Simulation Studies in Ferroresonant Phenomena on Distribution Transformers

Mr. Phinnakhone Phomvongsy

A Thesis Submitted in Partial Fulfillment of the Requirements
for the Degree of Master of Engineering in Electrical Engineering
Department of Electrical Engineering
Faculty of Engineering
Chulalongkorn University
Academic Year 2019

การศึกษาจำลองปรากฏการณ์เฟอร์โรเรโซแนนซ์ที่หม้อแปลงจำหน่าย

นายพินนะคอน พมวงสี

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิศวกรรมศาสตรมหาบัณฑิต
สาขาวิชาวิศวกรรมไฟฟ้า ภาควิชาวิศวกรรมไฟฟ้า
คณะวิศวกรรมศาสตร์ จุฬาลงกรณ์มหาวิทยาลัย
ปีการศึกษา 2562

Thesis Title	Simulation Studies in Ferroresonant Phenomena on Distribution Transformers
By	Mr. Phinnakhone Phomvongsy
Field of Study	Electrical Engineering
Thesis Advisor	Channarong Banmonkol, Ph.D.

Accepted by the Faculty of Engineering, Chulalongkorn University in Partial Fulfillment of the Requirement for the Master of Engineering

.... Dean of the Faculty of Engineering
(Professor SUPOT TEACHAVORASINSKUN, Ph.D.)

THESIS COMMITTEE

.... Chairman
(Assistant Professor KOMSON PETCHARAKS, Ph.D.)
.... Thesis Advisor
(Channarong Banmonkol, Ph.D.)
.... External Examiner
(Assistant Professor Nutthaphong Tanthanuch, Ph.D.)

พินนะคอน พมวงสี : การศึกษาจำลองปรากฏการณ์เฟอร์โรเรโซแนนซ์ที่หม้อแปลงจำหน่าย. (Simulation Studies in Ferroresonant Phenomena on Distribution Transformers) อ.ที่ปรึกษาหลัก : ดร.ชาญณรงค์ บาลมงคล

ปรากฏการณ์เฟอร์โรเรโซแนนซ์เกิดขึ้นบ่อยในระบบจำหน่ายไฟฟ้าทั่วไปที่ประกอบด้วย ฟิวส์คัทเอาท์ สายไฟฟ้าเหนือศีรษะหรือสายเคเบิลใต้ดิน และหม้อแปลงจำหน่าย การสับฟิวส์คัทเอาท์ทีละเฟสหรือการทำงานของฟิวส์ในเฟสหนึ่งเฟสใดอาจกระตุ้นให้เกิดปรากฏการณ์เฟอร์โรเรโซแนนซ์ ซึ่งสร้างแรงดันเกินสูงพอที่จะสร้างความเสียหายกับอุปกรณ์ไฟฟ้า โดยขึ้นกับหลายปัจจัย เช่น ขนาดของตัวนำ ความยาวสายไฟฟ้า ขนาดพิกัดกำลังและชนิดของหม้อแปลง เป็นต้น วิทยานิพนธ์นี้นำเสนอผลการศึกษา 2 เรื่องที่เกี่ยวข้องกับปรากฏการณ์เฟอร์โรเรโซแนนซ์

เรื่องแรกคือการใช้การจำลองด้วยโปรแกรมคอมพิวเตอร์และการคำนวณด้วยมือเพื่อประเมินความยาวของสายไฟฟ้าเหนือศีรษะและสายเคเบิลใต้ดินที่จะมีค่ารีแอกแตนซ์คาปาซิทีฟมากพอที่จะก่อให้เกิดปรากฏการณ์เฟอร์โรเรโซแนนซ์ ซึ่งจะเรียกว่าความยาววิกฤต ผลการศึกษาพบว่าสายเคเบิลใต้ดินมีความยาววิกฤตน้อยกว่าสายไฟฟ้าเหนือศีรษะมาก ความยาวสายวิกฤตจะลดลงตามขนาดของตัวนำที่เพิ่มขึ้นและขนาดกำลังพิกัดของหม้อแปลงที่ลดลง

เรื่องที่สองคือการศึกษาผลของการใช้หม้อแปลงจำหน่ายชนิดความสูญเสียต่ำเปรียบเทียบกับหม้อแปลงแบบดั้งเดิม ผลการศึกษาพบว่าการใช้หม้อแปลงชนิดความสูญเสียต่ำจะทำให้ความยาวสายวิกฤตมีค่าลดลง หรือมีโอกาสที่จะเกิดปรากฏการณ์เฟอร์โรเรโซแนนซ์มากขึ้น

สาขาวิชา วิศวกรรมไฟฟ้า ลายมือชื่อนิสิต ....
ปีการศึกษา 2562 ลายมือชื่อ อ.ที่ปรึกษาหลัก ....

5970482521 : MAJOR ELECTRICAL ENGINEERING

KEYWORD: Ferroresonance iron core distribution transformer overhead line underground cable

Phinnakhone Phomvongsy : Simulation Studies in Ferroresonant Phenomena on Distribution Transformers . Advisor: Channarong Banmonkol, Ph.D.

Ferroresonance phenomena often appear in any typical distribution systems consisting of drop-out fuse cutouts, overhead lines or power cables and a distribution transformer. Single-pole energization and fuse operation may lead to ferroresonance overvoltages, resulting in electrical equipment damage. The occurrence of ferroresonance depends on several factors including size and length of line, power rating and type of distribution transformer. This thesis presents two case studies involving ferroresonance phenomena.

The first case studies the lengths of overhead lines and underground cables which create enough capacitive reactance for ferroresonance. The critical lengths are estimated by hand calculation and computer simulation. The obtained results show that the system with underground cables has much lower critical length in comparison with that of overhead lines. The critical length decreases with increasing conductor size and decreasing power rating of transformer.

The second case studies the effect of low-loss transformer in comparison with the conventional one. It is found that using the low-loss transformer has more chance to face ferroresonane phenomena.

Field of Study:	Electrical Engineering	Student's Signature ....
Academic Year:	2019	Advisor's Signature ....

ACKNOWLEDGEMENTS

Writing a thesis, as with any other large project, requires the coordinated efforts of many people. I would like to thank the following people. Without their efforts and guidance, this thesis would never have been completed.

I would like to express my indebted gratitude to my advisor Channarong Banmongkol, Ph.D. for his outstanding support, contribution and invaluable assistance in the achievement and development of my master thesis. His wise experience in the field of electrical power engineering has enlightened me throughout the project.

I would like also to express my special thanks to the ASEAN Scholarship, Government of Thailand for providing a government scholarship to pursue my master's research at Chulalongkorn University.

Last but not least, my special thanks to my family for their patience and encouragement. This thesis took a great deal of time away from them. All involved gave me confidence and unending support.

Phinnakhone Phomvongsy

TABLE OF CONTENTS

Page

LIST OF TABLES

Page

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

1.1. Introduction

Power systems have an important duty in delivering energy to customers. So, electrical engineer must design the power systems that safety and reliability. Because of electrical systems are a part of the development and driving of the economy. Economic growth affects the city to grow up. As a result, the demand for electricity increases and must install new distribution systems.

Nowadays, power devices installed on distribution system can help in protect overvoltages, causing from the lightning strike, switching, etc.… But can’t be completely prevented. Especially, case of the transient phenomena results from the attended power system parameters such as inductance of transformers, capacitance of distribution line, capacitive shunt reactors, inductive shunt reactors, etc... This phenomenon is caused by lightning and switching overvoltages, resulting in serious damage to the power devices.

One of the transient phenomena named ferroresonance which known as a low-frequency transient. Ferroresonance is resonance between inductance of the transformers and capacitance of the cables, resulting from open or close switches, load rejection, fault clearing, transformer energization and loss of system grounding, etc. In practice, the ferroresonant oscillations may be initiated by momentary saturation of the iron core resulting from e.g. switching operation result in a transient event in the systems.

This thesis focuses on studies in ferroresonance phenomena on distribution transformers connected with distribution line by drop out fuse cutout. The first case is estimate critical length of the distribution line connected with distribution transformers. By using data, process and difficulty in calculating and various methods, method. The second case is comparison between conventional and low-losses transformer. low-loss transformers have been developed with reducing core losses by improvement in design, assembling process and core materials. The changes in properties of iron core are expected to have some impact on the occurrence of ferroresonance phenomena. All the results of calculate critical length can use in a guideline for avoiding ferroresonant phenomena.

1.2.Motivation

The literature review in Chapter 2 is a survey of power system components cause ferroresonance phenomena. The researches have a consistent opinion that the power devices lead to ferroresonance consist of the power network, drop out fuse cutouts, distribution line and distribution transformers. It is shown that the main problems of ferroresonance studies employing digital simulation programs face is the lack of real information on the power system components for using in make models. Especially, the magnetizing curve of transformers must be come from the manufacture testing only. In addition, ferroresonance is a complex phenomenon, highly sensitive to values of parameters. To prevent the consequences of ferroresonance it is necessary to: understand the phenomenon, predict it identify it and avoid or eliminate it.

One more the reason, step-by-step systematic approaches of selecting an appropriate simulation model are still not explained in the literatures. Therefore, the motivation devoted in this thesis is directed towards achieving the following objectives:

1.3. Objective

1. To study in ferroresonant phenomena on distribution transformers and mitigation techniques
2. To determine the critical lengths of underground cables or overhead feeders connected to distribution transformers
3. To study influence of magnetizing core on ferroresonance phenomena.

