DETERMINING CORRECTION FACTOR OF POWER CABLE SIZING UNDER NONLINEAR LOAD CONDITION

by

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Thesis submitted in fulfillment of the requirements for the degree of Masters of Science

December 2008

ACKNOWLEDGEMENTS

السلام عليكم ورحمة الله وبركاته

In the name of Allah, the most Compassionate and the Most Merciful;

I would like to express my sincere gratitude and endless thanks to my main supervisor Dr. Ir. Syafrudin Masri and co-supervisor Associate Professor Dr. Soib Taib for their guidance, encouragement, and continuous support throughout the completion of this thesis. Their contributions have been invaluable help to this research work.

I also would like to extend my appreciation towards the technical staffs at the School of Electrical and Electronics Engineering, Universiti Sains Malaysia (USM) for their assistance and cooperation, not only from technical point of view, but also giving this thesis moral support and pleasant working atmosphere. My thanks are also reserved for other academic and administrative staffs, which have been helping me directly and indirectly towards completion of this thesis. Another group to be appreciated are my friends which have been continuously providing me help and guidance, whether in personal or formal matters.

Finally, my deepest gratitude and special thank you are for my family for their support, understanding, and encouragement during the past months and Insya Allah, for the future.

Muhammad Mokhzaini Bin Azizan

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LIST OF SYMBOLS

I_{1m}	Amplitude of Fundamental Current
I_{nm}	Amplitude of nth Harmonic Current
ω	Angular Speed
k	Constant
cos	Cosinus
A	Cross Sectional Area
i_R	Current for Phase R
i_Y	Current for Phase Y
i_B	Current for Phase B
i_N	Current for Phase N
φ_1	Desired Power Cable Size
D	Diode
I_o	Fundamental Current
f	Fundamental Current Frequency
I_h	Harmonic Current
φ_0	Initial Power Cable Size
ℓ	Length
i_L	Load Current
V_{max}	Maximum Voltage Magnitude
µF	MicroFarad
h	Number of Harmonic
Ω	Ohm
ϑ_n	Phase Angle of nth Harmonic
π	Pie
sin	Sinus
β	Slope of Current vs Temperature of Power Cable
ρ	Static Resistivity
t	Time
	Total

LIST OF ABBREVIATION

AC	Alternating Current
AWG	American Wire Gauge
A	Ampere
C	Capacitance
CBEMA	Computer and Business Equipment Manufacturer Associaton
°C	Degree Celcius
DC	Direct Current
HDF	Harmonic Derating Factor
Hz	Hertz
HV	High Voltage
IHD	Independent Harmonic Distortion
IEEE	Institute of Electrical and Electronic Engineers
IEC	International Electric Code
LV	Low Voltage
PMU	Main Intake Station
MVA	Megavolt Ampere
MCB	Miniature Circuitbreaker
NEC	National Electric Code
N	Neutral
PC	Personal Computer
PV	Photovoltaic
PCC	Point of Common Coupling
Pf	Power Factor
R-Y-B	Red-Yellow-Blue
R	Resistance
RMS	Root Mean Square
S/S	Static Switch
SMPS	Switch Mode Power Supplies
TV	Television
TNB	Tenaga Nasional Berhad
THD	Total Harmonic Distortion
V	Volt
W	Watt

LIST OF PUBLICATIONS & SEMINARS

International Conferences and Journal

1. Mokhzaini, A., Syafrudin, M., and Soib, T (2007) Effect of THD towards temperature properties of power conductor under harmonic influence. Proceedings of the International Conference on Engineering and ICT (ICEI 07). Malacca, Malaysia. Nov. 27-28. 401-404

2. Mokhzaini, A., Syafrudin, M., Soib, T., and Nazir, A. (2007) Effect of harmonic current on the power cable. Proceedings of the International Conference on Robotics, Vision, Information, and Signal Processing (ROVISP 2007). Penang, Malaysia. Nov. 28-30.

3. Mokhzaini A., Syafrudin, M., and Soib, T. (2008). Additional Loss At Power Cable Due to Current Harmonic Contents. Proceedings of the 2nd International Conference on Science And Technology (ICSTIE 2008). Penang, Malaysia. Dec. 12-13.

4. Al-Mofleh, A., Soib, T., and Mokhzaini, A. (2009). Prospective of Energy Efficiency Practice, Indicator and Power Supplies Efficiency. *Journal of Modern Applied Science.* Vol. 3 (4). Canada

MENENTUKAN FAKTOR PEMBETULAN PENSAIZAN KABEL KUASA UNTUK BEBAN TIDAK LINEAR

ABSTRAK

Peralatan elektrik yang berasaskan peranti elektronik telah mengundang masalah kualiti kuasa yang serius iaitu harmonik. Peralatan berkenaan dikenali juga sebagai beban tidak linear mampu mengenakan herotan pada parameter voltan dan arus. Herotan pada arus sangat berbahaya pada sistem kuasa dan antara yang paling terjejas adalah kabel kuasa. Komponen harmonik meningkatkan nilai RMS arus yang mana akan membahayakan penebat kabel. Ia mungkin mendedahkan kawasan pengaliran arus dan di dalam paip kabel tertutup, sentuhan pada kabel lain mungkin terjadi dan litar pintas akan menyebabkan sistem kuasa terjejas. Melihat pada penyelesaian yang mungkin, tesis ini menghasilkan satu faktor pembetulan untuk pensaizan kabel kuasa, terutama pada keadaan beban tidak linear. Beberapa sampel kabel kuasa dijalani ujian melibatkan komponen harmonik untuk litar satu fasa dan tiga fasa. Kenaikan THD_i dan suhu kabel direkod. Hasil tesis adalah satu pemalar yang mengaitkan suhu operasi kabel kuasa dan kandungan harmonik di dalam arus (THD_i). Untuk litar kuasa satu fasa, pemalar yang diperolehi hasil variasi THD_i dari 0% hingga 80%, adalah 0.40 ± 0.015. Litar tiga fasa mempunyai komplikasi yang rumit memandangkan kabel neutral memainkan peranan yang penting. Untuk jumlah THD_i dari rangka 0% hingga 40%, nilai pemalar adalah 0.41 ± 0.009 dimana pensaizan kabel adalah berdasarkan saiz kabel fasa hidup. Namun, pada jumlah THD_i di kabel fasa dalam lingkungan 50% hingga 80%, satu pemalar berlainan diperolehi kerana pengaruh kabel neutral, dan didapati pemalar adalah 0.47 ± 0.004. Hasil yang lain termasuklah kadar penurunan arus untuk kedua-dua litar satu dan tiga fasa, dimana ianya di aplikasi secara inversi untuk mendapatkan arus samaan beban. Satu perhubungan antara pensaizan kabel kuasa dan harmonik (THD_i) telah dihasilkan; melalui parameter suhu operasi kabel kuasa. Penyelesaian pensaizan kabel kuasa dibawah beban tidak linear telah dilaksanakan dengan jayanya.

