A NEW DESIGN OF THREE PHASE TRANSFORMER UNDER NONLINEAR LOAD CONDITION

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A NEW DESIGN OF THREE PHASE TRANSFORMER UNDER NONLINEAR LOAD CONDITION

By

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LIST OF SYMBOL

θ	Angle
ω	Angular
Δ	Difference
R_c	Core Resistance
R_1	Primary Resistance
R_2	Secondary Resistance
Z_T	Transformer Impedance
X_T	Transformer Reactance
X_m	Magnetizing Inductance
η	Efficiency
Ω	Ohm
μ	Permeabiliy
π	Pie
ρ	Statis Resistivity
$\sum$	Sum

LIST OF ABBREVIATION

$\mathcal{R}$	Reluctant
A	Area
A_t	Effective area
AWG	American Wire Gauge
B	Flux density
f	Frequency
h	Harmonic order
I	Rms current
$i(t)$	Instanteneous current
i_h	Harmonic current
P_C	Transformer core Loss
P_{COP}	Transformer copper loss
$P_{EC,C}$	Transformer core eddy current loss
$P_{EC,W}$	Transformer winding eddy current loss
$P_{H,C}$	Transformer core hysteresis loss
P_{LL}	Transformer load loss
P_{NL}	Transformer no load loss
P_{OSL}	Transformer other stray loss
P_T	Total transformer loss
T	Temperature
t	Time
THDi	Total Harmonic Distortion in Current
V	Voltage
VA	Volt-Ampere (Transformer capacity)

REKABENTUK BAHARU PENGUBAH TIGA FASA DI BAWAH KEADAAN BEBAN TIDAK LINEAR

ABSTRAK

Penggunaan beban beban tidak linear seperti peranti elektronik menyebabkan arus pada sistem pengagihan kuasa terherot dan mengandungi harmonik. Kesan arus harmonik ini ialah pemanasan lampau kepada pengubah yang terdapat pada sistem pengagihan kuasa. Pemanasan lampau ini adalah disebabkan oleh peningkatan pada kehilangan kuasa tembaga pada dawai lilitan dan kehilangan kuasa teras (histerisis dan arus eddy). Akibatnya berlaku kemerosotan penebat dan risiko kerosakan kekal pada pengubah (terbakar).Penyelesaian semasa berkenaan permasalahan ini ialah pengurangan dan penambahan kapasiti pengubah and pengurangan beban pengubah. Ini memberikan ruangan yang lebih untuk menampung kesan arus harmonik. Tesis ini mengutarakan satu rekabentuk baharu pengubah tiga fasa tanpa mengubah kapasiti. Ini boleh dicapai dengan pensaizan semula dawai lilitan dan teras. Pengubah yang direka adalah khas untuk muatan beban tidak linear dengan kandungan arus harmonik (THD_i) sebanyak 40%. Kaedah pensaizan semula dilakukan pada bahan pengubah iaitu dawai lilitan dan teras magnetik supaya pertambahan kehilangan akibat arus harmonik dapat ditampung. Ini juga dapat mengurangkan kehilangan tembaga pada dawai lilitan dan kehilangan histeris pada teras pengubah. Teknik pensaizan semula ini berasaskan kepada suatu penentuan faktor pensaizan yang merupakan fungsi THD_i yang berkadar terus kepada suhu operasi julat pengubah. Ianya adalah pengkadaran antara suhu pengoperasi pengubah dibawah beban tidak linear. Hasil eksperimen terhadap sebuah pengubah tiga fasa 2 kVA, 415V, 50Hz diperolehi faktor pensaizan untuk dawai lilitan ialah 0.012 dan 0.075 untuk teras. Dengan penggunaan faktor pensaizan yang ditemui, satu pengubah baru telah direkabentuk dengan saiz dawai lilitan AWG 19 dan teras berdimensi 1358sm^2. Ianya mampu menampung kelebihan kehilangan kuasa pengubah akibat arus harmonik sebanyak 40% THD_i pada suhu operasi julat 55°C. Kaedah rekabentuk ini boleh ditambahbaik dengan mengambil kira pemilihan bahan teras yang mempunyai kebolehtelapan yang lebih tinggi sehinggakan dimensi rekabentuk pengubah menjadi lebih kecil (lebih ekonomi).

A NEW DESIGN OF THREE PHASE TRANSFORMER UNDER NONLINEAR LOAD CONDITION

ABSTRACT

Usage of nonlinear loads such as electronic device causes current at power distribution system to be distorted and contains harmonic. Effect of current harmonic is overheating of transformer at power distribution system. Overheating is caused by the increase of copper power loss at winding wire and core power loss (hysteresis and eddy current). As result insulation is degraded and risk of permanent malfunction at transformer (burn). Existing solutions regarding this problem is by reducing and increasing transformer capacity and the reduce of transformer loading. This gives bigger area to sustain effect of current harmonic. This thesis proposes a new design three phase transformer without changing of capacity. This can be achieved by resizing of winding wire and core. This transformer is specially design for nonlinear loading with current harmonic content (THD_i) of 40%. Resizing method is performed at transformer material of winding wire and magnetic core in order to sustain the additional loss caused by current harmonic. It also reduces copper loss at winding wire and hysteresis loss at transformer core. Resizing technique is based on the determination of sizing factor with the function of THDi that is proportion to rated transformer operating temperature. It is the ratio between transformer operating temperatures under nonlinear loading. Experimental result on a three phase 2 kVA, 415V, 50Hz transformer yields sizing factor of 0.012 and 0.075 for winding wire and core respectively By utilizing the determined sizing factor, a new transformer is designed with winding wire AWG 19 and core with dimension 1358cm^2. It is able to sustain additional transformer power loss caused by current harmonic as much 40% THDi at rated operating temperature 55°C. This design method can be improved by considering selection of material with higher permeability to the extent design dimension of transformer is made smaller (more economical).

