMC) technique can perform better than P+Resonant controller. The compensation of voltage sag has a wider range with less disturbance compared to other conventional control systems. It can improve the voltage profile by about 59.88%, without any disturbance (Shahgholian & Azimi, 2016).

2.9 Summary

In this section, it included the general power system, and 3 types of topologies for distribution system which are radial, ring and mesh network. Additionally, it also consists of faults in the power system and power quality problems. Lastly, it discussed the study on the voltage sag which provides a brief idea of what analysis has been conducted previously and its findings.

CHAPTER 3: METHODOLOGY

3.1 Introduction

The PowerWorld software is used to simulate this study. The IEEE-14 bus system as shown in Figure 3.1 is taken for simulation of power flow analysis and fault analysis.

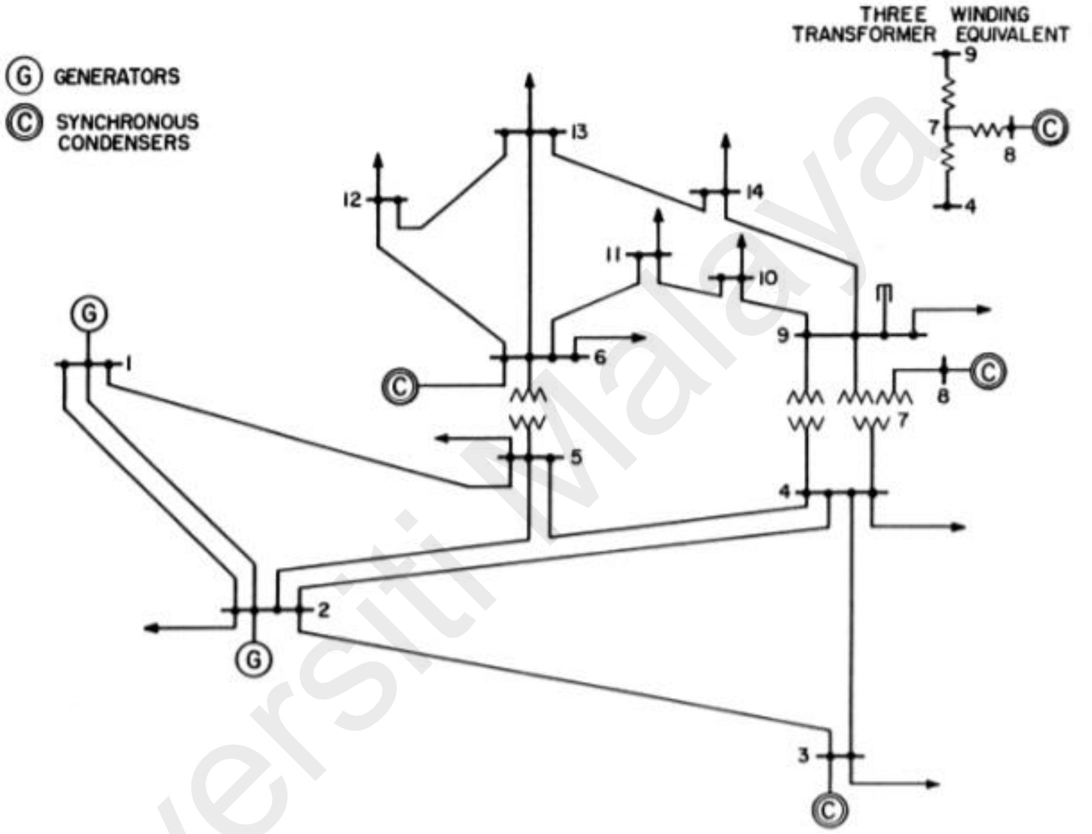

Figure 3.1: Single line diagram of an IEEE-14 bus system

The IEEE 14-bus system will be modeled in Power World which consists of 5 generators, 5 transformers, 14 buses, and 11 constant impedance loads (Anuar, Wahab, Arshad, Romli, Bakar & Bakar, 2020). The parameter of generators, transformer data, bus data, and line data will be filled in the system for the simulation. All the parameters as shown in Appendix A, Appendix B, and Appendix C

3.2 Process Flow Chart

In this study, the process flow of the works carried out is as shown below.

