การประเมินสายเคเบิลใต้ดินแรงสูงที่ฉนวนด้วย XLPE โดยการศึกษากระแสรั่ว

นายสินทะนู กองลีสาน

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิศวกรรมศาสตรมหาบัณฑิต
สาขาวิชาวิศวกรรมไฟฟ้า ภาควิชาวิศวกรรมไฟฟ้า
คณะวิศวกรรมศาสตร์ จุฬาลงกรณ์มหาวิทยาลัย
ปีการศึกษา 2559

XLPE INSULATED HIGH VOLTAGE UNDERGROUND CABLE ASSESSMENT BY LEAKAGE CURRENT STUDIES

Mr. Sinthanou Konglysan

A Thesis Submitted in Partial Fulfillment of the Requirements
for the Degree of Master of Engineering Program in Electrical Engineering
Department of Electrical Engineering
Faculty of Engineering
Chulalongkorn University
Academic Year 2016

Thesis Title	XLPE INSULATED HIGH VOLTAGE UNDERGROUND CABLE ASSESSMENT BY LEAKAGE CURRENT STUDIES
By	Mr. Sinthanou Konglysan
Field of Study	Electrical Engineering
Thesis Advisor	Assistant Professor Weerapun Rungseevijitprapa, Dr.-Ing.

Accepted by the Faculty of Engineering, Chulalongkorn University in Partial Fulfillment of the Requirements for the Master's Degree

_______________________Dean of the Faculty of Engineering

(Associate Professor Supot Teachavorasinskun, D.Eng.)

THESIS COMMITTEE

_______________________Chairman

(Assistant Professor Komson Petcharaks, Ph.D.)

_______________________Thesis Advisor

(Assistant Professor Weerapun Rungseevijitprapa, Dr.-Ing.)

_______________________External Examiner

(Aphibal Pruksanubal, Dr.-Ing.)

สินทะนู กองลีสาน : การประเมินสายเคเบิลใต้ดินแรงสูงที่ฉนวนด้วย XLPE โดยการศึกษากระแสรั่ว (XLPE INSULATED HIGH VOLTAGE UNDERGROUND CABLE ASSESSMENT BY LEAKAGE CURRENT STUDIES) อ.ที่ปรึกษาวิทยานิพนธ์หลัก: วีระพันธ์ รังสีวิจิตรประภา, 60 หน้า.

งานวิจัยนี้ได้ทำการศึกษาลักษณะสมบัติของกระแสรั่วของสายเคเบิลแรงสูงใต้ดิน เพื่อใช้ในการประเมินสภาพฉนวน หลังจากที่ได้มีการใช้งานเป็นระยะเวลาหนึ่ง ซึ่งอาจใช้เป็นข้อมูลสำคัญในการตัดสินใจที่จะขยายอายุการใช้งาน หรือทำการเปลี่ยนสายเคเบิลใต้ดินแรงสูงใหม่ การศึกษาได้กระทำบนวงจรจำลองที่เลียนแบบพฤติกรรมความเสียหายที่เกี่ยวข้องกับการใช้งานของสายเคเบิลใต้ดินแรงสูงที่ฉนวนด้วยครอสลิ้งค์พอลีเอทธีลีนแบบไม่เบรกดาวน์ได้แก่ การเกิดต้นไม้น้ำ ต้นไม้ไฟฟ้า การเกิดดีสชาร์จบางส่วน การเสื่อมสภาพของฉนวนจากการใช้งาน และการเกิดกระแสรั่วตามผิวบริเวณอุปกรณ์ประกอบสายเคเบิล เป็นต้น การศึกษาได้กระทำบนโปรแกรม Proteus 8.0 สำหรับเคเบิล 1 เฟส โดยการปรับเปลี่ยนทั้งขนาดของแรงดัน และความถี่ ผลของการวิเคราะห์ในแต่ละกรณีได้นำมาเปรียบเทียบกับสายเคเบิลปกติ เพื่อดูแนวโน้มลักษณะจำเพาะเพื่อใช้เป็นเครื่องมือในการระบุประเภทของความเสียหายที่อยู่ในเนื้อ ฉนวน ที่สามารถระบุเหตุแห่งความเสียหาย (ถ้ามี) จากพฤติกรรมขนาดที่เปลี่ยนแปลงของกระแสรั่ว และมุมเฟส โดยการเปรียบเทียบกันของกระแสรั่วที่ได้จากแต่ละเฟสของเคเบิลทั้งสามเส้นในหนึ่งระบบที่มีโครงสร้างคล้ายกัน ความยาวเท่ากัน การจำลองผลของกระแสรั่วจากสายเคเบิลทั้งสามเส้น โดยมีการสมมติให้เส้นใดเส้นหนึ่งผิดปกติแบบสุ่ม เพื่อนำข้อมูลป้อนให้กับเครื่องมือวิเคราะห์นี้ ซึ่งพบว่าระบบที่ได้ทำการพัฒนาขึ้นสามารถระบุเฟส และลักษณะของความบกพร่องได้อย่างถูกต้องแม่นยำ

ภาควิชา	วิศวกรรมไฟฟ้า	ลายมือชื่อนิสิต	....
สาขาวิชา	วิศวกรรมไฟฟ้า	ลายมือชื่อ อ.ที่ปรึกษาหลัก	....
ปีการศึกษา	2559		

5670517621 : MAJOR ELECTRICAL ENGINEERING
KEYWORDS: MAGNITUDE OF CURRENT, PHASE SHIFT, WATER TREES, ELECTRICAL TREES, PARTIAL DISCHARGE,AGEIG,TERMINATION

SINTHANOU KONGLYSAN: XLPE INSULATED HIGH VOLTAGE UNDERGROUND CABLE ASSESSMENT BY LEAKAGE CURRENT STUDIES. ADVISOR: ASST. PROF. WEERAPUN RUNGSEEVIJITPRAPA, Dr.-Ing., 60 pp.

The leakage current characteristic of high voltage underground cable was studied in this research. It is quite useful to assess the status of insulation after using for a while. This is an important data to do a decision making to prolong its lifetime or replacement a new one. A study was taken with the simulation circuit established from each none breakdown failure in XLPE insulated high voltage underground cable such as water treeing, electrical treeing, partial discharge, aging according to usage and surface leakage current along the cable's accessories, etc. This study was performed with Proteus 8.0 on single phase cable with variation of voltage and frequency. The results of leakage current from each case were compared with a healthy cable in order to establish a specific tendency characteristic. These characteristics were used to be a tool to classify the failure type in the insulation. Moreover, an analytical tool was developed with Excel@ in order to evaluate the status of an insulation with failure type (if any) from the change behavior of leakage current and phase angle. This was done by comparison the leakage currents obtained from each cable in a three-phase cable system with has a same construction and length. The simulation of leakage current data from a three-phase cable system integrated with any failure type in any phase in random was putted in to the developing tool. The obtained result could be determined correctly both in the failure phase and failure type.

Department:	Electrical Engineering	Student's Signature	....
Field of Study:	Electrical Engineering	Advisor's Signature	....
Academic Year:	2016		

ACKNOWLEDGEMENTS

This thesis could not be completed without the kind support and suggestion from many people and organization. First and foremost, I would like to express my sincere thanks to my thesis advisor, Asst. Prof. Dr-Ing. Weerapun Rungseevijitprapa, who gave good device and be guidance of this thesis since start until successful. His trust and support me inspired me in the most important moments of making right direction and I am glad to work under his supervisor.

Furthermore, I am also very gratefully acknowledge the JICA project for the financial support during my study at Chulalongkorn University in Thailand under the AUN/SEED-Net scholarship.

Finally, my graduation would not be achieved without my best wish from my family, who help me everything and always give me greatest love. And last gratefully special thanks to my friends for their help and encouragement.

CONTENTS

Page

THAI ABSTRACT ... iv

ENGLISH ABSTRACT ... v

ACKNOWLEDGEMENTS ... vi

CONTENTS ... vii

CHAPTER 1 INTRODUCTION ... 1

1.1 Overview XLPE insulation system ... 1

1.2 Objectives of the thesis. ... 2

1.3 Scope of the thesis ... 2

1.4 Process and method of the thesis ... 2

1.5 Expectation and benefit from the thesis ... 2

1.6 Outline of the thesis ... 3

CHAPTER 2 BASIC THEORY ... 4

2.1 XLPE insulated cable component and construction ... 4

2.2 XLPE insulated power cable ... 5

2.3 Characteristics and advantages of XLPE cable. ... 6

2.3.1 Excellent electrical and physical properties. ... 6

2.3.2 Capability of carrying large current. ... 6

2.3.3 Ease of installation. ... 7

2.3.4 Free from height limitation and maintenance. ... 7

2.4 Failure causes in XLPE insulated cable. ... 7

2.4.1 Internal partial discharge. ... 7

2.4.2 Electrical trees. ... 9

Page

2.4.3 Water trees. 10

2.4.4 Surface leakage in accessory. 11

2.4.5 Chemical and electrochemical deterioration and breakdown. 12

2.5 Phase difference. 12

CHAPTER 3 RESEARCH METHODOGY 14

3.1 simulation method 14

3.1.1 The Healthy cable. 15

3.1.2 The water trees. 16

3.1.2 The electrical trees. 17

3.1.3 The partial discharge. 18

3.1.5 The termination. 20

3.2 The fault in one phase cable. 21

3.2.1 To determine the different magnitude and phase shift. 21

3.2.2 The leakage current under frequency and voltage variation. 21

CHAPTER 4 SIMULATION RESULTS AND DISCUSSION 23

4.1 The magnitude and phase of leakage current in single phase cable 23

4.1.1 Water Trees. 23

4.1.2 Electrical Trees. 26

4.1.3 Partial discharge. 29

4.1.4 Ageing. 32

4.1.5 Termination. 35

4.2 Overview all cases of failure in XLPE insulation. 38

4.4 Three phase simulation. 43

Page

4.5 Procedure for cable testing. 45

CHAPTER 5 CONCLUSION 47

5.1 Conclusion. 47

REFERENCES 49

VITA 60

LIST OF TABLES

Table 4.1 The leakage current with a water tree failure at frequency of 10Hz, 1 cycle....23

Table 4.2 At frequency of 50Hz, 1 cycle....24

Table 4.3 At frequency of 200Hz, 1 cycle....24

Table 4.4 At frequency of 500Hz, 1 cycle....24

Table 4.5 The magnitude of currents and their difference time between healthy and faulty cable of water trees....25

Table 4.6 Comparison on phase shift in µ radian between healthy and faulty circuit with water trees....25

Table 4.7 The leakage current with a failure electrical trees at frequency of 10Hz, 1 cycle....26

Table 4.8 At frequency of 50Hz, 1 cycle....26

Table 4.9 At frequency of 200Hz, 1 cycle....26

Table 4.10 At frequency of 500Hz, 1 cycle....27

Table 4.11 The magnitude of current and their difference between healthy and faulty circuit of electrical tree....28

Table 4.12 Comparison on phase shift in µ radian between healthy and faulty circuit of electrical trees....28

Table 4.13 The leakage current with partial discharge a failure at frequency of 10Hz, 1 cycle....29

Table 4.14 At frequency of 50Hz, 1 cycle....29

Table 4.15 At frequency of 200Hz,1 cycle....29

Table 4.16 At frequency of 500Hz, 1cycle....30

Table 4.17 The magnitude of current and their difference between healthy and faulty circuit of partial discharge........31

Table 4.18 Comparison on phase shift in μ radian between healthy and faulty circuit of partial discharge........31

Table 4.19 The leakage current with a failure ageing at frequency of 10 Hz, 1 cycle........32

Table 4.20 At frequency of 50 Hz, 1 cycle........32

Table 4.21 At frequency of 200 Hz, 1 cycle........32

Table 4.22 At frequency of 500 Hz, 1 cycle........33

Table 4.23 The magnitude of currents and their difference between healthy and faulty circuit of ageing........34

Table 4.24 Comparison on phase shift in μ radian between healthy and faulty circuit of ageing........34

Table 4.25 The leakage current with a failure terminator at frequency of 10 Hz, 1 cycle........35

Table 4.26 At frequency of 50 Hz, 1 cycle........35

Table 4.27 At frequency of 200 Hz, 1 cycle........35

Table 4.28 At frequency of 500Hz, 1 cycle........36

Table 4.29 The magnitude of current and their difference between healthy and faulty circuit of termination........37

Table 4.30 Comparison on phase shift in μ radian between healthy and faulty circuit of termination........37

Table 4.31 Sample of the leakage currents from three cables simulation with termination leakage in phase B........46

LIST OF FIGURES

Figure 2.1 The construction of XLPE underground cable 4

Figure 2.2 Polyethylene Molecular structure (A,B), XLPE Molecular structure (C,D) and Crystallinity model of cross-liked (E) 6

Figure 2.3 Equivalent circuit of dielectric with void 8

Figure 2.4 Internal discharge 8

Figure 2.5 Electrical trees in XLPE cable 9

Figure 2.6 Water Tree in XLPE Cable 10

Figure 2.7 The equivalent circuit of surface discharge 11

Figure 2.8 Phase shift between two sine waves with phase angles of 45° a 13

Figure 3.1 The workflow diagram 14

Figure 3.2 The circuit model of healthy cable 15

Figure 3.3 The circuit model of water trees 16

Figure 3.4 The circuit model of electrical trees 17

Figure 3.5 The circuit model of healthy cable or applied voltage less than 25 kV 18

Figure 3.6 The circuit model of Faulty cable or applied voltage more than 25 kV 18

Figure 3.7 The circuit model of ageing 19

Figure 3.8 The circuit model of termination 20

Figure 3.9 The comparison of leakage current between healthy and faulty by vented water trees 22

Figure 4.1 The different of leakage current with Partial discharge, Termination and water trees....38

Figure 4.2 The different of leakage current for case Electrical trees and ageing....39

Figure 4.3 The leakage current due to water trees in term of voltage and frequency....40

Figure 4.4 The leakage current due to electrical trees in term of voltage and frequency....40

Figure 4.5 The leakage current due to Partial discharge in term of voltage and frequency.....41

Figure 4.6 The leakage current due to Aging in term of voltage and frequency.....41

Figure 4.7 The leakage current due to Termination in term of voltage and frequency....42

Figure 4.8 The procedure of the assessment of XLPE insulation....43

Figure 4.9 The test circuit on-site leakage current mesurement....45

Figure 4.10 The result from surface leakage of termination....46

LIST OF APPENDIX FIGURE

Figure A 1. The simple circuit on the Proteus program 53

Figure B 1. The Editing Window of ISIS professional 54

Figure B 2. The circuit model of water trees 55

Figure B 3. The bowser libraries button 55

Figure B 4. The Device Library Browser 56

Figure B 5. The Browser Library dialogue form 56

Figure B 6. The Object Selector containing a MINRES 100K 57

Figure B 7. The Rotation icons with anti-clockwise rotation selected. 57

Figure B 8. The Mouse cursor indicating that the mouse is over the pin tip 58

CHAPTER 1
INTRODUCTION

1.1 Overview XLPE insulation system

The Cross-linked polyethylene (XLPE) insulation system is an important and usage in high voltage system. The XLPE become the globally preferred insulation for power cables, both in distribution and transmission system. This insulation system provides cost efficiency in operation and procurement. Moreover, it is an environmental friendly usage and has less maintenance requirements compared to the impregnated paper systems.

The insulation has a high electric strength, mechanical strength, high-aging resisting, and environmental stress. With simple construction for convenient usage and for can be used up to 90°C. It can be laid with no drop restriction. XLPE cable can be manufactured with three technologies as follows: peroxide, vulcanization and irradiation crosslinking.

The damage of XLPE cable is caused by water treeing, electrical treeing, partial discharge and so on[1]. Another damage cause is concerning to the long time operation. Cable insulation can be damaged due to the impact of internal electrical Thermal, Mechanical and electrical stress effect to the insulation system[2].

The studying on assessment in XLPE high voltage cable is very valuable. The studying of leakage current was taken by using of electric circuit simulation in the maintenance period[3]. In order to understand the relationship characteristic of each failure type in function of applied voltage and frequency. Therefore, its health status can be determined. This can be applied to assess the exist cable system.

1.2 Objectives of the thesis.

The objectives of the thesis are:

- To simulate the circuit model of each cause.
- To study the leakage current behavior, both in magnitude and phase with a variation of voltage and frequency.
- To identify the specific failure case though leakage current by developing tools.

1.3 Scope of the thesis

The scope of this thesis is considered the most well-known causes in XLPE insulation. The studies were performed only on circuit model simulation.

1.4 Process and method of the thesis

To understand the leakage current behavior due to each failure by simulation.

Experiment with a circuit model of XLPE insulated cable system with the Proteus Program with in the function of applied voltage and frequency.

The failure type and phase from the leakage current measurement of three cables in simulating system were specified by developing tools.

1.5 Expectation and benefit from the thesis

1. Being able to develop an assessment tool for the underground cable system.
2. Being able to technically consider to extend an insulation usage life.

1.6 Outline of the thesis

This thesis consists of five chapters in which each chapter has its own way of describing and analyzing the fundamentals of the work which followed the theories, experimental setup and simulation results.

CHAPTER 1: The thesis overview is provided such as: the basic introduction, motivation, objective, scope, process, method, expectation and benefit of the thesis.