1.4. Methodology

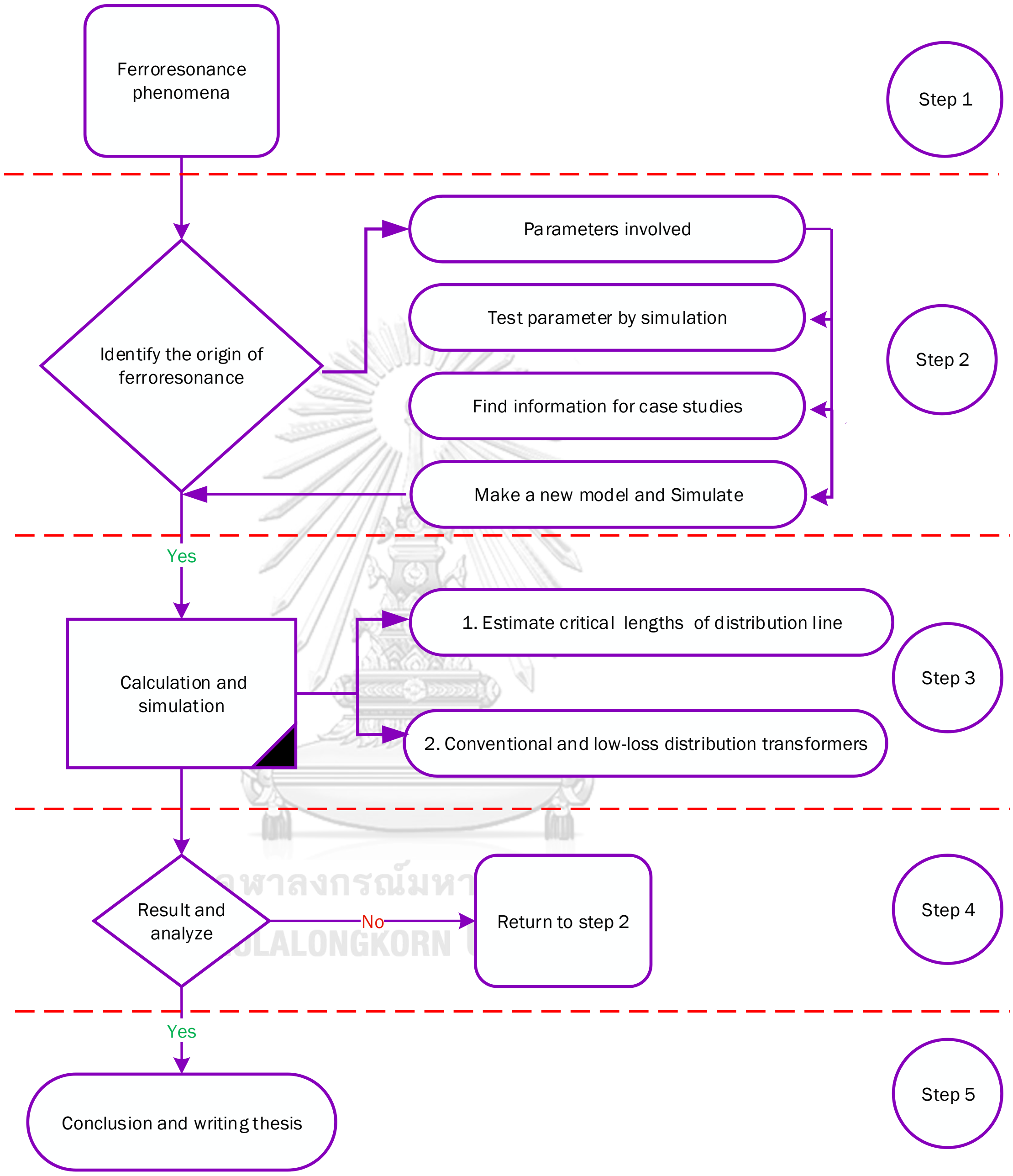


Figure 1. 1 The outline of steps for studies ferroresonance.

Figure 1.1 shown the outline of the steps for studies this phenomenon. There are five steps for studies in ferroresonance phenomena on distribution transformers. First of all, finding researches on the background and documents involving with the ferroresonance phenomenon to understand the source of this problem. In addition, using them on references. The second, Studies parameters result in ferroresonance phenomena with simulation, find information for thesis studies and make new model for studies. Next, the studies estimate critical lengths of distribution line connected with distribution transformers by using three methods (Baitch, Ferracci and ATP-EMTP) and study the ferroresonance phenomena in conventional and low-loss distribution transformer by using computer simulation with ATP-EMTP program. Then, analyzing result of studies. Finally, conclusion and writing a thesis.

1.5. Expectation and Benefit

In studies this thesis, I hope that:

1. Better understanding about ferroresonant phenomena.
2. A guideline for avoiding ferroresonant phenomena.

1.6. Thesis Outline

1.6.1. Chapter 1 Introduction

In the first chapter, an overview important of the power system, the dangerous from transient problems to power equipment and the causes of the ferroresonance phenomena occurrence. In addition, the motivation together with the objective, the methodology, expectation, and benefit of studies are explained this chapter.

1.6.2. Chapter 2 Literature Review

The second chapter presents background and literature reviews involving ferroresonant phenomena. In addition, the chapter shown four types of this phenomenon which consist of: fundamental mode, subharmonic mode, quasi-periodic mode and chaotic mode. Lastly, the dangerous of the problem to power systems and mitigation.

1.6.3. Chapter 3 Estimation Critical Cable Lengths of Distribution Line

The main aims of this chapter are estimate critical lengths of distribution line supplied distribution transformers result in ferroresonance phenomena by comparison with three methods include A.Baitch, Ph. Ferracci and ATP-EMTP method. The first is A. Baitch presented the process to estimate the critical length of the distribution line. This method uses the technique in analysis the magnetizing curve of transformers and linear reactance of the distribution line. The next, Ph. Ferracci method considers magnetizing curve and reactance linear of the distribution line, using information similar to A. Baitch method. But, the steps of calculation are more than Baitch method. Lastly, ATP/EMTP method uses real magnetizing curve data of transformer. The data can be calculated from result of manufacture testing. The result of three method can use in a guideline for avoiding ferroresonant phenomena.

1.6.4. Chapter 4 Conventional and Low-losses Distribution Transformers

This chapter is to study the ferroresonance phenomena in conventional and low-loss distribution transformer by using computer simulation with ATP-EMTP program. The minimum lengths of overhead line and underground cable that can cause ferroresonance in conventional and low-loss distribution transformers are determined and compared.

1.6.5. Chapter 5 Conclusion

The last chapter is conclusion results of study the ferroresonance phenomena which the result of this work uses in the papers published.

CHAPTER 2

LITERATURE REVIEW

2.1. Introduction

Ferroresonance is a nonlinear transient phenomenon which often appears in distribution systems from interaction between the inductance of iron-core in a power transformer and the capacitance of cable or overhead line[1-4]. Many ferroresonance events have been reported in the systems with a no-load or lightly loaded distribution transformer connected to overhead line or underground power cable and supplied via drop-out fuse cutouts or disconnecting switches. Energizing step by step in each phase as well as fuse operation in one phase or two phases can initiate ferroresonance, leading to high overcurrents and overvoltages. These can cause failures in transformers and surge arresters.

Ferroresonance phenomena are beginning analyzes since 1907 by J.Bethenod that is a first work was published[5] . The word “ferroresonance” is caused by French researcher named P.Boucherot in 1920 which describes a complex resonant oscillation in an RLC circuit with a non-linear inductance[6]. After that many researches about ferroresonance phenomena have been studied. For example, in 2000, A. Baitch studied a maximum cable length that can be safely switched in conjunction with lightly loaded distribution transformers[7]. In 2003, R.C. Dugan illustrated three different cases of ferroresonance problems commonly encountered on distribution systems, including the case of the underground distribution system with Δ–Y transformers[8]. In 2010, L.B. Viena presented behavior of ferroresonance phenomenon obtained from the simulation with different transformer models in the ATP-EMTP program[9].

2.2. Ferroresonance Theory

Figure 1 shows a basic of ferroresonance circuit. It is a series connection of a voltage source, a resistance, a capacitive reactance of cable and a non-linear inductive reactance of iron core of transformer. At some point, the transformer inductance and cable capacitance may be sufficient to support ferroresonance. As a result, the voltages across cable (V_C) and transformer (V_L) are higher than the source voltage E.

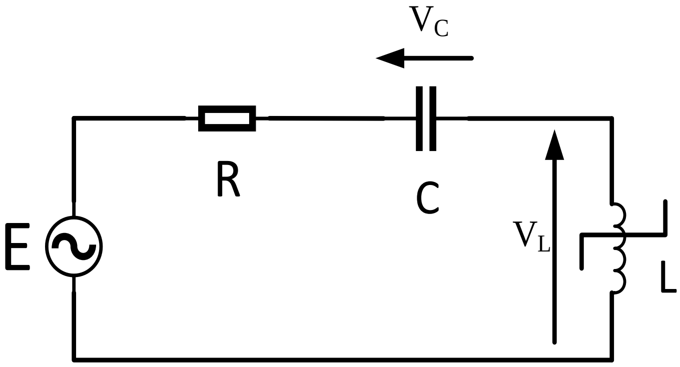


Figure 2. 1 Ferroresonance circuit

$$E= \overleftarrow{V}_R + \overleftarrow{V}_C + \overleftarrow{V}_L \tag{2.1}$$

From equation (2.1) if R is so less and $X_C = X_L$ result in overvoltages and overcurrents at C and L which this case called ferroresonance.

$$I = \frac{E}{j(X_C - X_L)} \tag{2.2}$$

$$L = \frac{1}{\omega_0 C} \tag{2.3}$$

$$f = \frac{1}{2\pi\sqrt{LC}} \tag{2.4}$$

Where

E = source voltage

X_L = reactance of L

X_C = reactance of C

Such circuit can occur in three-phase systems as shown in figure 2.2 An electric source is supplied to the high-voltage side of distribution transformer with delta connection via distribution lines and drop-out fuses.