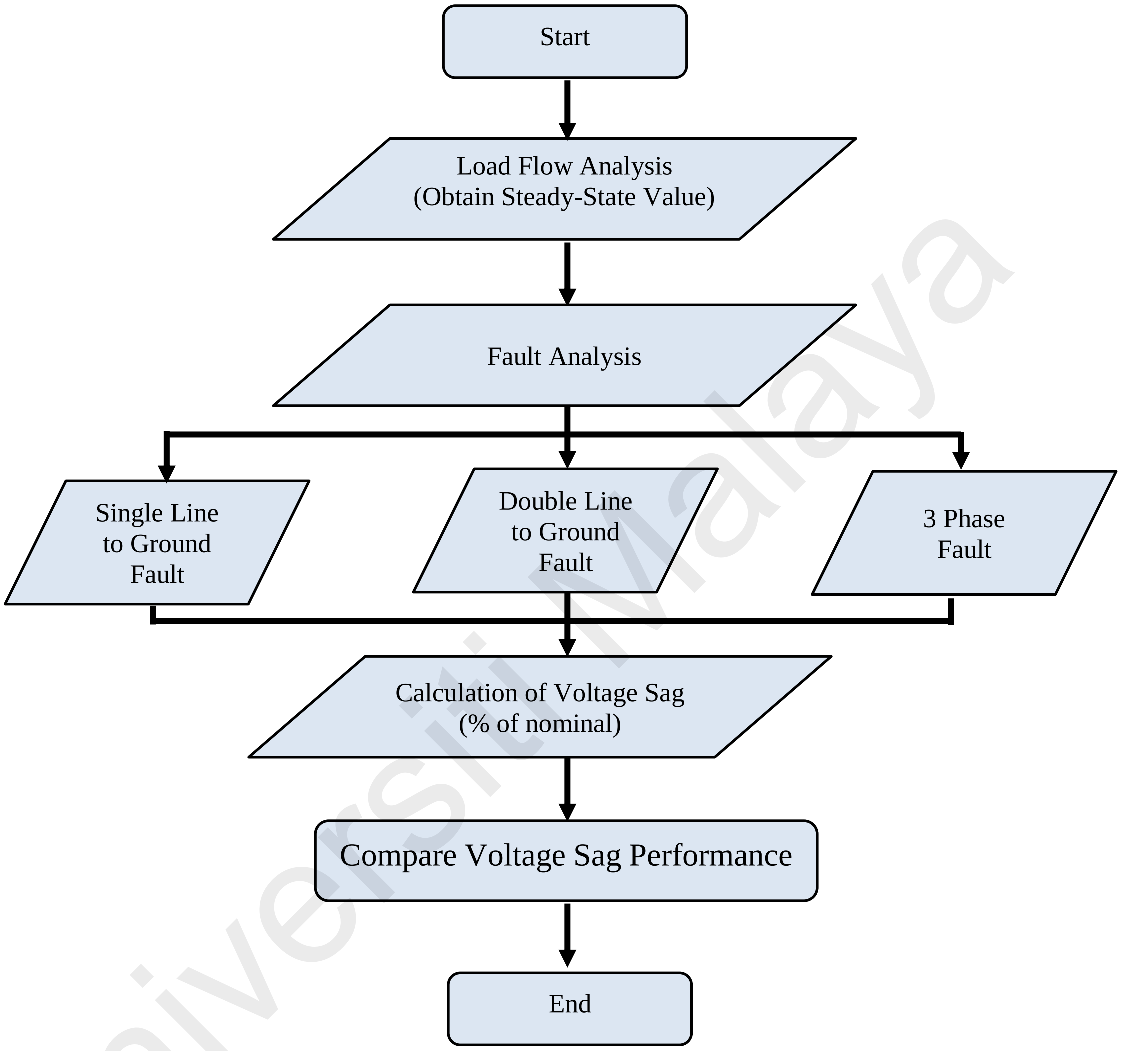

Figure 3.2: Process Flow Chart

In beginning, the modeling of the 14-bus system will be carried out by the load flow analysis, following by fault analysis. Three types of faults will be applied into the system which are single line to ground fault, double line to ground fault, and 3 phase fault. Lastly, the voltage sag in % of nominal will be calculated, compared, and observed.

3.3 Load Flow Analysis

The load flow analysis will be executed on the IEEE 14-bus system with Power World to determine the steady-state value. There are many power flow methods available in the Power World simulator such as Gauss-Seidel, Newton Raphson, Fast Decoupled power flow, and DC power flow method.

Gauss-Seidel is the most basic load flow method however, the convergence rate is much slower than other methods. The advantage is that it involves a little amount of memory and does not involve solving matrices (Talukdar, 2019).

Newton Raphson's load flow method is a landmark in the load flow method as few of the methods are based on this technique. The convergence rate is much faster than other methods (Talukdar, 2019).

Fast Decoupled load flow method is also known as the approximate newton method as the iteration procedure is the same as Newton Raphson. Additionally, it required lesser memory and lesser storage requirements compared to the Newton Raphson (Talukdar, 2019).

DC power flow method is a simplification and linearization of an AC power flow as it is only focusing on active power flows and neglecting voltage and reactive power (Hertem, Verboomen, Purchala, Belmans & Kling, 2006).

In this study, Newton Raphson is chosen to perform the load flow analysis. The phase voltage will be recorded and used to calculate the voltage sag.

3.4 Fault Analysis

The fault analysis will be executed in the Power World simulator as shown in figure 3.3. The fault location is set to be bus fault in this study. The fault type will be single-line-to-ground, 3 phase balanced, and double-line-to-ground. Each fault will be carried out 14 times with 14 faulted buses starting from bus 1 to bus 14. All the fault voltage will be recorded for further study.