CHAPTER 2: The theoretical background of the XLPE insulated cable, Characteristics and advantages of XLPE cable, failure causes in XLPE insulated cable, and are decided the XLPE insulated cable component and construction.

CHAPTER 3: The equivalent diagrams experimental circuit equivalent diagram of experimental circuit, and the simulating results are presented.

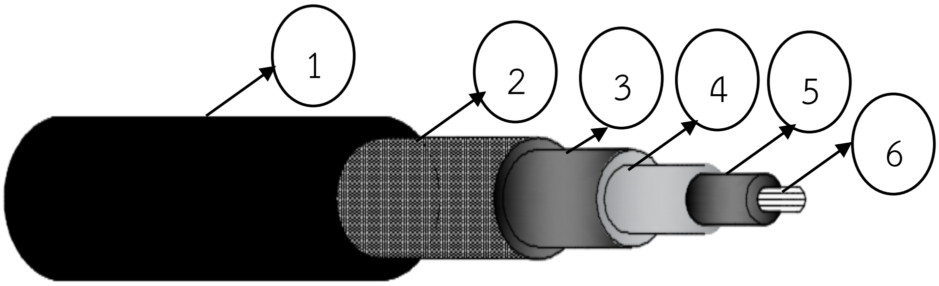
CHAPTER 4: The experimental results are discussed.

CHAPTER 5: The conclusion and the suggestion of the research work are shown.

CHAPTER 2
BASIC THEORY

2.1 XLPE insulated cable component and construction.

In general, the shape and structure of XLPE underground cable are shown in figure: 2.1.



1. Jacket 2. Metalic ground 3. Insulation screen

4. XLPE insulation 5. Conductor screen 6. Conductor

Figure 2.1 The construction of XLPE underground cable

Jacket: the jacket can be polyvinyl chloride or polyethylene to suit the cable application. Underneath the jacket a layer of compound filled fabric tape may be provided, if required.

Conductor: the conductor can be copper concentric strand, compressed strand or compacted strand type. The conductor size is specified in square millimeters. The cross-sectional area of the conductor cannot be too small for a certain cable voltage rating due to pre-determined criteria.

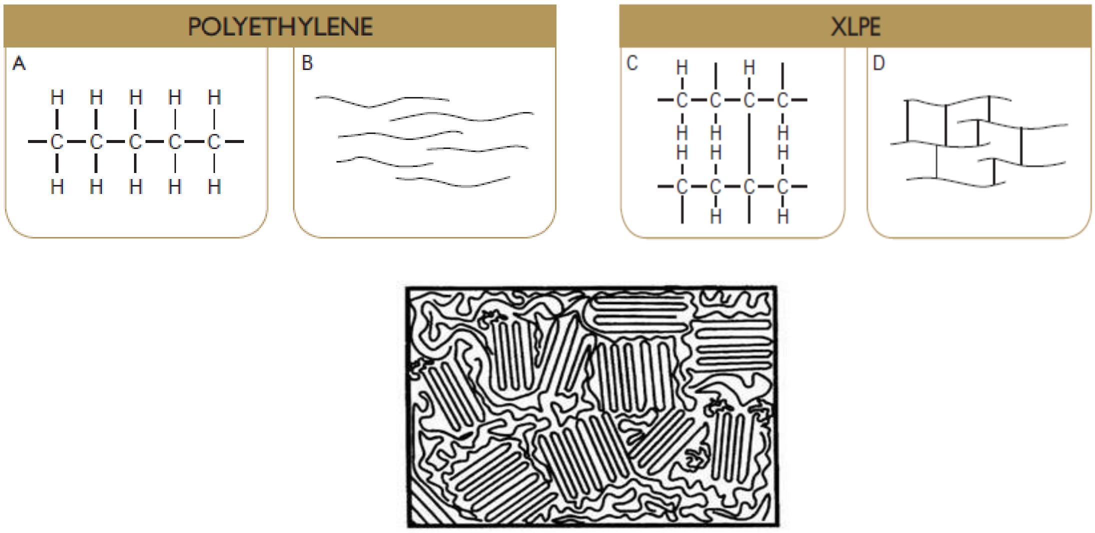
Conductor Screen: the conductor screen is an extruded layer of conducting XLPE compound applied in tandem with and firmly bonded to the insulation.

Insulation: the insulation is one of the most important component in the cable assembly, manufacturing precautions must be made during the insulating process. In short, the insulating compound will be delivered to the extruder through a metal detector in order that any possible metallic particles be detected.

Insulation Screen: the insulation is shielded with a layer of conducting XLPE applied directly over the insulation, and one and more bare copper tapes applied with a lap over the conducting XLPE. In a particular system where order configurations of the insulation shield are required, the manufacture can be consulted for satisfactory cable performance.

2.2 XLPE insulated power cable.

LDPE is an abbreviated form low density Polyethylene. Polyethylene has a linear molecular structure as shown in figure 2.2 (A). Molecules of polyethylene are not chemically bonded as shown in figure 2.2 (B) can be easily deformed at over melting temperature, while XLPE molecules bonded in a three dimensional network as shown in figure 2.2 (C) and figure 2.2 (D), making strong resistance to deform even at high temperature. Crystallinity refers to the degree of structural order in a solid figure 2.2 (E) [4]. In a crystal, the atoms or molecules are arranged in a regular, periodic manner. The higher degree of crystallinity is an effect on increasing hardness, higher density but decreasing transparency.



(E)

Figure 2.2 Polyethylene Molecular structure (A,B), XLPE Molecular structure (C,D) and Crystallinity model of cross-liked (E)

2.3 Characteristics and advantages of XLPE cable.

2.3.1 Excellent electrical and physical properties.

XLPE cable constitutes the best cable for transmission and distribution lines because of its excellent electrical and physical properties. The main features of XLPE are: Excellent electrical properties maintained over the full temperature range, resistance to thermal deformation at high temperature, Excellent water resistance and low permeability to water, and high durability and long operational life.

2.3.2 Capability of carrying large current.

The excellent resistance to thermal deformation and the excellent aging property of XLPE cable permit it to carry the large current under normal (90°C), emergency (130°C) or short circuit (250°C) conditions. Owing to the cross-link, XLPE is a very heat-resistant material. It cannot melt like polyethylene but decomposes and carbonizes if exposed for long periods to temperatures above 300C.

2.3.3 Ease of installation.

XLPE cable can be installed smaller bending radius and light weight. Furthermore, the splicing and terminating methods for XLPE cable are simpler in comparison with oil cables.

2.3.4 Free from height limitation and maintenance.

XLPE cables can be installed anywhere without special consideration of the route profile (height limitation), since it does not contain oil and thus is free from failures due to oil migration found in oil-filled cables.

2.4 Failure causes in XLPE insulated cable.

In solid dielectrics, highly purified and free of imperfections, the breakdown strength is high, in order of 10 MV/cm[5]. The highest breakdown strength obtained under carefully controlled conditions is known as the “intrinsic strength” of the dielectric. Dielectric usually fails at stress well below the intrinsic strength due to one of the following causes.

a. Water treeing

b. Electrical treeing

c. Internal partial discharges

d. Chemical and electro-chemical deterioration breakdown

c. Breakdown due to Surface breakdown (tracking)

These are discussed in the following sections:

2.4.1 Internal partial discharge.

Solid insulating sometimes contains voids or cavities in the medium or boundaries between the dielectric and the electrodes. These voids have a dielectric constant of unity and a lower dielectric strength[6]. Hence the electric field strength in the void is higher than that across the dielectric. Thus, even under normal working voltages, the field in the voids may exceed their critical electric field stress and partial discharge may occur. The mechanism can be considering the following equivalent circuit of the dielectric with the void, shown in figure 2.3.

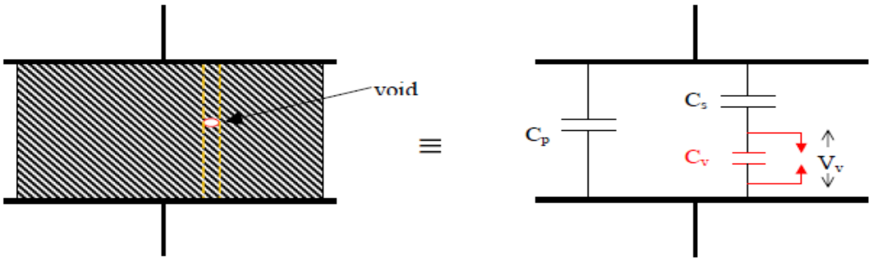


Figure 2.3 Equivalent circuit of dielectric with void

When the voltage across the void exceed V_V the critical voltage V_C, a discharge is initiated and the voltage collapses. The discharge extinguishes very rapidly (say 0.1 us). The voltage across the void again builds up and the discharges recur. The number and frequency of the discharges will depend on the applied voltage. The voltage and current waveforms (exaggerated for clarity) are shown in figure 2.4.

There will be heat dissipated in the void on each discharge which will cause carbonization of the surface on the void wall and erosion of the material will be occurred. The gradual erosion of the material and consequent reduction in the thickness of the insulating material eventually leads to final breakdown.

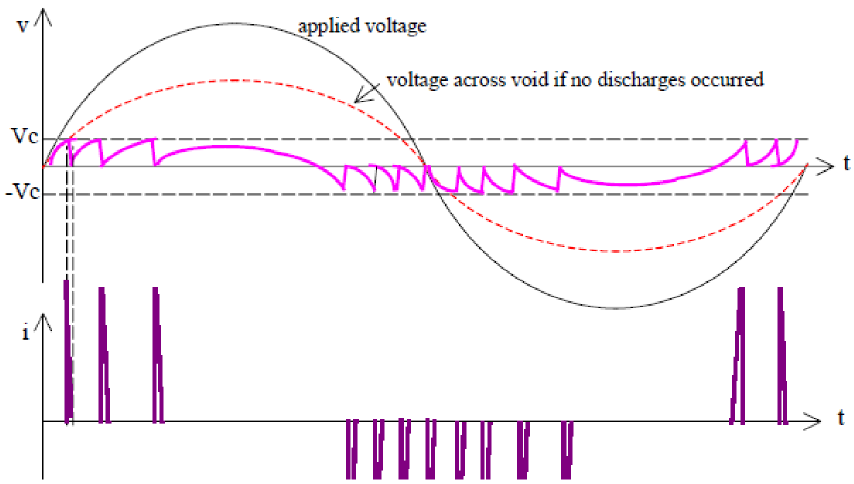
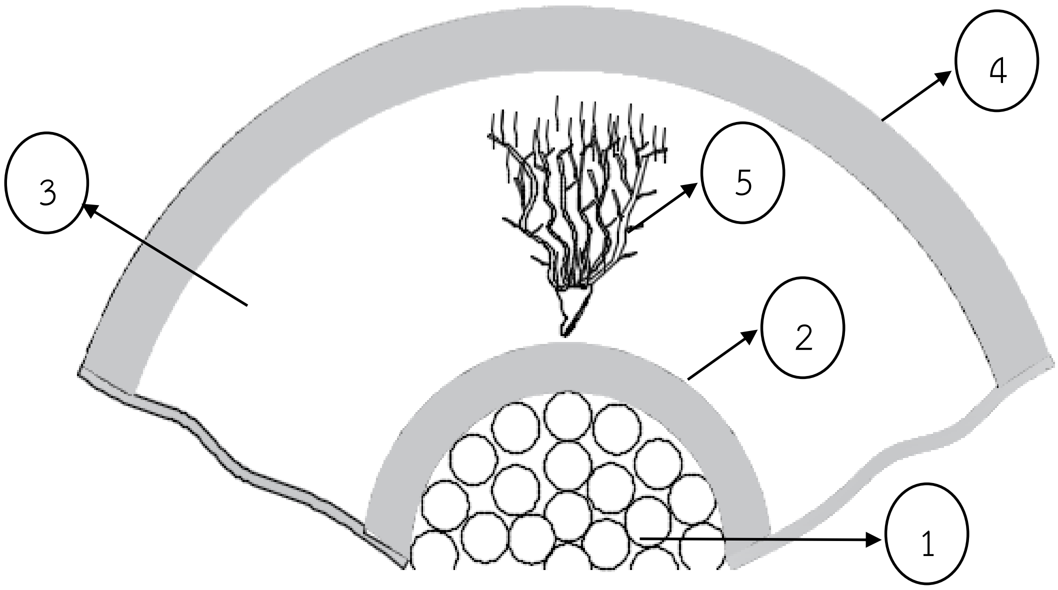


Figure 2.4 Internal discharge

2.4.2 Electrical trees.

Electrical trees are dark, branch-like structure with readily apparent channels. Carbonization is often evident; thus, these do not change appearance as noticeable as water trees on drying or wetting[7]. There is substantial evidence that a water or electrochemical tree may transform[8] into or initiate[8], an electrical tree, and that a dielectric failure is imminent after this event.

Electrical tree occurs due to the erosion of material at the tip of the spark. Erosion results in the roughening of the surfaces, and hence become a source of dirt and contamination. This causes increased conductivity resulting either in the formation of a conducting path bridging the electrodes or in a mechanical failure of the dielectric, as shown the figure 2.5.



1. Conductor 2. Conductor screen 3. Insulator

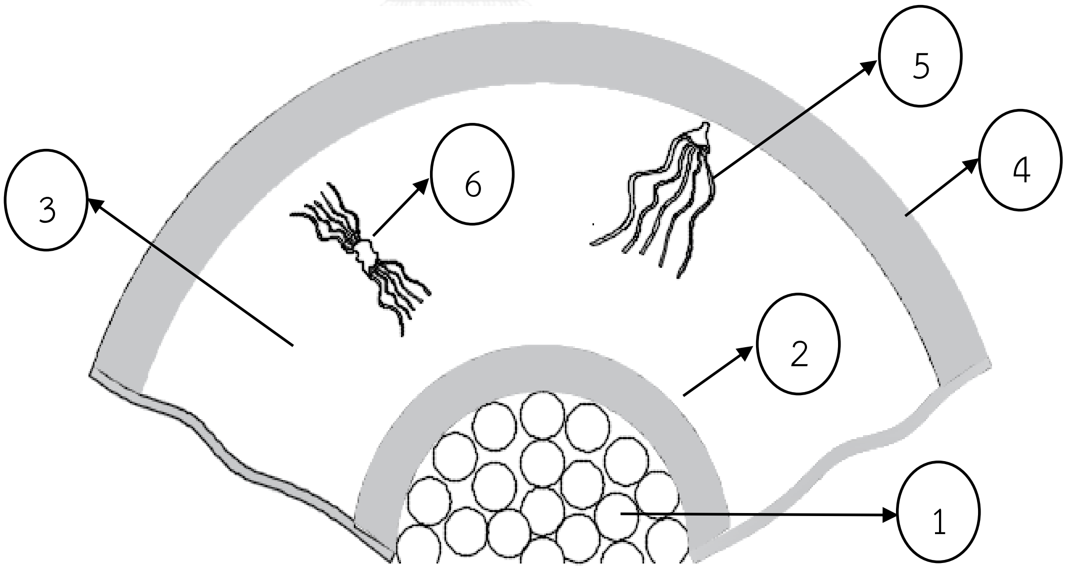
4. Insulation screen 5. Electrical trees

Figure 2.5 Electrical trees in XLPE cable

2.4.3 Water trees.

Water trees have different structures with a bush or fan-like appearance and bow-tie tree. Typically, they are in the 0.1 to 1 mm size range and are usually they "rooted" at an interface between the insulation and another substance. Water trees are known to disappear on drying of the insulation, reappear on rewetting, and are rendered permanently visible by various water-soluble dyes, most commonly, methylene blue, as shown in figure 2.6.

Degradation of XLPE cable by water trees gives rise to harmonics in the loss current. As results the harmonic components occurring in the loss current provide an extremely good indication of the state of degradation. Harmonic components arise as a result of the nonlinear voltage current characteristic of the water trees. An equivalent circuit which incorporates this nonlinearity of water trees faithfully reproduces the loss current waveforms obtained in experiments. When a voltage at a frequency differing from commercial frequencies is superposed, a degradation signal occurs at a characteristic frequency [9].



1. Conductor 2. Conductor screen 3. Insulator

4. Insulation screen 5. Vented trees 6. Bow-tie trees

Figure 2.6 Water Tree in XLPE Cable

2.4.4 Surface leakage in accessory.

Gas or air provide high electric field stress. It occurs partial discharge in air, surface discharge occurs when electric field stress on insulator surface exceed, critical value as figure 2.7.

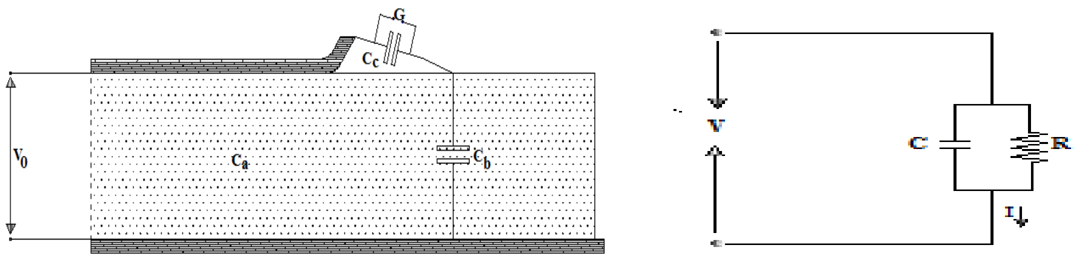


Figure 2.7 The equivalent circuit of surface discharge

When a solid dielectric is subjected to electrical stress for a long time, two kinds of visible marking are observed.

a. Presence of conducting path.

b. Trace whereby leakage current passes through the conducting path, finally leading to the formation of spark.

