DETERMINATION OF CORRECTION FACTOR FOR DIFFERENTIAL RELAY SETTING ON DISTRIBUTION TRANSFORMER PROTECTION SYSTEM UNDER HARMONIC CONDITION

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by

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A	Cross Sectional Area of the Core
AC	Alternating Current
ASD	Adjustable speed drives
AFD	Adjustable Frequency Drives
ANSI	American National Standards Institute
B	Flux Density
CT	Current Transformer
CT_p	Current Transformer at Primary
CT_s	Current Transformer at Secondary
CFL	Compact Fluorescent Lamps
CF	Correction Factor
CTR	Current Transformer Ratio.
DC	Direct Current
DBR	Diode Bridge Rectifier
EHV	Extra High Voltage
e.m.f	Electromotive Force

f	Nominal Frequency
f_h	Harmonic Frequency
H	Magnetic Field Strength
HPS	Hammond Power Solution
Hz	Hertz
ICT	Information and Communication Technology
i_a	Sencondary Current of CTp
i_A	Secondary Current of CTs
i_o	Operating Current
I_h	Harmonic Current
I_1	Fundamental Current
I_A	Secondary Current of Power Transformer
I_a	Primary Current of Power Transformer
$I_{exci,p}$	Excitation Current of CT_p
$I_{exci,s}$	Excitation Current of CT_s
I_p	CT primary Current
I_{mag}	Magnetization Current

I_s	CT secondary current
IEEE-Std	Institute of Electrical and Electronics Engineers standard
I_S	Secondary Current
I_{sc}	Short Circuit Current
I_h	Harmonic Current Component
I_{mp}	Magnetization Current of CT_p
I_{ms}	Magnetization Current of CT_s
I_{s1}	Minimum Setting Differential Current.
I_{s2}	Transition Point From First to Second Slope.
$I_{prim, rating}$	Primary Current Rating
$I_{sec, rating}$	Secondary Current Rating
I_{sscmax}	Maximum Secondary Symmetrical Short Circuit Current
I_N	CT Secondary Nominal Current.
i_r	Restraining Current
IEC	International Electrotechnical Commission
I_F	Fault Current
I_{Fs}	Fault Current at Secondary
I_{base}	Based Current
I_F	Fault Current
kV	Kilo Volt
kVA	Kilo Volt Ampere
Kssc	Short Circuit Factor
K_{REM}	Remanent Flux Factor
KTF	Asymmetry Transient Factor

L_m	Magnetization Inductance
LV	Low Voltage
LTC	Load Tap Changer
MVA	Mega Volt Ampere
m_1	First Slope Setting.
m_2	Second Slope Setting.
n	Turns Ratio
N_p	Primary Number of Turns
N_s	Secondary Number of Turns
N_r	Restrain Winding
N_o	Operating winding
n_p	transformation ratio of CT_p
n_{sp}	number of secondary turn CT_p
n_{pp}	number of primary turn CT_p
n_s	transformation ratio of CT_s
OC	Over Current
OLTC	On Load Tap Changer

P_{Fe}	Magnetic Core Hysteresis and Eddy Current Losses
P_{SR}	Conduction Losses
PC	Personal Computers
PCC	Point of Common Coupling
PAVC	Phase Angle Voltage Controllers
PT.PLN	Perseroan Terbatas Perusahaan Listrik Negara (Indonesia Electricity Company)
PM	Power Meter
PC	Personal Computer
pu	Per Unit
RMS	Root Mean Square
R_{CT}	CT secondary resistance
RCF	Ratio Correction Factor
R_m	Magnetization Resistance
R_h	Conductor Resistance for h Order Frequencies
R_S	Secondary Resistance
R_B	Burden Resistance
SCR	Silicon Controlled Rectifiers
SLP_i	Slope of the *i-th* characteristic of the differential relay
S	Transformer Capacity
SCT_P	Secondary Current CT at Primary Power Transformer
SCT_S	Secondary Current CT at Secondary Power Transformer

THD	Total Harmonic Distortion
THD_i	Total Harmonic Distortion of current
THDv	Total Harmonic Distortion of voltage
TNB	Tenaga Nasional Berhad
TV	Television
T_{rtot}	Total Restraining Torque
T_{spring}	Spring Torque
T_o	Operating torque
UniMAP	Universiti Malaysia Perlis
u	Mean Length of a Turn
VA	Volt Ampere
V_S	Secondary Voltage
V_k	Knee Point Voltage
$V_{CTmax,}$	Maximum Secondary Internal e.m.f
V_s	CT Secondary terminal voltage
$V_{LL,prim}$	Line to Line Voltage of Primary Power Transformer
$V_{LL,sec}$	Line to Line Voltage of Secondary Power Transformer
V_{sat}	Saturation Voltage
V_h	Voltage Drop Across Impedance For Each Order Harmonic
V_C	Maximum Terminal Voltage the CT
V_{base}	Base Voltage
V_f	Fault Voltage
X	Reactance.
X_h	Reactance for h Order of Harmonic
$X_{L,h}$	Inductive Reactance for h Order of Harmonic