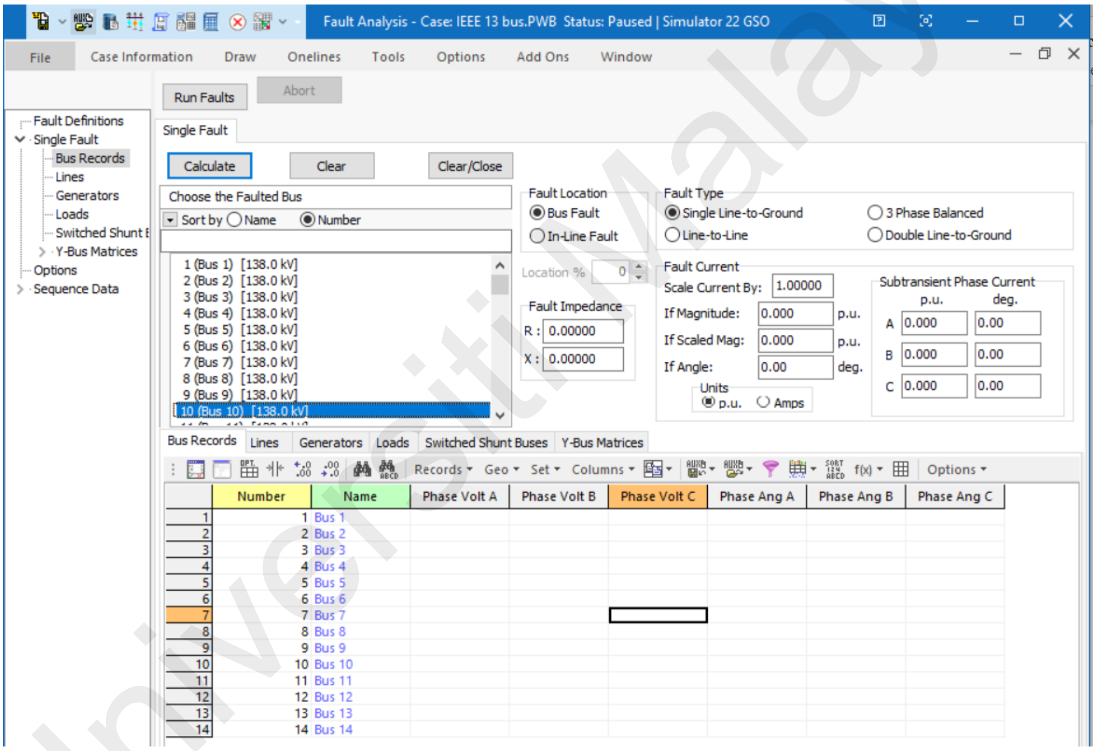

Figure 3.3: Fault Analysis in POWER WORLD Simulator

3.5 Calculation of Voltage Sag

The calculation of voltage sag will be carried out in Microsoft excel. The simulation output for load flow analysis and fault analysis would be used for voltage magnitude in term of % calculation.

The voltage magnitude in terms of % is given by equation 3.1.

$$Voltage\ (\%\ of\ nominal):\ \frac{Phase\ Fault\ Voltage\ \ (p.u)}{Phase\ Voltage\ in\ Steady\ State\ \ (p.u)} \times 100\% \qquad (3.1)$$

The lowest phase fault voltage will be chosen for the calculation. When the voltage magnitude （%）is below 90%, it will be voltage sag.

3.6 Voltage Sag Performance

In this study, the voltage sag performance will not be presented as the magnitude of voltage magnitude in terms of % but summarized into event impacts. The past study expressed that the event impact summary can be categorized into 4 statuses which are: OK (80% to 90%), MAYBE (70% to 80%), PROBABLY (60% TO 70%), and DEFINITELY (less than 60%). The status of OK (80% to 90%) means that the voltage sag event is captured but it will not cause any problem to the industries. The status of MAYBE (70% to 80%) generally also does not become a problem to industries. The status of PROBABLY (60% TO 70%), will cause the interruption to the industries but will occur rarely. The status of DEFINITELY (less than 60%) indicated that the voltage sag event will cause the interruption and breakdown on plant operation to the industries (Muhamad, Mariun, & M.Radzi, 2007). Furthermore, when the voltage magnitude is more than 90%, it will be categorized into the status of ‘no-sag”.

CHAPTER 4: RESULTS AND DISCUSSIONS

4.1 Introduction

In this chapter, discussions will be carried out on the different types of faults introduced in the earlier chapters. As stated in the methodology chapter, the faults: single line to ground fault, double line to ground fault, and 3 phase fault will be applied into the 14-bus distribution system. Comparisons will be drawn and summarized based on the severity of voltage sag (% of nominal) to decide the best location for industries that required high power quality such as the semiconductor industry.

4.2 Base Value: 14-Bus Distribution System's Steady State

To obtain the output of this research, a power flow analysis of the 14-bus distribution system is carried out in the POWERWORLD simulator to determine the steady-state value. The function of solve power flow-newton in POWERWORLD was chosen to complete power flow analysis as shown in figure 4.1.