DETERMINING CORRECTION FACTOR OF POWER CABLE SIZING UNDER NONLINEAR LOAD CONDITION

ABSTRACT

The invention of electronic equipment has lead to a serious power quality problem in harmonics. The equipments, also known as the nonlinear loads have the ability to distort parameters such as voltage and current. Distortion of current, particularly, is lethal to power system and among the power system parameters to be having direct impact of harmonic in current is power cables. Component of harmonics might increase RMS value of current, thus jeopardizing insulation of cable. The conducting part of cable might be exposed and in a confined cable trunking pipe; contact with other cable is possible and short circuits would cause power system break down. Looking at the possible solution, this thesis has come up with a correction factor for power cable sizing, particularly under nonlinear load condition. Few power cable samples are to be undertaken series of tests involving harmonic content in current, for both single phase and three phase power system. The increment of THD_i is measured as well as its corresponding increase of temperature. The result of the thesis is the constant that relates power cable operating temperature and content of harmonic (THD) in current. For single phase power system, K value obtained as variation of THD_i from 0% to 80%, equals 0.40 ± 0.015. More complicated power cable solution reserved for three phase power system where neutral cable plays a big part in sizing method. For injection of THD_i at phase ranging from 0% to 40%, the constant value is 0.41 ± 0.009 where mostly the sizing would be referred to phase cable's size. However, as harmonic content at phase amounted from 50% to 80%, a different constant is obtained due to the influence of neutral cable current loading, which yields constant is 0.47 ± 0.004. Another finding is the current reduction rate for both single and three phase power system which it to be applied in inverse, so that equivalent load current can be determined. A relation between power cable sizing and THD_i has been established; through power cable's operating temperature parameter. Power cable sizing solution under nonlinear load condition has been successfully determined.

CHAPTER 1
INTRODUCTION

1.0 Introduction

Energy conversion or simply addressed as power generation starts from a combination of oil fired thermal, wind power gas turbine, hydro, diesel, and combined cycle plants. With the exception of small diesel and mini hydro plant, the rest are interconnected via high voltage transmission lines which form The National Grid Network (Yusof et al., 1995). This network consists of a main artery which stretches among main generation, transmission, and distribution points across the nation. Transmission system consists of many lines that form networks to transport the electricity from the generating plants to the area in which it will be used or the main incoming station including PMUs (Main Distribution Station). Transmission of electricity may involve long and short distance delivery methods that use power cables and supporting pylons (Faulkenberry and Coffer, 1996). The voltage levels of main transmission networks are 275kV, 132Kv, and 66kV. In big industrial area such as Gurun, Kedah the level of voltage has been increased to 500kV due to great demand from industrial players. Electricity is then transported to the general area of use by the distribution system where the voltage is stepped down using transformer on-load tap changers at the distribution substations. Voltage levels are at 33kV, 22kV, 11kV, 6.6kV, and 415/240 volts (Yusof et al., 1995).

There are two levels of system used for distribution of electricity. The first level is the primary distribution system, which uses 3-phase, 3-wire configurations. Overhead lines and underground systems are used extensively to smoothen the delivery and also as protective measures. Main mode of transmission is by using the pylons across the highways and roads. The conversion to underground cabling system is made by the time the line has to serve big cities which certainly do not have enough place for big structures such as pylons. Underground system also helps to preserve the beautiful scenery in cities and towns. The next type is the secondary low voltage (L.V) which uses 3-phase, 4-wire configurations with the neutral is solidly grounded at the source substations. It serves medium commercial premises as well as residential users. The voltage level is 415/240 volts and very similar to the primary system, it also uses overhead and underground cables for low voltage distribution. Maximum demand for low voltage consumers could be as high as 1500kVA supplied at either single phase 240V or three phase 415V.

Distribution system ends with the load being supplied with electricity, which the load is varied from industrial to domestic consumers. The demand of industrial users is very opposite to the individuals, as commercial areas need more power and has bigger loads. There are two types of load that are linear and non-linear. Linear load is described as a category of loads, which if supplied by sinusoidal source at fundamental frequency, produce only fundamental sinusoidal current (Burch et al., 2003). Examples of linear load resided very much in domestic and commercial users which include incandescent lamps (purely resistive), induction motors, resistive heater, and boilers. Meanwhile, nonlinear load is defined as; a class of load which result the input current waveform to be significantly distorted compared to the ideal sinusoidal current waveform. Nonlinear load such as computers, arc furnace, switch mode power supplies (SMPS), and adjustable speed drives are used largely by industrial consumers and they created harmonic.

While linear load pose no serious threat to the quality of power delivered, it is nonlinear load that has the capacity to reduce the efficiency of power and cause several disruptions towards power system, for example harmonics. Nonlinear loads are the cause of harmonic existence. It is because; electronic devices contain switching mechanism which would trigger the surge of pulses that cause the distortion of the current (Desmet et al., 2002). For example, a single phase electronic load power supplies are typically configured with a front-end full wave bridge rectifier with significant capacitor filtering on the dc side of the rectifier. The distortion of current takes place at the moment of switching between rectifier diodes and the dc bus capacitors. The rectifier diodes are forward biased only when the input voltage exceeds the total of capacitor's voltage and diode's forward voltage drop. During the conduction, a large pulse of current occurs, which comprised of capacitor charge current and load current being drawn from the dc bus. The pulse of current has caused the current to be distorted and subsequently the linearity of current and voltage waveform compromised. The distorted current and the voltage waveforms are not of the same shape and contain fundamental frequency as well as non - fundamental frequencies, known as harmonics. Nonlinear load have the characteristics such as it draws non sinusoidal current as it connected to sinusoidal source, supply voltage would be distorted and becomes non sinusoidal. The resulted voltage and current waveforms are not same in shape and frequency, and they contain fundamental frequency component as well as non fundamental frequency components (Knaeschke, 1999).