CHAPTER 1

INTRODUCTION

1.1 Background

In general, sources of power system come from combinations of plants utilizing oil fired thermal, gas turbine, hydro and mini hydro, diesel, and combine cycle plants. Advance nations opt for nuclear generated plants and renewable energy sources such as wind turbine, and solar farming. Through several stages of transmission lines, power system reaches intended consumer through segregations of voltage levels that varies in accordance to demands. Main transmission network often involves 66kV – 500kV voltage levels, while distribution stage includes 33kV downwards until household level of 415/240V(Sulaiman, 2004). At the consumer end, distribution of electricity is separated to primary and secondary system. A single primary distribution system is capable in feeding several secondary distribution systems. Secondary distribution system serves residential and commercial consumers, with variations of load types. Power distribution transformers are important equipments in stepping down voltage levels from the higher level right to the consumer loads. Delta primary and wye secondary (Δ-Y) is the common winding configuration for power distribution transformers. One of the reasons is for the primary delta to trap harmonics from going upstream and its secondary wye provides neutral grounding for unbalance loading at the phases.

In general, at power distribution system there are two types of loads – linear and nonlinear loads. Burch explained linear load is a load that supplied by sinusoidal source at fundamental frequency, produces only fundamental sinusoidal current or voltage (Burch *et al.*, 2003). For example, they are incandescent lights, induction motors, heaters, and boilers and mostly available at residental and commercial premises. The other type is nonlinear load. It is electric loads that significantly changes current waveforms in power system. They cause distortions at current waveforms through either switching procedures in the equipment installed, changes in electromagnetic properties of the nonlinear load, non periodic current consumption by the load or simply by the combinations of the three. Flourescent lighthing, air conditioning system, and variable speed drives (VSDs) are examples of nonlinear load commonly available at industrials, commercials, and residential premises. Between the two types of load, it is the nonlinear load that causes bad effect towards the operation of distribution power transformers. Nowadays there are a lot of loads with nonlinear characteristic connected to power system and they affected distribution transformers. Distorted current waveforms means current harmonic exist and circulates inside the delta-wye transformer. At a large distribution system, typical Total Harmonic Distortion in current (THD_i) ranges from 23.2% to 90.5% (Kushare *et al.*, 2005) and EPR predicted 85% of all power electric flows through combinations of nonlinear loads (Priyadharshini *et al.*, 2012). With such amount of harmonic distortion in current, the effects towards operation of power transformer are substantial and the consequences are severe.

Desmet et al., described that nonlinear loads trigger the surge of pulses which cause the distortion of current (Desmet *et al.*, 2002). As results, observation to the distorted current yields that there are combinations of fundamental and harmonic components and multiples of frequencies to the fundamental frequency (Kneschke, 1999). Harmonic components in current are a real risk towards power system reliability where they can easily adds up in neutral conductor inside a three phase four wire system as neutral conductor is filled with current nearly 2 times compared to line conductors, thus overcapacity occurred at neutral line and greatly affecting material insulation properties (Ngandui & Paraiso, 2004). With respect towards power system equipment such as power transformers, harmonic components in current cause root mean square (RMS) of current to rise (Abbas & Saqib, 2007; Masri & Chan, 2011). Variations in harmonic frequencies also increase hysteresis losses and inductance values at transformers. An example of nonlinear load rising rms current magnitude is observation by Grady that net harmonic current by personal computers and light dimmers at 3rd, 5th, and 7th harmonic orders are about 81%, 53%, and 25% higher compared to fundamental rms current (Grady *et al.*, 2002). Thus, electrical loads that possess nonlinear characteristics have become prime concern towards several essential power system equipments such as power transformer (Islam *et al.*, 2000).

IEEE Recommended Practice for Establishing Liquid-Filled and Dry-Type Power and Distribution Transformer Capability When Supplying Nonsinusoidal Load Currents or known as IEEE Std C.57.110 is a reference document referred by this thesis in determining rms value of current at transformer under nonlinear load operation (IEEE, 2008). Several other documents include Std C.57.110 – 1996, and Std 519-1992. Summarization of total rms current at harmonic 'h' at each harmonic order constitutes overall rms load current at transformer under nonlinear load operation. The level of distortion in current is measured in percentage of Total Harmonic Distortion in current (% THD_i) where bigger harmonic components in current indicate bigger percentage of THD_i. As value of THDi increase, harmonic components in current become bigger and this translates into worse distortions at current waveforms. A main effect of harmonic current towards power transformer is the increment of power losses which directly cause transformer operating temperature to rise. Normal transformer design considers only rated values in load current, and operating voltage and frequency and calibrations are made under rated operating condition (Said & Nor, 2008). Harmonic components existence increase power transformer losses beyond rated values thus causing transformer to operate beyond its rated condition operating values. Transformer losses are as the sum of copper loss (P_{COP}), eddy current loss (P_{EC}), other stray loss (P_{OSL}), and core loss (P_C). Dissipation of higher amount of heat at windings and core affect the transformer insulation system and should the rise in temperature continues, degradation of insulation becomes very rapid and permanent malfunction may occurs at transformers in the form of winding short circuit and reduced core lamination insulation. At times, the loading capacity is reduced so that the amount of additional loss can be sustained by the unit. However, this solution proved to be limited and unsuccessful due to insufficient of power which results sensitive loads are not functioning.

Life expectancy of transformer also greatly reduced due to insulations and magnetic materials having to sustain bigger losses than they were designed for. Therefore, it is acceptable to conclude that transformer operation often limited by the amount of temperature it is designed for. During operations with nonlinear loads, increase in temperature at power transformer goes beyond its rated values indicating the substantial rise in its operating temperature (Geduldt, 2005).

1.2 Objectives

A few objectives are set for the completion of this thesis and they are:

(a) To produce a new design of power distribution transformer under nonlinear load condition operation.

(b) To design a new transformer that is capable to operate at rated servicing temperature with variations of THD_i with a maximum of 50%

(c) To obtain a sizing factor to increase the sizes of magnetic core and winding wire of transformer. The increase in sizes is emphasis with the new sizes to produce rated servicing temperature.

(d) To find the relation between content of harmonic in current (THD_i) with properties of transformer such as temperature rise, and losses of magnetic winding and core.