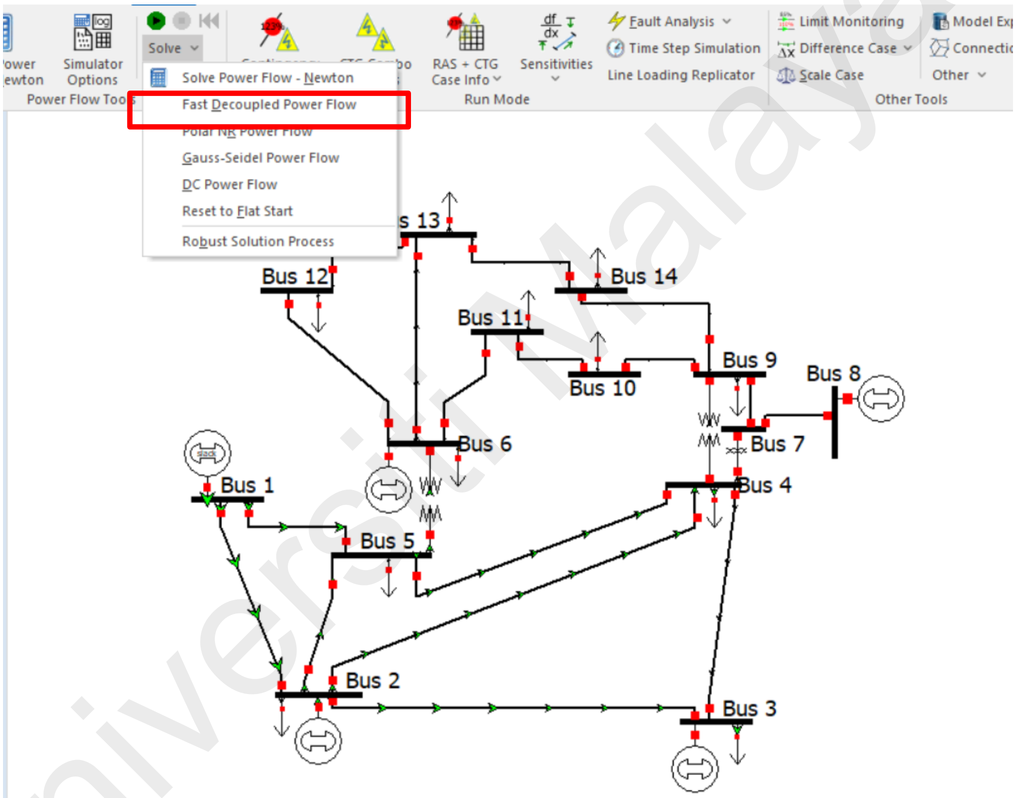

Figure 4.1: Modelling of the 14-bus distribution system in POWER WORLD

While the simulation resulted in the steady-state power flow values of the 14-bus distribution system's buses and branches, the important information is specified in the per unit voltage magnitude. The following table is the compiled power flow data of the buses.

Table 4.1: Power flow data of buses

Bus Number	Bus		Generation		Load	
	Magnitude *(p.u)*	Phase angle *(degree)*	Real Power *(MW)*	Reactive Power *(MVAR)*	Real Power *(MW)*	Reactive Power *(MVAR)*
1	1.06000	0	232.39	-16.55		
2	1.04500	-4.98	40	43.56	21.7	12.7
3	1.01000	-12.73	0	25.08	94.2	19.0
4	1.01767	-10.31			47.8	-3.9
5	1.01951	-8.77			7.6	1.6
6	1.07000	-14.22	0	12.73	11.2	7.5
7	1.06152	-13.36				
8	1.09000	-13.36	0	17.62		
9	1.05593	-14.94			29.5	16.6
10	1.05098	-15.1			9.0	5.8
11	1.05691	-14.79			3.5	1.8
12	1.05519	-15.08			6.1	1.6
13	1.05038	-15.16			13.5	5.8
14	1.03553	-16.03			14.9	5.0

As indicated in the table above, bus 1 is recognized as slack bus as the phase angle (degree) is zero. The negative sign in the reactive power of the generator at bus 1 indicates that the reactive power is flowing from the utility grid to the generator. To note, in this study, it is not necessary to consider the phase angle.

4.3 Result of POWER WORLD Simulation- Fault Analysis

In this section, the POWERWORLD simulated outputs of fault analysis will be recorded, observed, and discussed. 3 types of faults: single line to ground fault, double line to ground fault, 3 phase fault will be applied into the 14-bus distribution system. The faults will be created on each bus. Therefore, the simulation of every fault will be going 14 times with 14 different bus fault locations. Each bus has a total of 13 events as when the fault is happening at its respective bus was not taken into consideration. The fault phase voltage obtained is as indicated in Appendix F, G, and H.

The lowest phase fault voltage will be taken into the calculation of voltage magnitude (% of nominal). The simulated outputs obtained will be presented as the number of events with different statuses at each bus when a fault occurred instead of per unit of voltage magnitude. In addition, the voltage sag severity will be divided into 4 statuses and no voltage sag is introduced in the earlier chapters.

4.3.1 Impact of Fault on Voltage Sags

In this section, we would take bus 2 and bus 5 as an example to discuss voltage sag performance toward 3 types of faults and how to obtain the voltage sag. 3 types of faults will be applied to various buses and the phase voltage at bus 2 and bus 5 will be recorded and discussed.

Table 4.2 showed the phase voltage of Bus 2 when 3 types of faults (single line to ground fault, second line to ground fault, and 3 phase fault) happened at 14 fault bus locations.

Table 4.2: Phase voltage of Bus 2 with different type of faults and fault location

Fault Location	Type of Fault					
	3 Phase Fault		Single to Ground		Double Line To Ground	
	Phase Voltage (pu)	Voltage %	Phase Voltage (pu)	Voltage %	Phase Voltage (pu)	Voltage %
Bus 1	0.1045	10.0%	0.1208	11.6%	0.0902	8.6%
Bus 2	0.0000	0.0%	0.0000	0.0%	0.0000	0.0%
Bus 3	0.4564	43.7%	0.5170	49.5%	0.4606	44.1%
Bus 4	0.3120	29.9%	0.3821	36.6%	0.3240	31.0%
Bus 5	0.3010	28.8%	0.3708	35.5%	0.3118	29.8%
Bus 6	0.6476	62.0%	0.9692	92.7%	0.6955	66.6%
Bus 7	0.6159	58.9%	0.9685	92.7%	0.6665	63.8%
Bus 8	0.7772	74.4%	0.9762	93.4%	0.7875	75.4%
Bus 9	0.6355	60.8%	0.9714	93.0%	0.6840	65.5%
Bus 10	0.6917	66.2%	0.9754	93.3%	0.7364	70.5%
Bus 11	0.7231	69.2%	0.9763	93.4%	0.7678	73.5%
Bus 12	0.7739	74.1%	0.9812	93.9%	0.8194	78.4%
Bus 13	0.7210	69.0%	0.9772	93.5%	0.7679	73.5%
Bus 14	0.7689	73.6%	0.9836	94.1%	0.8085	77.4%

