EFFECT OF HARMONICS ON POWER MEASUREMENT

Oleh

Ting Guan Ket

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ABSTRACT

Harmonic has become a serious problem in electrical power system due to the rapid growth of non-linear loads from year to year. This final year project dealt with the effect of harmonics on power measurement. The objective of this research was to identify the presence of harmonic voltage and harmonic current when non-linear load is connected to the power system. This research also analysed the effect of harmonic current on power measurement by using a set of THD current value to test the measurement of power system quantities such as power factor PF, active power P, reactive power Q and apparent power S. The suitability of power measuring instruments under the effect of harmonics in power system was also be analysed. In this project, the derivation of mathematic equations was carried out to analyse the effect of harmonics on the measurement of power system quantities. Laboratory experiment was also carried out and experimental results were compared with theory and mathematical equations. A single phase bridge rectifier was built to implement the laboratory experiments. The output load of the rectifier was connected to variable resistors and capacitors. The source of the rectifier was a voltage supply of 240V, 50Hz. This rectifier circuit was used as non-linear load in this research. The total harmonic distortion for input voltage and current would change when the value of variable resistors and capacitors were adjusted. Power system quantities for a set of THD current values were collected to analyse the effect of harmonic current on power measurement. The experimental results showed that non-linear load is normally causing harmonic current distortion in the power system. The distortion of input voltage is very low and can be ignored. Fluke meter is the most suitable equipment which used to measure the distorted waveforms. The results also show that when harmonic current distortion is increasing, the value of power factor PF and active power P would decrease. But reactive power Q would decrease and apparent power S remains constant as the level of harmonic current increases.

ABSTRAK

Harmonik telah menjadi satu masalah yang serius dalam sistem elektrik kuasa disebabkan oleh perkembangan beban tak linear yang pesat dari tahun ke tahun. Projek tahun akhir ini bertujuan untuk mengkaji pengaruh harmonik terhadap pengukuran kuasa. Objektif Penyelidikan ini adalah bertujuan untuk memastikan kehadiran voltan harmonik dan arus harmonik apabila beban tak linear disambungkan kepada sistem kuasa. Penyelidikan ini juga menganalisis pengaruh harmonik terhadap pengukuran kuantiti sistem kuasa seperti faktor kuasa PF, kuasa aktif P, kuasa reaktif Q dan kuasa ketara S. Kesesuaian alat pengukur kuasa dalam keadaan kehadiran harmonik juga ditentukan dan dianalisiskan. Dalam projek ini, penerbitan persamaan matematik telah dilaksanakan untuk menganalisis pengaruh harmonik terhadap pengukuran kuantiti sistem kuasa. Eksperimen makmal telah dijalankan dan keputusan eksperimen dibanding dengan kenyataan teori dan persamaan matematik. Satu rektifier titi satu fasa telah dibina untuk menjalankan eksperimen makmal ini. Keluaran rektifier ini disambungkan kepada perintang dan kapasitor boleh laras. Punca rektifier ini merupakan bekalan voltan sebanyak 240V, 50Hz. Litar rektifier ini digunakan sebagai beben tak linear dalam penyelidikan ini. Jumlah herotan harmonik bagi voltan dan arus masukan akan berubah apabila nilai perintang dan kapasitor boleh laras diubah. Kuantiti sistem kuasa bagi satu set nilai arus THD tertentu telah dikumpulkan untuk mengkaji pengaruh harmonik terhadap pengukuran kuasa. Keputusan eksperimen menunjukkan bahawa beban tak linear biasanya menyebabkan herotan harmonik pada arus sahaja dalam sistem kuasa. Herotan pada voltan input adalah sangat kecil dan boleh diabaikan. Meter Fluke merupakan alat yang paling sesuai digunakan untuk megukur gelombang-gelombang terherot. Keputusan juga menunjukkan bahawa apabila herotan arus harmonik meningkat, nilai faktor kuasa PF dan kuasa aktif P akan menurun. Tetapi, nilai kuasa reaktif Q akan meningkat dan kuasa katara S kekal sama apabila herotan arus harmonik meningkat.