1.3 Problem Statement

Widespread use of nonlinear loads has caused alarming cautions towards the operation of power distribution transformers. Characteristic of loads has become more to nonlinear and this causes severe effects towards transformer (Astorga *et al.*, 2006). Noticeable effects include rise of operating temperature of magnetic winding and core of transformer (Al-Mousaoy, 2011), which leads to derating and reducing its capacity. Now that it has to feed loads with much nonlinear characteristics, additional losses occur at power transformers causing them to rise. KVA rating of transformer is determined by the full load current which contains only fundamental components drawn at the primary winding (Rama Rao, 2003). With the inclusion of nonlinear loads and current harmonics, the rating is no longer applicable. Thus the transformer rating has changed (El-Saadawi *et al.*, 2008) and has to increase to accommodate current harmonic (Masri and Chan, 2011) .

This thesis explains a new solution to solve the problems of power transformer operating under nonlinear load conditions. A new design of transformer is proposed where it is capable to operate under nonlinear load. This new design is able to sustain the additional losses caused by current harmonics. It produces similar amount of losses as rated operation condition. By having a larger size of winding wire size and a larger magnetic core dimension, the effects of harmonic losses can be sustained. The bigger sized materials can accommodate the additional harmonic losses caused by nonlinear load and solve the issue of increase in operating temperature. In the end, a new power transformer is produced and tested under nonlinear load condition. Novelty of this new design is that it is a specially designed unit to operate at full load current with variations of THD_i. Unlike the existing in-transformer solutions which emphasis on rising transformer kVA capacity or reducing transformer loading, the new design also maintains its capacity and at the same time operates at rated servicing temperature.

1.4 Scope of Research

In completing this thesis, a few scopes of research are determined in order to gather the attention to the desired focus. They are:

a) In analyzing the effect of harmonics towards operation of transformer, only distortion in current is considered. Level of voltage is assumed to be sinusoidal without harmonic contents.
b) Testing and analysis considers dry type power distribution transformers. The winding configuration is delta wye.

c) For the transformer testing, the content of harmonic is raise to a maximum 50% THDi.

d) Pattern of THDi is assumed to be inversely proportional to the order of the harmonics.

e) Typically available surveys on harmonic contents in current at small power distribution system are taken as the THD_i limits for the new power transformer.

1.5 Thesis Contribution

The contributions of this thesis varied from technical point of view as well as field education as general. They are listed as follow.

a) A new design of transformer under nonlinear load condition is produced.

b) The new transformer is also another dimension for in-transformer harmonic current mitigation methods.

c) A new transformer specially designed for nonlinear load operation is possible to be produced with normal material type (ρ)

d) New knowledge relating THD_i and loss parameters of transformer are found.

e) Effect of nonlinear load towards operating temperature of transformer is established.

1.6 Thesis Layout

This thesis is divided into five chapters. The first is the Introduction which presents brief insight to the introductory of power system, harmonics, and transformer, and problem statement which provide an impetus for this thesis development. The second chapter is the Literature Reviews undertaken by this thesis. Previous researchers' findings are discussed and used to enhance this thesis progression and direction. Third is Methodology which explains methods executed by this thesis in achieving objectives set. Flow charts are presented in describing steps taken in mathematical analysis, finite element modeling, and experimentations. Chapter 4 is the Results and Discussion which represents the findings of this thesis in meeting the objectives set. Under this chapter the new design of transformer under nonlinear load condition is proposed in detail. Final chapter is the Conclusion where it summarizes the work of this thesis. It concludes overall accomplishment of this thesis with an elaboration on future work in this research with more specific complete with added value to current work.

CHAPTER 2

LITERATURE REVIEW

2.1 Electrical Power System

Electrical power system serves as a main framework in changing and transferring electric energy from one form or one level to another level. Normally it is formed by three main sub systems: generation, transmission, and distribution. Marizan (2004) explains that three of them coexist with each other where transmission system delivers power generated by generation systems, and distribution system spreads the power to consumers. This delivery system is made possible with the inclusion of power transformer at distribution points. Figure 2.1 shows placement of power transformer in a typical power system.