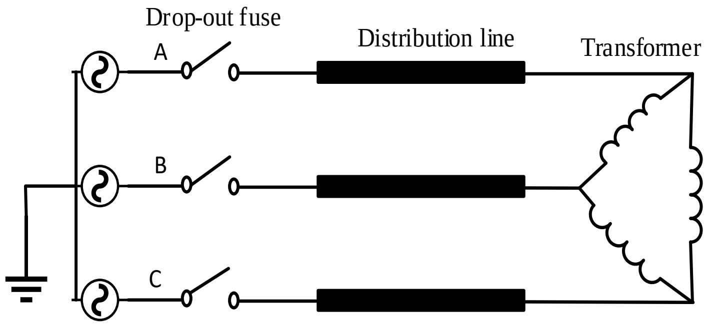


Figure 2. 2 Connection of drop-out fuses, distribution lines and a distribution transformer

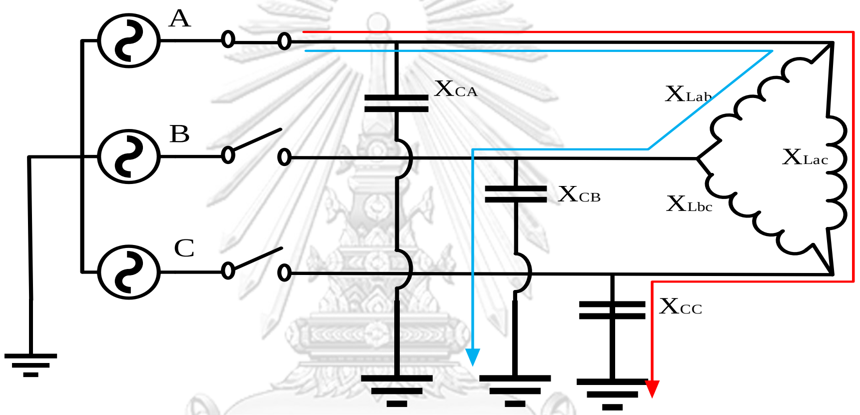


Figure 2. 3 Ferroresonance phenomena after one-phase closing or two-phase opening

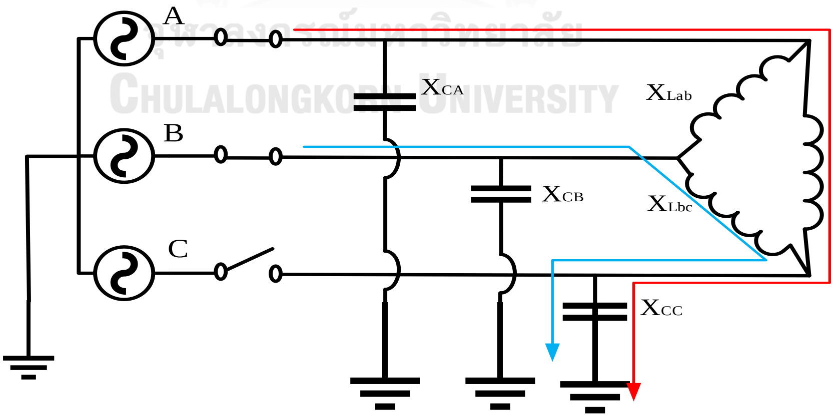


Figure 2. 4 Ferroresonance phenomena after two-phase closing or one-phase opening

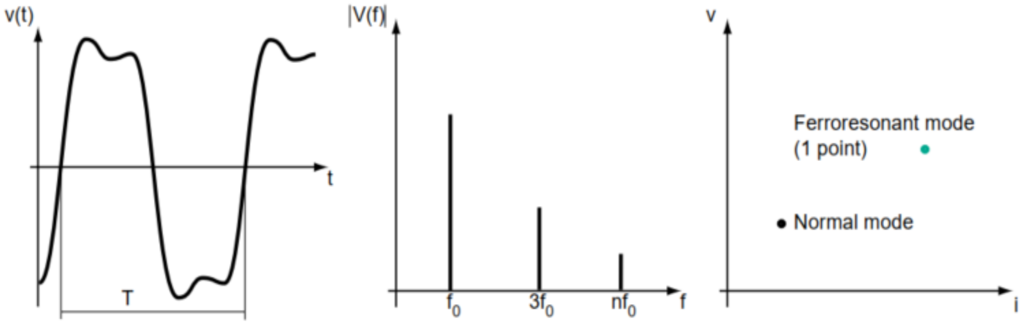
When the drop-out fuse in phase A is closed for energizing the transformer, this yields the circuit configuration for ferroresonance as shown in figure 2.3. If the capacitive reactance (X_C) of the line matches with the inductive reactance (X_L) of the transformer core, ferroresonance occurs. As a result, overcurrents and overvoltages appear in the transformer and lines of phases B and C. In the next step, the drop-out fuse in phase B is closed as shown in figure 2.4. The ferroresonance still exists in the transformer and line of phases C until the last phase drop-out fuse in phase C is closed. The one-phase and two-phase openings, as shown in figures 2.3 and 2.4, can also occur when the transformer is de-energized, or fuses blow.

2.3. Type of Ferroresonance Mode

The result of studies waveform occurrence from ferroresonance phenomena in power systems and simulation with computer program by using numerical method see that pattern of ferroresonance in steady state can classify by used analysis from frequency spectrum of waveform current and voltage. The pattern of ferroresonance depends on parameters in the circuit which can classification of ferroresonance states into four different types are:

2.3.1 Fundamental Mode[10]

The waveform of voltage and current have characteristics and period T likewise the power systems. But this type has the sequence different harmonic consist of 3rd, 5th, 7th and nth odd harmonic which result in making discontinuous of the frequency spectrum. In addition, this type of response can also be identified by using the stroboscopic diagram of Figure. 2.5 (c) which is also known as Poincarè plot. For the stroboscopic diagram shown 1 point of occurring ferroresonance phenomena which stay away from normal mode.

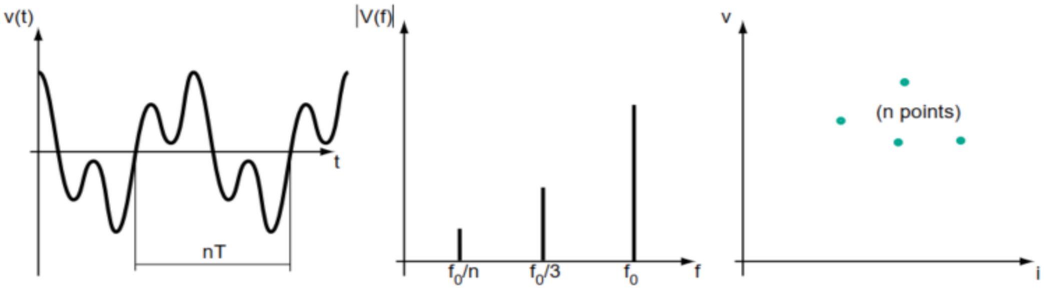


(a). Periodic signal (b). Frequency spectrum (C). Stroboscopic diagram

Figure 2. 5 Fundamental mode[10]

2.3.2 Subharmonic Mode[10].

This type has waveform of voltage and current have characteristic as period which period T of source equal to nT of this type is called a Period-n (i.e. f_0/n Hz) ferroresonance which n is odd integer. Therefore, the frequency contents are described having a spectrum of frequencies equal to f_0/n with f_0 denoting the fundamental frequency. Figure 2.6 shown all point of occurring ferroresonance phenomena by the stroboscopic diagram.

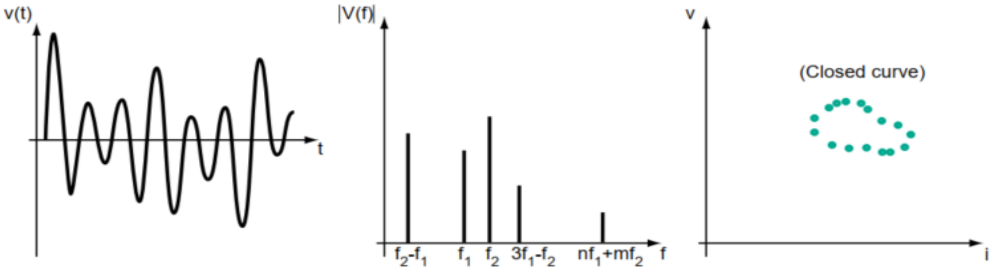


(a) Periodic signal (b) Frequency spectrum (C) Stroboscopic diagram

Figure 2. 6 Subharmonic mode [10]

2.3.3 Quasi-periodic Mode[10].

This mode (also called pseudo-periodic) is not periodic. The spectrum is a discontinuous spectrum whose frequencies are expressed in the form: nf1+mf2 (where n and m are integers and f1/f2 an irrational real number). The stroboscopic image shows a closed curve which shown on figure 2.7 (C).

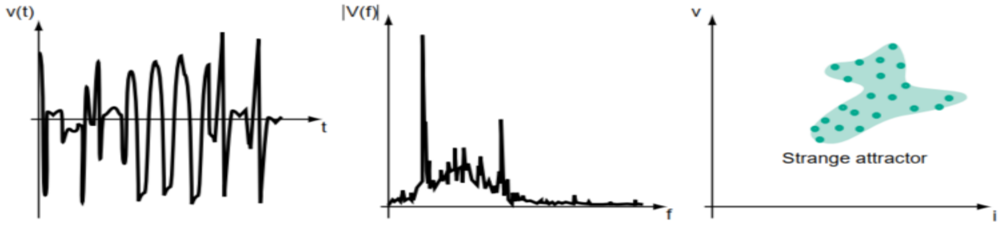


(a) Periodic signal (b) Frequency spectrum (C) Stroboscopic diagram

Figure 2. 7 Quasi-periodic mode[10]

2.3.4 Chaotic Mode[10].

This kind has a signal exhibiting non-periodic with a continuous frequency spectrum i.e. it is not canceled for any frequency. The stroboscopic plot consists of n points surrounding an area known as the strange attractor which appears to skip around randomly.



(a) Periodic signal (b) Frequency spectrum (C) Stroboscopic diagram

Figure 2. 8 Chaotic mode[10]

2.4 Ferroresonance on Power Systems

Power systems has risk to occur ferroresonance due to the systems have capacitances (cables, long lines, capacitor voltage transformers, series or shunt capacitor banks), inductances (Power transformers, voltage measurement inductive transformers (VT), shunt reactors) and switch (Drop out fuse, circuit breaker). due to if the capacitances and inductances of power systems has equal value while opening or closing drop out fuse cutout in single-phase will occurs ferroresonance phenomena on transformers. They are examples ferroresonance on power systems as follow:

- [11] Reported occurrence of ferroresonance at the Dorsey HVdc converter station 230 kV ac bus is comprised of four bus sections on which the converter valves and transmission lines are terminated. At 22:04, May 20, 1995, bus A2 was removed from service to commission replacement breakers, current transformers and to perform disconnect maintenance and trip testing. At approximately 22:30, a potential transformer (V13F) failed catastrophically causing damage to equipment up to 33 m away. The switching procedure resulted in the deenergized bus and the associated PTs being connected to the energized bus B2 through the grading capacitors (5061 pF) of nine open 230 kV circuit breakers. A station service transformer, which is normally connected to bus A2, had been previously disconnected. A ferroresonance condition caused the failure of the PT.
- [12] Reported that the 12 kV distribution feeder consists of a cable of 350 meters in length. The power rating of the station service transformers is

112.5 kVA. The incident was due to the switching operations by firstly opening the circuit breaker and then the disconnector switch located at the riser pole surge arrester. The first ferroresonance test without arrestor installation has induced both the chaotic mode appeared on phase R after closing phases Y and B. The peak value of overvoltages was about 4.14 per unit. The 3rd sub-harmonic overvoltages appeared on phases R and B after opening phases R and B. They had a peak value of about 2.69 per unit. The peak value of overvoltages from both modes was high enough for arresters to operate. As a result, the affected transformer creating loud noises like sound of crack and race engine. While for the second test, with the arrester, a sustained fundamental mode has been generated and thus has caused the explosion of riser pole arrester. The physical impact of the explosion has caused the ground lead of the disconnector explodes and the ruptures of the polymer housing.