Conductors such as power cables are the most likely to be worst hit by harmonic content in current, which is termed as in percentage of current total harmonic distortion (% of THD_i). The degradation in power cable performance due to current distortion lies within the generation of additional harmonic components in current of 3^{rd}, 5^{th}, 7^{th}, and etc, which causes additional power loss by the increased RMS value of current waveform (Abbas and Saqib, 2007). Estimation of net harmonic currents produced by PCs and light dimmers has shown that, harmonic orders of 3^{rd}, 5^{th}, 7^{th}, and 9^{th}, had magnitude of 81%, 53%, 25%, and 9% times the operating fundamental current respectively (Grady et al., 2002). Third order of harmonics, in particular, generates large neutral currents as in three phase power distribution system, affecting the performance of neutral conductor. Thus, recommendation of cross sectional area of neutral conductor must be 50% of the cross sectional of phase conductor as the neutral current would be 1.73 times the phase current (CBEMA, 1998) (Wegner et al., 1993) (Gruzs, 1990). The increase RMS value of current has causes additional loss in power cables in the shape of increase operating temperature. In order to maintain them operating at standard operating temperature, steps of current reduction and increase the conductor's circular size must be performed. In three phase distribution system, effect of current harmonics may be a bit worse, where proximity effect takes place. In a common conduit where life and neutral conductors are put together, heat dissipation of live and phase conductors due to harmonic components totaled. In a certain circumstance, neutral conductor current is overwhelmingly bigger than phases', thus contribute to massive heat dissipation. Poor air ventilation would cause the heat to damage the insulation of each conductor, and continuous high current harmonics would cause the insulations to break and contact between conductors is made possible. Once they are short circuited, explosion may happen and power system is damaged and service is disrupted.

The interest of the thesis is to investigate the effect of current harmonic content towards power cables' current capability as well as the compromise of their operating temperature during harmonic availability in the system. The provided technical data on current capability and thermal properties provided by the manufacturers' are without acknowledging the effect of harmonic or in short, they are the capabilities without the interference of harmonic. Injection of harmonic content in current has cause the increment of operating temperature of cables, thus presenting a great concern over power cables which have to feed continuously increasing number nonlinear loads, such as in offices and housing estates.

Determination of correction factor for power cables under nonlinear load condition involves generation constants of K for each percentage of harmonics in current (% THD_i), for both single phase and three phase circuit application. A relationship of K in the function of THD_i is realized, where the value of constants, as well as harmonic content in percentage of THD_i and the slope value of temperature and current graph, to be inserted in a formula. The formula, then, would determine the appropriate size of power cable to sustain both ampacity as well as harmonic content, without exceeding standard operating temperature of power cable.

1.1 Objective

The initial aim of the thesis is to provide new findings in term of power cable sizing adjustment which later is deemed right for normal operating purposes. There are a few objectives that the thesis should meet upon completion:

A. To obtain a certain value of constant, K which can be use in determining appropriate size of power cable that is being subjected to harmonic influence. The constant also take issues of safety and reliability into consideration.
B. To investigate the correlation between THD content (harmonic in percentage) to the temperature properties of power cable. This is made possible by designing a specific experiment for this purpose.
C. To perform a method of selection of power cable size that is deemed safe and proportional to the ability to contain particular magnitude of current.

1.2 Scope

The problem with harmonic existence in power cables is that every component which frequency is dependent, namely current and voltage is easily manipulated. As the frequency rises, magnitude of current also increases and the temperature heats up. The heat variable in power cable is the result of I^2R loss where the losses are normal if harmonic current is none, which is understandably correct as the cable is delivering sinusoidal fundamental current. However, under harmonic influence, the loss is no longer the same as the sinusoidal current transmission loss as in the power cable, there is a combination of fundamental and harmonic current. The additional harmonic current certainly causes more loss and it is a concern of the thesis. Thus, this thesis tends to concentrate on the determination of proper sizing of power cable, subject to the harmonic content. The correlation between THD and temperature properties of power cable is found by experiments performed during data collection process. The project conducted thorough examination upon cable size(s) that seemed to be able to contain additional magnitude of current and the resulting loss (temperature) under harmonic influence.

1.3 Problem Statement

Historically, power cable sizing, especially neutral line is based on the understanding of the harmonic current can be at most, 1.73 times the phase current (Gruzs, 1990). Meaning, the usual sizing would be the neutral cable to be twice the same of phase current, and eliminating every possibility that harmonic may cause the magnitude to be higher than two times phase current. A certain calculation of ampacities and sizing of line and neutral cable in the presence of harmonics has open the path of determining the exact requirement in term of cable sizing toward certain amount of harmonic (Hiranandani, 1995).

Under normal working ampicity of cable, the loss is already predicted by the manufacturers. The information provides manufacturers valuable information to design their products and market them accordingly. However, by stating normal working ampicity, it is known that it is meant for sinusoidal current or voltage, thus the loss of the power cable is meant for non harmonic environment. Under harmonic influence, the predicted loss is no longer applicable as there is harmonic current and the fundamental sinusoidal current delivered by the cable. Thus, the loss supposedly increased to a certain magnitude. The resultant loss needed to be investigated so that the maximum permissible loss is not exceeded or else the operation of cable is under possible severe damage.

1.4 Thesis Layout

The thesis is constructed in five chapters, beginning with Introduction, followed by Literature Review, Project Methodology, and Result and Discussion respectively. The last chapter is the Conclusion. The first chapter, Introduction largely tells about the basic distribution system, harmonics, and the direction of thesis in general. Objectives and scope of the thesis are mentioned with great emphasis as the two items would dictate the execution of the experiments. Brief explanation of project methodology is also stated with the intention of describing the steps taken in concluding the thesis. A flow chart of methodology can be analyzed for better understanding. Contribution of the project also mentioned so that the benefits of the project can be seen and practiced later on.

Chapter 2, Literature Review basically contains in detail of previous work done by previous researchers which are related to the existing project. Information and knowledge gained during previous researches are collected, discussed, and studied so that this project can be beneficial of them. The knowledge proved to be invaluable as the thesis progressed as some of the hurdles faced, had been solved by the previous researches.