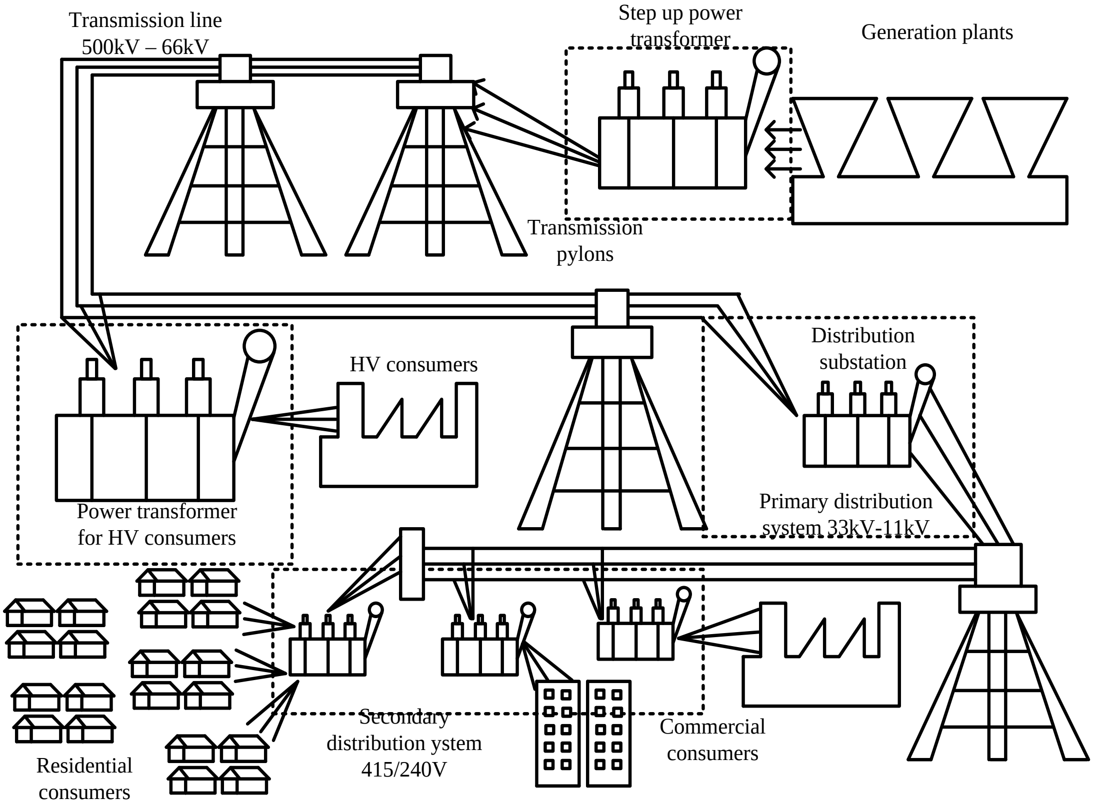


Figure 2.1 Power transformer locations in a typical power system network

VA rating of power transformer varies according to its requirements of voltage, and full load current at the load side (Electric, 2012). While the primary voltage rating follows the voltage value at the distribution system, the secondary voltage is determined by the voltage required at the load for the transformer to deliver its rated capacity (TWSEG, 2008). In mathematically the VA rating of three phase transformer can be determined by:

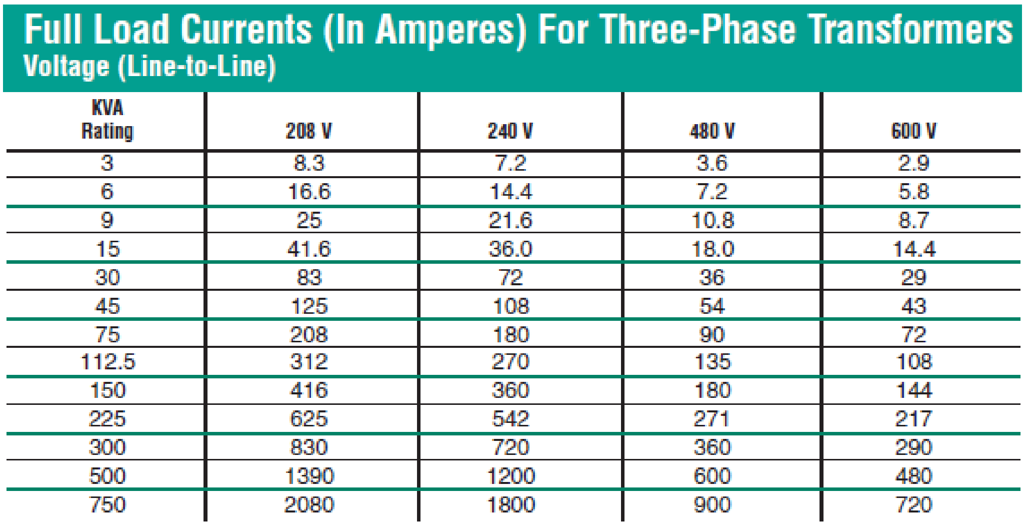
$$S_{TR} = \sqrt{3}\, V_L I_{FL} \tag{2.1}$$

Where:

S_{TR} is the kVA rating of transformer
V_L line voltage of system
I_{FL} is full load current of transformer

Similarly in order to determine rated current of transformer, equation (2.1) can be utilized as well. Table 2.1 shows an example of transformer VA rating commonly available from a transformer designer Jefferson Electric (Electric, 2012).

Table 2.1 VA rating for three phase transformer (adapted from (Electric, 2012)



Full Load Currents (In Amperes) For Three-Phase Transformers
Voltage (Line-to-Line)

KVA Rating	208 V	240 V	480 V	600 V
3	8.3	7.2	3.6	2.9
6	16.6	14.4	7.2	5.8
9	25	21.6	10.8	8.7
15	41.6	36.0	18.0	14.4
30	83	72	36	29
45	125	108	54	43
75	208	180	90	72
112.5	312	270	135	108
150	416	360	180	144
225	625	542	271	217
300	830	720	360	290
500	1390	1200	600	480
750	2080	1800	900	720

Transformer VA rating as in Table 2.1 considers voltage source of 480V. For voltage source of 415V, transformer VA rating and rated current can be tabulated as in Table 2.2.

Table 2.2 Transformer rating and rated current

Transformer (kVA)	**Rated current i_L (A)**
1	1.39
2	2.78
3	4.17
6	8.34
9	12.5
15	20.8

* For rating voltage 415 V

Generally VA rating of transformer is determined by the transformer current carrying capacity with the assumption of voltage source is constant. Content of current is capable to raise the temperature of transformer due to accumulation of internal losses as rated current results in rated transformer losses. The losses in transformer are proportional to the amount of current, which means as the amount of current increase the loss is also increases. Thus, limitation of transformer capacity is determined by its temperature. Capacity of kVA of one particular transformer is its capability to provide an output with rated frequency, and current. Insulation material that built the unit serves as indication to its temperature rating which reflects its thermal capacity and kVA rating. Practical limitation on a power transformer is the ability of it to deliver load current, I_L without exceeding an already rated temperature value. Thus, in selecting a unit of power transformer, attention must also be given towards it temperature rating. Table 2.3 shows classification of transformer class.