From table 4.1, it showed that the nominal voltage of bus 2 at steady-state condition is 1.045 pu. From the table above, the phase voltage of bus 2 when 3 phase balanced fault happened at fault location bus 1 is 0.1045 pu. An example of calculation of voltage magnitude in terms of % at bus 2 is shown below

$$Voltage\ Magnitude\ (\%\ of\ Nominal) = \frac{0.1045}{1.0450} \times 100\% = 10\%$$

When 3 phases fault happened at bus 1, the voltage magnitude at bus 2 is only 10%. It is considered as voltage sag. From figure 4.1, it showed that the bus 2 are connected to bus 1, 3, 4 and 5. Therefore, when the fault happened at bus 1, 3,4, and 5, it caused severe voltage sag to bus 2 compared to other buses. Additionally, as the generator at bus 1 is supplying power to bus 2, therefore, bus 2 experienced the highest severity voltage sag when the fault happened at bus 1. Lastly, as the fault happened at further bus locations, the voltage sag severity is reduced.

Next, will discuss the voltage sag performance at Bus 5. Table 4.3 showed the phase voltage of Bus 5 when 3 types of faults (single line to ground fault, double line to ground fault, and 3 phase fault) happened at 14 fault bus locations.

Table 4.3: Phase voltage of Bus 5 with 3 types of faults and 14 fault locations

Fault Location	Type of Fault					
	3 Phase Fault		Single to Ground		Double Line to Ground	
	Phase Voltage (pu)	Voltage %	Phase Voltage (pu)	Voltage %	Phase Voltage (pu)	Voltage %
Bus 1	0.1261	12.4%	0.1426	14.0%	0.0933	9.2%
Bus 2	0.1228	12.0%	0.1378	13.5%	0.1052	10.3%
Bus 3	0.4031	39.5%	0.4417	43.3%	0.3962	38.9%
Bus 4	0.1166	11.4%	0.1374	13.5%	0.1178	11.6%
Bus 5	0.0000	0.0%	0.0000	0.0%	0.0000	0.0%
Bus 6	0.4915	48.2%	0.9170	89.9%	0.5703	55.9%
Bus 7	0.4792	47.0%	0.9218	90.4%	0.5601	54.9%
Bus 8	0.6803	66.7%	0.9315	91.4%	0.7000	68.7%
Bus 9	0.4979	48.8%	0.9242	90.7%	0.5770	56.6%
Bus 10	0.5651	55.4%	0.9286	91.1%	0.6367	62.5%
Bus 11	0.5980	58.7%	0.9283	91.1%	0.6689	65.6%
Bus 12	0.6594	64.7%	0.9338	91.6%	0.7298	71.6%
Bus 13	0.5902	57.9%	0.9284	91.1%	0.6649	65.2%
Bus 14	0.6612	64.9%	0.9388	92.1%	0.7226	70.9%

From table 4.1, it showed that the nominal voltage of bus 5 at steady-state condition is 1.01951 pu. From the table above, the phase voltage of bus 5 when a single line to ground fault happened at fault location bus 1 is 0.0933 pu. An example of calculation of voltage magnitude in terms of % at bus 5 is shown below

$$Voltage\ Sag\ (\%\ of\ Nominal) = \frac{0.0933}{1.01951} \times 100\% = 9.2\%$$

When a single line to ground fault happened at bus 1, the voltage sag at bus 5 is 9.2%

From figure 4.1, it showed that the bus 5 are connected to bus 1, 2, and 4. Therefore, when the fault happened at bus 1, 3, 4, and 5, it caused severe voltage sag to bus 5 compared to other buses. The fault happened at a further bus location; the voltage sag severity is reduced. Additionally, the average overall phase voltage at bus 5 with 3 phases fault has the lowest voltage which is 0.4609 pu compare with 0.5033 for a double line to ground fault and 0.7086 pu for single line to ground fault. It can conclude that the 3 phases fault has the highest severity voltage sag,

4.3.2 Voltage Sag due to Single Line to Ground Fault

The number of voltage sag events on each bus due to a single line to ground fault is showed in Table 4.4. The total number of events is 182 events. 139 events caused voltage sag (0 to 90%) which is about 76.4%. 43 events would not cause any voltage sag as it is above 90% which is approximately 23.6%.

Table 4.4: Number of voltage sag events on each bus due to single line to ground fault

Status	Definitely	Probably	Maybe	Ok	No Sag
Voltage Sag (%)	(< 60%)	(60-70%)	(70-80%)	(80-90%)	(>90%)
Bus 1	3	1	0	0	9
Bus 2	4	0	0	0	9
Bus 3	4	0	0	0	9
Bus 4	4	0	0	1	8
Bus 5	4	0	0	1	8
Bus 6	12	0	1	0	0
Bus 7	12	0	1	0	0
Bus 8	11	0	2	0	0
Bus 9	13	0	0	0	0
Bus 10	12	0	1	0	0
Bus 11	12	0	1	0	0
Bus 12	12	0	1	0	0
Bus 13	12	0	1	0	0
Bus 14	12	0	1	0	0
TOTAL	**127**	**1**	**9**	**2**	**43**

From the table above, it can be summarized that bus 1 to 5 has the least frequency of voltage sag that happened when a single line to ground fault occurred in the 14-bus distribution system which is about 4 events out of 13 events. It is approximately a 31% of chance to have voltage sag when a fault happened. However, from Bus 6 to Bus 14, there is a higher chance for voltage sag to occur when a fault occurred, which is more than 85%.