Approach and method in thesis execution are described in Chapter 3. Every single step taken during the completion of project is mentioned, whether in sentences or in flow charts. Chapter 4 provides the results of experiments and analysis of data collected. Data are presented in tables and graphs are drawn so that the significant of certain variables can be visualized better. Figures and diagrams are presented in great detail in order to help in understanding the whole project and its benefits.

The final chapter; Conclusion tells of the end product of thesis. It provides an overview of achieved objectives set earlier in the thesis. The level of successfulness of thesis can be determined in this chapter. It also provides suggestions for further future work in similar field.

CHAPTER 2
LITERATURE REVIEW

2.0 Introduction

This chapter tells about the review of the past researches which had contributed greatly to the thesis. Power delivery system sole purpose is to channel current and power towards the intended consumer where the whole system consist of thousands of miles of power system network. The level of current and power delivered to consumers is defined by the characteristic of loads the consumers possessed. The direct effect of power quality problem of harmonics towards power cables is that the RMS value of current flowing through it may be higher due to nonlinear load connectivity. Current harmonics, resulted by nonlinear loads, may cause additional loss in term of increment of conducting temperature of power cables, resulted from increase of their resistance.

Thus, in order to realize a factor to select power cables under nonlinear load, a constant is to be proposed, according to the percentage of harmonic content in current (THD_i). The constant, K is to be utilized to determine the size of power cable which is able to sustain certain amount of current with certain amount of harmonic content, without exceeding the required standard. At the end of the chapter, a summary is given as to briefly conclude the literature review done for this thesis.

2.1 Power Distribution System in Malaysia

Power authority such as Electricity Generating Authority of Thailand (EGAT) and Tenaga Nasional Berhad (TNB) in Malaysia, their initial service is to provide power related services to the consumers, such as good quality power supply that enables houses, offices, and industrial players execute their operations smoothly. However, the task of maintaining good quality of current and power at national frequency, is not as easy as it may heard, as there are a lot of factors to be considered, such as peak demand, generation aspects, and also load character at consumer's end. In reality, major load is of nonlinear character, due to intensive use of variable speed drivers by industrial users, power conversion based equipments such as personal computers and televisions in houses and offices, and many more (Yusof et al., 1995).

TNB, through its Power Quality Book guide, explains that, as voltage level of Malaysia's distribution system starts at 33kV and to be stepped down by distribution substation generators to 11kV and eventually to 415/ 240 volts (Yusof et al., 1995). At several places, 22kV and 6.6kV levels are still employed, according to load of consumers. 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). 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 50Hz with maximum and minimum of 0.5Hz (Yusof et al., 1995). 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. Primary distribution system (33kV to 6.6kV) uses 3 phase, 3 wire network configuration, and it is either solidly grounded or grounded through impedance (Yusof et al., 1995). Both overhead and underground lines are used for distribution medium from stations to consumers.

In power distribution and transmission system, power cables are the main media for the purpose of channeling current and power towards consumers. The sustainability of power cables to deliver current to consumers' loads is important, and it depends on the RMS value of current. The higher the current RMS, the higher the operating temperature of power cables. Thus, it is important for the cable to load such amount of current that does not violate the standard required temperature. Any violation of standard operating temperature means it has to deliver excessive current and to avoid unnecessary incidents, resizing of cable must be performed.

2.2 Consumer Load Characteristics

Load of a power system is represented by the usage of three groups of consumers; namely industrial, commercial and domestic (Sulaiman, 2004) (Ngandui and Paraiso, 2004). Industrial loads are composite loads, and contain numerous number of induction motors to make up the large proportion of the loads. Commercial and domestic loads are the loads that independent of frequency and consume very little small reactive power, and that includes for the purposes of lighting and cooling (Saadat, 1999). The example of delivery system that channels power to load at consumers' side can be illustrated as in Figure 2.1.

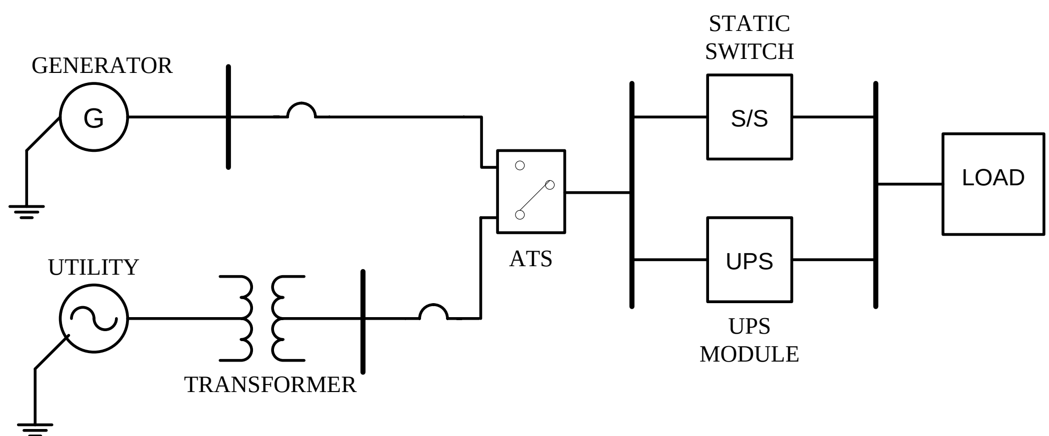


Figure 2.1: An electrical one-line diagram for a simple system used by many facilities that use computers extensively

Figure 2.1 shows a simple electrical one line diagram to accommodate extensive load of computers, where it consist of standby generator, automatic transfer switch (ATS), uninterruptible power supply (UPS) module, and a static bypass switch (S/S). Power electronic based equipments, such as ATS, UPS, and S/S do contain diodes which are capable of making voltage and current waveform distorted and become non sinusoidal. For that, they are the nonlinear loads which eventually contribute greatly towards current harmonics. However, they are essential in order to prevent shortage of power, as well as to serve as emergency back up system the moment power system is interrupted.

Type of loads normally found possessed by industrial consumers are motors, pumps, arc furnaces, and ASD. Their electrical characteristics are inductive and nonlinear (Burch et al., 2002). Meanwhile, domestic and commercial consumer uses a lot of equipments for daily and social usage, which includes lightings, coolers, and heaters. Types of load and their electrical characteristics are best simplified as in Table 2.1.