Table 2.3 Transformer Class (adapted from (TWSEG, 2008)

Class		Allowance of temperature rise	Transformer kVA
105	A	55°C at winding 10°C at hotspots	Very small kVA
150	B	80°C at winding 30°C at hotspots	Up to 2kVA
185	F	115°C at winding 30°C at hotspots	3 kVA – 15 kVA
220	H	150°C at winding 30°C at hotspots	More than 15kVA

Classification as in Table 2.3 also considers the ambient temperature of between 25°C and not higher than 40°C at the time of loading. Temperature plays a very important aspect in operation of power transformer. It also classifies class of transformer into Class 105 or Class A, Class 150 or Class B, Class 185 or Class C, and Class 220 or Class H. The numerical of 105, 150, 185, and 220 represents the temperature limitation upon transformer insulation (°C). Hotspots temperature on the winding refers to the hottest section of insulations due to the in-uniform distribution of temperature. It is capable to reduce insulation strength, and continuously operating above its rating risk of failed insulation causing permanent malfunction. ANSI/IEEE C.57.1981 suggested in reducing 1.5% of rated kVA for any operation at ambient temperature of over 30°C and to increase 1% of rated kVA for operation within ambience temperature of lower than 30°C. There are several standards available in the purpose of determining transformer loading and efficiency. ANSI standards (ANSI/IEEE C.57.91) mentioned that modern day power distribution transformers should be operating at a maximum of 65°C average winding rise at rated kVA in temperature of operation within 30°C ambience (Galloway & Mulkey, 2004). NEMA TP 1 and CSL 3 stated the efficiency of transformer must at minimum of 97.0 % and 97.9% with loading at 35% of maximum capacity respectively. Power transformers are the type of equipments that are load derived. Their types, winding configurations, sizing, temperature and kVA ratings, and related standards are often considered the load characteristics. This further highlights the importance of characteristics of load in determining the capacity of power transformers.

2.2 Characteristics of Load in Power System

The kVA rating of power transformer is related to the types of load available in power system. Older units which dealt with linear types of load produce less power quality problems and they have lower kVA and temperature ratings. Due to low possibility in current harmonic problems, they possess lower overloading capacity (CRC Press, 2004). Generally, in power system, there are two types of loads and they are linear load and nonlinear loads. Combination of both type of loads exist in power system. However the combinations of the loads are producing nonlinear characteristics.

Linear load has characteristic of drawing sinusoidal current whenever it is connected to the voltage source of the power system (Kneschke, 1999). Burch mentioned that linear load produces sinusoidal wave current at fundamental frequency, where it is similar to power system frequency (Burch, 2003). Both voltage and current waveforms are of the same shape at fundamental frequency. Figure 2.2 shows similarity of voltage and current waveforms within fundamental frequency.

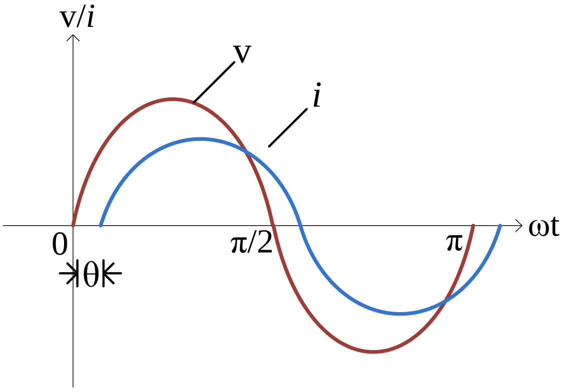


Figure 2.2 Linear load voltage and current waveforms

Mathematically the voltage and current waveforms drawn from linear load can be expressed as:

$$v(t) = v_1 \sin \omega t \tag{2.2}$$

$$i(t) = i_1 \sin \omega t - \theta \tag{2.3}$$

Where:

$i(t)$ is the instantaneous current

i_1 is current fundamental component

$v(t)$ is the instantaneous voltage

v_1 is the voltage fundamental component

ω_1 is the angular velocity equals $2\pi f_1$ and f_1 is power system fundamental frequency

θ is the phase angle between voltage and current

With reference to the waveforms in Figure 2.2, only fundamental components of i_1 and v_1 exist. Both contain only fundamental frequency, f_1 (power system frequency). For example, fundamental frequency of Malaysia power system is 50Hz. Linear loads are often resistive, capacitive, or inductive in nature. Typically available linear loads are motors, heaters, and incandescent lighting.

Instead, nonlinear loads produce distortions towards the current drawn and the current waveform becomes nonsinusoidal, which consists of harmonic components. Consider Figure 2.3 shows an example of nonlinear load nonsinusoidal current waveform from an ASD heat pump unit.

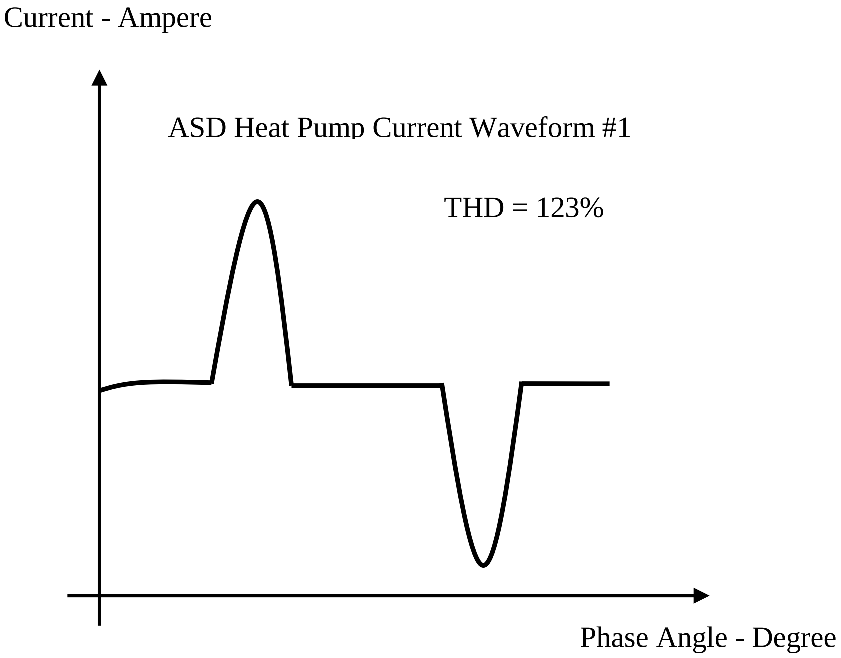


Figure 2.3 An example of sinusoidal current waveform drawn from ASD heat pump unit

Common nonlinear loads available in power distribution network can be classified into three categories; a) consisting filtered bridge rectifiers and single phase capacitor – example PCs and TVs, b) consisting three phase power converter – example ASDs, and c) consisting phase controlled single phase load – example heating loads and light dimmers.