Spreading of spark channels during tracking in the form of the branches of a tree is called *treeing*.

Normally, the surface of the solid dielectric material always having the polluted film, which is formed due to dust and moisture. An applied voltage, the film starts conducting, resulting in the generation of heat, and the surface starts becoming dry. The conducting film becomes separate due to drying, and so sparks are drawn damaging the dielectric surface. With organic insulating material, the dielectric carbonizes at the region of sparking, and carbonized regions act as permanent conducting channels. This is a cumulative process, and insulation failure occurs when carbonized tracks bridge the distance between the electrodes. This phenomenon is called tracking [10].

2.4.5 Chemical and electrochemical deterioration and breakdown.

In the presence of air and other gases, dielectric materials undergo chemical changes when subjected to continuous electrical stress. Chemical reactions may occur as[11]:

Oxidation: In the presence of air or oxygen, materials such as rubber and polyethylene undergo oxidation giving rise to surface cracks.

Hydrolysis: when moisture or water vapor is present on the surface of the solid dielectric, hydrolysis occurs and materials lose their electrical and chemical properties. Materials like paper, cotton tape and other cellulose materials deteriorate very rapidly due to hydrolysis.

Chemical Action: Progressive chemical degradation can occur due to a variety of processes such as chemical instability at high temperature, oxidation, cracking and hydrolysis.

Chemical and electrochemical deterioration increase very rapidly with higher temperature.

2.5 Phase difference.

When comparing two sine waves having the same frequency, the difference between their respective phase angles is called the phase shift and is expressed in degrees (°) or radians (rad). The phase difference between two leakage currents can be positive or negative which depends on the relationship between the change of capacitive and resistive currents.

The phase shift between two sine waves is expressed as an angle representing a portion of a complete cycle of the sine waves. One of the two sine waves is used as the reference for phase shift measurements. The phase shift is calculated by subtracting the phase angle θ_{ref} of the reference sine wave from the phase angle θ of the sine wave of interest[12]. This is written as an equation below.

$$Phase\,shift = \theta - \theta_{ref} \tag{1}$$

Where θ is the phase angle of the sine wave of interest, expressed in degrees (°) or radians (rad)

θ_{ref} is the phase angle of the reference sine wave, expressed in degrees (°) or radians (rad).

Figure 2.8 is an example showing how the phase shift between two sine waves (X and Y) can be calculated using their phase angles.

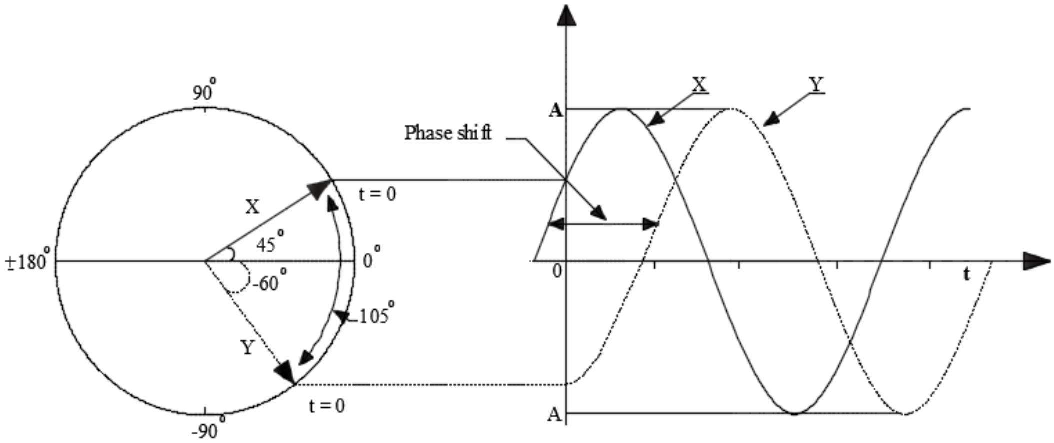


Figure 2.8 Phase shift between two sine waves with phase angles of 45° a

CHAPTER 3
RESEARCH METHODOGY

3.1 simulation method

This chapter utilized the theory from Chapter 2 in determining any issue that occurred in the XLPE insulation. It was essential to determine many methods and processes in considering the characteristics of the insulator that lead to assessment and solution to those issues. This research utilized various software to create simulation circuit for an individual case and used the results in finding the cause of each condition. The processes and methods are as following figures: 3.1

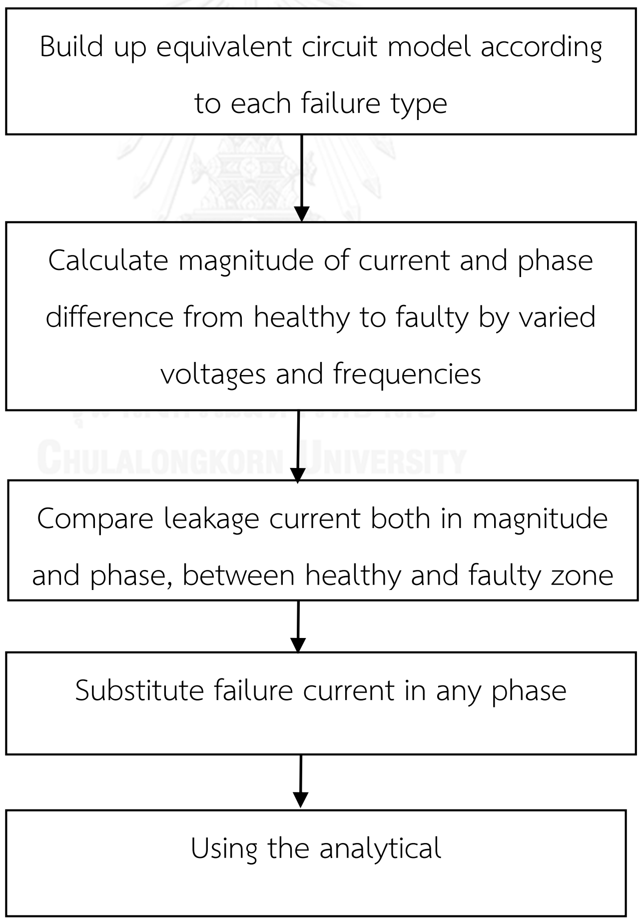


Figure 3.1 The workflow diagram

The equivalent circuits were used to simulate both in healthy and faulty classified into the following cases:

3.1.1 The Healthy cable.

The value parameters were determined by the real cable, which has a capacitance of 300 nF/km with a length of 1 km. The dielectric loss tangent of XLPE according to IEC std. 60502-2 [13] has been defined about $1x10^{-4}$ at power frequency of 50 Hz with a voltage of 10 kV·. Therefore, the volume resistance per kilometer of this cable in total was about 6082 MΩ.

The leakage current in healthy cable which flows through the resistance and capacitor in cable was calculated as shown in the following formula:

$$I_R = tg(\delta)xI_C \tag{2}$$

$$I_C = Vx2\pi fxC \tag{3}$$

The simulation was prepared by 6 parallel circuits, with a total length of 6 km Each circuit was divided into three parts in series, as shown in figure 3.2.

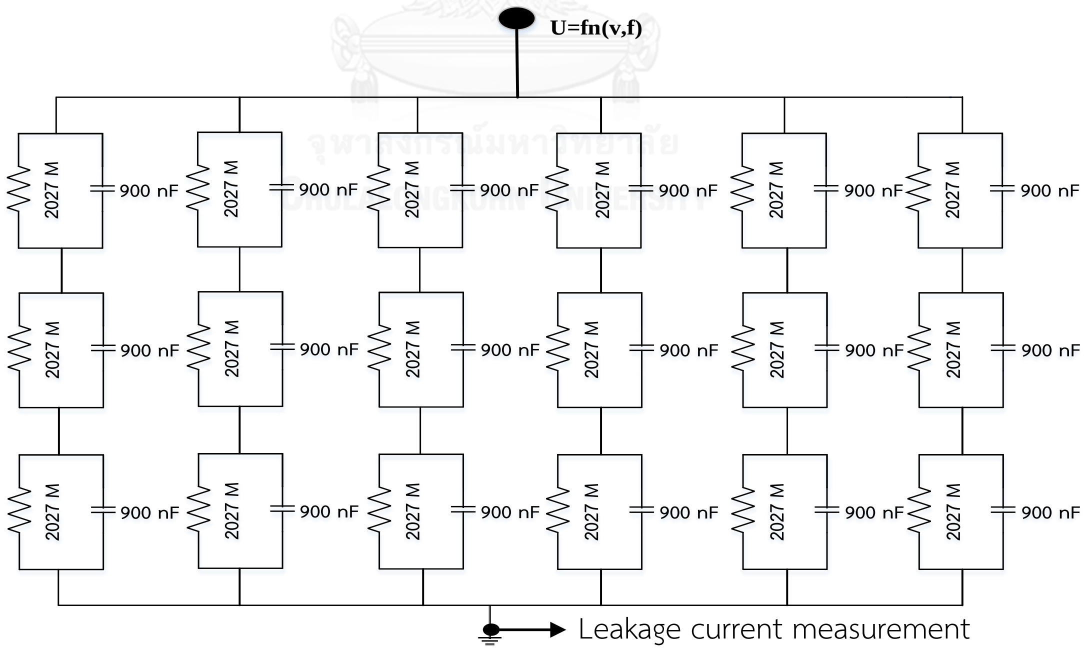


Figure 3.2 The circuit model of healthy cable

3.1.2 The water trees.

The Proteus software was used to simulate on the equivalent circuit of the water trees. The characteristic of cable insulation were divided in two zone such as healthy zone and faulty zone in the simulation. The parameters in faulty zone were changed according to the characteristic of water tree: air channel($\varepsilon_r = 1$), higher resistance, higher electrical stress, etc, therefore, has fault the two blocks were consider to be water tree in order to clearly increase the failure current, as shown in figure 3.3.

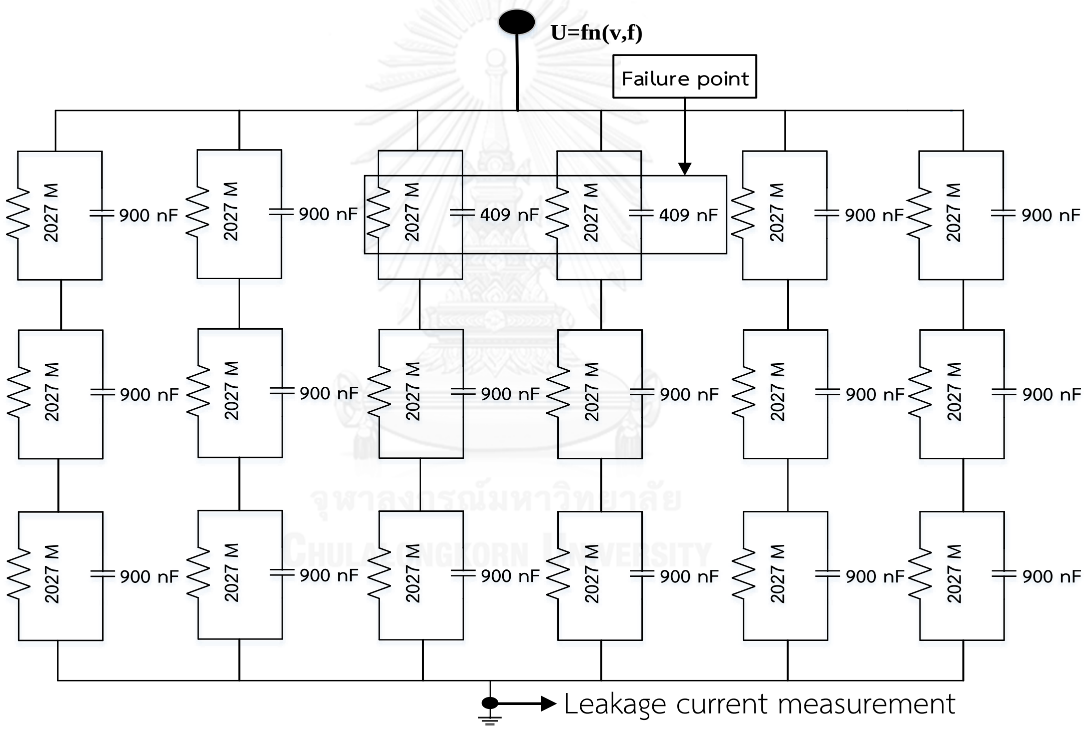


Figure 3.3 The circuit model of water trees

3.1.2 The electrical trees.

Electrical tree are similar to water tree in the air channel($\varepsilon_r = 1$), But the short-circuit of resistance is lower due to conductive part from the carbon tube. Therefore, the resistance and capacitor value were defined by 10 % of the defined resistance and 409 nF, respectively, as shown in figure 3.4.

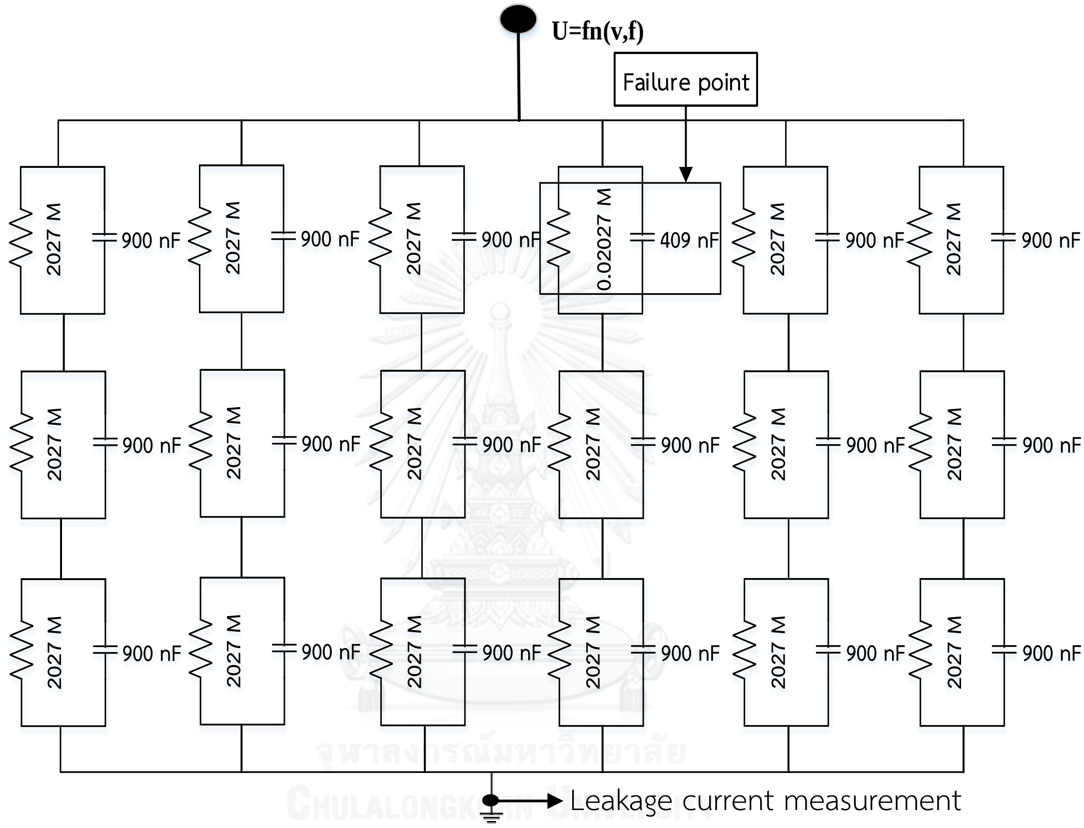


Figure 3.4 The circuit model of electrical trees

3.1.3 The partial discharge.

The partial discharge was simulated into two parts according to inception voltage at 25 kV. The lower voltage range, the circuit was treated as a normal. The simulation was defined to use first circuit (lower than inception voltage) as shown in figure 3.5. When the apply voltage above inception voltage, the second circuit was used. The circuit parameter of partial discharge was considered as capacitor of 136 nF and lower resistor 50 kΩ as shown in figure 3.6.