As a result, the overall voltage sag severity for the 14-bus distribution system towards the single line to ground fault has been affected. The chances of voltage magnitude fall under the category of status “definitely” (voltage sag < 60%) when a single line to ground fault happens is about 70 %. Additionally, only 24% of chances no occurring voltage sag when the fault happened. The detail of overall sag severity in the 14-bus distribution system toward the single line to ground fault is showed in figure 4.2

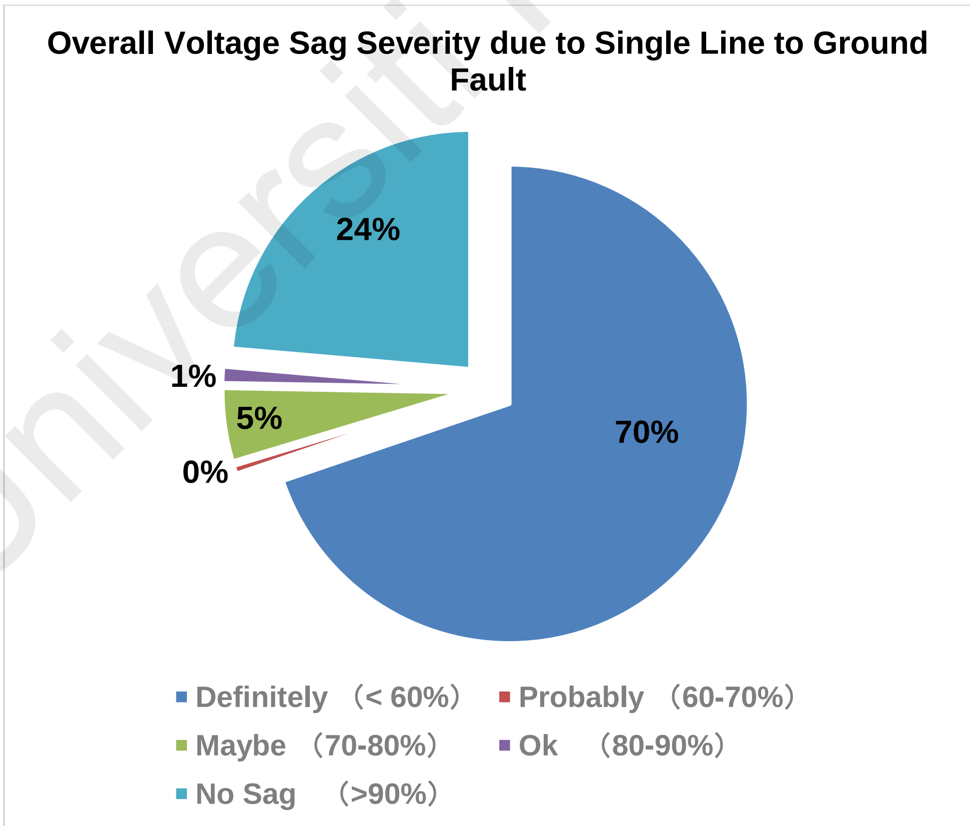

Figure 4.2: Overall voltage sag severity due to single line to ground fault

4.3.3 Voltage Sag due to Double Line to Ground Fault

The number of voltage sag events on each bus due to the double line to ground fault is showed in Table 4.5. When the double line to ground fault occurred at the bus location in the 14-bus distribution system, there was a 100% chance for a voltage sag to occur with different levels of severity toward the equipment and production process.

Table 4.5: Number of voltage sag event on each bus due to double line to ground fault

Status	Definitely	Probably	Maybe	Ok	No Sag
Voltage Sag (%)	(< 60%)	(60-70%)	(70-80%)	(80-90%)	(>90%)
Bus 1	4	0	6	3	0
Bus 2	4	0	3	6	0
Bus 3	4	4	3	2	0
Bus 4	7	4	2	0	0
Bus 5	7	4	2	0	0
Bus 6	13	0	0	0	0
Bus 7	13	0	0	0	0
Bus 8	13	0	0	0	0
Bus 9	13	0	0	0	0
Bus 10	13	0	0	0	0
Bus 11	13	0	0	0	0
Bus 12	13	0	0	0	0
Bus 13	13	0	0	0	0
Bus 14	13	0	0	0	0
TOTAL	**143**	**12**	**16**	**11**	**0**

From the table above, it can be summarized that the double line to ground fault has caused high severity level of voltage sag from bus 6 to 14 in the 14-bus distribution system. All the voltage sag that occurred during fault are fall under the category of status "definitely" which is voltage sag less than 60%. Bus 1 and 2 had experienced the least severity of voltage sag as only approximately 31% of the opportunity to have voltage sag less than 60%.

Overall, there has approximately 78% of chances to have voltage sag less than 60% which falls under the category of status "definitely". In addition, only 6% of the voltage sag is between 80 to 90%. The detail of overall sag severity in the 14-bus distribution system toward the double line to ground fault is showed in figure 4.3