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CHAPTER 1

INTRODUCTION

1.1 Background

Power system harmonics are a continuous state problem with dangerous results. Harmonics can be present in current, voltage, or both. It is estimated that as many as 60% of all electrical devices operate with non-linear current draw. Utility companies invest millions of dollars each year to ensure that voltage supplied to their customers is as close as to a sinusoidal waveform. If the power user connects loads to the system which are resistive, such as incandescent light bulb, the resulting current waveform will also be sinusoidal. However, if the loads are non-linear, which is typically the case, the current is drawn in short pulses and current waveform will be distorted. [1]

The usage of non-linear loads has increased rapidly from year to year. These non-linear loads such as personal computer, battery charger and so on are connected to AC power supplies which supply pure sine wave voltage. A non-linear load is one in which the current is not proportional to the applied voltage. This is because these loads are using rectifiers to convert alternating current (AC) to direct current (DC). This conversion will generate harmonic and the waveform become non-sinusoidal. For example, non-linear loads such as electronic power converter can chop the current into seemingly arbitrary waveforms [2].

Total current that is drawn by the non-linear load would be the fundamental as well as all the harmonics. Harmonic distortion can cause serious problems for the users of electric power. Harmonics can cause problems that are easy to recognize but though to diagnose. It is becoming increasingly important to understand the fundamentals of harmonics, and to be able to recognize and monitor the presence of damaging harmonics. Harmonics within an electrical system vary greatly within different parts of the same distribution system and are not limited simply to the supply producing device. Harmonics can interact within the system through direct system connections or even through capacitive or inductive coupling [1]

Most single phase office equipment draws non-linear current. While fluorescent lighting with electronic ballasts and many types of office equipment contribute to create harmonic, personal computer power supplies are the largest contributor within the office environment. Although THD levels will be lower than in an industrial setting, the susceptibility of office equipment to variations in power quality is extremely high. In the industrial environment, there can be many three phase, non-linear loads drawing high levels of load current. The most prevalent harmonic frequencies are the odd integer multiples of the 60Hz frequency. The third harmonic is always the most prevalent and troublesome [1].

In power system, the power measurement of electrical equipment has become very important seems over current fault due to harmonic can cause severe damage to the equipment. This is because most of the power measuring instruments are designed and calibrated under pure sinusoidal conditions. An electrical meter is designed and adjusted to operate in circuits of standard frequency and voltage with little or no waveform distortion exists. These conditions are usually closely approximated in practical systems and the errors in energy measurement due to the approximations are negligible. However, the increasing industrial application of electronic and high frequency equipment causing harmonic distortion in the load current has caused concern regarding the performance of the meters used to measure the energy required [7]. Harmonic will affect the measurement value of power system quantities such as power factor PF, active power P, reactive power Q and apparent power S and incorrect data or result would be received and collected. Therefore, the effect of harmonics on power measurement has to be considered and analyzed in order to provide protection to the power system.

1.2 Objective

The objective of this research is to analyse the effect of harmonics on power measurement. The presence of harmonic voltage and harmonic current when non-linear load is connected would be identified in this research. This research would also analyse the effect of harmonic current on power measurement by using a set of THD current value to test the measurement of power system quantities such as power factor PF, active power P, reactive power Q and apparent power S. The suitability of power measuring instruments under the effect of harmonics in power system would also be analysed.

1.3 Scope of Research

The power measuring instruments used in this final year project are Fluke 43B, wattmeter, AC voltmeter and AC ammeter. These instruments would be used to measure the input voltage and input current. A single phase bridge rectifier is built and connected to variable resistors and capacitors. This was done to create harmonic for voltage and current with total harmonic distortion (THD) ranged from 0% to 120%. Experiment is implemented to analyse the characteristics of voltage and current in the presence of harmonic voltage and harmonic current.