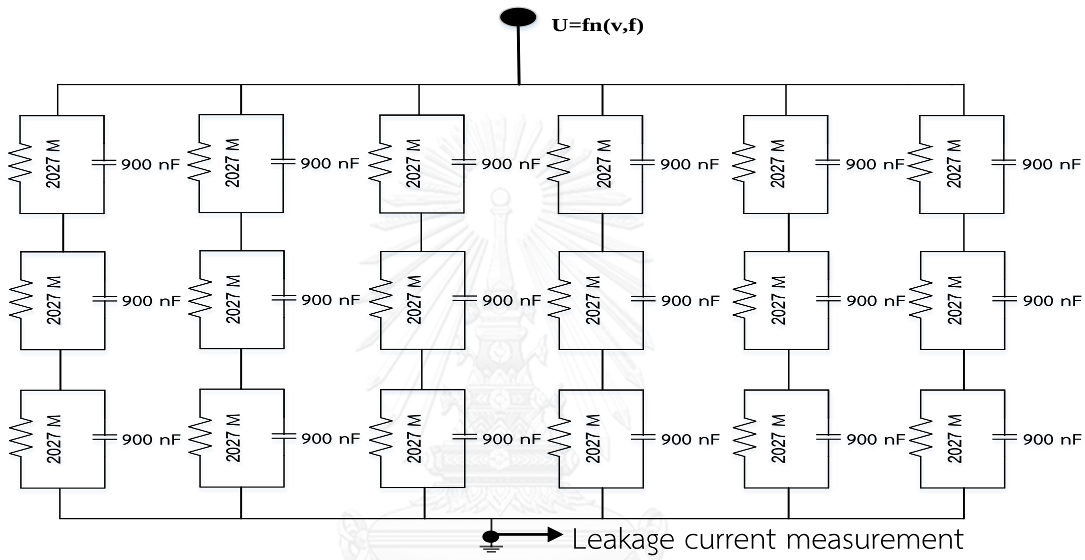


Figure 3.5 The circuit model of healthy cable or applied voltage less than 25 kV

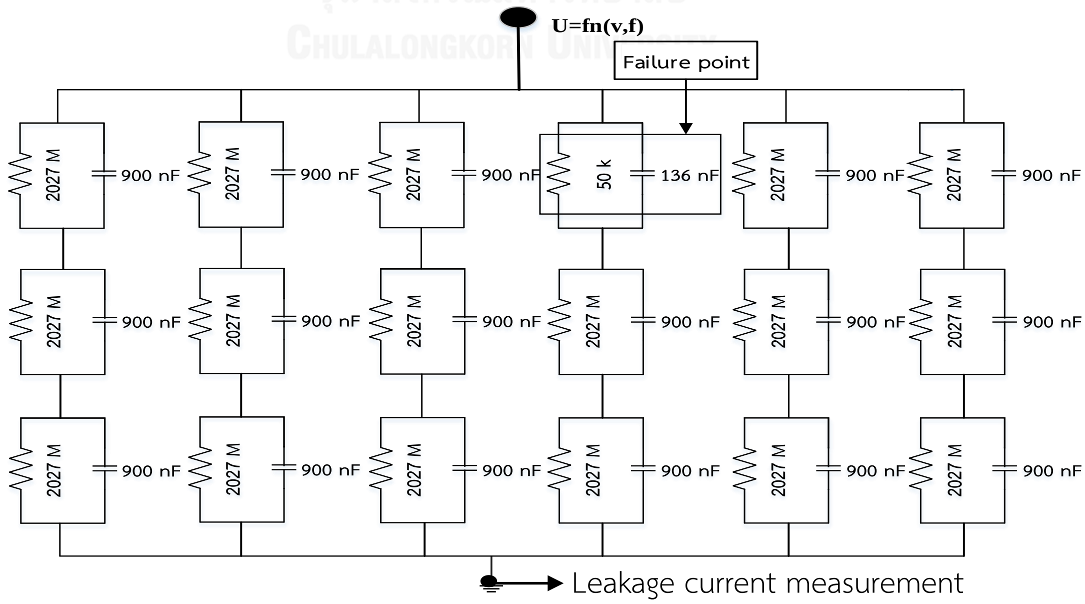


Figure 3.6 The circuit model of Faulty cable or applied voltage more than 25 kV

3.1.4 The ageing.

Ageing in XLPE can be occurred in the insulation system by overheated above crystalline melting temperature. The physical and chemical of insulation are changed, The dielectric constant goes higher and the resistance of insulation is decreased, Therefore, the simulation for the case of ageing was applied with a higher capacitance 10 % and a lower resistance about 100 times as shown in the figure 3.7.

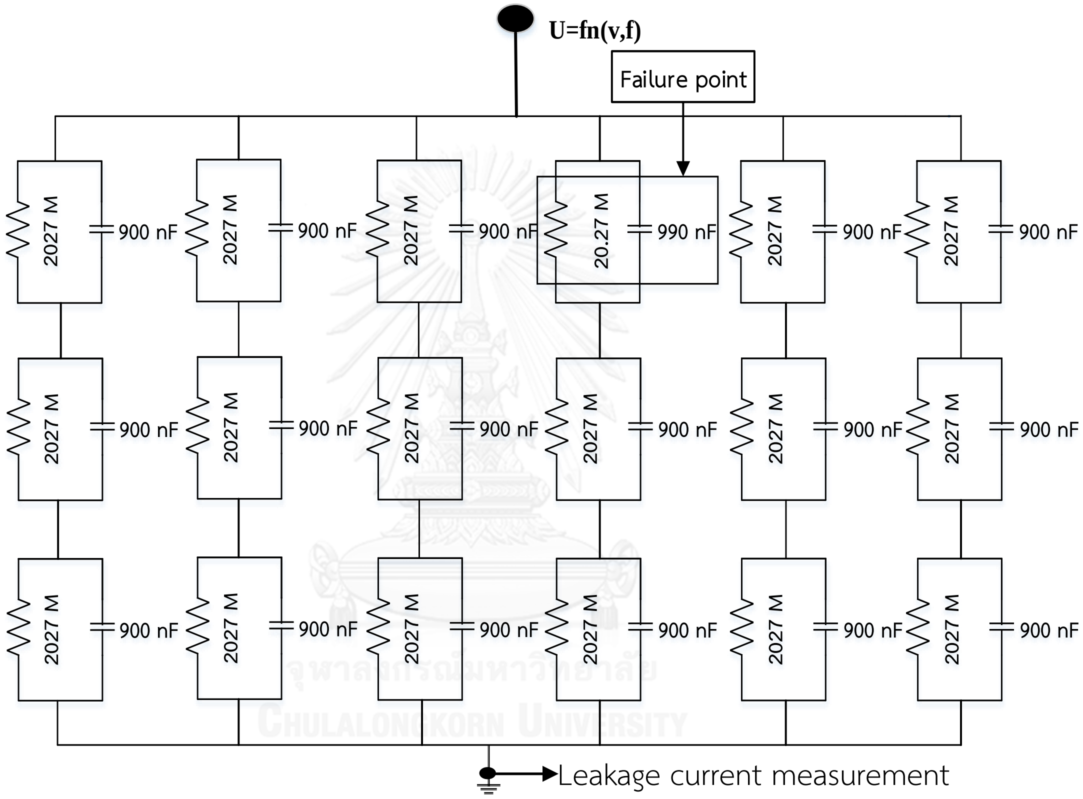


Figure 3.7 The circuit model of ageing

3.1.5 The termination.

Terminations were divided into two sides, one good and one bad. In the simulation the resistance in bad side was decreasing 10 %, but the capacitive was the same compared to normal termination, as shown in figure 3.8

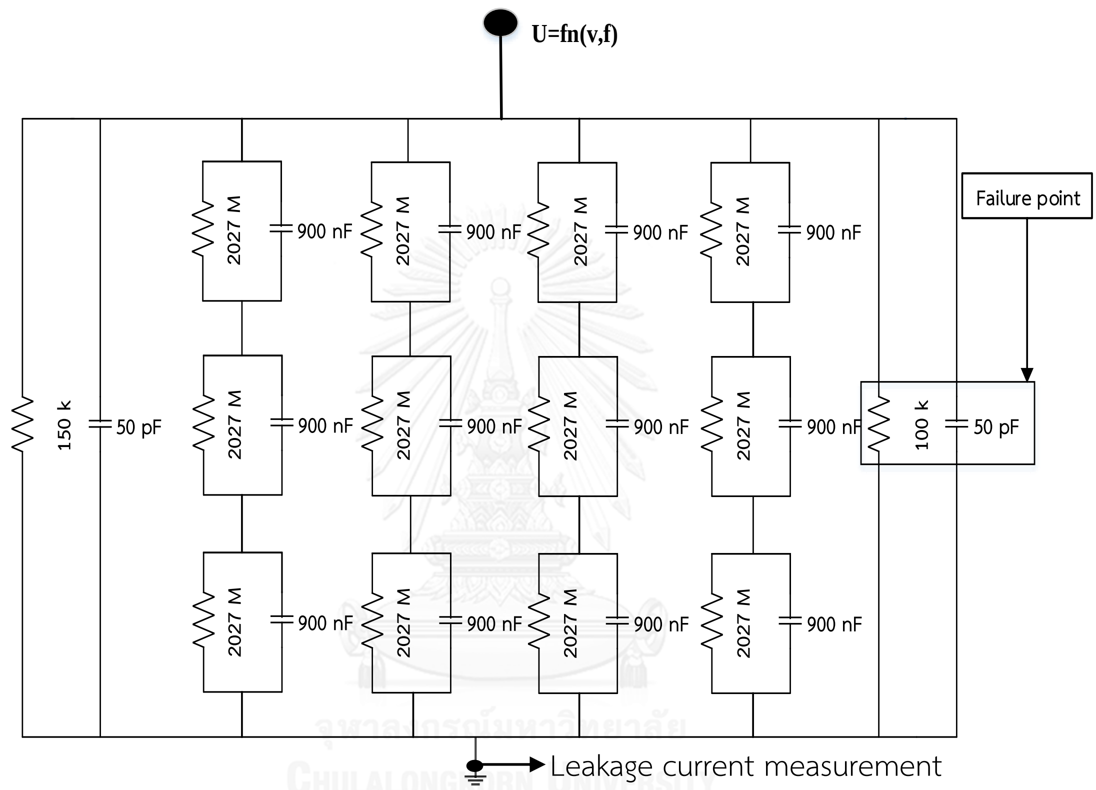


Figure 3.8 The circuit model of termination

3.2 The fault in one phase cable.

The study of simulation was taken on single phase cable, by using Proteus software for building the circuit model in the all cases of none breakdown failure of XLPE insulation on failure characteristic were. The magnitude of leakage current and phase shift in the different type of failure by variation of the applied voltage and frequency were studied and the results of each case were recorded.

3.2.1 To determine the different magnitude and phase shift.

The consideration in magnitude of leakage current or phase shift in each case can be studied on the simulation results by Proteus software. The treason of parameter variation was getting the different results and using to establish the criteria to identify the failure type in analytical tool.

3.2.2 The leakage current under frequency and voltage variation.

The understanding of leakage current of the cable in function of voltage and frequency can exhibit the behavior of cable insulation. Different leakage currents can be used to identify type of failure from different the circuit models. Therefore, the voltages from each phase 10, 30 and 50kV at the frequency of 10, 50, 200 and 500Hz were applied to the circuit model and got the leakage current results. All the leakage currents were compared to establish the nature of each.

In order to obtain the correct magnitude and phase shift, the data from zero to first peak of leakage current were collected by developed tool and were analyzed the different both in magnitude and phase. The maximum of leakage current could be obtained by “maximum” function in Excel and using the “Vlookup” function to find the time. The different time to peak was determined the phase shift in radian as shown in figure 3.9.

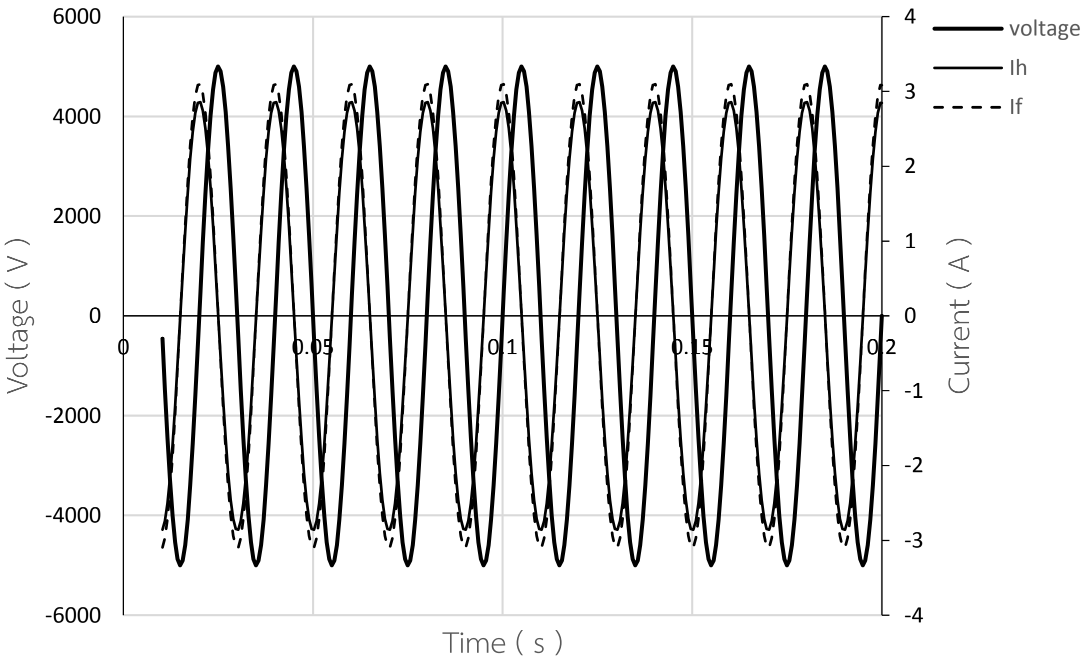


Figure 3.9 The comparison of leakage current between healthy and faulty by vented water trees

CHAPTER 4
SIMULATION RESULTS AND DISCUSSION

4.1 The magnitude and phase of leakage current in single phase cable

The magnitude and phase of leakage current was compared with a good condition for each case, as:

4.1.1 Water Trees.

From simulating of the occurrence of water trees in the insulation of XLPE Cable by using Protues Program, the magnitude of current and phase shift could be obtained. The study was conducted by adjusting the value of voltage source from 10 kV_{peak} to 50 kV_{peak} and recorded the result in Microsoft Excel. Then adjusted the frequency from 10 Hz to 500 Hz and recorded the result into Microsoft Excel as well. Since there were many values obtained from the result of simulation, the study only focused in the interested area as demonstrated in the table 4.1-table 4.4.

Table 4.1 The leakage current with a water tree failure at frequency of 10Hz, 1 cycle

F = 10Hz	*V=10kV*		*V=30kV*		*V=50kV*	
TIME (S)	I_H (mA)	I_F (mA)	I_H (mA)	I_F (mA)	I_H (mA)	I_F (mA)
0.0209	0.1462	0.1253	0.4387	0.3760	0.7312	0.6267
0.0243	0.0277	0.0238	0.0831	0.0713	0.1386	0.1188
0.0276	-0.0920	-0.0789	-0.2760	-0.2366	-0.4601	-0.3943
0.0309	-0.2077	-0.1780	-0.6232	-0.5341	-1.0386	-0.8902

Table 4.2 At frequency of 50Hz, 1 cycle

F = 50Hz	*V=10kV*		*V=30kV*		*V=50kV*	
TIME (S)	I_H (mA)	I_F (mA)	I_H (mA)	I_F (mA)	I_H (mA)	I_F (mA)
0.0042	0.731	0.627	2.193	1.880	3.656	3.133
0.0049	*0.138*	*0.119*	*0.416*	*0.356*	*0.693*	*0.594*
0.005	*-0.460*	*-0.394*	*-1.380*	*-1.183*	*-2.301*	*-1.972*
0.0062	-1.039	-0.890	-3.116	-2.671	-5.193	-4.451

Table 4.3 At frequency of 200Hz, 1 cycle

F = 200Hz	*V=10kV*		*V=30kV*		*V=50kV*	
TIME (S)	I_H (mA)	I_F (mA)	I_H (mA)	I_F (mA)	I_H (mA)	I_F (mA)
0.0010	2.925	2.507	8.774	7.520	14.623	12.533
0.0012	***0.554***	***0.475***	***1.663***	***1.425***	***2.771***	***2.375***
0.0014	***-1.840***	***-1.577***	***-5.521***	***-4.732***	***-9.202***	***-7.887***
0.0015	-4.155	-3.561	-12.464	-10.683	-20.773	-17.805

Table 4.4 At frequency of 500Hz, 1 cycle

F = 500Hz	*V=10kV*		*V=30kV*		*V=50kV*	
TIME (S)	I_H (mA)	I_F (mA)	I_H (mA)	I_F (mA)	I_H (mA)	I_F (mA)
0.0004	7.311	6.267	21.934	18.800	36.557	31.333
0.0005	***1.385***	***1.188***	***4.156***	***3.563***	***6.927***	***5.937***
0.0006	***-4.601***	***-3.944***	***-13.803***	***-11.831***	***-23.005***	***-19.718***
0.0006	-10.387	-8.902	-31.160	-26.707	-51.933	-44.511

From table 4.1-4.4, it can be seen that when increased the value of voltage source and frequency in the circuit, the magnitude of current in the faulty cable was smaller than the value of the magnitude of current in healthy cable. Therefore, it could be said that the occurrence of water trees would lead to the reduction of magnitude of current in relation to the rising of voltage and frequency. This also led to an occurrence of shifting phase a little bit as showing in table 4.5 to 4.6.