Z_B	Burden Impedance
Z_{S}	Total Secondary Burden
Z_{base}	Based Impedance

LIST OF SYMBOLS

Δ	Delta
Y	Wye
θ	Phase Angle
γ	Angle between I_{mag} and Secondary Voltage of CT
∞	Infinity Value
ϑ	Angle between Secondary Voltage and Secondary Current of CT
λ	Linkage Flux
λ_M	Linkage Flux Maximum
ε_t	Transformer Error
δ	Angular Error
μ	Magnetic Permeability
η	Graphically Determined Coefficient
δ_h	Harmonic Phase Difference
ε_h	harmonic Phase Angle Error
ω	Angular Frequency
β	Phase Angle Different between Primary Current and Secondary Current
ϕ_s	Saturation Flux
ϕ_R	Remanent flux
θ	Phase Angle Difference between Two Side Current Infeeds
δ	Phase angle error due to CT saturation

PENENTUAN FAKTOR PEMBETULAN BAGI PENGESETAN GEGANTI PEMBEZA PADA SISTEM PERLINDUNGAN PENGUBAH AGIHAN DI BAWAH KEADAAN BERHARMONIK

ABSTRAK

Dalam tesis ini satu kaedah baru dilaksanakan untuk mengatasi masalah terlepas-operasi geganti pembeza bagi pengubah kuasa agihan yang beroperasi di bawah keadaan berharmonik. Faktor pembetulan sebagai satu kaedah baru untuk mengatasi masalah ini telah diperkenalkan dan dilaksanakan bagi pengesetan geganti supaya geganti berfungsi dengan baik walaupun beroperasi dalam keadaan berharmonik. Dalam usaha untuk menentukan faktor pembetulan tersebut, kesan harmonik ke atas semua ralat komponen telah diperolehi melalui ujian makmal. Ujian tersebut telah dilaksanakan untuk menentukan ralat-ralat yang berlaku pada pengubah kuasa dan CT apabila beroperasi di bawah keadaan berharmonik. Dari ralat yang diperolehi maka ralat perbezaan arus yang mengalir melalui geganti telah ditakrifkan dan penetapan geganti pembeza juga telah ditentukan. Keputusan ujian untuk julat THD_i dari 4.6% hingga 40.88% menunjukkan bahawa ralat maksima yang berlaku pada CT di sisi sekunder pengubah kuasa didapati 27.21% dan CT pada sisi primer pengubah kuasa ialah 10.12%. Ralat maksima pada pengubah kuasa pula ialah 8.5%. Bagi THD_i yang sama, faktor pembetulan yang telah dilaksanakan ialah 30.14. Hubungan antara THD_i dan penetapan geganti pembeza telah dirumuskan melalui ralat arus perbezaan yang berlaku disebabkan oleh arus harmonik. Kaedah faktor pembetulan telah berjaya mengatasi masalah terlepas operasi geganti pembeza bagi pengubah kuasa agihan sehingga THD_i 40%.

DETERMINATION OF CORRECTION FACTOR FOR DIFFERENTIAL RELAY SETTING ON DISTRIBUTION TRANSFORMER PROTECTION SYSTEM UNDER HARMONIC CONDITION

ABSTRACT

In this thesis a new method is implemented to overcome the miss-operation problem of differential relay for distribution power transformer operates under harmonic condition. Correction factor as a new method to overcome this problem is introduced and implemented for the relay setting, so that the relay works properly even though operates under harmonic conditions. In order to determine the correction factor, the effects of harmonics to all components error has been obtained through laboratory test. The tests have been conducted to determine the errors that occur in power transformers and CT when operating under harmonic condition. From the error obtained, the differential current error flow through the relays was defined and differential relay setting was also determined. Experimental results for THD_i ranging from 4.6% to 40.88% show that the maximum errors occurred on CT at secondary power transformers is found to be 27.21% and CT at primary power transformers is 10.12%. The maximum error occurred at power transformer found to be 8.57%. For the same THD_i the correction factor which was implemented is 30.14. A relationship between THD_i and differential relay setting has been established through the differential current error occurred caused by harmonic currents. Correction factor method has able to overcome the miss-operation problem of differential relay for distribution power transformer up to 40% THD_i.

CHAPTER 1

INTRODUCTION

1.1 Background

The advancement of technologies in power electronics over the past decade, the application of power electronics in industrial, commercial, office premises, educational institutions and residential areas have increased. Power electronic equipments are usually producing harmonics due to its switching devices known as nonlinear load. Nonlinear loads are broadly classified as loads, which draw non-sinusoidal current even when the supply voltage is perfectly sinusoidal. These load use power semiconductor like diodes, silicon controlled rectifiers (SCR), power transistors, power mosfet, insulated gate bipolar transistor, etc. Because of their extraordinary gains in efficiency and control, power electronics loads are expected to be significant in the future. Currently, power electronic loads can be found at all level of power system, ranging from low voltage appliances up to a high voltage converter. Non-linear devices now typically comprise more than 50%, and in some cases as much as 90% of total load in the premises [Aeillo et al., 2005]. Therefore, most likely some important distribution transformers will operate in high harmonics. Heavy use of power electronic equipment in the industrial, commercial and office premises can lead to considerable distortions in the distribution feeder. The higher harmonic distortion level in the distribution system has caused a serious problem in power system quality and stability [Medina and Martinez, 2005]. The distortion of sinusoidal voltage and current waveforms caused by nonlinear load is one of the major power quality concerns in distribution system.

Increased levels of harmonic currents in distribution systems, creates concern for electricity distribution network service providers that will face malfunction in protection system components. During fault and normal conditions, the harmonic in distribution system might cause miss-operation of protection relay as well as relay calibrations become inaccurate. Other effects of harmonic currents in distribution systems are to customers who have equipment sensitive to voltage and current distortion.