Table 2.1: Typical Load of User

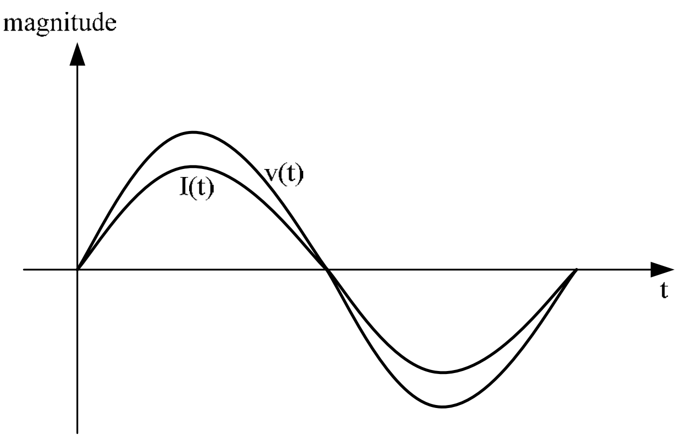
Type of User	Type of Load	Electrical Characterisitcs
Domestic	Inscandescent lamps Water heaters	Resistive Resistive
Commercial	Computers Flourescent lamps Water heaters	Nonlinear Nonlinear Resistive
Industrial	Motors ASDs Arc Furnaces Pumps	Inductive Nonlinear Nonlinear Inductive

(Source: Butch et al., 2001)

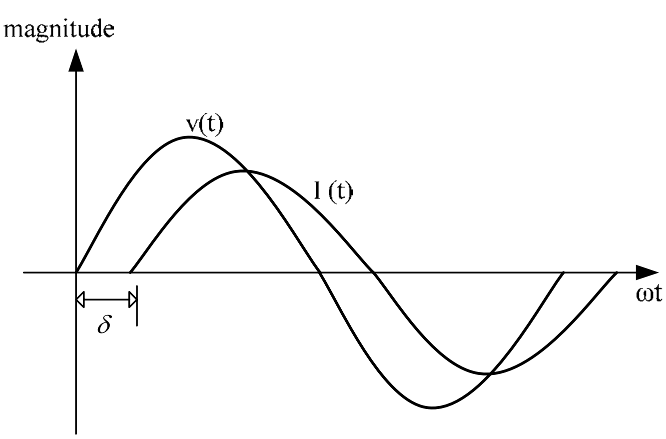
Load characteristics of consumers would determine the sort of quality of supplied power from power system authority (Faulkenberry and Coffer, 1996). For instance, in city distribution system, there are overwhelmingly many nonlinear loads such as trolley buses, microcomputers, fluorescent lamps, and etc (Yong, 1997) (Mansoor et al., 1995). The degree of current and voltage distortion is so bad that harmonic problem that caused various effects such as neutral conductor overload and major power black out.

2.2.1 Linear Load

Generally, distribution system ends with supplement of power to consumer’s load, regardless any type of consumer they are. The type of load is extremely important, at least from power cable sizing method point of view. Linear loads, when connected to sinusoidal source, draw sinusoidal current. Meaning, the source voltage and current produced are in perfect sine wave shape and contain only fundamental frequency (Kneschke, 1999). Any sort of disturbance to the either shape or smoothness of both voltage and current is null, and in fact, the only difference is the magnitude of either current or voltage, and that is caused by the load resistance itself. In other words, the shape of load current and source voltage is pure sinusoidal, with the same frequency of swing, and the same degree of a half cycle or a complete cycle (Edminister and Nahvi, 1997). Loads of residential and commercial users are mainly linear, thus power quality problem is not a big concern. The linearity of voltage and current from linear load connectivity can be observed at Figure 2.2.



(a)



(b)

Figure 2.2: (a) Pure resistive network where there is no difference in phase angle between voltage and its corresponding current, and (b) Impedance-loaded network where there is a difference in phase angle between voltage and current

A sinusoidal voltage or current function that is dependent to time, t can be represent by the following mathematical expression:

$$v(t) = V_m \sin(\omega t) \tag{2.0}$$

$$i(t) = I_m \sin(\omega t \pm \delta) \tag{2.1}$$

Where the ω=2πf and f is the frequency of system. δ is the difference in phase angle between voltage and its corresponding current waveform from a particular common axis. As for the purpose of power cable sizing, the only concern for network with linear load is the magnitude of RMS current, where from the derivation of equation (2.2), it is expressed as:

$$I = i_{rms} = \frac{I_m}{\sqrt{2}} \tag{2.2}$$

The size of power cable as to sustain sinusoidal current is by determining the magnitude of RMS current. The selection of power cable also heavily influenced by the magnitude of RMS current alone.

2.2.2 Nonlinear Load

This type of load is very much in demand all over the world, regardless whether they are industrial, commercial, or domestic users. Computers, air conditioners, and televisions are examples of this type of load and it is understandably impossible to eliminate them away, even their impact to power system is already well documented. Nonlinear load, is define as, a class of load that, when subjected to sinusoidal voltage source, would draw non-sinusoidal current into the system (Kneschke, 1999) (Umeh and Mohamad, 2003) (Bollen, 2003).

The current drawn by nonlinear load is not sinusoidal, meaning; it is distorted to a certain degree and differs in shape from the applied voltage. However, it is periodic, meaning the current looks the same from cycle to cycle (Izhar et al., 2003). Periodic means, the current is deviated to a certain degree in intervals, and overall deviation level could in seconds, and hours. This phenomenon is caused by the character of the nonlinear load itself, as it tends to switched on and off for some intervals, thus resulting changes as time varies (Wagner et al., 1993). Nonlinear load majorly found in industrial user in the form of arc furnaces and ASDs, while at offices and homes, televisions, computers, and air conditioners are common examples. Those loads distort current and voltage waveforms to such extend that they can cause additional loss, hence introduce harmonics (Bachry et al., 2000) (Ghijselen et al., 2003). Thus, power quality problem especially harmonics in unavoidable due to the need of nonlinear loads. Distortion to voltage and current can be illustrated at the following Figure 2.3.