1.4 Steps of Implementing the Research

Figure 1.1 shows the flow chart on steps to implement the research. The first step that I needed to do is to understand the title of my final year project. This is done by having discussions with my project's supervisor. The discussions are held to discuss on type of research should be implemented. I am also required to study the connection of experiment circuit and operation of the laboratory equipments such as Fluke meter, rectifier circuit and other power measuring instruments. The location of the research is power laboratory.

Next, the planning of the research has to be carried out. Design of experiment's circuit is carried out to find a suitable circuit to implement the research. Equipments and tools that are required and types of data should be collected are also planned. In the third step, the examination and adjustment on the power measuring instruments such as Fluke meter, wattmeter, AC voltmeter and AC ammeter are carried out. Explanations are given by the laboratory technicians on ways to use the equipments and tools.

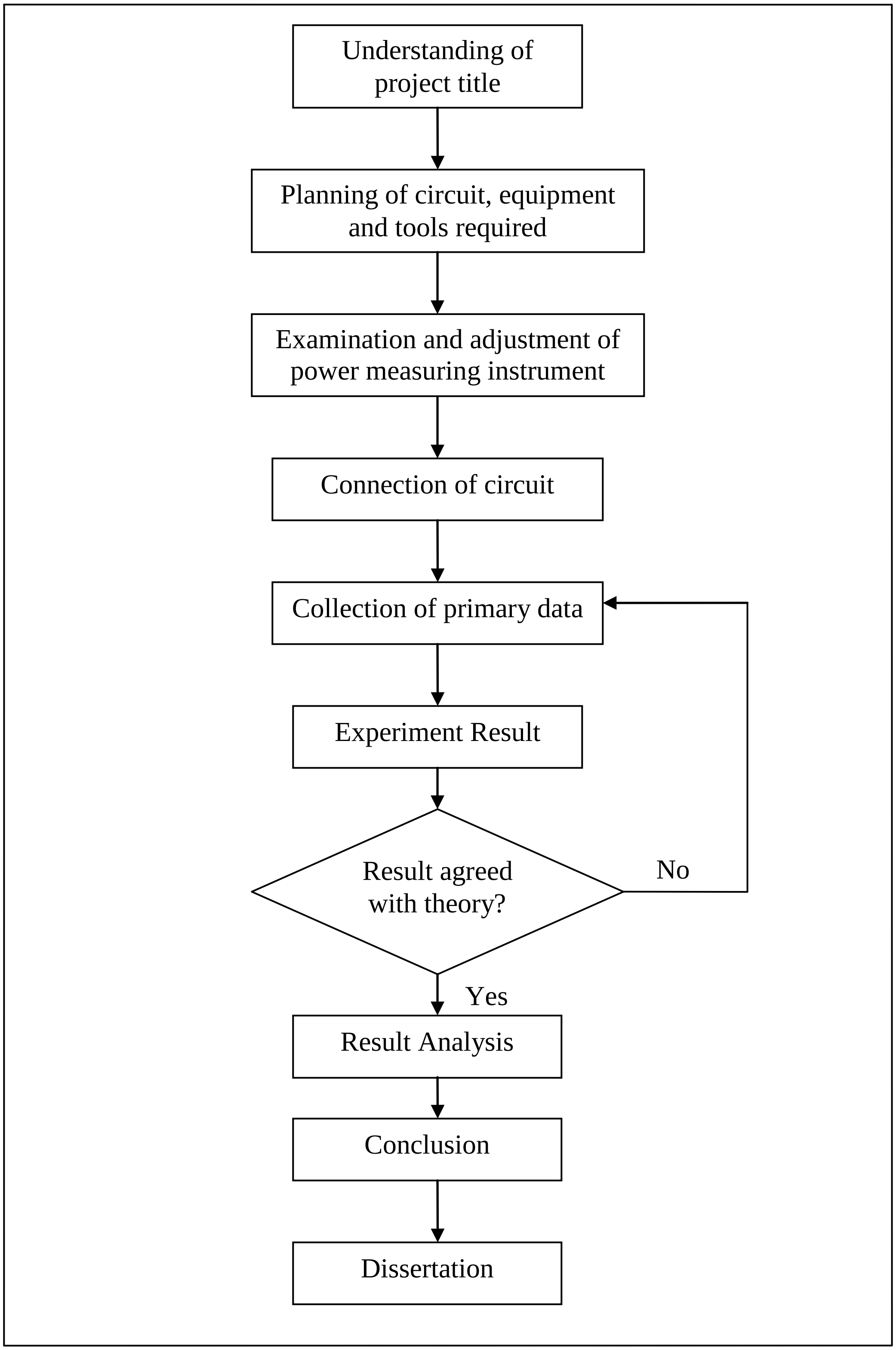

Figure 1.1: Flow chart on steps of implementing the research

The connection of experiment's circuit is done in fourth step. Basically, a bridge rectifier is built with four units of diodes and connected to the loads of variable resistors and capacitors. Input of the circuit is connected to a voltage supply of 240V, 50Hz. The next step is the collection of primary data from the experiment. Measurement of power system quantities such as power factor PF, active power P, reactive power Q and apparent power S are collected and recorded. Data would be processed in form of tables, graphs and equations to produce secondary data and followed by experiment results.