- [13] reported that problem occurring in a 50-kV network in the Hafslund area near Moss, Norway. The clearing of a short circuit removed the only remaining source of grounding on the system. After the fault was cleared, the only remaining zero sequence impedance was due to capacitive coupling to earth. After operating in this way for only 3 min, ferroresonance had destroyed 72 of the VT's used for measurement and protective relaying. All 72 of the damaged VT's were from the same manufacturer. The VT's of two other manufacturers that were also in service during this time were not damaged.
- Ferroresonance experienced in [14], was due to the switching events that have been carried out during the commissioning of a new 400-kV substation. It was reported that two voltage transformers (VT) terminating into the system had been driven into a sustained fundamental frequency ferroresonance of 2 p.u. The adverse impact upon the initiation of this phenomenon was that a very loud humming noise generated from the affected voltage transformer, heard by the local operator.
- [15] reported that the ferroresonance phenomena occurring on 33 kV Provincial Electricity Authority distribution network in Satun province.

> The installations of 1000 kVA and 500 kVA delta-wye transformers, 300 meters underground cable and capacitor in the low side of the transformers cause the overvoltage while there are single-phase or two-phase switching events. The result of overvoltage damages surge arresters that are installed at the both transformers and the connection point between Partial Insulated Conductor (PIC) and underground cable in several times.

From the reviews in many papers. All of the research also said that the main cause of ferroresonance phenomena results from shutdown or open drop out fuse cutout in a different time. In addition, the literatures presented in [13, 14, 16] that the existence of the phenomena can also result from some symptoms as follow:

- If power networks have high value of capacitance refer to the systems have a risk to occur ferroresonance [16].
- Arcing across open phase switches or over surge arresters, particularly the use of the gap less Z_nO [14].
- A short circuit has removed grounding system [13].

2.5 Mitigation of Ferroresonance

The initiation of ferroresonance phenomena can cause distorted overvoltages and overcurrents to be induced into a system. which are considered to be catastrophic when it occurs. There are generally three main ways of preventing the occurrence of ferroresonance.

- Avoid suspect resonant circuits is to avoid opening three-phase transformers one phase at a time from potheads or lateral taps.
- Avoid, by proper design and/or switching operations, configurations susceptible to ferroresonance
- Ensure that system parameter values are not included (even temporarily) in an area at risk and if possible provide a safety margin with respect to danger areas.

CHAPTER 3

ESTIMATION OF LINE/CABLE CRITICAL LENGTHS

3.1. Introduction

Ferroresonance between distribution lines and a distribution transformer is a common phenomenon in distribution systems. This phenomenon results in overvoltage and overcurrent, leading to serious equipment damage. The opportunity of ferroresonance depends on many factors such as type, size and length of distribution line. This chapter studied the critical length estimation of the line and cable with three different methods.

3.2. Distribution Line

3.2.1 Underground cable

The cable can be represented by a pi equivalent model. Inductance and capacitance of the cable are shown in equation (3.1) and (3.2).

$$L = \frac{\mu_r \mu_0}{2\pi} \ln \frac{r_2}{r_1} \qquad \text{(H/m)} \qquad (3.1)$$

$$C = \frac{2\pi\varepsilon_0\varepsilon_r}{\ln(\frac{r_2}{r_1})} \qquad (\mu\text{F/m}) \qquad (3.2)$$

Where:

μ_0 = vacuum permeability =$4\pi \times 10^{-7}$ (H/m)

μ_s = relative permeability of insulator = 1.0

ε_0 = vacuum dielectric constant = 8.854×10^{-12} (F/m)

ε_r = relative dielectric constant of insulator

r_1 = outer radius of conductor (mm)

r_2 = inner radius of sheath (mm)

3.2.2 Overhead Line

A single transmission line is modeled by using lumped elements as shown in Figure 3.1. This thesis used Pi model for simulation because the model has efficient accuracy when the frequency of calculation phenomena is sufficiently smaller than the inverse of propagation time of the line. Figure 3.2 is a single transmission line model by the four terminal equivalent circuits and figure 3.3 are three-phase transmission line which the equivalent circuit is modeled by the mutual coupling.

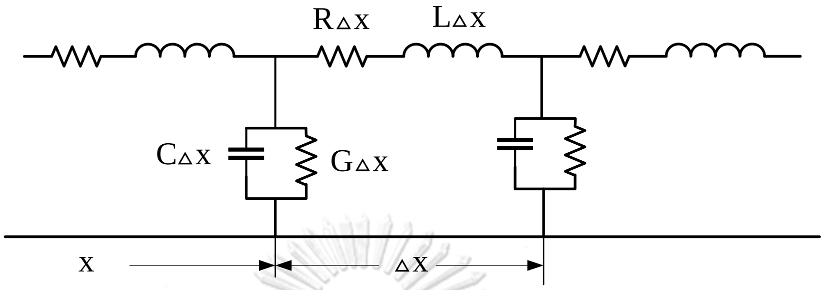


Figure 3. 1 Equivalent circuit of a single-phase transmission line

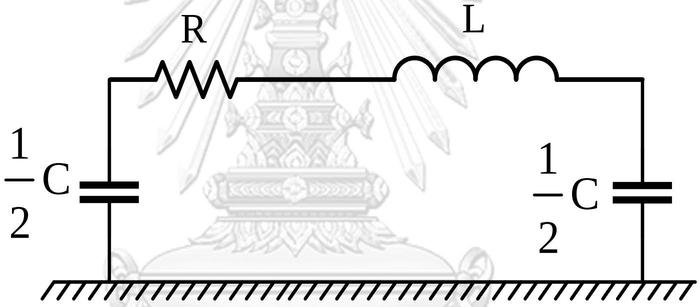


Figure 3. 2 Pi equivalent circuit.

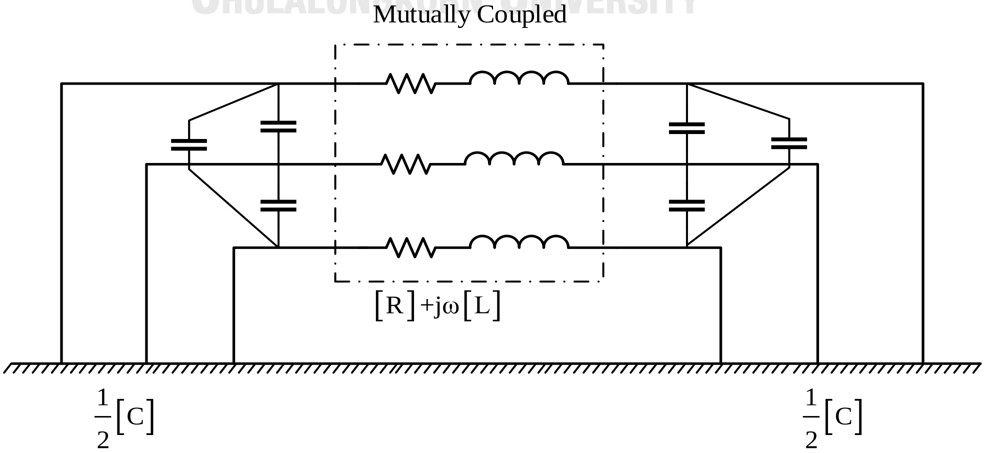


Figure 3. 3 Pi equivalent circuit for three-phase lines

3.3 The critical length estimation

Opportunity assessment to ferroresonance occurrence accurately is difficult because ferroresonance is a nonlinear complex phenomenon. Therefore, the calculation is extremely confusing. In addition, it's very sensitive to various devices. This chapter focuses on estimation of the critical length of overhead lines and underground cables. Three methods are applied, i.e. Baitch method, Ferracci method, and simulation using ATP-EMTP. Parameters of distribution transformers and distribution lines are shown in Table 3.1 to Table 3.3

Table 3. 1 Parameters of distribution transformers

Rating of Transformer	Current No Load Loss	Power No Load Loss	Power Load Loss	Impedance
(kVA)	(A)	(W)	(W)	(%)
100	0.48	250	1150	2.11
300	0.9	480	1860	4.26

Table 3. 2 Parameters of underground cables

Size	Parameters	Conductor	Insulation
35 mm^2	Inner radius (mm)	0	12.285
	Outer radius (mm)	3.475	13.5
	Resistivity (Ω.m)	1.834×10^{-8}	1.72×10^{-8}
	Overall radius (mm)	-	14
70 mm^2	Inner radius (mm)	0	13.835
	Outer radius (mm)	4.865	14.5
	Resistivity (Ω.m)	1.876×10^{-8}	1.72×10^{-8}
	Overall radius (mm)	-	15.5
240 mm^2	Inner radius (mm)	0	18.565
	Outer radius (mm)	9.235	19.5
	Resistivity (Ω.m)	1.836×10^{-8}	1.72×10^{-8}
	Overall radius (mm)	-	20.5

Table 3. 3 Parameters of overhead lines

Size	Radius of conductor	Conductor resistance
	(cm)	(Ω/km)
185 mm^2	0.804	0.164
240 mm^2	0.93	0.125

3.3.1 Baitch method [7]

A. Baitch presented the process to estimate the critical length of the distribution line. This method uses the technique in analysis the magnetizing curve of transformer and linear reactance of the distribution line by calculating mathematically the electrical circuit without considering load loss. Then, the length of the distribution line having capacitance making the overvoltages around 2.73 times per phase voltage is determined. This voltage level is an acceptable overvoltage for the insulation of the power devices in the switching period.

Figure 3.4 shows the construction to determine what is referred to as the “Critical Cable Length”.