1.2 Problem Statement

Harmonics distortion can have both short-term and long-term effects on distribution system equipments and connected customer loads. Short-term effects are mainly concerned with immediate damage, equipments malfunction, and the associated power losses due to harmonic current and voltage. Long-term effects are thermal losses and reduced life span of equipments.

Harmonics current and voltage can distort or degrade the operating characteristic of protective relays which is depending on the design features and principles operation of the relay [Schweitzer and Daqing, 1993]. The differential protection systems may be subjected to a miss-operation due to the presence of voltage and current harmonics [Arrillaga et al., 1997], [Kennedy and Barry, 2000], [Sankaran, 2002]. Differential relay will become less sensitive for internal fault if working frequencies are not at fundamental frequency. Besides that, the harmonic current can increase differential current during normal condition so that the differential protection might miss operates for external fault or normal conditions.

High content of harmonic currents in power distribution systems will lead to the phenomenon of saturation of current transformers that can cause some errors in the operation of differential relays. The current transformer (CT) errors are strongly influenced by the waveform of the primary current. Harmonic current distortions are strongly affects the value of percentage secondary current error. The error signal produced by CT will be sent to the differential relay and make relay to mis-operations. Besides that, harmonic distortion may change the tripping current of differential relay as total harmonic distortion (THD) varies for the frequencies and when the frequencies continues increase will cause the relay trip for any current values. The most important thing is that the tripping time would be delayed if the harmonics enter into the equipments.

Typically, delta-star transformer connection is used in distribution system. Star connection is connected to the loads, this is due to requirement of neutral point for single phase load and delta connection is connected to the supply. In each node of the delta connection, the zero sequence harmonic currents compensate for one another, and the current in the line therefore contains no zero sequence harmonics current. Zero sequence harmonics current do not normally propagate into the higher voltage levels of the distribution system. Instead, these currents trapped in the delta primary windings and therefore cause an additional temperature rise, increasing transformer losses and change the power transformer current ratio that may effect to operation of differential protection.

In addition, due to the zero sequence harmonics trapped in the delta winding will result in different levels of percentage harmonic distortion on both sides of the power transformer. This will cause the difference level of CT saturation that are installed on both sides of the power transformer that could lead the differential currents to flow under normal conditions.

1.3 Significant of this Research

The important of protection system is to keep the power system stable by isolating only the components under fault or normal conditions, whilst leaving as much of the network as possible still in operation. Transformer as an essentials component in power system needs to be properly protected to avoid power system failure. One of the protection systems that were used in a power transformer is differential protection. Differential protection is a main protection for large power transformers or some important power distribution transformers with capacity less than 10 MVA [Ho and Liu, 2001]. The importance of distribution transformers is distribution transformers are used for special loads that require continuity of supply such as hospital, important government buildings and industry with very sensitive to power disconnections. For the purposed of this protection the differential relay provides the fastest and most secure type of protection [Arrillaga et al., 1997], [Kennedy and Barry, 2000].

One of the requirement in electrical system design is to meet the recommended levels set out in IEEE- Std 519-1992, IEEE recommended practices and requirements for harmonic control in electrical power system [Sachdev, 1997]. This standard sets out the limits for voltage and current harmonic levels at different points in the electrical system [McLaren et al., 2001]. However, the advanced technologies in power electronics development over the past decade, the application of power electronics in distribution systems has lead to the harmonic distortion for the load voltage and load current exceeding the standards set above [Hayward, 1941].

The sources of harmonic emissions in the distribution system not only commercial, office and residential loads, but also come from distributed generation installations and the component of power system itself. Saturated magnetic circuits such as those in power transformers and rotating machines are also harmonic sources in the distribution system.

Differential relay for power transformers must maintain basic operations under harmonic condition to provide excellent protection and reliability required by the power transformer. The current harmonics and voltage harmonic can distort or degrade the operating characteristic of current transformer and protective relays [Hayward, 1941]. Therefore, the response of the current transformer and differential protection relays to distorted current or voltage must be studied clearly.

Current transformer as one component in protection system plays a very important role in transformer differential protection. The proper operation of a current transformer as a part of protection component is very important because protection relay will receive signal from current transformer. However, current transformer does not perform well when operating under harmonic condition. Thus, the percentage of CT errors for different harmonic levels must be known clearly. If the current transformer is excited by nonlinear current will result to current transformer error. If protection relay receive the improper signal from current transformer will cause malfunction operation of protection relay. These relays are calibrated based on sinusoidal currents and their response to harmonic distortion is not well known. In order to adequately prepare for harmonic increment in the future, the reliability of transformer differential protection operates under harmonic condition must be studied clearly. Besides that, it is very important to evaluate the existing relay setting to accommodate the differential current error due to harmonic distortion in the distribution system.

Generally, protective relays has been designed for sine wave operation and their performance is not specified for other waveforms. The performance of differential relay for a transformer protection when operated under non-sinusoidal condition cannot be predicted without a detailed knowledge on current transformer and relay. For this reason the evaluation of the behavior of current transformer and differential relay when operates under harmonic condition become significant and necessary task in this research.

1.4 Objectives of the Research

The aim of this research is to ensure the differential relay used for distribution transformers protection does not operate if there is no internal fault, even though operating under harmonics condition.

1. To obtain the percentage magnitude current errors that occurs in power transformers and current transformers when operated under harmonics condition. This is necessary because the ratio current error on current transformer and power

transformer will result in the current imbalance on both sides of power transformers, although under normal condition.

2. To determine the correction factor for differential relay settings to make the relay works properly if there are imbalances current exist caused by harmonic distortion.

3. To implement the correction factor on differential relay setting operates under harmonic conditions, so that the differential relay operates correctly.