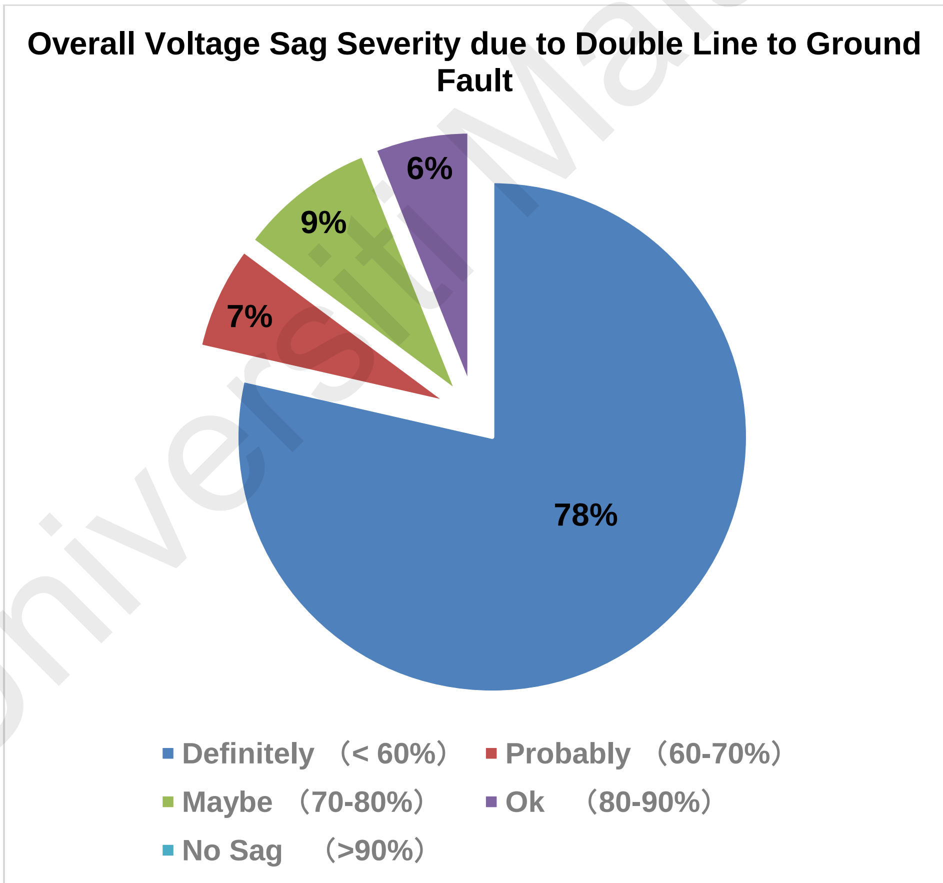

Figure 4.3: Overall voltage sag severity due to double line to ground fault

4.3.4 Voltage Sag due to 3-Phase Fault

The number of voltage sag events on each bus due to 3 phase fault is showed in Table 4.6. When the 3-phase fault occurred in the 14-bus distribution system, there were 100% chances to have voltage sag with different levels of severity. All the voltage sag occurred is less than 80% of nominal voltage.

Table 4.6: Number of voltage sag events on each bus due to 3 phase fault

Status	Definitely	Probably	Maybe	Ok	No-Sag
Voltage Sag (%)	(< 60%)	(60-70%)	(70-80%)	(80-90%)	(>90%)
Bus 1	4	3	6	0	0
Bus 2	5	5	3	0	0
Bus 3	7	3	3	0	0
Bus 4	10	3	0	0	0
Bus 5	10	3	0	0	0
Bus 6	13	0	0	0	0
Bus 7	13	0	0	0	0
Bus 8	13	0	0	0	0
Bus 9	13	0	0	0	0
Bus 10	13	0	0	0	0
Bus 11	13	0	0	0	0
Bus 12	13	0	0	0	0
Bus 13	13	0	0	0	0
Bus 14	13	0	0	0	0
TOTAL	**153**	**17**	**12**	**0**	**0**

From the table above, it indicated that from bus 6 to 14 would experience the highest severity level of voltage sag when 3 phase fault occurred in the 14-bus distribution system. All the voltage sag that occurred during fault fall under the category of status “definitely” which is voltage sag less than 60%. In addition, there was not any voltage sag that fell under the category of status “ok” and “no-sag”.

Overall, 84% of the voltage sag that occurred fall under the category of status "definitely". In addition, only 7% of the voltage sag is between 70 to 80%. The detail of overall sag severity in the 14-bus distribution system toward 3 phase fault is showed in figure 4.4.

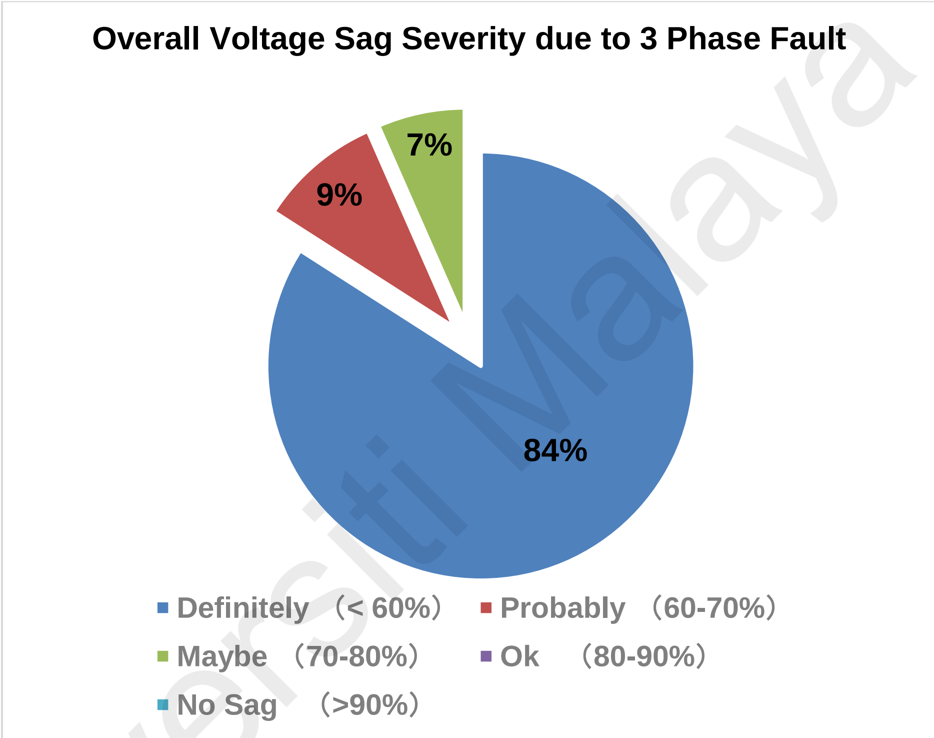

Figure 4.4: Overall voltage sag severity due to 3 phase fault

4.3.5 Summary of Voltage Sag Severity

The summary of voltage sag severity toward the fault is showed in table 4.7

Table 4.7: Total Number of voltage sag events on each bus for a different types of faults