Table 4.5 The magnitude of currents and their difference time between healthy and faulty cable of water trees

case 1	*Healthy cable*		*Faulty cable*		
Peak	Time (s)	I_H (mA)	Time (s)	I_F (mA)	Different
voltage(kV)	*10 Hz*				
10	0.1009	0.573	0.1009	0.491	-0.0818
30	0.1009	1.718	0.1009	1.473	-0.2455
50	0.1009	2.864	0.1009	2.454	-0.4092
50 Hz					
10	0.0202	2.864	0.0202	2.454	-0.4092
30	0.0202	8.591	0.0202	7.363	-1.2276
50	0.0202	14.320	0.0202	12.272	-2.0461
200 Hz					
10	0.005	11.454	0.005	9.818	-1.6369
30	0.005	34.363	0.005	29.453	-4.9105
50	0.005	57.272	0.005	49.088	-8.1841
500 Hz					
10	0.002	28.636	0.002	22.272	-6.364
30	0.002	85.908	0.002	73.632	-12.276
50	0.002	143.180	0.002	111.362	-31.818

Table 4.6 Comparison on phase shift in μ radian between healthy and faulty circuit with water trees

Peak	Changed Phase shift (u Radian)			
voltage (kV)	*10 Hz*	*50 Hz*	*200 Hz*	*500 Hz*
10	2.117	0.542	0.090	0.008
30	2.050	0.371	0.103	0.023
50	2.112	0.515	0.103	0.043

4.1.2 Electrical Trees.

The method in considering the occurrence with electrical trees in the insulation of XLPE cable was applied the same principle as water tree but it was a little bit different in terms of the obtained magnitude of current and phase shift. The study was conducted by adjusting the value of voltage source and frequency from 10 Hz to 500 Hz and recorded them. Since there were many values obtained from the result of the simulation, the study only focused in the interested areas as demonstrated in table 4.7 – 4.10.

Table 4.7 The leakage current with a failure electrical trees at frequency of 10Hz, 1 cycle

F = 10Hz	*V=10kV*		*V=30kV*		*V=50kV*	
TIME (S)	I_H (mA)	I_F (mA)	I_H (mA)	I_F (mA)	I_H (mA)	I_F (mA)
0.0209	0.146	0.125	0.439	0.376	0.731	0.627
0.0243	***0.028***	***0.024***	***0.083***	***0.071***	***0.137***	***0.119***
0.0276	***-0.092***	***-0.079***	***-0.276***	***-0.237***	***-0.4601***	***-0.394***
0.0309	-0.208	-0.178	-0.623	-0.534	-1.039	-0.890

Table 4.8 At frequency of 50Hz, 1 cycle

F = 50Hz	*V=10kV*		*V=30kV*		*V=50kV*	
TIME (S)	I_H (mA)	I_F (mA)	I_H (mA)	I_F (mA)	I_H (mA)	I_F (mA)
0.0042	0.731	2.943	2.193	8.828	3.656	14.714
0.0049	***0.139***	***2.709***	***0.416***	***8.129***	***0.693***	***13.548***
0.0089	***-2.682***	***-0.597***	***-8.045***	***-1.790***	***-13.409***	***-2.983***
0.0095	-2.835	-1.217	-8.504	-3.653	-14.173	-6.088

Table 4.9 At frequency of 200Hz, 1 cycle

F = 200Hz	*V=10kV*		*V=30kV*		*V=50kV*	
TIME (S)	I_H (mA)	I_F (mA)	I_H (mA)	I_F (mA)	I_H (mA)	I_F (mA)
0.001	2.925	11.423	8.774	34.268	14.623	57.114
0.0012	**0.554**	**10.239**	**1.663**	**30.716**	**2.771**	**51.193**
0.002	**-9.647**	**-0.973**	**-28.941**	**-2.919**	**-48.234**	**-4.864**
0.0022	-10.727	-3.528	-32.181	-10.583	-53.635	-17.639

Table 4.10 At frequency of 500Hz, 1 cycle

F = 500Hz	*V=10kV*		*V=30kV*		*V=50kV*	
TIME (S)	I_H (mA)	I_F (mA)	I_H (mA)	I_F (mA)	I_H (mA)	I_F (mA)
0.0004	7.311	30.510	21.934	91.531	36.557	152.552
0.0005	***1.386***	***30.174***	***4.156***	***90.523***	***6.927***	***150.872***
0.0010	***-28.346***	***-1.479***	***-85.039***	***-4.438***	***-141.731***	***-7.397***
0.0010	-28.636	-7.900	-85.908	-23.700	-143.180	-39.500

From table 4.7 – 4.10, it can be noticed that when increased the value of voltage and frequency in circuit, the magnitude of currents in the faulty cable are bigger than the magnitude of current in healthy cable. Then it can be concluded that the occurrence of electrical tree would lead to increase the value of the magnitude of current and phase shift regarding to voltage and frequency. In this case, when there is an increasing in frequency, this will lead to an increasing phase shift, as shown in table 4.11 to 4.12.

Table 4.11 The magnitude of current and their difference between healthy and faulty circuit of electrical tree

case 2	*Healthy cable*		*Faulty cable*		
Peak voltage(kV)	Time (s)	I_H (mA)	Time (s)	I_F (mA)	Different
	10 Hz				
10	0.1000	0.574	0.1000	0.621	0.0478
30	0.1000	1.721	0.1000	1.864	0.1434
50	0.1000	2.868	0.1000	3.107	0.2390
50 Hz					
10	0.0203	2.857	0.0203	3.095	0.2381
30	0.0203	8.571	0.0203	9.285	0.7142
50	0.0203	14.285	0.0203	15.475	1.1904
200 Hz					
10	0.0050	11.469	0.0050	12.424	0.9557
30	0.0050	34.406	0.0050	37.273	2.8671
50	0.0050	57.343	0.0050	62.122	4.7786
500 Hz					
10	0.0020	28.635	0.0020	31.021	2.3861
30	0.0020	85.905	0.0020	93.063	7.1583
50	0.0020	143.174	0.0020	155.105	11.9310

Table 4.12 Comparison on phase shift in μ radian between healthy and faulty circuit of electrical trees

Peak voltage (kV)	Changed Phase shift (u Radian)			
	10 Hz	*50 Hz*	*200 Hz*	*500 Hz*
10	0.883	6.743	26.798	67.107
30	2.345	6.835	26.805	67.158
50	4.667	6.741	26.747	66.950

4.1.3 Partial discharge.

In the case of partial discharge that occurred in the insulation of XLPE cable, the finding of magnitude of current and phase shift by determining an increase in magnitude of current and phase shift when changed the voltage from 10 kV_{peak} to 50 kV_{peak}. After that the frequency was changed from 10 Hz to 500 Hz and recorded the result. This result was then recorded in Microsoft Excel and analyzed the result to find errors as in table 4.13 – 4.16.

Table 4.13 The leakage current with partial discharge a failure at frequency of 10Hz, 1 cycle

F = 10Hz	*V=10kV*		*V=30kV*		*V=50kV*	
TIME (S)	I_H (mA)	I_F (mA)	I_H (mA)	I_F (mA)	I_H (mA)	I_F (mA)
0.0209	0.146	0.968	0.439	1.453	0.731	1.816
0.0243	0.028	0.471	0.083	0.707	0.139	0.884
0.0276	-0.092	-0.046	-0.276	-0.070	-0.460	-0.087
0.0309	-0.208	-0.5621	-0.623	-0.843	-1.039	-1.054

Table 4.14 At frequency of 50Hz, 1 cycle

F = 50Hz	*V=10kV*		*V=30kV*		*V=50kV*	
TIME (S)	I_H (mA)	I_F (mA)	I_H (mA)	I_F (mA)	I_H (mA)	I_F (mA)
0.0042	0.731	3.562	2.1935	5.936	3.656	8.904
0.0049	0.139	1.693	0.416	2.822	0.693	4.232
0.0055	-0.460	-0.250	-1.380	-0.416	-2.301	-0.625
0.0062	-1.039	-2.1817	-3.116	-3.636	-5.193	-5.454

Table 4.15 At frequency of 200Hz,1 cycle

F = 200Hz	*V=10kV*		*V=30kV*		*V=50kV*	
TIME (S)	I_H (mA)	I_F (mA)	I_H (mA)	I_F (mA)	I_H (mA)	I_F (mA)
0.0010	2.925	12.737	8.774	21.229	14.623	31.843
0.0012	0.554	5.175	1.663	8.624	2.771	12.936
0.0014	-1.840	-2.614	-5.521	-4.357	-9.202	-6.535
0.0015	-4.155	-10.288	-12.464	-17.147	-20.773	-25.720

Table 4.16 At frequency of 500Hz, 1cycle

F = 500Hz	*V=10kV*		*V=30kV*		*V=50kV*	
TIME (S)	I_H (mA)	I_F (mA)	I_H (mA)	I_F (mA)	I_H (mA)	I_F (mA)
0.0004	7.312	31.361	21.934	52.269	36.557	78.403
0.0005	1.386	12.457	4.156	20.762	6.9274	31.143
0.0006	-4.601	-6.994	-13.803	-11.656	-23.005	-17.484
0.0006	-10.387	-26.139	-31.1595	-43.565	-51.933	-65.348

From table 4.13 – 4.16, it can be noticed that when increasing the voltage and frequency in circuit, the magnitude of current in the faulty cable was 5 times bigger than the magnitude of current in the case of healthy cable. Then it can be concluded that the occurrence of partial discharge would lead to an increase in the value of the magnitude of current and phase shift regarding to voltage and frequency. In this case, when there is an increase in frequency, this will lead to an increase highly in shifting phase compared to other cases. As shown in table 4.17 to 4.18.

Table 4.17 The magnitude of current and their difference between healthy and faulty circuit of partial discharge

case 3	*Healthy cable*		*Faulty cable*		
Peak voltage(kV)	Time (s)	I_H (mA)	Time (s)	I_F (mA)	Different
	10 Hz				
10	0.100	0.574	0.100	0.574	0.000
30	0.100	1.721	0.100	3.096	1.375
50	0.100	2.868	0.100	4.644	1.775
50 Hz					
10	0.020	2.857	0.020	2.857	0.000
30	0.020	8.571	0.020	15.488	6.918
50	0.020	14.285	0.020	23.233	8.948
200 Hz					
10	0.005	11.469	0.005	11.47	0.000
30	0.005	34.406	0.005	62.091	27.685
50	0.005	57.343	0.005	93.137	35.794
500 Hz					
10	0.002	28.635	0.002	28.635	0.000
30	0.002	85.905	0.002	155.068	69.163
50	0.002	143.174	0.002	232.602	89.428

Table 4.18 Comparison on phase shift in μ radian between healthy and faulty circuit of partial discharge

Peak voltage (kV)	Changed Phase shift (u Radian)			
	10 Hz	*50 Hz*	*200 Hz*	*500 Hz*
10	0.000	0.000	0.000	0.000
30	81.729	1380.321	6351.331	16179.385
50	81.729	1380.269	6351.277	16179.363

4.1.4 Ageing.

An occurrence of ageing in the insulation of XLPE cable could be observed by putting parameters in the program in order to find the value of magnitude of current and phase shift in each range. Then the results of the observation were analyzed. The determining of phenomenon was conducted by dividing the circuit into two parts and each part had its own parameters then the results of these two parts were compared to find the conclusion as table 4.19 – 4.22.

Table 4.19 The leakage current with a failure ageing at frequency of 10 Hz, 1 cycle

F = 10Hz	*V=10kV*		*V=30kV*		*V=50kV*	
TIME (S)	I_H (mA)	I_F (mA)	I_H (mA)	I_F (mA)	I_H (mA)	I_F (mA)
0.0209	0.146	0.146	0.439	0.439	0.731	0.731
0.0243	**0.028**	**0.028**	**0.083**	**0.083**	**0.139**	**0.139**
0.0276	**-0.092**	**-0.092**	**-0.276**	**-0.276**	**-0.460**	**-0.460**
0.0309	-0.208	-0.208	-0.6232	-0.623	-1.039	-1.039

Table 4.20 At frequency of 50 Hz, 1 cycle

F = 50Hz	*V=10kV*		*V=30kV*		*V=50kV*	
TIME (S)	I_H (mA)	I_F (mA)	I_H (mA)	I_F (mA)	I_H (mA)	I_F (mA)
0.0042	0.731	0.731	2.194	2.194	3.656	3.656
0.0049	**0.139**	**0.1386**	**0.416**	**0.416**	**0.693**	**0.693**
0.0055	**-0.460**	**-0.460**	**-1.380**	**-1.380**	**-2.301**	**-2.301**
0.0062	-1.039	-1.039	-3.116	-3.116	-5.193	-5.193

Table 4.21 At frequency of 200 Hz, 1 cycle

F = 200Hz	*V=10kV*		*V=30kV*		*V=50kV*	
TIME (S)	I_H (mA)	I_F (mA)	I_H (mA)	I_F (mA)	I_H (mA)	I_F (mA)
0.0010	2.925	2.925	8.774	8.774	14.623	14.623
0.0012	**0.554**	**0.554**	**1.663**	**1.663**	**2.771**	**2.771**
0.0014	**-1.840**	**-1.840**	**-5.521**	**-5.521**	**-9.202**	**-9.202**
0.0015	-4.155	-4.155	-12.464	-12.464	-20.773	-20.773

Table 4.22 At frequency of 500 Hz, 1 cycle

F = 500Hz	*V=10kV*		*V=30kV*		*V=50kV*	
TIME (S)	**I_H (mA)**	**I_F (mA)**	**I_H (mA)**	**I_F (mA)**	**I_H (mA)**	**I_F (mA)**
0.0004	7.312	7.312	21.934	21.934	36.557	36.557
0.0005	1.3855	**1.3855**	**4.1564**	**4.1564**	**6.9274**	**6.927**
0.0006	-4.601	**-4.601**	**-13.803**	**-13.803**	**-23.005**	**-23.005**
0.0006	-10.387	-10.387	-31.160	-31.160	-51.933	-51.933

From table 4.19 – 4.22, it can be noticed that when increasing voltage and frequency in circuit, the magnitude of current in the faulty cable was three times smaller than the magnitude of current in healthy cable in water tree. In this case, there was an occurrence of shift phase as showing in table 4.23 to 4.24.

Table 4.23 The magnitude of currents and their difference between healthy and faulty circuit of ageing

case 4	*Healthy cable*		*Faulty cable*		
Peak voltage(kV)	Time (s)	I_H (mA)	Time (s)	I_F (mA)	Different
	10 Hz				
10	0.101	0.565	0.101	0.568	0.003
30	0.101	1.718	0.101	1.727	0.009
50	0.101	2.864	0.101	2.879	0.015
50 Hz					
10	0.020	2.864	0.020	2.879	0.015
30	0.020	8.591	0.020	8.636	0.045
50	0.020	14.318	0.020	14.393	0.075
200 Hz					
10	0.005	11.454	0.005	11.514	0.060
30	0.005	34.363	0.005	34.542	0.179
50	0.005	57.272	0.005	57.570	0.298
500 Hz					
10	0.002	28.636	0.002	28.785	0.149
30	0.002	85.908	0.002	86.355	0.447
50	0.002	143.180	0.002	143.925	0.745

Table 4.24 Comparison on phase shift in μ radian between healthy and faulty circuit of ageing

Peak voltage (kV)	Changed Phase shift (u Radian)			
	10 Hz	*50 Hz*	*200 Hz*	*500 Hz*
10	41.349	8.402	2.090	0.833
30	41.313	8.285	2.089	0.887
50	41.429	8.375	2.049	0.833

4.1.5 Termination.

The result of simulating of the errors of terminator can be done by an increasing magnitude of current and phase shift. The analyzing of characteristic was taken from variation of voltage from 10 kV_{peak} to 50 kV_{peak} and frequency from 10 Hz to 500 Hz. After that the magnitude of current and phase shift were calculated by Microsoft excel as showing in table 4.25 – 4.28.

Table 4.25 The leakage current with a failure terminator at frequency of 10 Hz, 1 cycle

F = 10Hz	*V=10kV*		*V=30kV*		*V=50kV*	
TIME (S)	I_H (mA)	I_F (mA)	I_H (mA)	I_F (mA)	I_H (mA)	I_F (mA)
0.0209	0.146	0.175	0.439	0.525	0.731	0.874
0.0243	0.028	0.036	0.083	0.108	0.139	0.180
0.0276	-0.092	-0.105	-0.276	-0.314	-0.460	-0.523
0.0309	-0.208	-0.240	-0.623	-0.721	-1.039	-1.202

Table 4.26 At frequency of 50 Hz, 1 cycle

F = 50Hz	*V=10kV*		*V=30kV*		*V=50kV*	
TIME (S)	I_H (mA)	I_F (mA)	I_H (mA)	I_F (mA)	I_H (mA)	I_F (mA)
0.0042	0.731	1.282	2.194	3.845	3.656	6.409
0.0049	0.139	0.611	0.416	1.833	0.693	3.055
0.0055	-0.460	-0.087	-1.380	-0.260	-2.301	-0.433
0.0062	-1.039	-0.780	-3.116	-2.341	-5.193	-3.902

Table 4.27 At frequency of 200 Hz, 1 cycle

F = 200Hz	*V=10kV*		*V=30kV*		*V=50kV*	
TIME (S)	I_H (mA)	I_F (mA)	I_H (mA)	I_F (mA)	I_H (mA)	I_F (mA)
0.0010	2.925	4.941	8.774	14.822	14.623	24.703
0.0012	0.554	2.246	1.663	6.739	2.771	11.231
0.0014	-1.840	-0.546	-5.521	-1.639	-9.202	-2.732
0.0015	-4.155	-3.315	-12.464	-9.945	-20.773	-16.576

Table 4.28 At frequency of 500Hz, 1 cycle

F = 500Hz	*V=10kV*		*V=30kV*		*V=50kV*	
TIME (S)	I_H (mA)	I_F (mA)	I_H (mA)	I_F (mA)	I_H (mA)	I_F (mA)
0.0004	7.312	12.258	21.934	36.775	36.557	61.291
0.0005	1.386	5.517	4.156	16.550	6.927	27.583
0.0006	-4.601	-1.466	-13.803	-4.398	-23.005	-7.330
0.0006	-10.387	-8.385	-31.160	-25.154	-51.933	-41.923

From table 4.25– 4.28, it can be noticed that when increasing the voltage and frequency in circuit, the magnitude of current in the faulty cable was bigger than the magnitude of current in healthy cable. Therefore, in this case it can be concluded that the magnitude of current will increase regarding to frequency. Phase shift was significantly increasing with frequency range between 10 Hz to 50 Hz as showing in table 4.29 to 4.30.