1.5 Scope of Research

This research introduced a new method known as the correction factor to increase the reliability of the differential relay used as a distribution transformer protection operating under harmonic condition. The performance differential relays will not be assessed for harmonic voltage because the harmonic voltage in the distribution system is very low or some time can be equal to zero. In this thesis, the performance differential relays will be assessed when the relay is operating under harmonic current conditions and considered the three phase system is balanced. To assess the performance of the differential relay for transformer protection, a power transformer with a capacity of 5.75kVA was used in this research. In addition, this study also has used the CT ratio 15/1A with 5VA rated load. To determine the errors that occur when the CT operates under harmonic current condition, a frequency response and actual tests was performed for 15/1 class1 CT with connected to relay. As for determining the error ratio of the distribution transformer due to harmonics, the distribution transformer will be tested with varying levels of THD_i. Due to errors accommodation that have occurred either at the distribution transformer or current transformer, there will be errors of the differential relay operation. To overcome this problem it is necessary to determine the correction factor for differential relay setting. Correction factor will be determined based on the error that occurred in the differential currents for a certain level of THD_i.

1.6 Thesis Structure

This thesis is divided into five chapters. The first chapter is concerned with the introduction of research as well as the problems faced by the differential protection system when operates under harmonics condition. This chapter is discussing about the importance and the purpose of the research to be done in the area of transformer differential protection. The scope of this research is also discussed in the final section of chapter one.

The second chapters discuss the research that have been done on the current transformer, differential relays and harmonics that have occurred in distribution systems. In the initial portion is to learn about the basic concepts of the current transformer, current transformer errors, accuracy limit of protection class CTs and steady state behavior of a CT. The detail theory of differential protection, harmonic distortion, effects of harmonic on current transformer and differential protection also presented in chapter 2. The effects of harmonics on current transformers, nonlinear model of current transformer, calculation of current transformer error and current transformer accuracy requirements for differential relays are also discussed in chapter 2.

While Chapter 3 is dedicated to the description of the approach and steps required to complete the research. Considerations of designing differential relay for delta-wye transformer connection as well as the stability boundary for differential safety during CT saturation are also studied in this chapter. In the final portion of this chapter, the imbalance current produced by tap changing, phase shift through the delta-wye transformer, zero sequence harmonic and effect of harmonic distortion on differential protection system are discussed. The working principle of differential protection relay for power transformer is also discussed in the earlier portion of this chapter.

Experiments on the effects of harmonics on current transformer behavior have been described in chapter 4. The effects of CT saturation on differential relays are also discussed. In this chapter the frequency response test of the current transformer with different burden is also discussed. In frequency response test, the frequency of input CTs were varied, ranging from 50Hz up to 1050Hz. In addition the CTs were tested with real situation, where the CTs were connected to the nonlinear load with different current THD_i.

Laboratory tests for a transformer differential protection system have been implemented and discussed in chapter 5. In this test the delta-wye connection power transformers was used. Differential relay which is connected perfectly to the power transformer has been tested with various levels of THD_i ranging from 0% to 70%. For the purposed of this research, the differential relay has been set with regular setting and was also set with correction factor. The performance of differential protection with two type of setting is also presented in this chapter.

Eventually the whole contents of this thesis is summarized and concluded in Chapter 6. The advantage of using a correction factor for the differential relay which operates in harmonics circumstance also highlighted in these conclusions.

1.7 Thesis Constributions

The following are the contributions of this thesis to the field of protection of distribution transformers.

The use of a correction factor for the differential relay settings can be apply for distribution transformers protection that are used in the industry. Because most of industrial loads is nonlinear load and probability of the differential protection system failure is very high. By using this correction factor the differential protection system failure can be overcome.

In addition, the use of this correction factor can be a new method for differential relay settings that are used in the power system, so that the relay may work properly when operating under harmonic conditions.

CHAPTER 2

LITERATURE REVIEW

2.1 Power Distribution System

Power authority as Tenaga Nasional Berhad (TNB) in Malaysia is to provide quality electrical services to consumers, such as provided a good quality power supply to the customer's houses, offices, and industrials. However, the task to maintain a good quality of power for the time being is not easy because there are several factors need to be consider, such as during peak demand, generating aspects and load characteristics of the consumers.

Voltage level of Malaysia's distribution system starts at 33 kV and to be stepped down by distribution transformer to 11 kV and eventually to 415/ 240 volts. At several places, 22 kV and 6.6 kV levels are still employed, according to load of consumers. Transformer on-load tap changers is used at main intake substations to hold the primary distribution voltage constant, as well as system's frequency at 50 Hz with maximum and minimum tolerance of 0.5 Hz. There are two types of systems currently for distribution of electricity; the first is secondary low voltage (LV) system (415/240V) which uses a 3 phase, 4 wire, with the neutral solidly grounded at the source substations. Both overhead and underground lines are used for LV distribution[TNB, 2007]. Primary distribution system (33 kV to 6.6 kV) uses 3-phase, 3 wire network configuration, and it is either solidly grounded or grounded through the impedance. The declared voltage at consumers' meters is stated as 415/ 240 Volt with allowable variation of 5% maximum and minimum of 10%. The margin is set due to fluctuation nature of power supplied by the authority due to various reasons [Sulaiman, 2004]. Single line diagram of distribution system is shown in Figure 2.1.