2.3 Current Harmonic Distortion

Nonsinusoidal waveform is periodic in nature where it is combination of sinusoidal waveforms with variation of frequencies. Thus, for such repetition waveforms, it can be represented by Fourier analysis as:

$$f(t) = F_O + \sum_{h=1}^{h=max} f_h(t) \tag{2.4}$$

Where:

F_o is the average value; $= \frac{1}{2} a_o$

$\sum_{h=1}^{h=\max} f_h(t)$ is the variations of waveforms with frequencies and magnitudes; $\sum_{h=1}^{h=\max} \left[a_h \cos(h\omega t) + b_h \sin(h\omega t) \right]$.

Similarly to current distortion caused by nonlinear load, harmonic current can be represented as:

$$i(t) = i_1(t) + \sum_{h \neq 1}^{h=\max} i_h(t) \tag{2.5}$$

Where:

i_1 is the fundamental component of current

i_h is the fundamental component of current at h order of harmonic.

Equation (2.5) also can be rewrite as the following:

$$i(t) = \sqrt{2}\, i_1 \sin(\omega_1 t - \theta_1) - \sum_{h \neq 1}^{h=\max} i_h (\sin h\omega_h t - \theta_h) \tag{2.6}$$

The rms value of current can be calculated by solving equation (2.5) and (2.6) and replacing the integral limit from T_1 to 0, with T_1 equals to $1/f_1 = 2\pi/\omega_1$:

$$I = \left(\frac{1}{T_1} \int_0^{T_1} i^2(t)\, dt\right)^{1/2} \tag{2.7}$$

Thus, by replacing *i(t)* in equation (2.7) with *i(t)* as in equation (2.5), rms value of current can be determined as:

$$I = (i_1^{\,2} + \sum_{h\neq 1}^{h=max} i_h^{\,2})^{1/2} \tag{2.8}$$

Distortion in current is quantified by the term THD$_i$ (Total Harmonic Distortion in current) and it is represented in percentage (%). The bigger percentage means more distortion the current is, thus indicating the large amount of harmonic components in current. THD$_i$ is the ratio between sums of rms harmonic currents to the rms of fundamental current and is described as:

$$THD_i = \frac{\sqrt{\sum_{h=2}^{h=max} I_h^{\,2}}}{I^1} x100\% \tag{2.9}$$

Where:

I_h is the rms harmonic current (from h=2nd order to h=maximum significant order)

I_1 is the rms fundamental current value.

2.4 Effects of Nonlinear Load to Power Distribution System

The widespread use of electronic devices which are the nonlinear loads has raised the concern over current harmonic problems. Equation 2.3 and 2.4 show that rms value of current rise with the existence of harmonic components as well as containing multiple harmonic frequencies.

Earliest discovery of power quality problems associated with harmonics was found with the saturation of irons in machines and transformers produced third harmonics current. Several common problems are capacitor failures, and interference in sensitive equipments such as meters and over current relays (Xu *et al.*, 1991). ANSI/IEEE Std 18-1980 indicates, including the inclusion of harmonic components, capacitor operation is limited at 180% of rated rms current, or 1.8 times to the rated rms current (Wagner *et al.*, 1993). Several surveys indicated that due to widespread use of nonlinear loads to perform desired tasks, current harmonics varies between 15% to 40% at selected small scale industries and domestic premises (Nasini *et al.*, 2012) (Gajanayake *et al.*, 2005). Harmonic currents have an abnormal high peak, according to (Desmet *et al.*, 2002) where it can be as high as triple to the RMS value of current. Harmonic producing loads are sensitive and immensely in used today after the emergence of the electronics in the past a few decades (Gul & Bayrak, 1999) . Single phase SMPS are big source of net harmonic currents which prompted the IEC to implement regulations such as standard IEC 1000-3-2 in maintaining the health of an ac system (Mansoor & Grady, 1998). Rectification process involves usage of diodes and thyristors in controlling the dc power. This procedure causes injection of current harmonics into system thus causing distortion in current and results in poor power quality. However by thoroughly examine the parameters of the rectification system, inject of current harmonics could be lessen (Kazem *et al.*, 2005). Characteristic of single phase nonlinear load has been studied to contain unbelievably high harmonic content between 102.8% THDi and 101.5% THDi for fluorescent lamp with electronic ballast and UPS load respectively (Umeh *et al.*, 2003). Commonly found single phase nonlinear loads in households, offices, and industrial places include fluorescent lighting, and equipments that possessed switch mode power supplies (SMPS) such as televisions, fridge, and air conditioners among the vast examples (Sankaran, 2002).

Among the examples of nonlinear loads available at industrial premises are static converters, rectifiers, furnaces, phase controller, and rotating machines. Upon machines, the rotor is impacted with some non negligible additional current that are induced in the damper winding. According to Girgis, et. al (1989) it is not uncommon for large industrial loads to produce high magnitude of current distortion, due to harmonics. An existence of 5th harmonic in at industrial level transformer and capacitor banks tend to increase transformer and capacitor rms currents to 91% and 132% respectively (Girgis *et al.*, 1990). In a literature explaining an experiment with VSD another common source of nonlinear loads at industrials it is found that significant 5th, 7th, and 11th order harmonic current are produced (Islam *et al.*, 2000).