Experiment results are analysed and compared with the theory analysis. Lastly, the conclusion of the research is made and the dissertation of my final year project is produced.

1.5 Report Guidance

This report is divided into 6 chapters. This chapter, as Chapter 1 is an introduction to the dissertation and the project title. Chapter 2 is the theory explanation about the project title. Concepts and the knowledge that used to implement the research would be presented in this chapter. In Chapter 3, implementation of research is explained in details. From the planning of experiment, the implementation of research is explained step by step until the collection of primary data from the experiment. Chapter 4 is the collection of primary data from laboratory experiment. Process of generating the experiment result is done in this chapter. Primary data are processed in the form of tables, graphs and equations. Chapter 5 is the analysis of the experiment results obtained from Chapter 4. This is done to reach the objective of this research. Lastly, Chapter 6 would give the conclusion to the project implemented.

CHAPTER 2

THEORY

2.1 Harmonic

Harmonic is a sinusoidal component of periodic wave or quantity having a frequency that is an integral multiple of the fundamental frequency. If the fundamental waveform is $a_1 = A_1 \sin wt$, the second harmonic will be $a_2 = A_2 \sin 2wt$. The frequency of second harmonic is double of the fundamental frequency [6]. Figure 2.1 and Figure 2.2 show the fundamental waveform and the distorted waveform.