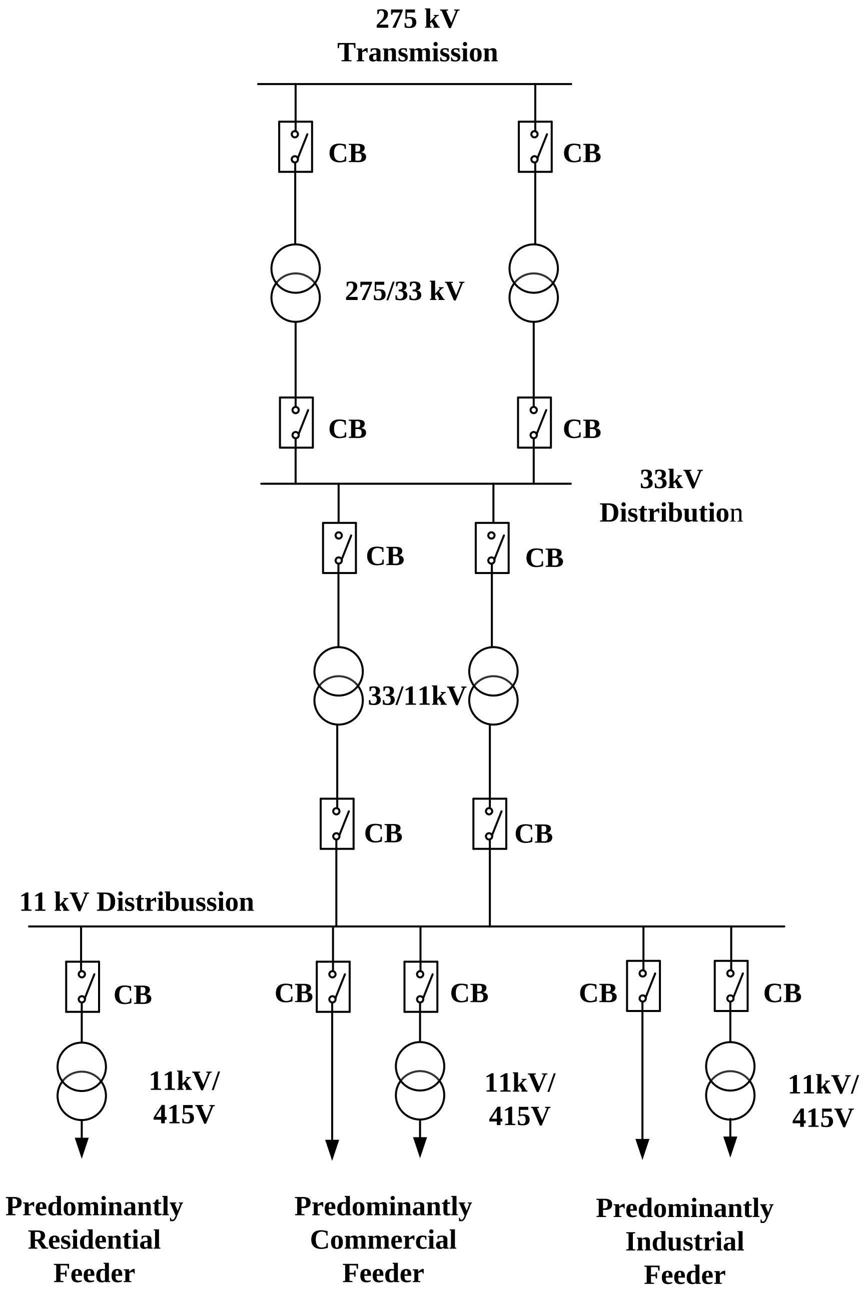

Figure 2.1: Single line diagram of power distribution system.

2.2 Harmonic in Power Distribution System

Harmonics are defined as sinusoidal waveforms of current or voltage, with frequencies that are integer multiples of fundamental power system frequency. For instance, in a system with fundamental frequency of 50Hz, sinusoidal current that contain frequency of 150Hz is called the 3rd harmonic current. Harmonic has detrimental effects on power distribution system and among the effects is will lead to the phenomenon of saturation of CTs that can cause some errors in the operation of differential relays. Modern industrial power systems, commercial buildings, industrial buildings, educational institution buildings and residential areas usually contain various types of nonlinear loads that will inject harmonics in to the distribution system. Increased penetration of non-linear loads in power distribution systems, utilities and manufacturing equipment resulted in an increased fear of harmonic distortion. Harmonic distortion is known to have many adverse effects on power systems and consumers, especially in areas where electricity is being liberalized trade. Therefore there is the worry that the harmonic distortion will increase in the near future.

For THD_i under 10% and in normal situation, then there is no risk of malfunctions of power system component. But, if THD_i ranging in between 10% to 50% it is significant harmonic pollution with a risk of temperature rise and the resulting need to oversize cables and sources. While if THD_i higher than 50% it is considered as major harmonic pollution and malfunctions of power system component are probable. In-depth analysis and the installation of attenuation devices are required [Schneider Electric, 2009].

2.2.1 Harmonic Components

Non sinusoidal periodic function *f(t)* in an interval of time (T) could be represented by the sum of fundamental component and a series of higher orders harmonic component at frequency (*f*) which are integral multiples of the fundamental component. Using Fourier series representation, a distorted waveform can be analyzed by equation below:

$$f(t) = A_0 + \sum_{h=1}^{\infty} [A_h \cos(h\omega t) + B_h \sin(h\omega t)] \tag{2.1}$$

$$f(t) = A_0 + \sum_{h=1}^{\infty} [C_h \cos(h\omega t + \theta_h)] \tag{2.2}$$

A_h and B_h is Fourier series coefficient.