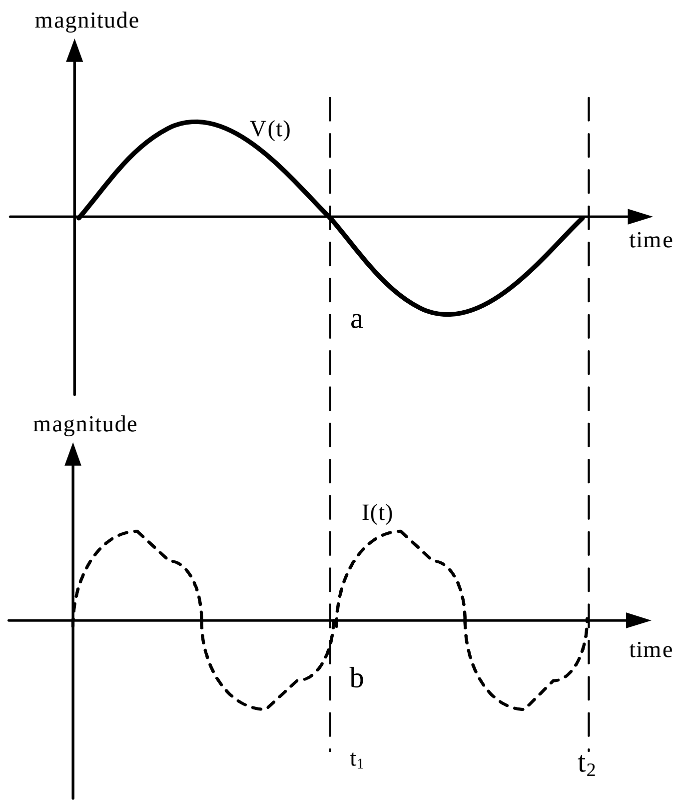


Figure 2.3: Example of waveform of (a) source voltage, and (b) distorted current at time interval t_1 and t_2.

Figure 2.3 (a) and (b) show the corresponding distortion of current as sinusoidal voltage being supplied to network. Mathematical expression as (2.0) and (2.1) is no longer valid to determine the distorted current magnitude; instead formulation of Fourier Series is used for the purpose. Below is the simplified expression of current:

$$i(t) = I_o + I_1 sin\ (\omega t) + I_2 sin\ (2\omega t) + I_3 sin\ (3\omega t) + \ldots$$

$$= I_n sin(n\omega t) + ... + I_{n+1} sin((n+1)\omega t) \tag{2.3}$$

The equation (2.3) goes on infinite, while I_0 is the DC component of the waveform, and I_1, I_2, I_3, and I_n are the peak values of successive term of expression. Notation n is to be referred to the integer of 1, 2, 3…n.

Nonlinear load produces harmonics, which is a severe power quality problem. Its effect includes increase power cable loss, condemning the rotation of machines, and causing neutral conductor to be overload due to high neutral current (Desmet et al., 2003) (Bollen, 2003) (Wagner et al., 1993). In term of power cable sizing, harmonic content in current has tremendously change the RMS value of current, thus, deriving from equation (2.3):

$$I_{rms} = \sqrt{\left(\frac{I_{m1}}{\sqrt{2}}\right)^2 + \left(\frac{I_{m2}}{\sqrt{2}}\right)^2 + ... \left(\frac{I_{mn}}{\sqrt{2}}\right)^2} \tag{2.4}$$

As the peak of current for each harmonic order increases, the overall value of RMS current also increases. I_{m1} is the first peak magnitude of current in a distorted current waveform, and it goes on until the n-th peak magnitude of current, I_{mn}. Therefore, harmonic content in current may cause additional loss in power cables. The relation this increment of RMS current is relate directly to the percentage of Total Harmonic Distortion of current (THD_i). The higher percentage of THD_i means higher RMS current, thus contribute to higher operating temperature of power cables.

2.3 Harmonic in Power Distribution System

Qualitatively, harmonics are defined as sinusoidal waveforms of either current or voltage, with frequencies that are integer multiples of fundamental power system frequency. Another widely used description of harmonics is that it is applied to term the distortive nature of voltage or current, which largely caused by nonlinear loads. Harmonics is actually a huge power system problems and documentation on it started way back in the early of the last centuries (Duffey, 1993). During the early 1920s and 1930s, harmonics were caused largely by transformers and inductive interference telephone systems. Fast forward today, it has detrimental effects on power distribution system and among the effects is reducing current capacity in power cables, thus resulting in reduced ability to channel current to consumers. Filtering harmonic could pave the way for higher efficient power system. Another way is to suit the equipments that affected by harmonics to contain its effect, for example, cable size.

2.3.1 Harmonic Definition

Harmonic is simplified as a sinusoidal component (current or voltage) of a periodic wave having a frequency that is an integral multiple of the fundamental frequency. For instance, in a system with fundamental frequency of 50Hz, sinusoidal current that contain frequency of 250 Hz is called the 5th harmonic current. In power quality scenario, harmonics is termed as the non sinusoidal state of current or voltage, as they combine both fundamental and harmonic components. Thus, in order to define harmonics in current or voltage, a special expression is needed to separate those components into single pieces. Fourier series expression of a periodic non sinusoidal waveform can be simplified as the following:

$$\begin{aligned} i(t) &= I_1 sin\,(\omega t) + I_3 sin\,(3\omega t) + I_5 sin\,(5\omega t) + \ldots \\ &= I_n sin(n\omega t) + \ldots + I_{n+1} sin((n+1)\omega t) \end{aligned} \tag{2.5}$$

Where each of the fundamental and component can be signified into their own expression, taking both sinus function as well as degree of deviation into consideration. Equation (2.5) also has given individual expression of fundamental and harmonic element, in order to indicate that there is combination of components in the current as nonlinear load is attached to network.

2.3.2 Harmonic Sequences

One of parameters regarding harmonics that is essential to look into is the sequences. The nature of 3rd, 5^{th}, and 7th…until n^{th} harmonic can be examined in order to define harmonic sequences, and it is extremely important particularly in three phase system and its applications, especially three phase motor.