Table 4.29 The magnitude of current and their difference between healthy and faulty circuit of termination

case 5	*Healthy cable*		*Faulty cable*		
Peak voltage(kV)	Time (s)	I_H (mA)	Time (s)	I_F (mA)	Different
	10 Hz				
10	0.101	0.576	0.101	0.663	0.088
30	0.101	1.727	0.101	2.015	0.288
50	0.101	2.879	0.101	3.359	0.481
50 Hz					
10	0.020	2.879	0.020	3.337	0.458
30	0.020	8.636	0.020	10.010	1.374
50	0.020	14.393	0.020	16.683	2.291
200 Hz					
10	0.005	11.514	0.005	13.358	1.844
30	0.005	34.542	0.005	40.074	5.532
50	0.005	57.570	0.005	66.790	9.220
500 Hz					
10	0.002	28.785	0.002	33.401	4.616
30	0.002	86.355	0.002	100.202	13.847
50	0.002	143.925	0.002	167.004	23.079

Table 4.30 Comparison on phase shift in μ radian between healthy and faulty circuit of termination

Peak voltage (kV)	Changed Phase shift (u Radian)			
	10 Hz	*50 Hz*	*200 Hz*	*500 Hz*
10	202.730	40.472	10.106	4.074
30	202.819	40.519	10.114	4.072
50	202.730	40.526	10.085	4.074

4.2 Overview all cases of failure in XLPE insulation.

The simulation results of single phase are concluded as shown in the figure 4.1, and 4.2.

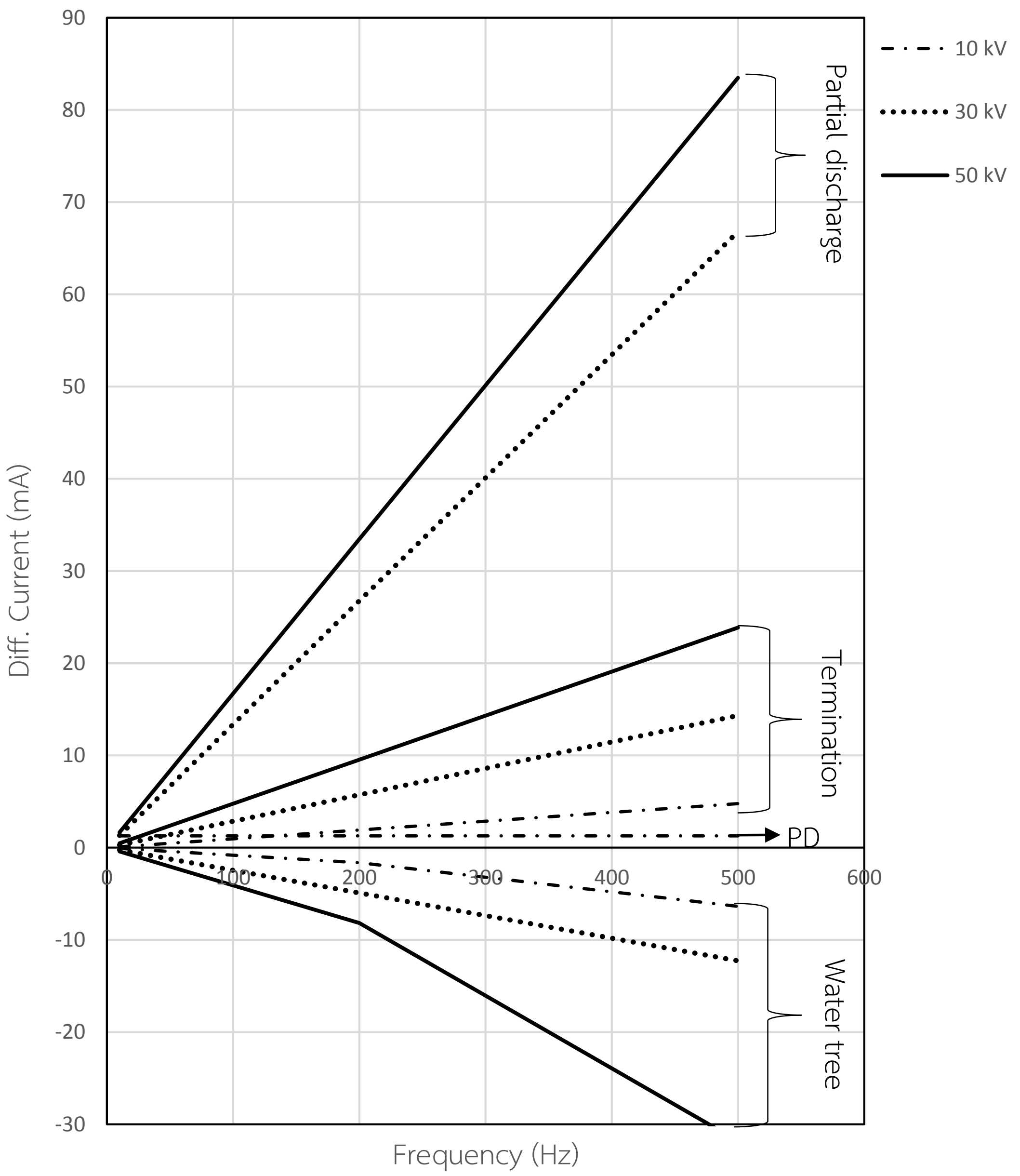


Figure 4.1 The different of leakage current with Partial discharge, Termination and water trees

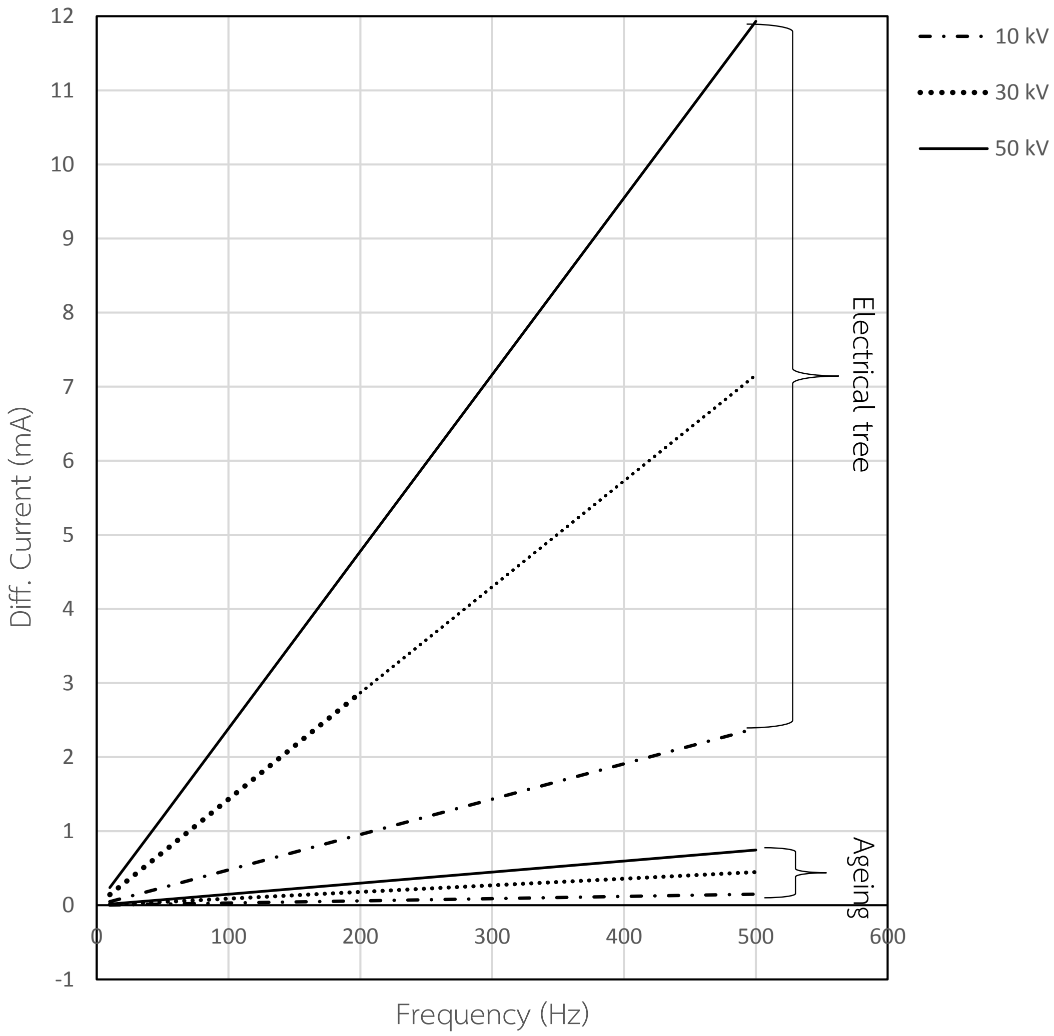


Figure 4.2 The different of leakage current for case Electrical trees and ageing

4.3 Criteria to specify failure case

From all a results of the circuit model and the simulation in each case, it will be getting the values for enter to the program to analyze of the behavior that happen with the cable simulation. Then, it divided the method into two parts such as the healthy cable and faulty cable. For the values of healthy cable in each case was in the same group and equal. After that, it will get the values of magnitude of current in case.

Finally, The different currents from all failure were shown in the figure 4.3 to 4.7.

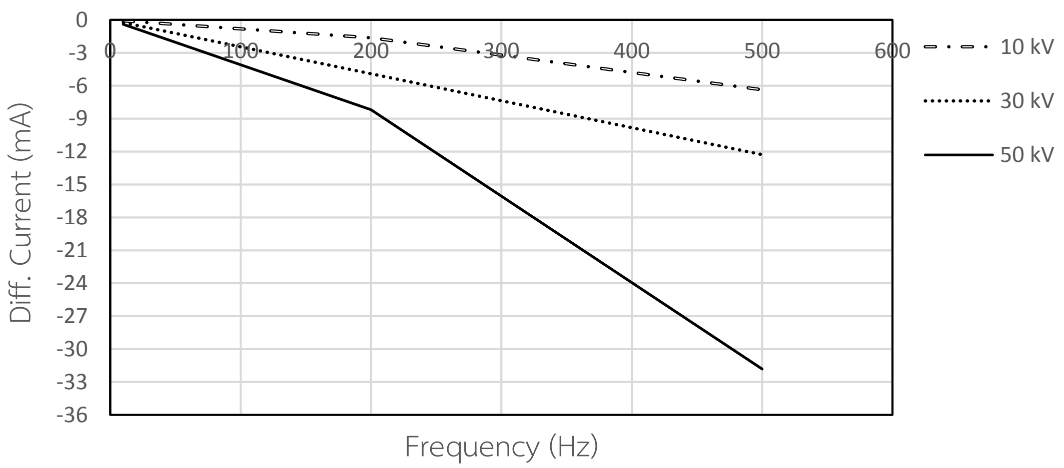


Figure 4.3 The leakage current due to water trees in term of voltage and frequency

The figure 4.3 shows the different current in XLPE cable failure with water tree according to the frequency and applied voltage. As the increasing frequency and voltage results in decreasing of the current decreasing the capacitive current.

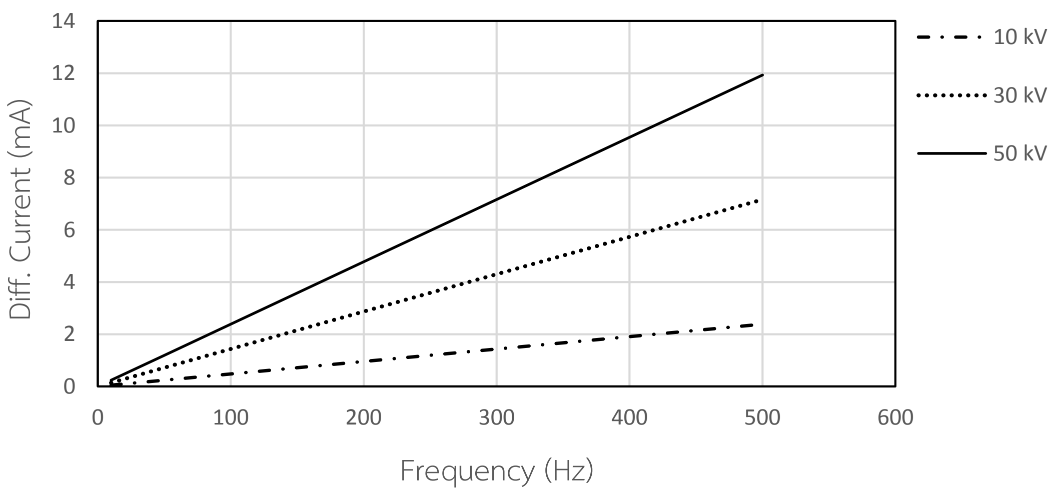


Figure 4.4 The leakage current due to electrical trees in term of voltage and frequency

The case of electrical tree in XlPE cable can be observed from increasing the applied voltage and frequency, the different current also increases. Because the increasing resistive current.

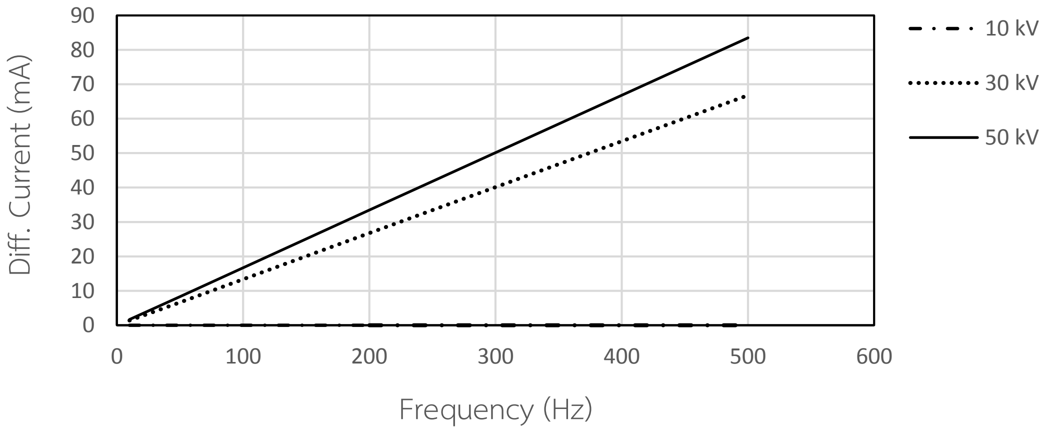


Figure 4.5 The leakage current due to Partial discharge in term of voltage and frequency.

Partial discharge in XLPE cable can be observed by analysis the value of the voltage in each point. The result shows that the different current at the above inception voltage is significantly higher than the different current at lower voltage.

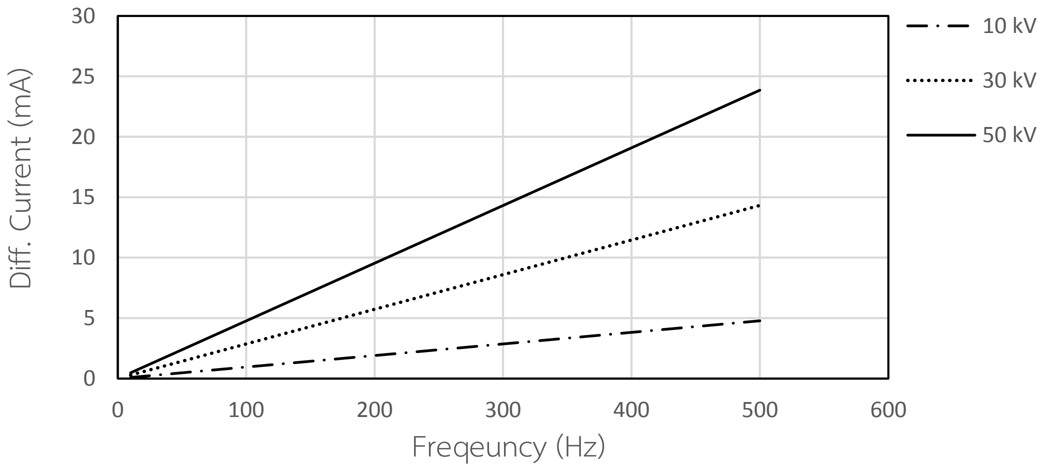


Figure 4.6 The leakage current due to Aging in term of voltage and frequency.