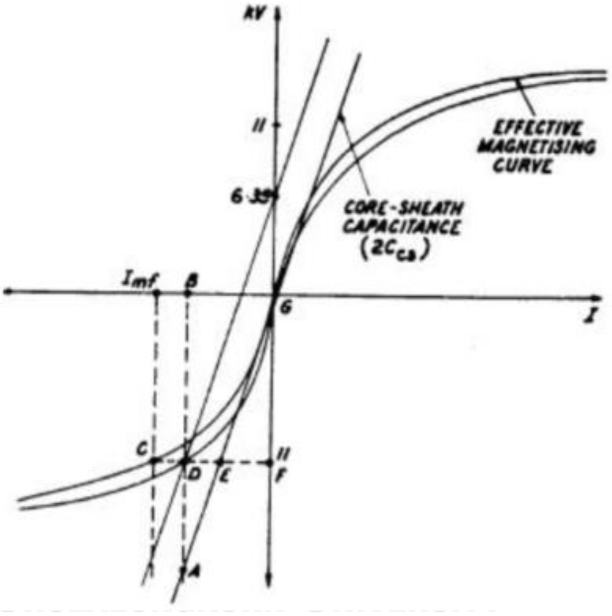


Figure 3. 4 Critical cable length[7]

The magnetizing current under ferroresonant condition (I_{mf}) with rated system voltage across the winding of the transformer is related to the three-phase magnetizing current as follows:

$$I_{mf} = \frac{y \times I_{mag\%} \times kVA}{100 \times kV} \tag{3.3}$$

Where y is the % of the core that is being excited under ferroresonant conditions. Typically, this is 0.6. Therefore, The Baitch Ferroresonance Critical Length can calculate by equation (3.4).

$$L_{crit} = \frac{0.6\times I_{mag\%}\times kVA\times 1000}{(1.58+\frac{C_{CC}}{C_{CS}})\times 6.28\times (kV)^2\times C_{CC}} \quad (3.4)$$

Where:

L_{crit} = Critical cable lengths, (m)

$I_{mag\%}$ = Transformers magnetizing current, (%)

kVA = Transformers rating, (kVA)

kV = Rated Voltage (kV)

C_{cc} = Specific cable core - to - core capacitance, (μF/km)

C_{cs} = Specific cable core - to - sheath capacitance, (μF/km)

3.3.1.1 Case of underground cable.

The critical length of 35 mm^2 underground cables connected with a 100 kVA distribution transformer can be calculated as follows:

1) 100 kVA Distribution Transformer

Using the data from Table 3.1, $I_{mag\%}$ can be calculated as follows:

$$I_{LV} = \frac{S}{\sqrt{3}\times V} = \frac{100\times 1000}{\sqrt{3}\times 400} = 144.34A$$

$$I_{mag\%} = \frac{I_{Noload}}{I_{LV}} \times 100\% = \frac{0.48}{144.34} \times 100\% = 0.33\%$$

2) 35 mm^2 Underground Cable

Using the data from Table 3.2, C_{CS} can be calculated from equation (3.2) as follow:

$$C_{CS} = \frac{2\pi\varepsilon_0\varepsilon_r}{\ln(\frac{r_2}{r_1})} = \frac{2\times 3.14\times 8.854\times 10^{-12}}{\ln(\frac{12.285\times 10^{-3}}{3.474\times 10^{-3}})} = 0.1012\ \mu F/km$$

C_{CC} = 0 for the case of single-core cable.

3) Critical length of underground cable

Therefore:

$$L_{crit} = \frac{0.6 \times 0.33 \times 400 \times 1000}{(1.58+0) \times 62.8 \times (22)^2 \times 0.1012} = 4.101\text{m}$$

Therefore, for this method, the length of 35 mm^2 underground cable connected with 100 kVA distribution transformers shall not be longer than 4 m.

The critical lengths of underground cables with different conductor sizes are shown in Table 3.4.

Table 3. 4 Critical lengths of underground cables from Baitch method.

22 kV system				Critical length of underground cable (m)	
Cable size (mm^2)	Outer radius of conductor (m)	Inner radius of insulator (m)	Capacitance (μF/km)	Transformers rating (kVA)	
				100	300
35	3.475 x 10^{-3}	12.29 x 10^{-3}	0.1012	4	8
70	4.865 x 10^{-3}	18.34 x 10^{-3}	0.122	3	6
240	9.235 x 10^{-3}	18.56 x 10^{-3}	0.183	2	4

3.3.1.2 Case of overhead line.

For overhead line, the capacitances C_{cc} and C_{cs} can be determined by ATP-EMTP. The 185 mm^2 overhead line has C_{cc} = 3.72 x 10^{-3} F/m and C_{cs} = 3.58 x 10^{-3} F/m.

So, the overhead-line critical length is:

$$L_{crit} = \frac{0.6 \times 0.305 \times 100 \times 1000}{(1.58 + \frac{3.72 \times 10^{-3}}{3.58 \times 10^{-3}}) \times 62.8 \times (22)^2 \times 0.154} = 70\text{ m}$$

Therefore, for this method, the length of 185 mm^2 overhead line connected with a 100 kVA distribution transformer shall not be longer than 70 m.

The critical lengths of overhead lines with different conductor sizes are shown in Table 3.5.

Table 3. 5 Critical lengths of overhead lines from Baitch method.

22 kV system				Critical length of overhead line (m)	
Cable size (mm^2)	Diameter of conductor (m)	Capacitance P to P (μF/km)	Capacitance P to E (μF/km)	Transformers rating (kVA)	
				100	300
185	16.08 x 10^{-2}	3.72 x 10^{-3}	3.58 x 10^{-3}	70	131
240	18.57 x 10^{-2}	3.76 x 10^{-3}	3.8 x 10^{-3}	67	126

3.3.2 Ferracci Method [10]

This method considers magnetizing curve and linear reactance of the distribution line as shown in Figure 3.5. Ferroresonance phenomenon will not occur as long as the capacitive reactance of the distribution line is still higher than the inductive reactance of the transformer in unsaturation range. This condition can be calculated from equations (3.5) and (3.6).

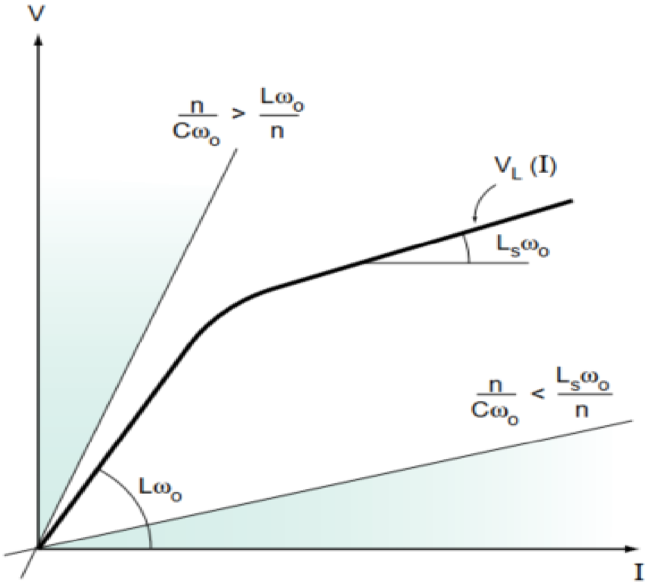


Figure 3. 5 Values of C incompatible with periodic ferroresonance[10]

$$\frac{n}{Cw_0} = \frac{Lw_0}{n} \tag{3.5}$$

$$\frac{n}{C\omega_0} = \frac{L_S\omega}{n} \tag{3.6}$$

The value L of transformers can be estimated from testing data of open circuit or no-load loss using equation (3.7).

$$L = \frac{1}{\omega_0} \frac{U_n}{\sqrt{I_0^2 - (\frac{p_0}{U_n})^2}} \tag{3.7}$$

Where

U_n = rated voltage (kV),

I_0 = No-load current under Un (A),

P_0 = power no load losses under Un (kW).

The obtained value of L is used to calculate value of C with no chance of ferroresonace using equation (3.5). Lastly, the line critical length is determined using equation (3.8).

$$L_{Crit} = \frac{Cd_{ins}}{2\pi r_{core}\varepsilon_0\varepsilon_r} \tag{3.8}$$

Where:

C = capacitance of distribution line (F)

d_{ins} = thickness of insulation (m)

r_{core} = radius of conductor (m)

ε_0 = vacuum dielectric constant = 8.854 x 10^{-12} F/m

ε_r = relative dielectric constant of insulation

3.3.2.1 Case of underground cable.

The critical length of 35 mm^2 underground cable connected with a 100 kVA distribution transformer can be calculated using the data from Table 3.1 and Table 3.2 as follows:

$$U_n = \frac{U}{\sqrt{3}} = \frac{400}{\sqrt{3}} = 230 \text{ V}$$

$$I_0 = 0.48 \text{ A}$$

From equation (3.7):

$$L_{LV} = \frac{1}{2\times 2.14\times 50}\frac{230}{\sqrt{(0.48)^2 - (\frac{250/3}{230})^2}} = 2.326 \text{ H}$$

So,

$$L_{HV} = L_{LV} \times \left(\frac{U_{HV}}{U_n} \right)^2 = 2.326 \times \left(\frac{22000}{230} \right)^2$$

$$L_{HV} = 21286.1 \text{ H}$$

Then,

$$C = \frac{1}{L_{HV}\omega_0^2} = \frac{1}{21286.1 \times (2 \times 3.14 \times 50)^2}$$

$$C = 4.765 \times 10^{-10} \text{ F}$$

Therefore,

$$L_{Crit} = \frac{Cd_{ins}}{2\pi r_{core}\varepsilon_0\varepsilon_r} = \frac{4.765 \times 10^{-10} \times 5.5 \times 10^{-3}}{2 \times 3.14 \times (3.475 \text{ x } 10^{-3}) \times 2.3 \times 8.85 \times 10^{-12}}$$

$$L_{Crit} = 6 \text{ m}$$

Therefore, for this method, the length of 35 mm^2 underground cable connected with a 100 kVA distribution transformer for this method shall not be longer than 6 m.

The critical lengths of underground cables with different conductor sizes are shown in Table 3.6

Table 3. 6 Critical lengths of underground cables from Ferracci method

22 kV system			Critical length of underground cable (m)	
Cable size	Radius of conductor	Thickness of insulation	Transformers rating (kVA)	
(mm^2)	(m)	(m)	100	300
35	3.475 x 10^{-3}	5.5 x 10^{-3}	6	11
70	4.865 x 10^{-3}	5.5 x 10^{-3}	4	8
240	9.235 x 10^{-3}	5.5 x 10^{-3}	2	5

3.3.2.2 Case of Overhead line.

For overhead line, $d_{ins} = 1$

So :

$$L_{Crit} = \frac{C}{2\pi r_{core}\varepsilon_0\varepsilon_r}$$

$$L_{Crit} = \frac{4.765\times10^{-10}}{2\times3.14\times(\frac{16.08\times10^{-3}}{2})\times2.3\times8.85\times10^{-12}} = 464m$$

Therefore, for this method, the length of 185 mm^2 overhead line connected with a 100 kVA distribution transformer shall not be longer than 464 m.

The critical lengths of overhead lines with different conductor sizes are shown in Table 3.7.