Overall THD_i of a typical single phase system is recorded at 77% which is typical to all single phase electronic equipments such as PC (Khan & Akmal, 2008) (Aintablian, 1996). However, the distortion of current can be reduce through attenuation and diversity as proved by Mansor, et.al., (Mansoor *et al.*, 1995). Work by Venkatesh, et. al, (2008) shows modeling of nonlinear loads ranging from industrial type of loads such as ASD to domestic loads of house hold appliances such as TV sets, lightning, and personal computers (Venkatesh *et al.*, 2008). Important power system observatory and safety equipments such as fusing system, and energy metering are also affected by nonlinear load existence inside power distribution system. Meter phase is no longer accurate due to current and voltage that flow through energy meter is no longer fundamental, but they contain harmonic components (Edwards *et al.*, 2011). The peak current value as high as 60% compared to rated has prompted the fuse to trip even only at non reaction setting (Desmet *et al.*, 2002). New developed applications in conventional vehicles and Electric Vehicle (EV) are also in danger with the existence of harmonic components in current. Nasiri in his literature discussed about harmonic producing loads in undersea vehicles and ship, among others are electromagnetic gun, ASD system, AC/DC rectifiers, and switching power supplies (Nasiri, 2005). Major power quality problem inside the battery chargers for the EV is current harmonics. It is said that in future, EV battery chargers still capable of producing distortion in current ranging from 10% - 100%. Although charging system and harmonic cancellation procedure operate at the same time, distortion in current still exist between 6% to 30% in tested models.

Design of modern electrical system must consider the characteristics of loads connected or predicted in the future to be installed in system. Based on the survey by Ling and Eldridge, predominant harmonics belongs to the triplens, however special attention must be accorded to high degree 5th and 7th harmonics (Ling & Eldridge, 1994). They also concluded that harmonic currents are capable to create voltage distortion where injection of harmonic components in current interacts to the power system impedance thus resulting distorted voltage of system. In a typical city distribution system, Yong mentioned that commonly available nonlinear loads exist in the form of trolley bus converting station, arc furnace, and equipments that contain SMPS such as TVs and microcomputers (Yong, 1997). The effect of harmonic current is more obvious during low load hours when the load current is low and voltage rises from many installed transformers in network (Wiechowski *et al.*, 2008). In a three phase four wire system, 3rd harmonics current returns through the neutral conductor and the three individual 3rd harmonic current from each phase add up for a bigger neutral current. Sometimes the amount could be 1.73 times or as much as 3 times the phase current. As result, common effect of nonlinear loads towards 3 phase 4 wire system is the severe damage to the neutral conductor as overheat and overcapacity occurred and cause failure insulation and short circuit (Spitsa & Alexandrovitz, 2004). Document BS 7671 524-020-03 stated that due to harmonic components in current, the neutral conductor must possess CSA (cross sectional area) of not less than of phase conductor CSA (BEAMA, 2004). In a suggested remedy towards big neutral current, modern system designer must consider neutral conductor as one of the current carrying conductor, and it must be monitored on time basis. In fact, all neutral components such as the terminals and busbars should be sized for the additional and hazardous neutral current (Gul & Bayrak, 2002). With respect to neutral conductor CSA, it is adequate to size it at 1.73 times to the phase conductor size, in order to protect the system (Gruzs, 1989a). An intriguing investigation yield that by adding more nonlinear loads into distribution network actually reduce the THD_i and subsequently cancel some of the harmonic currents. This is due to the nature to the 5th and 7th harmonic current from single and three phase nonlinear loads often act counter phase (Hansen *et al.*, 2000). Limiting the amount of harmonic current at point of common coupling (PCC) from 5% to 20% is another approach by IEEE Std 519 in controlling load connectivity to preserve power system harmonic current absorption capacity (Gruzs, 1989b).

In safeguarding power distribution system from the problem of harmonic currents, advance modeling and estimations of harmonic are two important aspects to be explored. Venkatesh produced network modeled after case study at the ISRO Cartosat 2A distribution system. The simulation showed installation of capacitor banks ease the effect of nonlinear loads in system where the data showed reduction of at least 1.0% at condition without the banks(Venkatesh *et al.*, 2008).

2.5 Power Transformer Losses

Thermal breakdown occurrence can be analyzed through a curve of energy as a function of time. It also defines any equipment's thermal breakdown point where failure of material or insulation properties to withstand dissipation of loss or heat occurs. Power transformer capabilities are thoroughly dependent to its thermal limit. As it nears the limit, risk of breakdown is real thus corrective measures must be undertaken to avoid permanently malfunction. Hotspot temperature is a term typically describes about power transformer temperature pattern under loading (Pierce, 1994).

Life of dry type or liquid filled transformer depends on operational temperature (Delaiba *et al.*, 1995). IEC document 60076 – 11:2004 indicates that insulations are classified according to their rated maximum operational temperature. It is an acceptable fact that the operation of transformer depends on its material insulation properties and majority of breakdowns are attributed to failure of insulating system (Geduldt, 2005). Rated kVA capacity is designed based on maximum current delivered at rated voltage. Limitation of a transformer operating capacity is the amount of current it is able to sustain without exceeding rated temperature rise (TSEWG, 2008). However, with nonlinear load, the rated kVA is no longer applicable due to the fact the current now no longer of rated value. Harmonic current produces additional losses which cause the transformer operating temperature to be bigger than operation under rated values.

High losses affecting the lifetime of power transformer which means signification reduction of operational years. Internal heating is known to be an important factor where cumulative of heat dissipation is able to reduce the strength of the dielectric materials and saturate the insulations. The main problem is design procedure of power transformer does not consider the nonlinear characteristic of current and voltage. Designers design and calibrate the unit based at rated condition, however these days current has become more non linear thus it is effecting the operation of power transformer. Losses of transformer can be classified into two; no load loss and load loss, and both form the total loss of transformer. Figure 2.4 illustrates categories of power transformer losses.