Fundamental angular frequency, $\omega_1 = 2\pi f_1$, f_1 is the fundamental frequency, typically 50 Hz and period is $T = \frac{1}{f_1} = \frac{2\pi}{\omega_1}$. $C_1 \cos(\omega_1 t + \theta_1)$ represents of fundamental component, and $C_h \cos(h\omega t + \theta_h)$ represents the h^{th} harmonic component of amplitude C_h, frequency $h\omega_1$ and phase θ_h relative to the fundamental.

Generally for power system, fundamental frequency is 50 Hz or 60 Hz. Malaysian power systems are typically operated at 50 Hz and thus harmonic frequencies will appear as multiplies of 50 Hz such as 150 Hz, 250 Hz, 350 etc. The Fourier series coefficient C_1, C_2, …, C_h make up the harmonic spectrum of the waveform and are found using equations:

$$A_o = \frac{1}{T}\int_0^T f(t)dt = \frac{1}{2\pi}\int_0^{2\pi} f(t)dx \tag{2.3}$$

$$A_h = \frac{2}{T}\int_0^T f(t)\cos(h\omega_0 t)dt = \frac{1}{\pi}\int_0^{2\pi} f(t)\cos(hx)dx \tag{2.4}$$

$$B_h = \frac{2}{T}\int_0^T f(t)\sin(h\omega t)dt = \frac{1}{\pi}\int_0^{2\pi} f(t)\sin(hx)dx \tag{2.5}$$

$$A_h = \frac{2}{T}\int_0^T f(t)\cos(h\omega t)dt = \frac{1}{\pi}\int_0^{2\pi} f(t)\cos(hx)dx \tag{2.6}$$

$$C_h = \sqrt{A_h^2 + B_h^2} \tag{2.7}$$

$$\theta_h = \tan^{-1}(\frac{A_h}{B_h}) \tag{2.8}$$

Conversely, if the harmonic spectrum of a given current or voltage waveform $f(t)$ is known the original waveform can be constructed using the Fourier series summation:

$$f(t) = \sum_{h=1}^{\infty} U_h \cos(h\omega t + \theta_h) \tag{2.9}$$

Where U_h is the h$^{\text{th}}$ harmonic peak current or voltage, θ_h is the h$^{\text{th}}$ harmonic phase. Based on Fourier analysis, non-sinusoidal current will consist of fundamental current and current component containing harmonic, which is expressed as [Mohan et al., 2003]:

$$i_s(t) = \sqrt{2}I_{s_1}\sin(\omega_1 t - \theta_1) + \sum_{h\neq 1}^{\infty}\sqrt{2}I_{sh}\sin(h\omega t - \theta_h) \tag{2.10}$$

Where:

i_s is line current

I_{s1} is RMS value of fundamental component

I_{sh} is RMS value harmonic component order h

h is harmonic order

Theoretically, h order harmonic current magnitudes is inversely proportional to the harmonic order, are:

$$I_h = \frac{I_1}{h} \tag{2.11}$$

Thus, the current from a single phase electronic load will consist of the fundamental current I$_1$ and harmonic components of a number of I$_{sh}$. Since the line current I$_s$ alternating wave-shaped symmetrical, only the odd-order harmonic current components are generates. Fourier series expression of a periodic non sinusoidal current can be simplified as the following:

$$\begin{aligned} i(t) = I_1 \sin(\omega t) + I_3 \sin(3\omega t) + I_5 \sin(5\omega t) + ... + I_n \sin(n\omega t) + \\ I_{n+1} \sin((n+1)\omega t + ... \end{aligned} \tag{2.12}$$

Equation (2.13) shows how to find the root-mean square (RMS) value of a current waveform where the RMS value of each of the harmonics, I_h, is known.

$$I_{RMS} = \left[\sum_{h=1}^{N} (I_h)^2 \right]^{1/2} \tag{2.13}$$

2.2.2 Total Harmonic Distortion

One measure of distortion in a waveform is given by (2.14) and called total harmonic distortion (THD). THD current (THD$_i$) is the ratio of the RMS value of the total harmonic currents (non fundamental part of the waveform) and the RMS value of the fundamental portion, I$_1$, of the waveform. This value is usually expressed as a percentage of the fundamental current.

$$THD_i = \frac{\left[\sum_{h=2}^{\infty} (I_h)^2 \right]^{1/2}}{I_1} x100\% \tag{2.14}$$

Two other measures of distortion are the crest factor and the form factor. The crest factor is the ratio of the peak of a waveform to its RMS value. For a linear sinusoidal waveform, the crest factor would be the square root of 2, or 1.414.

$$Cress\_factor = \frac{I_{peak}}{I_{RMS}} \tag{2.15}$$

The form factor, or distortion factor, is the ratio of the RMS value of a waveform to the RMS of the waveform's fundamental value, I_1. For a linear sinusoidal waveform, the form factor would be 1.0 [Ho and Liu, 2001].

$$Form\_factor = \frac{I_{RMS}}{I_1} \tag{2.16}$$

2.2.3 Harmonic Sequences

One of parameters regarding harmonics that essential to look into is the sequences. All electronic loads generate positive and negative sequence harmonic currents. Single-phase electronic loads, connected phase to neutral in a three-phase four-wire distribution system, also generate zero sequence harmonic currents. The harmonic currents and voltages produced by balanced three phase non-linear loads are positive sequence harmonics (phasors displaced by 120 degrees, with the same rotation as the fundamental frequency), and negative sequence harmonics (phasors displaced by 120 degrees, with a reversed rotation). However, harmonic currents and voltages produced by single phase, non-linear loads, which are connected phase to neutral in a three phase four wire system are third order zero sequence harmonics (the third harmonic and its odd multiples 3rd, 9th, 15th, 21st, etc., phasors displaced by zero degrees). These third order, zero sequence harmonic currents, unlike positive and negative sequence harmonic currents, do not cancel but add up arithmetically at the neutral bus [Hammond Power Solution, 2013].