Table 3. 7 Critical lengths of overhead lines from Ferracci method

22 kV system		Critical length of overhead line (m)	
Cable size	Diameter of conductor	Transformers rating (kVA)	
(mm^2)	(m)	100	300
185	16.08 x 10^{-3}	464	841
240	18.57 x 10^{-3}	401	728

3.3.3 Computer Simulation Method with ATP/EMTP Program

This method uses real magnetizing curve data of transformer. The data can be obtained from testing. For example, Figure 3.6 is a magnetizing curve for making a saturation model of transformer with ATP/EMTP program. Overhead lines and underground cables are lumped as a PI equivalent models. The overhead line are installed on a pole with 9.8 m in height, and phase separation of 0.6 m and 1.5 m. The underground cables are arranged in trefoil formation with 1 m in depth. This 22kV system is assumed to have a short-circuit level of 235 MVA with X/R ratio of 5.63.

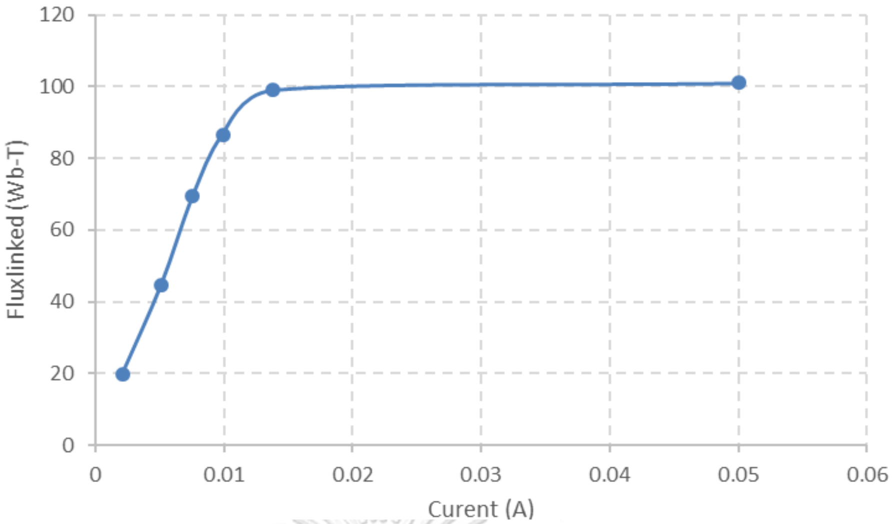


Figure 3. 6 The curve characteristic of distribution transformer 100 kVA delta-wye.

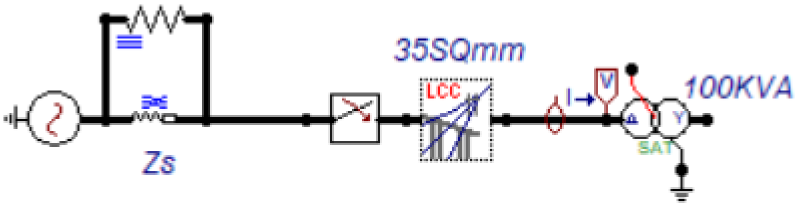


Figure 3. 7 The ATP/EMTP program for ferroresonance study.

Figure 3.8 shows an example of overvoltages due to ferroresonant condition between a 100 kVA distribution transformer with 35 mm^2 underground cable with 50 m in length. The red, green and blue lines are voltages of phases A, B and C, respectively. When the drop-out fuse cutout in phase A is opened at 20 ms result in an overvoltage in phase A due to ferroresonance. Then the drop-out fuse cutout in phase B is opened at 45 ms, ferroresonance still occurs in phase A and phase B, resulting in overvoltages in phase A and phase B. After the drop-out fuse cutout in phase C is opened at 300 ms, overvoltages caused from ferroresonance disappeared.

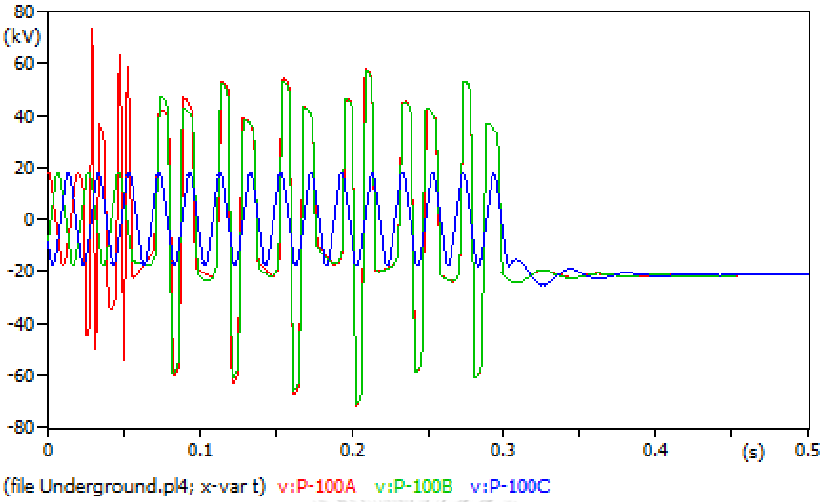


Figure 3. 8 Overvoltages from ferroresonance between a 100 kVA distribution transformer and 35 mm^2 underground cable with 50 m in length

Table 3. 8 The critical length between 100 kVA distribution transformer and overhead line 240 mm^2 be caused by open/close dropout fuse cutout

	Switch phase A (deg)	Switch phase B (deg)	The Critical length (m)
Close	-	-	-
	90	165	340
Open	175	-	263
	175	165	262

For this method, the line length, that creates ferroresonance overvoltages around 1.25 time normal phase voltage, is called the critical length. Because this voltage level can damage surge arresters that protect the transformer. The line length can closing/opening angles are varied to check ferroresonance condition and the shortest critical length. The obtained results are shown in Table 3.8. It is found that the case of tow-phase opening gives the shortest critical length. Therefore, this case is used to determine the critical length.

Table 3. 9 Critical lengths of distribution line from ATP/EMTP program.

Type of distribution line	Size (mm^2)	Critical Length of distribution line (m)	
		100 kVA	300 kVA
Underground	35	4	7
	70	3	6
	240	2	4
overhead	185	275	520
	240	262	505

3.4 Analysis and Discussion

Table 3.10 show results of the critical lengths of distribution lines. The words “Baitch”, “Ferracci” and “ATP-EMTP” refer to Baitch, Ferracci and ATP-EMTP methods, respectively. The comparative critical lengths shown in Table 3.10 come from rounding to an integer.

Table 3. 10 Comparison of the estimated critical lengths of distribution line**s**

Type of distribution line	Size (mm^2)	Critical Length of distribution line (m)					
		100 kVA			300 kVA		
		Baitch	Ferracci	ATP	Baitch	Ferracci	ATP
Underground	35	3	6	4	6	11	7
	70	2	4	3	5	8	6
	240	1	2	2	3	4	4
overhead	185	70	464	275	131	841	520
	240	67	401	262	126	728	505

The results from Table 3.10 can be summarized as follows:

1) The critical length increases with increasing rated power of distribution transformers. This can be attributed to the reduction in inductive reactance.

2) The critical cable length decreases with increasing conductor size. This can be attributed to the increase in capacitive reactance.

3) The critical length of the underground cable is obviously shorter than that of the overhead line. Because, the value of capacitive reactance of the underground cable is bigger than the overhead line. Therefore, the underground cable must be carefully taken into consideration.

4) In comparison with ATP-EMTP method, the critical lengths obtained from Ferracci method are longer, while those obtained from Baitch method are obviously shorter.

3.5 Summary

This chapter focuses on estimating the critical length of distribution line using three methods, i.e. Baitch method, Ferracci method and ATP-EMTP Simulation. Comparison of these three methods on the viewpoints of required data, difficulty in calculating and accuracy is summarized in Table 3.11.

Table 3. 11 Comparison among Baitch, Ferracci and ATP-EMTP methods

Method	Data	Difficulty in calculating	Accuracy
Baitch	+	+	-
Ferracci	0	0	0
ATP-EMTP	-	-	+

(-) = inferior, (0) = fair and (+) = superior

1) Baitch method requires less data and the calculation is simple. However, the result of critical length seems to have poor accuracy, especially for the case of overhead line that the critical length is extremely shorter than other methods.
2) Ferracci method requires more data and steps in calculation as compared with Baitch method. The results of critical length are closer to the ATP-EMTP method.
3) ATP-EMTP method required the actual data of excitation curve. It takes time to create models with complexity. Furthermore, the simulation must be conducted carefully because ferroresonance phenomena are highly sensitive to parameters. However, with using detailed data and calculation, the results obtained from this method are expected to have the highest accuracy.

CHAPTER 4

COMPARISON BETWEEN CONVENTIONAL AND LOW-LOSSES DISTRIBUTION TRANFORMERS

4.1. Introduction

For energy-saving purpose, low-loss transformers have been developed with reducing core losses by improvement in design, assembling process and core materials. The changes in properties of iron core are expected to have some impact on the occurrence of ferroresonance phenomena. The aim of this chapter is to study the ferroresonance phenomena in conventional and low-loss distribution transformer by using computer simulation with ATP-EMTP program. The minimum lengths of overhead line and underground cable that can cause ferroresonance in conventional and low-loss distribution transformers are determined and compared.

4.2. Model systems

The system under study are common installation for large buildings or factories to have a transformer fed by overhead lines or underground cables as shown in figure 4.1. Drop-out fuse cutouts are applied for energization/de-energization and protection purpose. This 22 -kV system is assumed to have a short-circuit level of 235 MVA with X/R ratio of 5.63.