Rotating magnetic flux is produced as balanced three phase voltages are applied to the stator of induction and synchronous motor. It goes on to produce mechanical force to rotate the rotor, and that rotation can be either forward, which is the usual and in accordance to manufacturer's specification for most of motors, or it can rotate to the opposite, depending on the supplied three phase voltage (Theraja, 1984) (Theodore, 2002). However, if the supply is distorted and contains harmonic elements, than there is a need to re-evaluate several parameters, including harmonic sequences and the nature of rotor rotation by them. Vector of generated harmonic current each phase can be resolve into sequences, namely positive, negative, and zero. For instance, below is the expression of phase harmonic currents:

$$I_r(t) = I_{1m}\sin(\omega t + \delta_1) + I_{3m}\sin(3\omega t + \delta_3) + I_{5m}\sin(5\omega t + \delta_5) + \ldots I_{hm}\sin(n\omega t + \delta_n) \quad (2.6)$$

$$I_y(t) = I_{1m}\sin\left(\omega t - \frac{2\pi}{3} + \delta_1\right) + I_{3m}\sin\left(3\left(\omega t - \frac{2\pi}{3}\right) + \delta_3\right) + I_{5m}\sin\left(5\left(\omega t - \frac{2\pi}{3}\right) + \delta_5\right)$$

$$= I_{hm}\sin\left(n\left(\omega t - \frac{2\pi}{3}\right) + \delta_n\right) \quad (2.7)$$

$$I_b(t) = I_{1m}\ sin\left(\omega t - \frac{4\pi}{3} + \delta_1\right) + I_{3m}\ sin\left(3\left(\omega t - \frac{4\pi}{3}\right) + \delta_3\right) + I_{5m}\ sin\left(5\left(\omega t - \frac{4\pi}{3}\right) + \delta_5\right)$$

$$= I_{hm}\ sin\left(n\left(\omega t - \frac{4\pi}{3}\right) + \delta_n\right) \tag{2.8}$$

Where ω is the angular speed, $\omega = 2\pi \cdot f$, t = time, and δ = phase difference between currents. The phase difference is measured between harmonic components to the fundamental components for each phase current. Current of phase R, Y, and B are expressed with harmonic current that consist of fundamental element, as well as each of the harmonic order of 3^{rd}, 5^{th}, 7^{th}…until n^{th}. Simplification of equation (2.7) and (2.8) will yield that 3^{rd} harmonics is the same for each of R, Y, and B phase. Rotation of phase current is made possible by taking the degree of the current and place it into a common axis for all. Thus, tabulation of harmonic sequence is as follow:

Table 2.2: Harmonic order and subsequent sequences

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

(Source: Sankaran, 2002)

As the nature of positive and negative sequence of harmonics cancel each other, then the only order of harmonic that relevant in three phase, four wire system is the third order, especially for neutral conductor current loading. Summation of equation (2.6), (2.7) and (2.8) will show that, third order harmonic will add up instead, while the first order will be cancel by the fifth harmonics due to their opposite phase properties.

2.3.3 Quantitative Term of Harmonic

There are two valid expressions to term the deviation of current and voltage due to harmonics those are Individual Harmonic Distortion (IHD) as well as Total Harmonic Distortion (THD). Standing by its initial, the difference between IHD and THD is IHD analyze individual harmonic order to its fundamental where in a single non sinusoidal current there could be up to 21st order of harmonics. THD in meantime refers to total deviation of current as the whole, and it is just a matter of totaling many IHD into one common entity. Individual Harmonic Distortion (IHD) is the ratio between the RMS values of individual harmonic order, to the RMS value of the fundamental. Going by the definition, the mathematical expression is as:

$$IHD_N = \frac{I_N}{I_1} \cdot 100\ \% \tag{2.9}$$

I_N is the n-th harmonic current, and I_1 fundamental current in one particular system. Quantification harmonic with accordance to this method is known as harmonic distortion based on the fundamental, and this is widely used by IEEE in its standard procedures (Duffey, 1993).

Total Harmonic Distortion (THD) is a term used to describe the net deviation of a nonlinear waveform, be it current or voltage, from ideal sine waveform characteristics (Sankaran, 2002) (Hoevernaars et al., 2003) (Waseem and Aqib, 2007). It represents the amount of harmonic in a signal as a percentage of the total RMS Value (THD-R) or as a percentage of the fundamental (THD-F). THD also is a measure of the degree to which a waveform deviates from a purely sinusoidal shape. The calculative THD (RMS) measure of harmonic current is as follows:

$$\begin{aligned} I_{rms,n} &= \sqrt{\left[\frac{1}{T_n}\int_0^{T_n} \left(I_h(t)\right)^2 dr\right]} \\ &= \sqrt{\left[\frac{1}{T_n}\int_0^{T_n}\left[I_{max,h}\ sin\left(n\,\omega\,t+\alpha\right)dt\right]\right]} \\ &= I_{\max,h}\sqrt{\left[\frac{1}{T_n}\left[\frac{1}{2}t - \frac{sin\,2n\,\omega\,t}{4\,\omega}\right]_0^{T_n}\right]} \end{aligned} \tag{2.10}$$

Equation (2.10) shows the RMS value of current at certain harmonic order n. It only represents calculation of RMS current of a particular frequency. The RMS value of current of all frequency can be determined as:

$$I_n = \frac{I_{max,n}}{\sqrt{2}} \tag{2.11}$$

$$I_{rms} = \sqrt{\left[\left(\frac{I_{max\,1}}{\sqrt{2}}\right)^2 + \left(\frac{I_{max\,2}}{\sqrt{2}}\right)^2 + \left(\frac{I_{max\,3}}{\sqrt{2}}\right)^2 + \ldots + \left(\frac{I_{max\,n}}{\sqrt{2}}\right)^2\right]}$$

$$= \sqrt{\sum_{h=1}^{m}\left(\frac{I_{max\,n}}{\sqrt{2}}\right)^2} \tag{2.12}$$

Equation (2.12) shows the fundamental equation of calculating harmonic current which contain several current with different frequencies, where if h=1, means the harmonic is first order and its frequency is the same as the fundamental's, while h=3 means, it is third order of harmonic and the carrying frequency is three times of fundamental's. THD of harmonic current also can be determined by totaling each of the IHD that obtained from each harmonic order in the distorted current, and thus, can be expressed as:

$$THD_i = \sqrt{\left(IHD_3^2 + IHD_5^2 + IHD_7^2 + \ldots + IHD_n^2\right)} \tag{2.13}$$

Where IHD^2_n refers to each of the harmonic component in a distorted waveform of current (n = number of harmonic order). Both IHD and THD share the same objective that is to measure distortion in waveforms. However, IHD is widely use for equipments and is sanctioned by IEC. THD meanwhile, is the standard used for power distribution system and been sanctioned by IEEE. THD is widely used to measure harmonics components at point of common coupling (PCC). Nonetheless, they are important parameters in order to determine the degree of deviation of current and voltage in power distribution system. However, most of harmonic measuring devices these days opt to give more emphasis on THD as it is the commonly used term to define harmonics.