The following relationships are true for the fundamental frequency current components in a three phase power system:

$$i_{a1} = I_{a1} \sin \omega t \tag{2.17}$$

$$i_{b1} = I_{b1} \sin(\omega t - 120^o) \tag{2.18}$$

$$i_{c1} = I_{c1} \sin(\omega t - 240^o) \tag{2.19}$$

The negative displacement angles indicate that the fundamental phasor i_{b1} and i_{c1} trail the i_{a1} phasor by the indicated angle. The fundamental frequency is known as positive sequence harmonics. The expression for the third harmonic current are:

$$i_{a3} = I_{a3} \sin 3\omega t \tag{2.20}$$

$$i_{b3} = I_{b3} \sin 3(\omega t - 120^o) = I_{b3} \sin 3\omega t \tag{2.21}$$

$$i_{c3} = I_{c3} \sin 3(\omega t - 240^o) = I_{c3} \sin 3\omega t \tag{2.22}$$

The expression for the third harmonic show that they are in phase and have zero displacement angles between them. The third harmonic is known as zero sequence harmonics due to the zero displacement angles between the three phasor. In the three-phase four-wire distribution power system, the three-phase zero-sequence currents (i_{a0}, i_{b0}, i_{c0}) have the same amplitude and the same phase, and they can be represented as: $i_{a0}(t) = i_{b0}(t) = i_{c0}(t)$. The neutral current ($i_n(t)$) is the sum of three-phase zero sequence currents, and it is represented as $i_n(t) = 3i_{a0}(t)$ [Hurng et al., 2005].

The expression for the fifth harmonic current are:

$$i_{a5} = I_{a5} \sin 5\omega t \tag{2.23}$$

$$i_{b5} = I_{b5} \sin 5(\omega t - 120^o) = I_{b5} \sin(5\omega t - 240^o) \tag{2.24}$$

Table 2.1: Harmonic order vs Phase sequence.

Harmonic Order	Sequence
1, 4, 7,10, 13, 16, 19 = $(3m + 1)^{th}$	Positive
2, 5, 8, 11, 14, 17, 20 = $(3m - 1)^{th}$	Negative
3, 6, 9, 12, 15, 18, 21 = $(3m)^{th}$	Zero

$$i_{c5} = I_{c5} \sin 5(\omega t - 240^o) = I_{c5} \sin(5\omega t - 120^o) \tag{2.25}$$

The phase sequence for the fifth harmonic current is clockwise and opposite to the fundamental. So, the fifth harmonic is known as negative sequence harmonics. Table below categorizes the harmonics in term of their respective sequence orders.

2.2.4 Harmonic Sources in Distribution System

Sources of harmonics in the secondary distribution system are modern housing loads. These loads usually contain various types of nonlinear loads that will inject harmonics to the distribution systems [Cotten et al., 1989]. In general, the main source of harmonics in distribution systems can be categorized as follows [Chang and Liu, 2003]:

1. Devices that generate harmonics during their switching processes. The most commonly seen are power electronic devices, such as rectifiers or switch mode power supplies used primarily for house entertainments units and home office equipments like computers, television sets, home theaters, communication equipments and other electronic devices.
2. Adjustable speed drives (ASD) and adjustable frequency drives (AFD) for residential applications such as compressors and fans in heat pumps, air conditioners, and refrigerators.

3. Devices such as rotating machines that harmonics are generated because of non-sinusoidal flux distribution in the stator and the harmonic interaction between the stator and field windings.

The poor power factor of the testing fixture is caused mostly by the inductive impedance of the electromagnetic ballast and partly by the harmonic distortion. The most simple and cost effective method for solving this problem is to parallel an external capacitor to the fixture. However, the added capacitor and the inductance of the transformer circuit will form a resonant circuit. This resonance will exaggerate the harmonic distortion at some specified frequencies. Therefore, the harmonics near the resonant frequency may significantly increase [Chang et al., 1993].

The most common load at secondary distribution systems are industrial, commercial, educational institution and residential loads. These loads that produce harmonic can be broadly divided into three groups. The first group contains those loads that utilize the single-phase capacitive-filtered diode bridge rectifier (DBR). These loads may be defined as an AC to DC converter such as the input stage found in ASD’s, battery chargers, Personal Computers (PC’s), color TV’s, etc. Color television and personal computer or laptop is a major source of harmonics in this loads group. From the television set that has been measured found that the current waveform has contains of high harmonics with THD_i of 266.58%, while the voltage waveform seem only too well sinusoidal. The growth application of these loads in distribution system is also increased the harmonic level. The pulsed current waveform generated by this loads is rich in harmonic and THD_i reaches more than 100% [Mori and Suga, 1991], [Don and Carter., 1997]. Microwave ovens, battery chargers and small adjustable speed drive (ASD) for heat pumps are also includes in this group [Arrillaga et al., 1997], [Kennedy and Barry, 2000], [Sankaran, 2002].