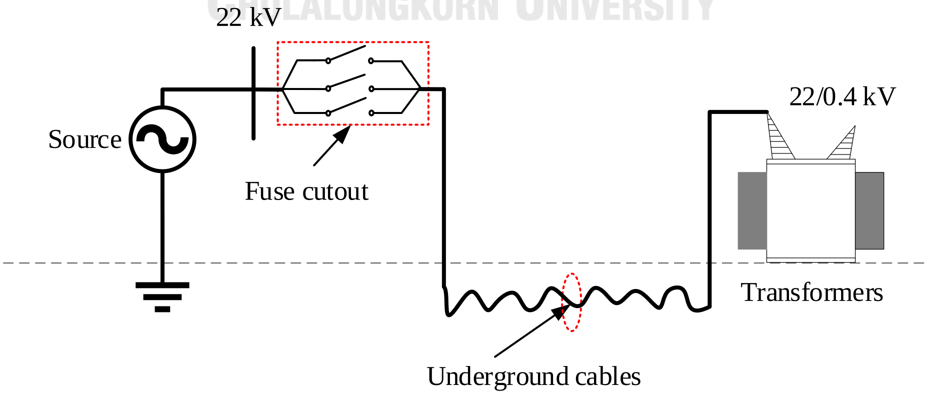


Figure 4. 1 Installation of system under study for underground cable

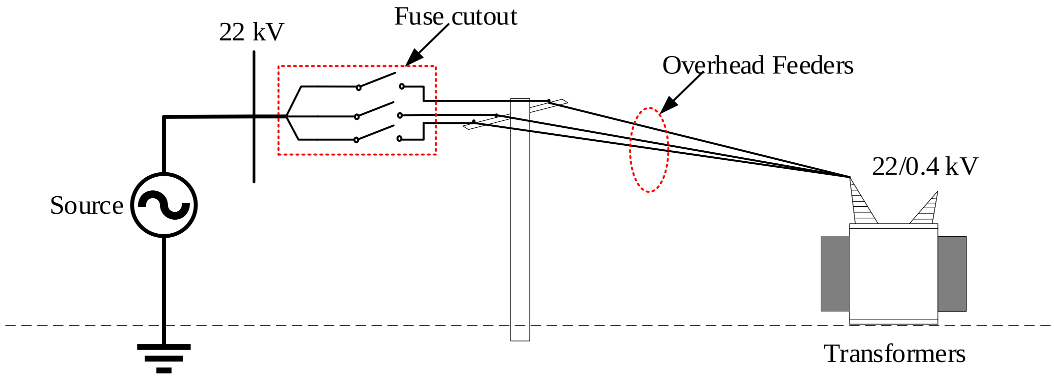


Figure 4. 2 Installation of system under study for overhead line

4.3 Information

4.3.1 Distribution line

Overhead lines and underground cables are lumped as a PI equivalent model. The overhead line are install on a pole with 9.8 m in height, and phase separation of 0.6 m and 1.5 m. The underground cables are arranged in trefoil formation with 1 m in depth. Parameters of overhead lines and underground cables are shown in Tables 4. 1 and Table 4.2

Table 4. 1 Parameter of underground cable

Size	Parameter	core	sheath
70 mm^2	Inner radius (mm)	0	13.835
	Outer radius (mm)	4.865	14.5
	Resistivity (Ω.m)	1.876×10^{-8}	1.72×10^{-8}
	Overall radius (mm)	-	15.5
240 mm^2	Inner radius (mm)	0	18.565
	Outer radius (mm)	9.235	19.5
	Resistivity (Ω.m)	1.836×10^{-8}	1.72×10^{-8}
	Overall radius (mm)	-	20.5
400 mm^2	Inner radius (mm)	0	21.105
	Outer radius (mm)	11.695	22.5
	Resistivity (Ω.m)	1.88×10^{-8}	1.72×10^{-8}
	Overall radius (mm)	-	23.5

Table 4. 2 Parameter of overhead lines

Size	Radius of conductor	Conductor resistance
	(cm)	(Ω/km)
185 mm^2	0.804	0.164
240 mm^2	0.93	0.125

4.3.2 Transformers

Ratings of conventional and low-loss distribution transformers in this study are 400 kVA 22/0.4 kV Dyn11. Magnetizing characteristics of both transformers, derived from the experimental data, are shown in figure 4.3. ATP-EMTP program has several transformer models. Because of the available transformer data, the saturable model is used in this study. The transformers are assumed to have no load.

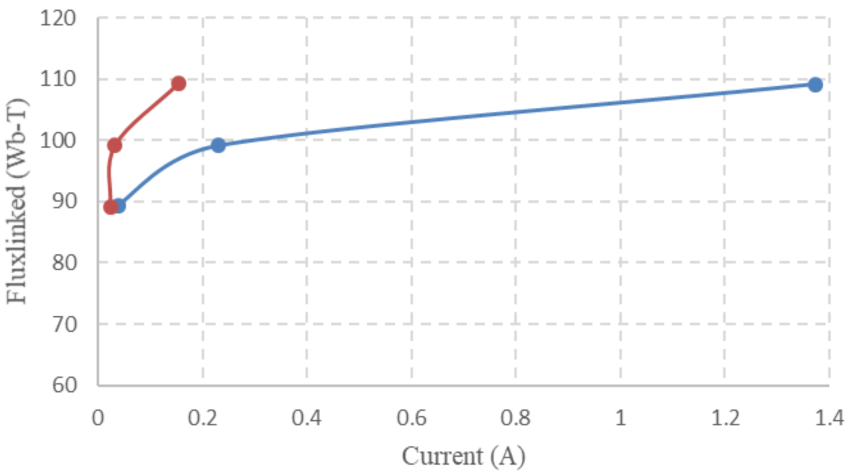


Figure 4. 3 Magnetizing characteristics of 400 kVA 22-0.416 kV conventional and low-loss distribution transformers

4.3.3 ATP/EMTP program

Ferroresonance has been often observed in distribution systems having line or cable fed transformers, provided with drop-out fuse cutouts for protection and switching purposes. Figure 4.4 shows the circuit of distribution systems making by the ATP/EMTP program.

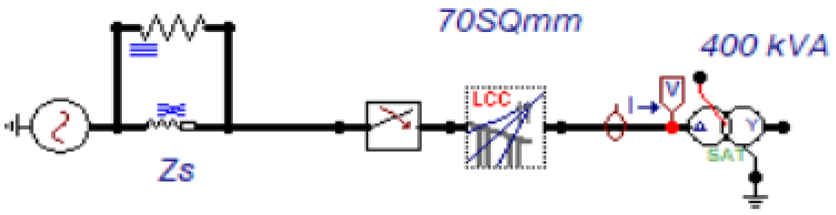


Figure 4. 4 The complete ATP/EMTP program for ferroresonance study

4.4. Results

4.3.1 Case of Underground cable

Figures 4.5 and 4.6 show an example of ferroresonance phenomena in 70 mm^2, 50 m long underground cables feeding to 400 kVA low-loss and conventional transformers, respectively. When the drop-out fuse cutout in phase A is opened or fuse blows, ferro-resonance occurs, resulting in an overvoltage in phase A. The critical lengths of underground cables with different sizes for conventional and low-loss transformers are shown in Table 4.2. It can be seen that the critical length in the case of low-loss transformer is shorter than that of conventional one. This result can be attributed to lower losses or less damping. For both conventional and low-loss transformer, the critical length decreases with increasing conductor size. It can be attributed to the increase in cable capacitance with increasing conductor size. However, there is a little difference in critical length for each conductor size.

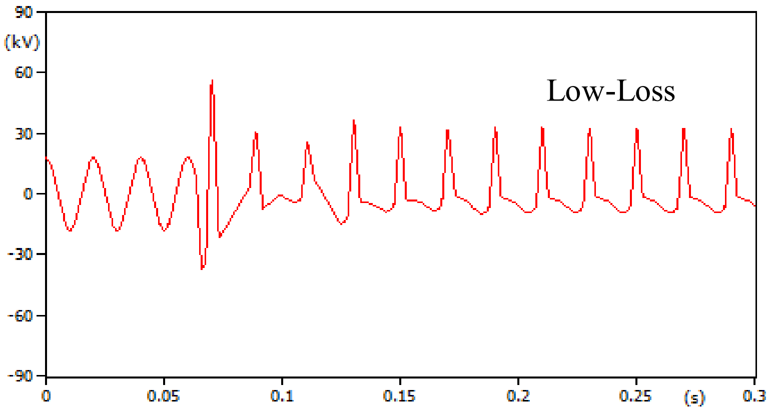


Figure 4. 5 Overvoltage due to ferroresonance between underground cable and low-loss transformer

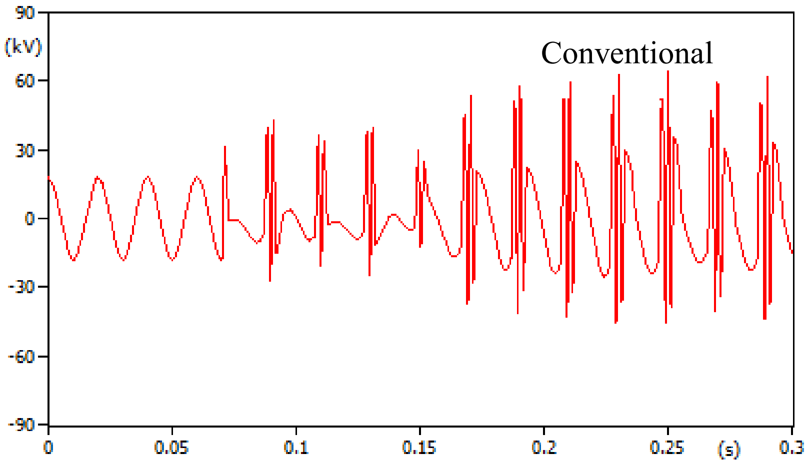


Figure 4. 6 Overvoltage due to ferroresonance between underground cable and conventional transformer

The simulation is conducted at a given line length by opening the drop-out fuse cutout in phase A at 60 ms. Then phase A voltage at the terminal of transformer are observed to check ferroresonance condition. The line length is increased until ferroresonance appears, making the overvoltages around 1.25 times normal phase voltage. This voltage level can damage surge arresters that protect transformer. This line length is called the critical length.

Table 4. 3 Critical underground cable lengths from simulations.

System voltage 22 kV			
Transformers	Critical Length of Underground Cable (meters)		
(kVA)	70mm^2	240mm^2	400mm^2
Low 400	8	6	5
Normal 400	10	7	6

4.3.2 Case of Overhead line

Figures 4.7 and 4.8 shows an example of ferroresonance phenomena in 185 mm^2 2,000 m long overhead lines feeding to 400 kVA low-loss and conventional transformers, respectively. The critical lengths of overhead lines with different sizes for conventional and low-loss transformers are shown in Table 4.3. Similar to the result of underground cable, the critical length in the case of low-loss transformer is shorter than that of conventional one. But for the case of overhead lines, the critical lengths are much longer than that of underground cables. This result can be attributed to much lower capacitance per length of overhead line in comparison with underground cable. Conductor size seems to have more effect on the critical length in comparison with the case of underground cable.