Status	Definitely	Probably	Maybe	Ok	No Sag
Voltage Sag (%)	(< 60%)	(60-70%)	(70-80%)	(80-90%)	(>90%)
LG	127 70%	1 1%	9 5%	2 1%	43 24%
LLG	143 79%	12 7%	16 9%	11 6%	0 0%
LLLG	152 84%	18 10%	12 7%	0 0%	0 0%

From the table above, it can be summarized that the 3 phase fault has higher voltage sag severity compared to the single line and double line to ground fault. As the chances of experiencing voltage sag fall under the category of “definitely” is much higher in 3 phase fault at 84% than the others as compared to 70% for single line to ground fault and 79% for a double line to ground fault. In addition, all of the voltage sag caused by the three-phase fault is less than 80%.

In addition, a single line to ground fault has the least severity of voltage sag to the 14-bus distribution system among those 3 types of faults. It also has a 24% of chance that it does not experience voltage sag in its specific location.

In conclusion, the 3 phase fault caused the highest level of voltage sag severity in the 14-bus distribution system and following by a double line to ground fault and a single line to ground fault. In other words, 3 phase fault has the biggest impact on the 14-bus distribution system in terms of voltage sag.

4.4 Evaluating the Voltage Sag Severity on Each Bus

The total number of voltage sag on each bus for 3 types of faults: single to ground fault, double line to ground fault, and 3 phase fault is showed in table 4.8

Table 4.8: Total number of voltage sag on each bus for 3 types of faults

Status	Definitely	Probably	Maybe	Ok	No-Sag
Voltage Sag (%)	(< 60%)	(60-70%)	(70-80%)	(80-90%)	(>90%)
Bus 1	11	4	12	3	9
	28%	10%	31%	8%	23%
Bus 2	13	8	9	0	9
	33%	21%	23%	0%	23%
Bus 3	15	7	6	2	9
	38%	18%	15%	5%	23%
Bus 4	21	7	2	1	8
	54%	18%	5%	3%	21%
Bus 5	21	7	2	1	8
	54%	18%	5%	3%	21%
Bus 6	38	0	1	0	0
	97%	0%	3%	0%	0%
Bus 7	38	0	1	0	0
	97%	0%	3%	0%	0%
Bus 8	36	1	2	0	0
	92%	3%	5%	0%	0%
Bus 9	39	0	0	0	0
	100%	0%	0%	0%	0%
Bus 10	38	0	1	0	0
	97%	0%	3%	0%	0%
Bus 11	38	0	1	0	0
	97%	0%	3%	0%	0%
Bus 12	38	0	1	0	0
	97%	0%	3%	0%	0%
Bus 13	38	0	1	0	0
	97%	0%	3%	0%	0%
Bus 14	38	0	1	0	0
	97%	0%	3%	0%	0%
TOTAL	422	34	40	7	43
	77%	6%	7%	1%	8%

From the table, it can be summarized that bus 1 has the least voltage sag severity toward the faults compared to the other buses. In bus 1, there is about 8% and 23% fall under the voltage sag severity category of “ok” and “no-sag” which had the highest chances of occurring compared to other buses. In other words, it has an approximately 31% chance of occurrence, the voltage sag in bus 1 will not cause the equipment to break down.

In addition, bus 1 has only a 28% chance to experience the highest severity of voltage sag when a fault occurs which has the lowest chance of happening among all the buses.

In conclusion, bus 1 has the lowest voltage sag severity toward the fault, followed by bus 2. However, bus 1 is the slack bus which is the best location to place a factory manufacturing electronic components.

CHAPTER 5: CONCLUSION

5.1 Conclusion

By carrying out this study, a 14-bus distribution system is modeled in Power World. 3 types of faults are applied into the distribution system which are single line to ground fault, double line to ground fault, and 3 phase fault. The fault phase voltages were recorded to calculate the voltage sag (% of nominal voltage). After the observation and analysis, 3 phase fault caused the most severe impact to the 14-bus distribution system in terms of voltage sag performance. Single line to ground caused the least impact to the system in terms of voltage sag performance.

Lastly, after compiled all the simulated output from all the fault analyses, bus 1 has the least severity in terms of voltage sag, following by bus 2. Therefore, we would like to recommend bus 1 to those industries that required high power quality such as electronic manufacturing

5.2 Future Works

In this study, we are only focusing on the magnitude of phase voltage. Therefore, the work carried out in this study can be extended to the duration of the fault and phase jump. Additionally, the proposed assessment should be carried out with different parameters as shown below.

i. Different power system networks

Different types of distribution systems of either larger or smaller networks or different topologies of the distribution system.

ii. Different power quality issue

Different types of power quality issues such as harmonics, voltage swell, and the impact of each on distribution systems should be assessed.

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