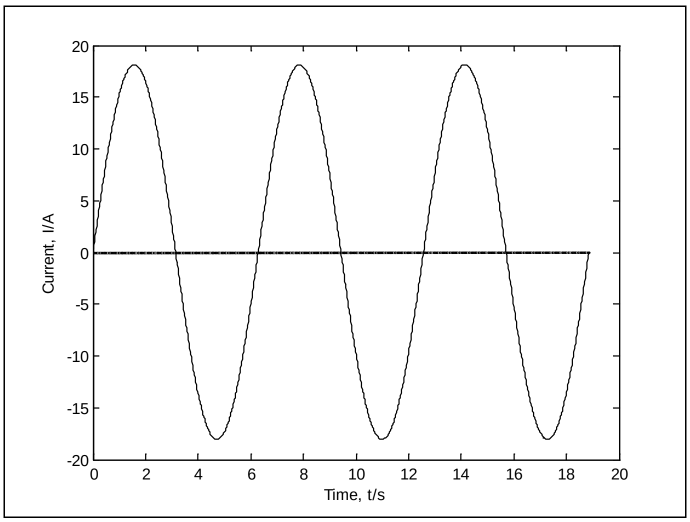

Figure 2.1: Pure sinusoidal waveform

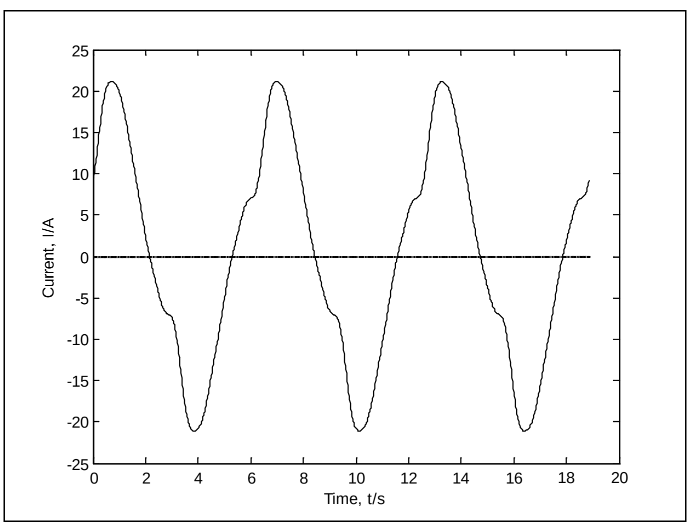

Figure 2.2: Distorted waveform with harmonics

In order to be able to analyse complex signals that have many different frequencies present, a number of mathematical methods were developed. One of the more popular is called the Fourier Transform [3].

2.1.1 Representation of Harmonic

The Fourier series represents an effective way to study and analyse harmonic distortion. It allows inspecting the various constituents of a distorted waveform through decomposition [3]. This is because periodic waveform can be represented by an infinite series of sine waves having frequencies which are multiples of the fundamental frequency, i.e., harmonics [5]. Generally, any periodic waveform can be expanded in the form of a Fourier series as

$$f(t) = A_0 + \sum_{n=1}^{\infty}\left[A_n \cos(nw_0 t) + B_n \sin(nw_0 t)\right] \tag{2.1}$$

or

$$f(t) = A_0 + \sum_{n=1}^{\infty} C_n \sin(nw_0 t + \varphi_n) \tag{2.2}$$

The Fourier coefficients are given by

$$A_0 = \frac{1}{T}\int_0^T f(t)dt \tag{2.3}$$

$$A_n = \frac{2}{T}\int_0^T f(t)\cos(nw_0 t)dt \tag{2.4}$$

$$B_n = \frac{2}{T}\int_0^T f(t)\sin(nw_0 t)dt \tag{2.5}$$

$$C_n = \sqrt{A_n^2 + B_n^2} \tag{2.6}$$

$$\varphi_n = \tan^{-1}\left(\frac{A_n}{B_n}\right) \tag{2.7}$$

where

$f(t)$ is a periodic function of frequency f_0

w_0 is the angular frequency of the waveform

T is the period of the waveform

$C_n \sin(nw_0 t + \varphi_n)$ is the nth harmonic of amplitude C_n , frequency nf_0 and phase φ_n .

2.1.2 Total Harmonic Distortion (THD)

Total Harmonic Distortion is defined as the ratio of root-mean square (RMS) of the harmonic content to the root-mean square value of the fundamental quantity. The fundamental is the system frequency of 50Hz. Harmonic distortion is caused by the introduction of waveforms at frequencies in multiplies of the fundamental i.e., 3rd harmonic is 3 times the fundamental frequency or equals to 150Hz. Total harmonic distortion is a measurement of the sum value of the waveform that is distorted. Frequently THD is expressed in percent [8]. For example, THD for the current is defined as

$$THD_i = \sqrt{\frac{\sum_{n>1} {I_n}^2}{I_1^2}} \times 100\% \tag{2.8}$$

or

$$THD_i = \sqrt{\frac{I_2^2 + I_3^2 + I_4^2 + I_5^2 + ...}{I_1^2}} \times 100\% \tag{2.9}$$

where I_1 is the fundamental current

I_2 is the second harmonic current

I_n is the nth harmonic current

2.1.3 Harmonic Limits

For low voltage level of 0.4kV at distribution system, the harmonic distortion level for voltage and current are as shown in Table 2.1 and 2.2 [16].