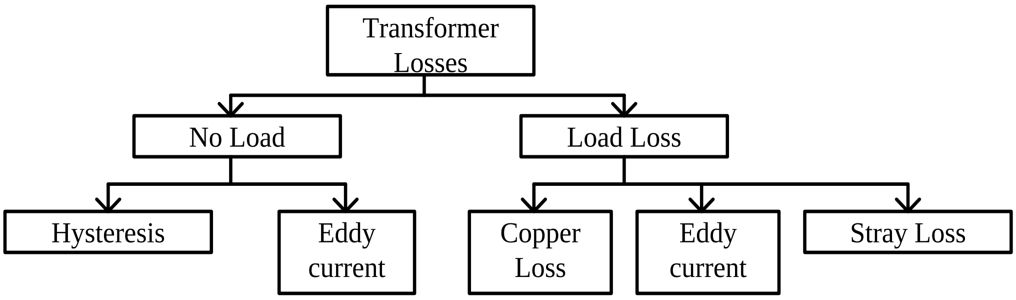


Figure 2.4 Categories of power transformer losses

Total transformer losses are divided into two categories No Load loss, P_{NL} and Load loss, P_{LL}. P_{NL} is the type of loss that happen inside the material that resembles the core of power transformer. It is also known as excitation loss. P_{LL} occurs internally at the windings, tanks, walls and other structural parts of the transformer. Under excitation loss or core loss, it further separates into hysteresis and eddy current losses at the core material. Copper, eddy current, and stray losses made up the three separation of load loss. Total expression of losses can be as follow:

$$P_T = P_{NL} + P_{LL} \tag{2.10}$$

Where:

P_T is total transformer loss

P_{NL} is the no load loss and the sum of $P_{H,C}$ and $P_{EC,C}$

P_{LL} is the load loss and the sume of P_{COP}, $P_{EC,W}$, and P_{OSL}

2.5.1 No Load Loss

This is the type of loss that occurred at power transformer during current excitation point. Loss includes dielectric loss, winding loss due to excitation and circulating current, and core loss. However the most dominant of these is the core loss, with the other two are very small and often negligible. Core loss or also known as iron loss is made of by combination eddy current loss and hysteresis loss at the laminated core sheets.

2.5.1.1 Hysteresis Loss in Core

Hysteresis loss happens due to resistive nature of core material to realignment of magnetic domains in it. However, to overcome this resistance, some amount of power is needed in order to change magnetic alignment due to existence of supply voltage at the primary end of transformer. Amount of power required in this process depends on the operating frequency, the amount and type of core material, and the magnitude of magnetic flux density. Hysteresis loss also dependent towards flux density which in turn also dependent to the voltage that supplied to the unit and the number of winding turns at primary end. Figure 2.5 shows BH characteristic curve of a core under hysteresis.

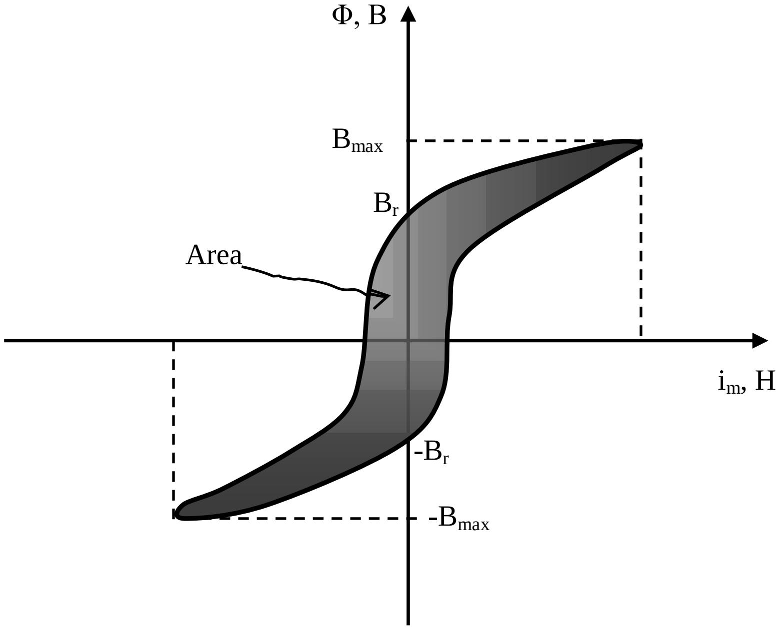


Figure 2.5 BH characteristic of power transformer core in hysteresis mode

The area mentioned at the BH depicts at Figure 2.5 shows the amount of power needed to oppose core material resistance to realign the changes in magnetism. It produces energy which exists in the form of heat and cause increase in temperature at the core. Figure 2.5 also shows with the increase of hysteresis, magnitude of ac magnetic flux B_{max} also increase as well as operating frequency. The amount of energy can be mathematically expressed as below.

$$W = \oint_{loop} (Hdb)\ (volume) \tag{2.11}$$

Where:

H is the energy stored in magnetic field

db is the variation of magnetic flux density of the measured loop area

Empirical justification upon total hysteresis energy loss in a certain volume can be found as:

$$W_H = b\,B_{max}^{n} \tag{2.12}$$

Where:

W_H	is the energy by hysteresis loss
b and n	are materials properties

Several agreements are made in relation to (2.12) where the flux density is uniformly distributed and varyingly in cycle with frequency *f*. Power loss per cycle then can be quipped as:

$$P_H = (b)\,(volume)\,(fB_{max}^{n}) \tag{2.13}$$

Equation (2.13) explains the hysteresis power loss is dependent on materials' efficiency, its volume, its operating frequency, and its magnetism properties. By knowing the B_{max} representation that relates to cross sectional area (CSA) of the core, applied voltage, frequency of operation and number of turns, (2.13) can be simplified into a more complete equation of hysteresis. While B_{max} is known as:

$$B_{max} = \frac{V}{4.44f\ NA_c} = \frac{\mu NI}{L} \tag{2.14}$$

Where:

V is the applied voltage

N is the number of turn

Ac is the area

μ is the material permeability

I is the current at solenoid turns

L is the solenoid length

Thus by combining (2.14) and (2.13), transformer core hysteresis power loss ($P_{H,C}$) can be mathematically defined as:

$$\begin{aligned} P_{H,C} &= (b)(volume)(f(\frac{V_{max}}{4.44fNA_c})n) \\ &= bVf\left(\frac{L\,x\,I_{max}}{NA_C}\right)^n \end{aligned} \tag{2.15}$$

As noted by equation (2.15), hysteresis power loss at transformer magnetic core depends on several parameters such applied voltage, solenoids' length and number of turn, operating frequency, and materials' size and magnetism properties. However there are assumptions are made in order to justify the hysteresis loss equations, and they are:

i. Each lamination that form stacked core has its own magnetic characteristics.

ii. Flux density across each lamination is assumed to be uniform.