2.4 Harmonic Sources

Principle of power system harmonic is that nonlinearity of current and voltage waveform to the perfect sinusoidal shape, which is caused by connection of nonlinear load. Power distribution system has to deal with several sources of harmonics, namely from two main areas such are:

i. Application of fast switching properties which related to various power electronic devices
ii. Modern and commonly used electronic based equipments

2.4.1 Harmonic Due to Application of Switching Equipments

Significant use of power electronic devices by industrial consumers has created alarming concern over harmonics impact toward power distribution system. Prediction in early 1990s indicated that in the coming millennium, more than 60% of industrial load will be controlled by power electronics applications (Lamarre, 1991). This is understandable as manual configuration is no longer efficient, thus major precision works are being relegated to electronic circuitry and devices (Nasiri, 2005) (Liew,1989).

Phase control rectifiers; be them for single phase or three phase network, function as to rectify the voltage or current waveform from alternating current (AC) to direct current (DC). Their contribution to power distribution are massive injection of harmonic, where previous researches have concluded that single phase full wave controlled rectifiers generated harmonics which are significant at lower frequency, while high powered three phase rectifiers produced large harmonics currents on 3^{rd}, 5^{th}, 7^{th}, up until 19^{th} (Yasuyuki et al., 1997) (Phillips et al., 1991). Domination of 3^{rd} harmonics that being injected to power distribution system has been intensified in speed control of portable hand tool driver and home and industrial applications of light dimmer and induction motor, with the latter is related to establishing appropriate voltage level for thyristor on and off gate current (Santoso and Mack, 2001) (Daniel, 1997). According to Sadeq, effect of controlling variable speed motor drives has caused the injection of 3^{rd}, 5^{th}, and 7^{th} harmonic component in currents to power distribution system (Sadeq, 2003).

Inverters, commonly used to convert direct current (DC) to alternating current (AC) are other industrial applications that contribute to harmonics in power distribution system. Desired output of voltage and frequency, as well as current magnitude is made possible by control strategies of inverters (Akira et al., 1996) (Omar, 2005). The switching between diodes has made the current and voltage, before and after inversion, vulnerable to distortion. However, reduction of distortion to current and voltage can be solve once the very high speed power semiconductor devices are applied to switching areas, and applying additional passive filters at the output of inverters (Liang et al., 1997). Conversion to another form of signal from one type of signal is done using converters. A 6 pulses thyristor controlled converter, consist of 3^{rd}, 5^{th}, 7^{th}…etc harmonics, while a 12 and 24 pulse converter will yield current with 11^{th}, 13^{th}, 23^{rd},…etc harmonics and 23^{rd}, 25^{th}, 47^{th}, ….etc harmonics respectively (Duffey, 1993). Cycloconverters contribute harmonics current on 3^{rd}, 5^{th}, 7^{th}, and 11^{th} to power network, thus caused considerable amount of current distortions (Rashid, 2002) (Ned et al., 1995) (Izhar, 2007).

Due to various industrial commonly use devices, it is appropriate to indicate that industrial consumers do contribute significant amount of current and voltage distortion in power distribution system (Mansoor and Grady, 1998). Realizing this, usually various passive and active filters are designed and applied by industrialists in order to keep harmonic content as low as possible, as permitted by standards and regulations.

2.4.2 Harmonics from Modern Electronic Based Equipments

Many of the loads that are being installed today, whether by domestic or commercial users, are harmonic current generators. With power system impedance (cable and network), there is also harmonic voltages, thus they are actually capable to produced current and voltage harmonics altogether. However, in actual world, those loads are in great demand for their specific and efficiency purposes. Adjustable speed drives (ASDs) perform its function to control machines speed very well, even though they are producing large amount of harmonic currents (Wagner et al., 1993) (Hansen et al., 2000). Adjustable speed drives (ASDs) primary objective is to regulate the speed of AC motors with the manipulation of voltage and frequency, with pulse width modulation (PWM) drive technology is the currently the most widely used. The problem is that, once frequency is reduced, there is sudden massive increase in total harmonic distortion (THD) of voltage. For instance, a reduced frequency from 50.0 Hz to 45.0 Hz would cause THD_v to be 74.2% which is very excessive and produce many harmful effects.

Domestic users opted for fluorescent lights due to less energy they consumed, but at the same time, they produce the same lumen strength as the normally used incandescent lights (Sankaran, 2002). However, as they succeed to reduce electrical bill, they produce substantial amount of harmonic currents in the process. Observation on distortion of current caused by this type of light has confirmed that the current is dominated by 3^{rd} and 5^{th} harmonic frequencies. Personal computers (PC) also an example of electronic based equipments nowadays that are very essential, however they cause distortion of current so great that power cable need to be resize in order to guarantee their operation as well as to ensure power system will not collapse (Aintablian, 2002) (Gruzs, 1991). A single PC consumed current at RMS value of 0.836A with current harmonic (THD_i) is equal 81.0%.

Due to distortion it made, the real value of current has peaked at more than 2.0A, and this may give problems in term of power cable ability to withstand the peaked current. At only 0.836A (RMS) drawn from one complete system of a PC, it may not represent a great danger, but in a typical high rise building or in a typical working office, the number of PC might be in hundreds (Spitsa and Alexandrovitz, 2004) (Gruzs, 1990) (Grady et al., 2002) (Izhar et al., 2003). Thus there is real concern over amount of current and harmonic content, and the need to evaluate size of power cable is intensified.

2.5 Harmonic Effect on Equipments and Power Distribution System

There is not much to deny that electronics load or nonlinear loads are pretty much in heavy demand, especially from industrial players, as well as commercial and domestic users. This is due to their massive contribution in term of high consistency execution various function such as motor speed control, and they also provide quick solution to problems such as data management with the invention of personal computers. However, their growth means, increase of cost control, quality control, higher consumption of electricity, as well as decrease quality of power. Several malfunctions of equipments are caused by harmonics, which includes:

a) Derating of power transformers
b) Overheating of rotating machineries
c) Tripping of circuit breakers and other safety devices
d) Ripple control and telecommunication interruptions
e) Increase the losses in power cables and power transmission
f) Excessive and overloading of neutral conductor in three phase network