In case ageing, the current is increasing with the higher voltage and frequency. However, this increasing rate is lower than from other case in range of a few milliamp compared to other cases. In addition the phase shift for ageing failure is also less than the other cases in the range of 50 micro radian.

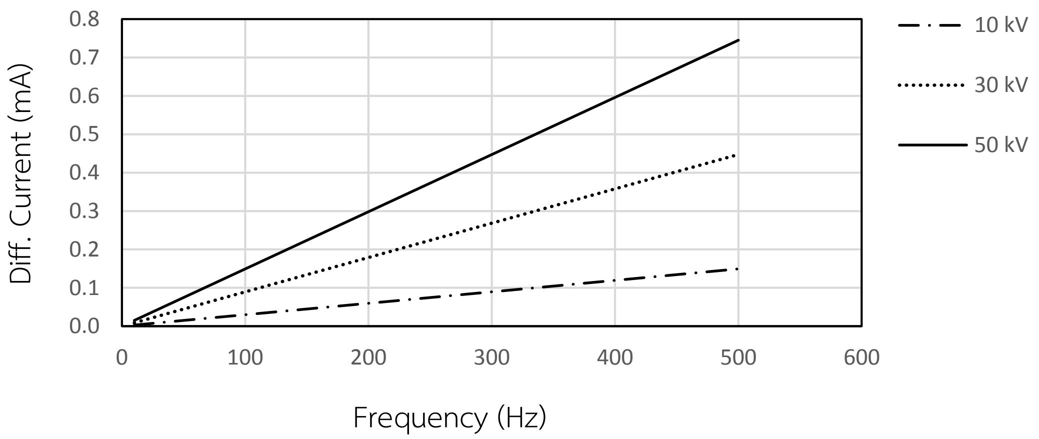


Figure 4.7 The leakage current due to Termination in term of voltage and frequency

The last case is called surface leakage on termination joint. This can be clearly observed in term of frequency. The result found that the higher frequency, the higher different current. The leakage current by surface leakage termination is obviously higher than electrical treeing case.

4.4 Three phase simulation.

The study of three phase simulation had performed with the detail from simulation results for each case. Then, this information was randomly substituted in any phase of three phase in Excel program. Finally, the analysis result of each case was compared in the following steps as shown in the figure 4.8.

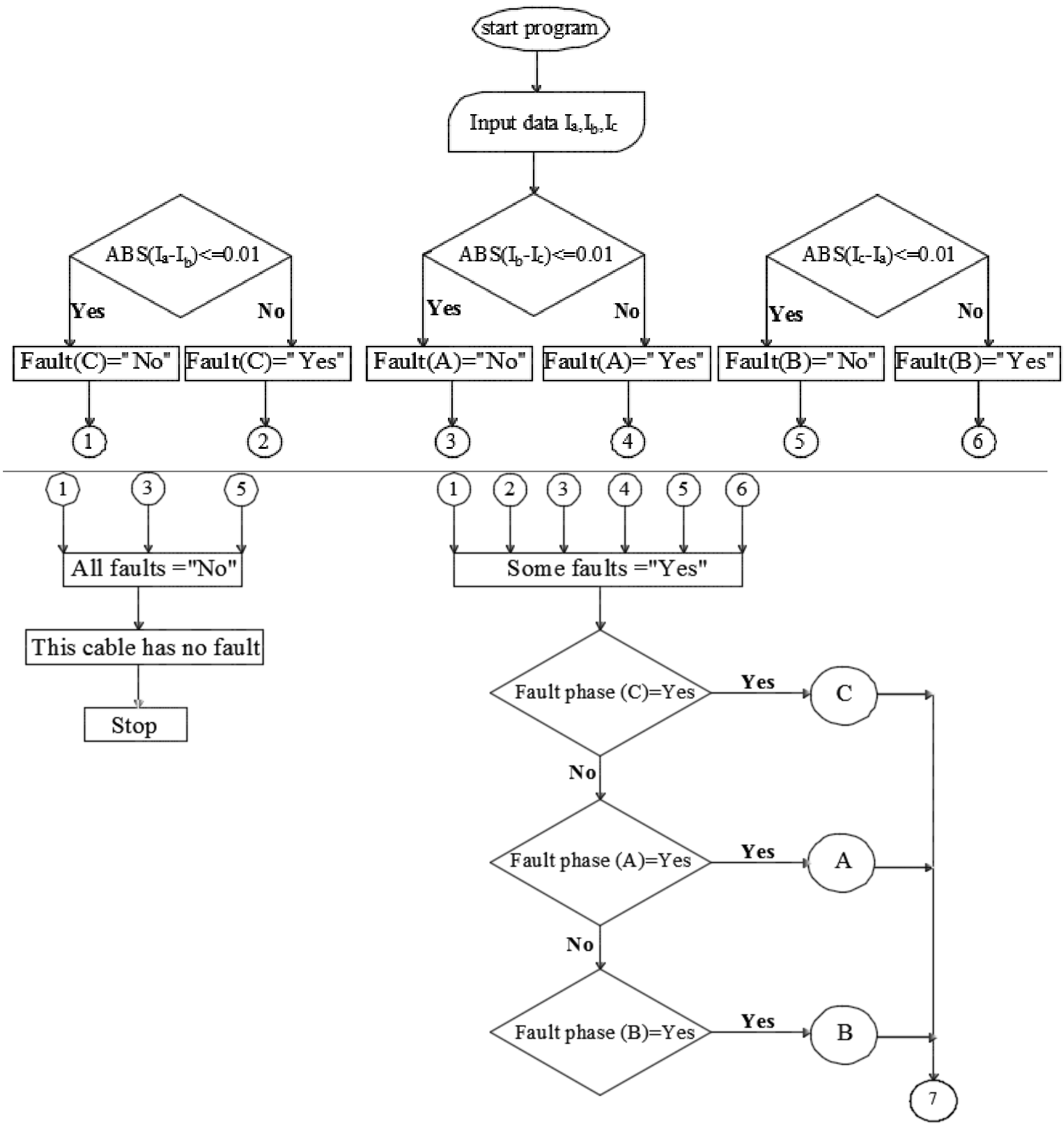


Figure 4.8 The procedure of the assessment of XLPE insulation

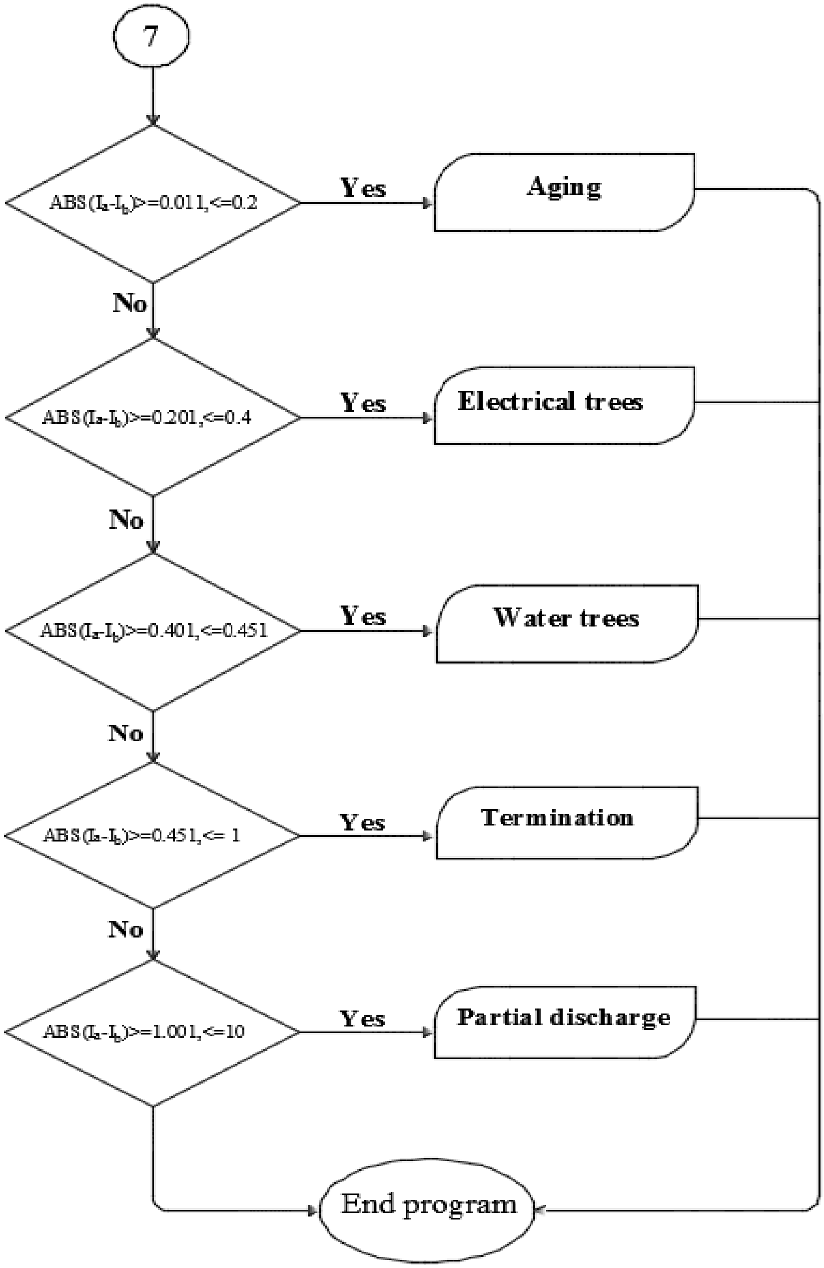


Figure 4.8 The procedure of the assessment of XLPE insulation (Cont)

4.5 Procedure for cable testing.

The testing procedure of on-site leakage current measurement for a cable system assessment can be done by circuit connection as shown in figure 4.9. The leakage currents on each voltage and frequency are recorder the apply voltage should be 10%, 50%, 80% and 100% of phase voltage. Was the frequency should be varied from 20 Hz, 50 Hz, 100 Hz, 200 Hz and 300 Hz.

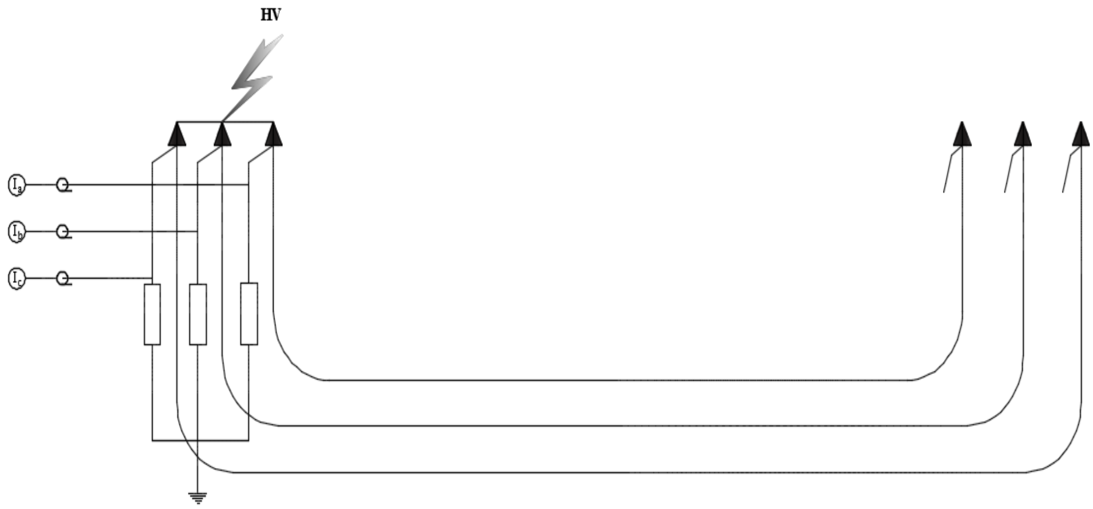


Figure 4.9 The test circuit on-site leakage current mesurement

All leakage currents are taken to assess and find out the failure case (if any). The simple flowchart for cable assessment at 50 Hz is presented in figure 4.8. An example on simulation results integrated with surface leakage termination in phase B is presented in table 4.31.

Table 4.31 Sample of the leakage currents from three cables simulation with termination leakage in phase B.

I_A (mA)	I_B (mA)	I_C (mA)
0	0	0
2.82743	1.88511	2.82743
2.82728	1.88504	2.82728
2.82709	1.88497	2.82709
2.82604	1.88461	2.82604
2.82188	1.88328	2.82188
2.80523	1.8781	2.80523
2.73892	1.85776	2.73892
2.54305	1.77762	2.54305
2.22167	1.60876	2.22167
1.79598	1.36105	1.79598
1.29179	1.05204	1.29179
0.731151	0.697041	0.731151
0.138552	0.311582	0.138552
-0.4601	-0.08749	-0.4601
-1.03865	-0.48275	-1.03865
-1.5718	-0.8569	-1.5718
-2.03625	-1.19361	-2.03625

- The result from the developing tool is shown in figure 4.11.

This cable system has faulted with Termination in phase B.

Figure 4.10 The result from surface leakage of termination

CHAPTER 5
CONCLUSION

5.1 Conclusion.

The study on leakage currents from a simulated cable system to assess the XLPE insulated high voltage underground cable was done with simulated water tree, electrical tree, partial discharge, ageing and surface leakage termination. The results from the study can be concluded as:

The water trees in an insulation of XLPE cable has a specific differentiate characteristic from the other cases. Its leakage current is lower than the leakage current form the healthy cable. The leakage current in the water tree damage cable provides the less leakage current, the higher frequency and voltage. The range of different leakage current form water tree is approximate not higher than -30 mA.

Electrical trees in an insulation of XLPE cable can be observed in positive of differentiate leakage current compare to the normal current the increasing of leakage current depends on the increasing the frequency and voltage. The range of different leakage current form electrical tree is approximate not higher than 12 mA.

An insulation of XLPE cable integrated with partial discharge provider the differentia leakage current quite low when the applied voltage is lower inception voltage and frequency independent. On the contrary, when the applied voltage is greater than the inception voltage the different leakage current strongly goes high with increasing voltage and frequency in the range of 100 mA.

An ageing insulation of XLPE cable shows the differntia leakage cuurrent slightly incrase n tha range of 1 mA. When increasing the voltage and freqeuncy.

Termination and insulation of XLPE cable with the surface leakage termiantion provides the higher different leakage current in the range of a few 10 mA, when incresing both in voltage and frquency

The developping tool with Execl are used to calculate and assess the stated of XLPE insulated cable after the leakage current data was putted into the tool. The resuft from the assessment tool was collect both in phase and type of failure.

REFERENCES

[1] R. Thiamsri, "Study of Electrical Treein in Crosslinked Polyethylene Insulating Material for 22 kV High Voltage Cable," Master Thesis, Department of Electrical Engineering, Faculty of Engineering, Suranaree University of Technology, 2012.

[2] R. C. Martin-German-Sobek, "Influence of ageing and water treeing to degradation of XLPE insulation," IEEE, vol. 2, pp. 26-30, 2013.

[3] A. Rawangpai, "Aeing Model Parameter Estimation of Cross-linked Polythylene Insulating Material for High Voltage Cables by Using Accelerated Ageing Test," Master Thesis, Department of Electrical Engineering, Faculty of Engineering, Suranaree University of Technology, 2010.

[4] S. P. a. A. M. Anjum2, "Analysis of Water Trees and Characterization Techniques in Xlpe Cables," Indian Journal of Science and Technology, Vol 7(S7), pp.127–135, 2014.

[5] H.N.Nagamani, " INVESTIGATIONS ON THE FAILURE MODES OF XLPE CABLES AND JOINTS," IEEE Transactions on Power Delivery, Vol. 13, pp. 706-711, 1998.

[6] M. T. Shaw and S. H. Shaw, "Water Treeing in Solid Dielectrics," IEEE Transactions on Electrical Insulation, vol. EI-19, pp. 419-452, 1984.

[7] T. P. Lanctoe, J. H. Lawson, and W. L. McVey, "Investigation of Insulation Deterioration in 15 KV and 22 KV Polyethylene Cables Removed from Service - Part III," IEEE Transactions on Power Apparatus and Systems, vol. PAS-98, pp. 912-925, 1979.

[8] J. Saetbak, "A Theory of Water Tree Initiation and Growth," IEEE Transactions on Power Apparatus and Systems, vol. PAS-98, pp. 1358-1365, 1979.

[9] A. B. J. Sletbak, "A Study of Inception and Growth of Water Trees and Electrochemical Trees in Polyethylene and Cross Linked Polyethylene Insulations," IEEE Transactions on Electrical Insulation, vol. EI-12, pp. 383 - 389, 1977.

[10] M. Ugur, D. W. Auckland, B. R. Varlow, and Z. Emin, "Neural networks to analyze surface tracking on solid insulators," IEEE Transactions on Dielectrics and Electrical Insulation, vol. 4, pp. 763-766, 1997.

[11] J R Lucas, " High Voltage Engineering," vol. 2, pp. 23-29, 2001.

[12] F. Didactic, "Single-Phase AC Power Circuits," Ltée/Ltd, Quebec, pp. 21-28, Canada 2010 .