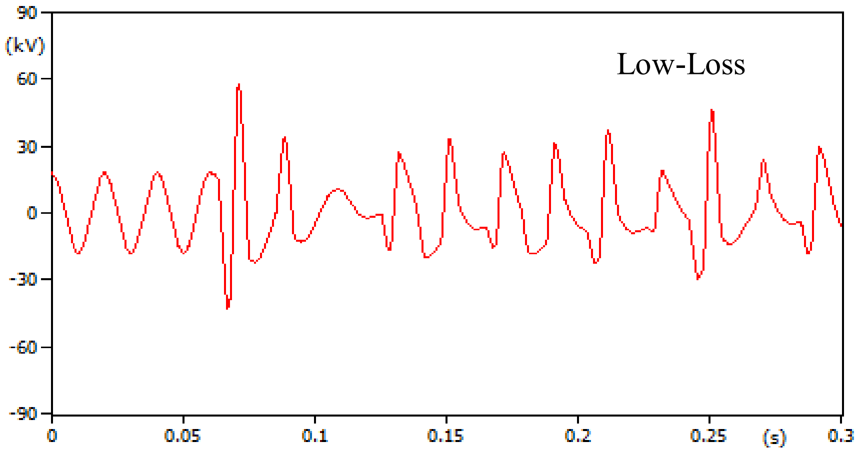


Figure 4. 7 Overvoltage due to ferroresonance between overhead line and low-loss transformer

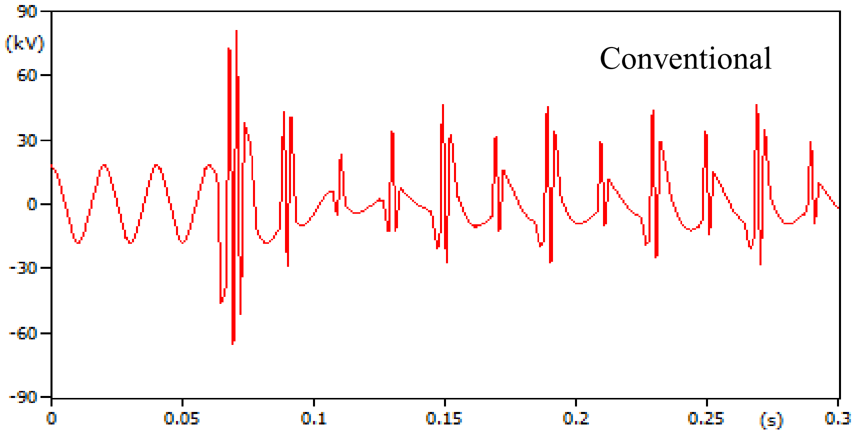


Figure 4. 8 Overvoltage due to ferroresonance between overhead line and conventional transformer

In the determine the critical length of overhead lines is similarly to case of underground cables. The results show on Table 4.3.

Table 4. 4 critical overhead feeder lengths from simulations

System voltage 22 kV		
Transformers	Critical overhead line Lengths (meters)	
(kVA)	185 mm^2	240mm^2
Low 400	1,090	1,080
Normal 400	1,065	1,060

4.5 Analysis and Discussion

Magnetizing characterisitic of iron core, type and size of distribution line have effects on ferroresonance phenomena between the distribution transformer and distribution lines. This chapter studied ferroresonance phenomena in conventional and low-loss distribution transformers connected to overhead lines or underground cables. Computer simulation was conducted to determine the critical length of distribution line. The results of simulation show on Table 4.4.

Table 4. 5 Summarize result of critical distribution line length

Type of cable	**Size (mm^2)**	**Critical length (m)**	
		Conventional 400 kVA	**Low-Loss 400 kVA**
Underground cable	70	10	8
	240	7	6
	400	6	5
Overhead line	185	1,090	1,080
	240	1,065	1,060

From Table 4.4 can be summarized as follows:

1) Ferroresonance is more likely to happen with the low-loss distribution transformer in comparison with the conventional one.
2) The critical length of undergroud cable is obviously shorter than that of overhead line. Therefore the combination of distribution transformer and underground cable must be carefully taken into consideration.
3) The critical length decreases with increasing size of conductor. The decrease is less for the case of underground cable.

4.6 Summary

Low-Loss transformers are designed to reduce energy, cost, and environmental impact. The install of a low-loss transformers can decrease energy consumption and use energy in the highest effectively. However, some problems of low-loss transformers were a risk to cause ferroresonace more than conventional transformers. because of the result of studies shown the critical length of line and cable of low-loss transformer shorter than that of conventional one, causing from design, an iron core given the abnormally low-loss. The low loss of an iron core results in the excitation current of transformers lower, affecting the value of inductive reactance increase. If inductive reactance (XL) of the transformer core increase matches with the capacitive reactance (XC) of the line, ferroresonance occurs. Therefore, the case of low-loss transformers, the critical length is less than conventional transformers. For this reason, in the select Low-Loss transformers for installing on power systems must be careful the problem from transient phenomena for example ferroresonance. Especially, the case of underground cable, the critical length is rather short.

CHAPTER 5
CONCLUSION

5.1 Conclusion

Ferroresonance phenomena in a typical distribution system, consisting of overhead line or underground cable fed transformer with drop-out fuse cutout, are studied. The obtained results can be summarized as follows:

The shortest line and cable lengths (critical lengths), that provide enough capacitive reactance to create ferroresonance overvoltage, are estimated by Baitch equation, Ferracci's method and simulation using ATP-EMTP. All three methods give the same tendency.

- The critical length increases with the increasing size of distribution transformer.
- The critical length decreases with the increasing size of conductor.
- As the underground-cable critical lengths are in the order of meters, the overhead-line critical lengths are in the order of tens to hundreds.

The comparison among three methods in different points of view is shown in the table below.

Method	Data	Simplicity	Accuracy
Baitch	+	+	-
Ferracci	0	0	0
ATP	-	-	+

Ferroresonance phenomena in conventional and low-loss distribution transformers are studies using computer simulation with ATP-EMTP. The simulation results illustrate that ferroresonance is more likely to happen when a low-loss transformer is supplied via distribution lines, especially the underground cables.

REFERENCES

[1] Z. Ali, S. A. Peng, and M. Norfauzi, "Graphical analysis of ferroresonance modes in a voltage transformer energized through grading capacitance using correlation function," in *TENCON 2015 - 2015 IEEE Region 10 Conference*, 1-4 Nov. 2015 2015, pp. 1-5, doi: 10.1109/TENCON.2015.7373195.

[2] I. M. Y. Negara, I. G. N. S. Hernanda, D. A. Asfani, D. Fahmi, Y. Afif, and M. Wahyudi, "Ferroresonance characteristics in unsymmetrical flux distribution of 150 KV three phase transformer," in *TENCON 2017 - 2017 IEEE Region 10 Conference*, 5-8 Nov. 2017 2017, pp. 78-81, doi: 10.1109/TENCON.2017.8227840.

[3] J. A. Corea-Araujo, F. González-Molina, J. A. Martínez, F. Castro-Aranda, J. A. Barrado-Rodrigo, and L. Guasch-Pesquer, "Single-phase transformer model validation for ferroresonance analysis including hysteresis," in *2015 IEEE Power & Energy Society General Meeting*, 26-30 July 2015 2015, pp. 1-5, doi: 10.1109/PESGM.2015.7285872.

[4] Z. A. Malek, S. J. Mirazimi, K. Mehranzamir, and B. Salimi, "Effect of shunt capacitance on ferroresonance model for distribution Voltage Transformer," in *2012 IEEE Symposium on Industrial Electronics and Applications*, 23-26 Sept. 2012 2012, pp. 124-129, doi: 10.1109/ISIEA.2012.6496613.

[5] P. Boucherot, "Éxistence de Deux Régimes en ferro-résonance," pp. R.G.E.,

pp. 827-828, 1920 (in French).

[6] J. Bethened, ""Sur le transformer à Résonance,”" vol. vol. 53, no. L’Éclairae Electrique,, pp. pp. 289-296, Nov. 1907 (in French).

[7] A. Baitch, "FERRORESONANCE-its Occurrence and Control in Electricity Distribution Networks," in *Annual Conference of the Electric Energy Society of Australia held in Canberra*, 2000, pp. 4-5.

[8] R. C. Dugan, "Examples of Ferroresonance in Distribution

Systems."

[9] L. B. Viena, F. A. Moreira, N. R. Ferreira, A. C. d. Castro, and N. C. d. Jesus, "Analysis and application of transformer models in the ATP program for the study of ferroresonance," in *2010 IEEE/PES Transmission and Distribution Conference and Exposition: Latin America (T&D-LA)*, 8-10 Nov. 2010 2010, pp. 738-744, doi: 10.1109/TDC-LA.2010.5762966.

[10] P. FERRACCI, "Cahier technique n° 190 Ferroresonance," March 1998.

[11] D. A. N. Jacobson, D. R. Swatek, and R. W. Mazur, "Mitigating potential transformer ferroresonance in a 230 kV converter station," in *Proceedings of 1996 Transmission and Distribution Conference and Exposition*, 15-20 Sept. 1998 1996, pp. 269-275, doi: 10.1109/TDC.1996.545946.

[12] K. B. Pattanapakdee, C, "Failure of Riser Pole Arrester due to Station Service Transformer Ferroresonance.

," (2007).

[13] M. R. Iravani *et al.*, "Modeling and analysis guidelines for slow transients. III. The study of ferroresonance," *IEEE Transactions on Power Delivery*, vol. 15, no. 1, pp. 255-265, 2000, doi: 10.1109/61.847260.

[14] M. Val Escudero, I. Dudurych, and M. A. Redfern, "Characterization of ferroresonant modes in HV substation with CB grading capacitors," *Electric Power Systems Research*, vol. 77, no. 11, pp. 1506-1513, 2007/09/01/ 2007, doi: https://doi.org/10.1016/j.epsr.2006.08.033.

[15] K. Laohacharoensombat, K. Tuitemwong, S. Jaruwattanadilok, C. Wattanasakpubal, and K. Kleebmek, "Case study of ferroresonance in 33 kV distribution network of PEA Thailand," in *2004 IEEE Region 10 Conference TENCON 2004.*, 24-24 Nov. 2004 2004, vol. C, pp. 417-420 Vol. 3, doi: 10.1109/TENCON.2004.1414796.

[16] M. Stosur, "ATP/EMTP study of ferroresonance involving HV inductive VT and circuit breaker capacitance," *Electrical Power Quality and Utilisation. Journal*, vol. Vol. 14, no. iss. 2, 2008.

VITA

NAME	Phinnakhone PHOMVONGSY
DATE OF BIRTH	19 Sep 1991
PLACE OF BIRTH	Houaphanh province, Lao P.D.R
INSTITUTIONS ATTENDED	Chulalongkorn University