The second load group contains the compact fluorescent lamps (CFL) that employ magnetic and electronic ballast. The CFL has three categories; high distortion electronic ballast, low distortion electronic ballast and magnetic ballast. Because of the non-linearity inherent in the semiconductor devices used in the electronic ballast (as well as other power electronic devices), the input current waveform will have some harmonic distortion [Rory and Afroz, 1995]. There are many gas discharge lamps used for lighting at residential and commercial building. A study by [Emanuel et al., 1992] evaluated the impacts of high distortion CFLs on typical distribution system. The results indicated that relatively low CFL penetration levels could cause the feeder voltage distortion to exceed 5%. The third harmonic is the most dominant a three-phase four-wire systems. Due to the non-linearity of the gas discharge, these lamps are considered as a significant harmonics contributor to the power system [Kennedy and Barry, 2000].

The third load group contains those loads that employ the phase-angle voltage controllers (PAVC). This device controls the input AC voltage and power utilizing the phase control of thyristors. The major loads appear in this group are heaters, light dimmers, single-phase induction motor control and refrigerator. These controllers produce waveforms with substantial harmonic content. The air conditioner is widely used at offices, hotels or housing on the tropical area. Therefore, the use of air conditioner is able to increase the harmonics distortion on power distribution systems. The electric motor that controlled by electronically has been used to drive the compressor on the air conditioner system. Electric motors controlled by static converter are also source harmonic in distribution system [Cataliotti et al., 2008].

Low-power diode rectifiers with smoothing DC capacitors are increasingly being used in consumer electronic equipment. Harmonics generated by these diode rectifiers have become a major problem in recent years. Other typical harmonic producing loads are thyristor converters in which a large inductance is installed on the DC side to produce a constant DC current. Because the impedance on the DC side for harmonics is much larger than that on the AC side, the harmonic current contents and characteristics are less dependent upon the ac side [Aiello et al., 2005].

Another typical harmonic source is diode rectifiers with smoothing dc capacitors. Generally, the impedance of capacitors becomes smaller at higher frequencies. Connecting a large capacity of capacitor to the DC side diode rectifier causes much lower impedance for harmonics. The amplitude of harmonic currents on the AC side is greatly affected by the impedance of the AC side. Therefore, a diode rectifier as shown in behaves like a voltage source rather than a current source [Aiello et al., 2005].

From the measurement of gas discharge lamp was found that current waveform 20 watt tube lamp with electronic ballast has a THD_i of 199.1%, while voltage waveform contains no harmonics. Next is the waveform of the 11-watt lamp 3U super light and super 18-watt spiral lamp light. Both lamps are recognized as the energy saving lamp. A 3U 11-watt super light lamp has a THD_i of 215.9% while the lamp 18-watt spiral super light lamp has THD_i of 219.08%. From the results of these measurements can be concluded that the electrical equipment used at home has huge potential to contribute harmonic to the distribution system.

2.2.5 Harmonic Measurement in Distribution System

To know the harmonics phenomenon on distribution system several harmonic measurements that have been published in some publications are reviewed in this chapter. The voltage THD (THDv) at American Electric Power Distribution System ranged from 1% to more than 5% and was dominated by the 5th harmonic. Beside that in this survey have reported the voltage distortion values at residential load were below 1% during the daytime hours, while voltage distortion factor at commercial load averaged between 1.92% and 2.44%. The current distortion factor averaged between 2.76% and 3.13%. The third harmonic was the dominant component [Shuter et al., 1989].

The voltage distortion factor at distribution circuit serving an industrial park was exceeded 1.3% in 90% of the measurements and exceeded 2.6% in 5% of the measurements. The average voltage distortion factor was 2.15% and 2.53% at the customer and station sites, respectively. The fifth harmonic dominated the voltage and current distortion factors [Shuter et al., 1989].

The voltage distortion factor for circuit which serves a combination of residential and commercial loads in 90% of the measurements, it exceeded 1.2%, and in 5% of the measurements, it exceeded 2.1%. The voltage distortion factor for circuit serving a mix of residential and commercial loads averaged between 1.68% and 2.79% [Shuter et al., 1989]. Maximum and average values of voltage and current distortion of 1120 spot measurements on the Sierra Pacific Power Co at 120V are given and the results suggest a 95% THDv of 3% [Amoli and Forence, 1990].

The THDv at one week measurements on the sending end of 5 New England Power Service Co feeders ranging 15-25 kV with samples taken every 3 minutes was found to be 1.2% [Emanuel et. al., 1991]. Later phases of the project are reported in [Emanuel, 1993] and [Medina and Martinez, 2005] concluding that THD_v is increasing at 0.1% per year. Hughes et al., has gives voltage measurements at the 120V service entrance of some BC Hydro customers over a week. Residential, Commercial and Industrial customers were found to have 95% THDv values of 2.9%, 1.9% and 3.9% [Hughes et al, 1991].

The harmonic voltages and currents were monitored at the sending end of distribution substations and each feeder supplies commercial, residential and industrial loads. At all the monitored locations it was found that 99% of the time the THDv is smaller than 2%. For the four feeder that has been monitored was found that the harmonics on some feeders has been exceeded the THD_i limit, while the other feeders are still below the set limit [Emanuel et al., 1991].

Monitoring at retail store equipped with a 5 kW photovoltaic inverter and modern electronic ballasts for the fluorescent lights was found that 99% of the time the THDv was much smaller than the 5% limit recommended by IEEE Std. 519. It is shows that the maximum voltage distortion and harmonics recorded during this survey. The fifth harmonic voltage was found to always the dominant harmonic, the largest value monitored being 2.2% at the mains of the accounting operation building