[13] IEC60502-2 "INTERNATIONALSTANDARD"

APPENDIX

Appendix A. Proteus Program

Proteus program is the Computer Aided Design (CAD) program can use to simulate any electronic circuit and including. It's used to design of the circuit and examine of work. In addition, this program can use for design of the circuit model that it will be suitable for learning and teaching of electronic and electrical model, useful for learners. It can save time and budget in providing the equipment simulating as before. As the sample will show in the figure A1.

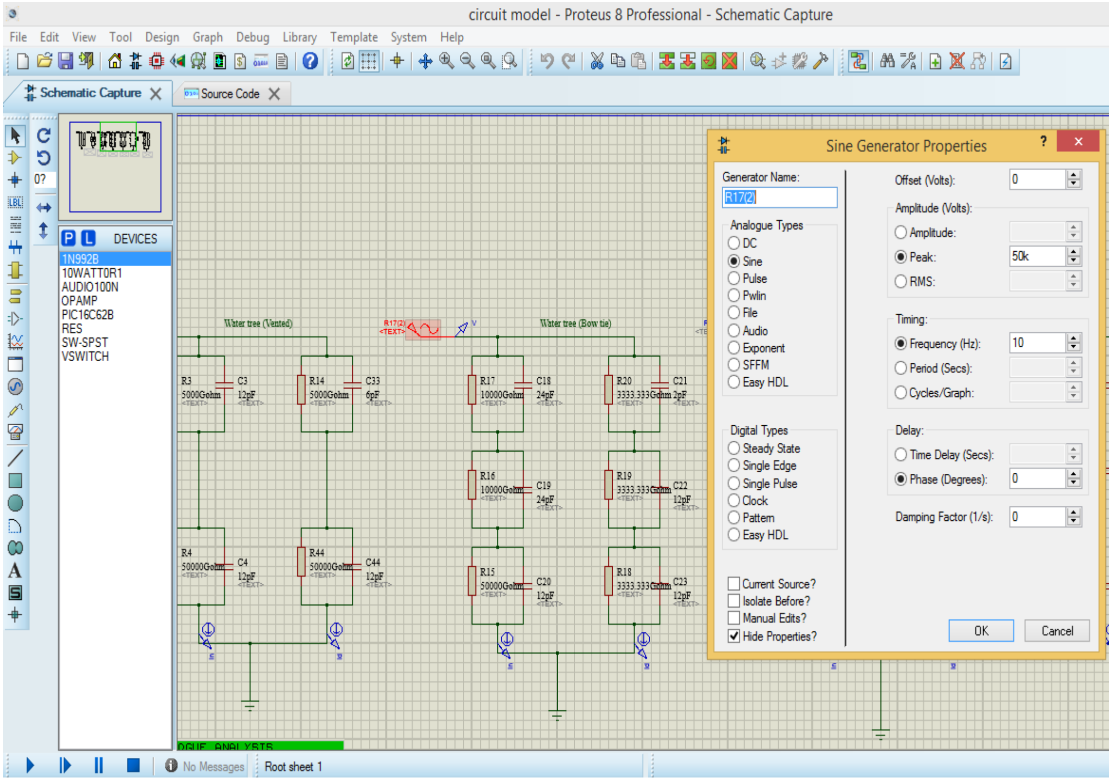


Figure A 1. The simple circuit on the Proteus program

Appendix B. Method of Proteus program

To study by using Proteus programs start with a menu, then choose the program into Proteus 8 professional and choose ISIS 8 professional, as shown in figure B1.

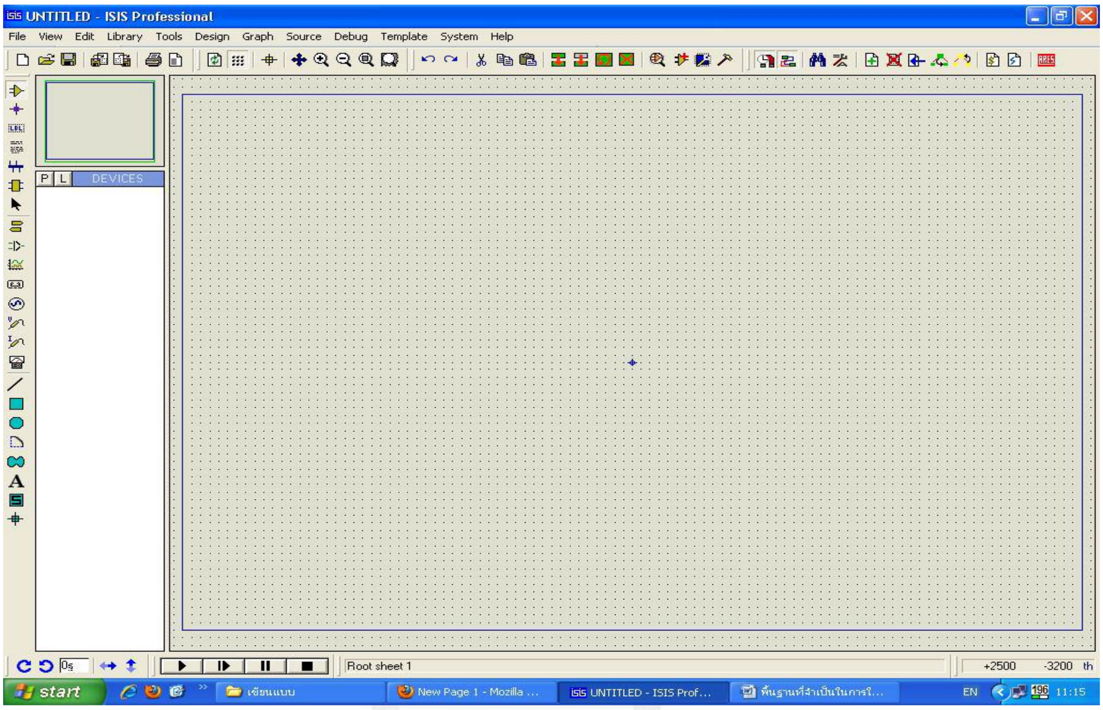


Figure B 1. The Editing Window of ISIS professional

In the major area is calling Editing Window. It’s used to design and draw the circuit connection on the top in the left side is calling Overview Window.

To restructure for drawing on editing window, such as in many ways:

1. Use mouse into the point of determine and then press F5
2. Press SHIFT to stay and move mouse to follow of Editing Window for Shift pan.
3. In the case, that we want to move Editing Window to other position of circuit into center point of new position and press LMB

To under Overview (left side) there are many icons show that object selectors that we choose for equipment, symbol and etc.

The circuit show figure B2 Shows the circuit model of Water Trees.

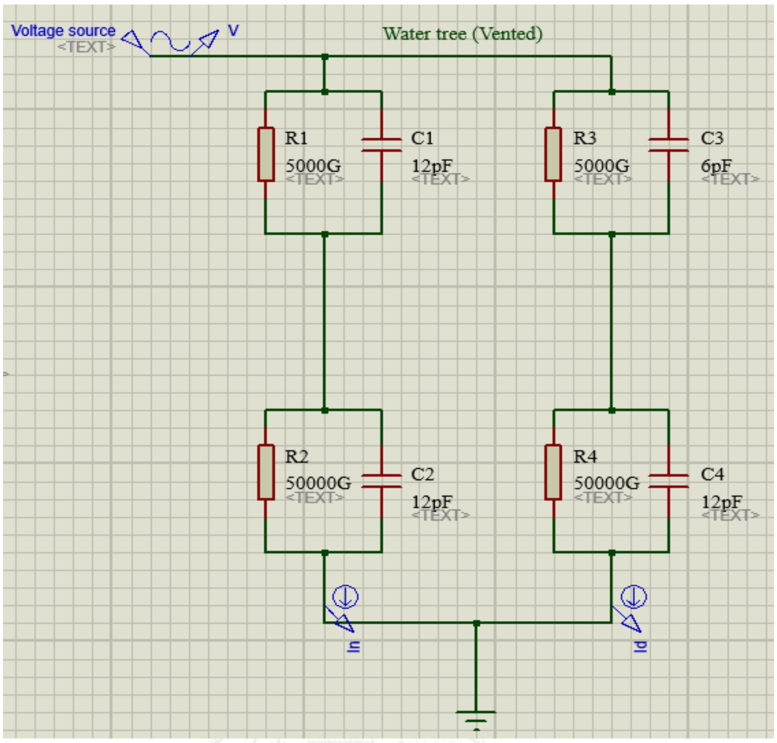


Figure B 2. The circuit model of water trees

1. Choose of the equipment from Library press “P” on the top in the left side to Object Selector, as show in the figure:

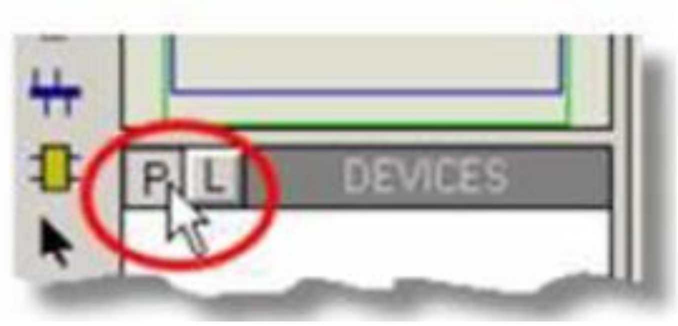


Figure B 3. The bowser libraries button

Will see the screen of Device Library Browser that use for choose the equipment

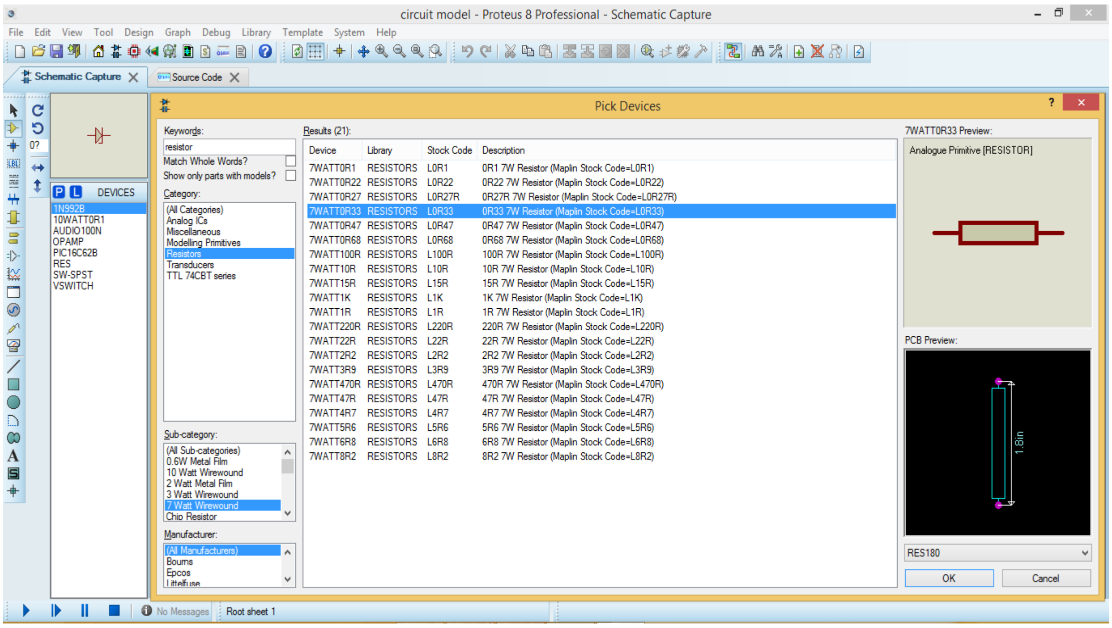


Figure B 4. The Device Library Browser

1. Choose the equipment from Device Library and then fine the equipment from Library in many way:

If know the name of equipment, we can put in the Keyword and we can see that one, as show in the figure:

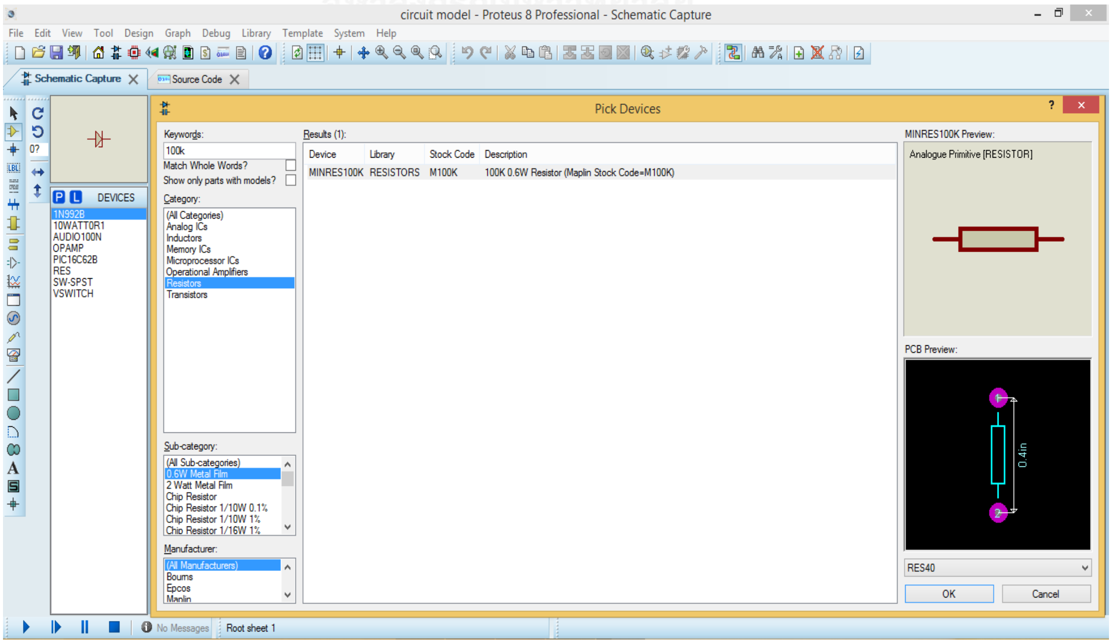


Figure B 5. The Browser Library dialogue form

To order double click in the equipment for choose that one in the Object Selector, as show in below:

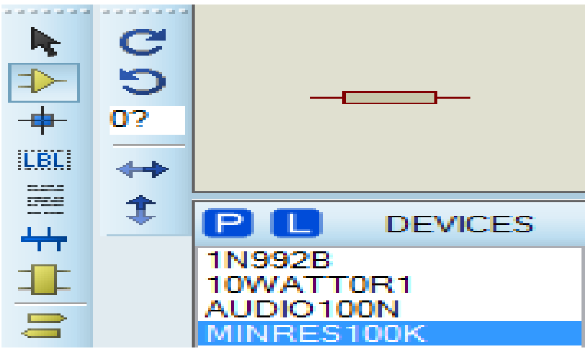


Figure B 6. The Object Selector containing a MINRES 100K

Look on the resistor, if we need many of resistor namely: 1k, 9k and 470 k, we can see use in the same way by using Keyword into '1K' we can see Library of 1k in many choice and then double click to the mane of equipment and then it will show on Object selector.

1. Put the equipment on the screen by start of 'MINRES 100K'from Object Selector then observed on Overview Window, we will show the equipment that we need and show the Rotate by use icon Rotation or Mirror. After that, Press "LMB" to stay and move mouse into

Figure B 7. The Rotation icons with anti-clockwise rotation selected.

To move of equipment on tag is mean using mouse into equipment and then press 'RMB' we will see the red color there, then press LMB to stay and move equipment to that location.

When finish put all the equipment, then point the mouse in the Editing Window and press 'RMB' to be loss of the tag equipment.

2. To connect line in the circuit by Wire Auto Router (WAR) System in tools using mouse to top of point and press the LMB and then look on resistor 1k, after that move line to capacitor and press RMB again, we can see the WAR system is will see this system connected.

Figure B 8. The Mouse cursor indicating that the mouse is over the pin tip

3. To connect of probe and equipment measurement into the main point by choose the icon Voltage Probe and then move next to direct on electrical line. In the time to connect of Probe into 3 points, in the 1^{st} point is voltage source, the second point is normal point and the third one is damage point.

Appendix C. Simulation

The equipment to show the result of simulation that we need including graph of magnitude of voltage and current in circuits for observe of voltage changing that we need is analog graph. When plot graph to press icon Graph, then choose the analog graph and move mouse to Editing Window, and after that that make the graph by press LMB to move mouse into sine Wave graph.

To determine Generator and Probe into the graph in 2 ways:

Choose the Generator or Probe and move to direct graph, to observe that signal in the last one will show in the last always final.

To order Add Trace to see the screen on Add Transient Trace for choose the Probe or Generator that put in graph, in this way did not need tag Probe or Generator.

To determine of time on Simulation by tag graph and press LMB for show the screen of Editing Transient Graph, we can put the name of graph, for the stop time to edit is 200ms because waveform into the frequency around 10

To order Simulate in above of graph, we will see the status bar as show the period of time was take long in simulate after finished its will the signal in the graph.

VITA

Sinthanou Konglysan was born in Phongsaly Province, Lao PDR, in 1987. He received the Bachelor's degree of Electrical Engineering from Faculty of Engineering, National University of Laos in 2009. In June 2013, he studied master's degree at Electrical Engineering, Faculty of Engineering, Chulalongkorn University.