Table 2.1: The harmonic distortion level at public distribution area

Public Distribution	
Residences, low voltage	THD_i: 5 – 30 %
Single larger customer, low voltage	THD_i: 2 – 20 %
Totally for a low voltage transformer	THD_i: 2 – 15 %
	THD_v: 1 – 6 %

Table 2.2: The harmonic distortion level at industrial distribution area

Industrial Distribution	
Single devices (converters)	THD_i: 25 – 200 %
Totally for a low voltage transformer	THD_i: 15 – 25 %
	THD_v: 3 – 6 %

The harmonic distortion level for voltage is not high both in public and industrial distribution, which is about 2 – 6%. However, the distortion level for current is ranged from 2% to a maximum of 30% at public distribution. For industrial distribution, the current distortion is much higher, which is ranged from about 15% to a maximum of 200%. The harmonic distortion level of 200% will occur in the industrial areas which normally use rectifier circuits to convert AC power to DC power.

In 1993, Institute of Electrical and Electronics Engineers (IEEE) has published a revised draft standard for limiting the amplitudes of current harmonics. It is an IEEE guide for harmonic control and reactive compensation of static power converters. Harmonic limits are based on the ratio of the fundamental component of the load current I_L to the short circuit current I_{SC} at the point of common coupling (PCC) at the utility. The odd harmonic limits are listed in Tables 2.3 and 2.4. The limits for even harmonics are 25% of the odd harmonic limits [9].

Table 2.3: IEEE-519 Maximum odd harmonic current limits for general distribution systems, which is from 120V to 69kV

I_{SC}/I_L	$n < 11$	$11 \le n < 17$	$17 \le n < 23$	$23 \le n < 35$	$35 \le n$	*THD*
<20	4.0%	2.0%	1.5%	0.6%	0.3%	5.0%
20–50	7.0%	3.5%	2.5%	1.0%	0.5%	8.0%
50–100	10.0%	4.5%	4.0%	1.5%	0.7%	12.0%
100–1000	12.0%	5.5%	5.0%	2.0%	1.0%	15.0%
>1000	15.0%	7.0%	6.0%	2.5%	1.4%	20.0%

where n is the order of harmonic
I_{SC} is the short circuit current at point of common coupling (PCC)
I_L is the maximum demand load current (fundamental) at PCC

Table 2.4: IEEE-519 Voltage distortion limits

Bus voltage at PCC	*Individual harmonics*	*THD*
69kV and below	3.0%	5.0%
69.001kV–161kV	1.5%	2.5%
above 161kV	1.0%	1.5%

Table 2.3 shows the maximum odd harmonic current limits for general distribution systems, which ranged from 120V to 69kV. The PCC can be considered as the connection point between linear and non-linear (harmonic producing) loads. Harmonic distortion limit for individual harmonic is decreasing as the order of harmonic is increasing. However, the THD_i level for the distribution system is increasing as the ratio of value I_{SC}/I_L is increased. The maximum allowed THD_i of the system is about 20%, for ratio of value I_{SC}/I_L more than 1000A.

The distortion limits for voltage is shown in Table 2.4. For bus voltage at PCC is 69kV and below, the maximum allowable distortion is 5%. This distortion level is far more less than the THD_i of 20%. This shows that the distortion level for voltage is low and THD_v is not distorted as much as THD_i. The voltage waveform from a stiff utility source usually will not contain harmonics. However, when the source is not stiff (such as an emergency generator) this may not be possible and voltage harmonics may exist [13].

2.1.4 RMS Value for Distorted Waveform

An electrical system supplies power to loads by delivering current at the fundamental frequency. Only fundamental frequency current can provide real power. Current delivered at harmonic frequencies doesn't deliver any real power to the load. When current of a single frequency is present in a system, you can use the measured values in Ohm's Law and power calculations. However, when currents of more than one frequency are present, direct addition of the current values leads to a summed value that doesn't correctly represent the total effect of the multiple currents. Instead, you need to add the currents in a manner known as the “root mean square” summation. The equation for the rms addition of currents is as follows [10]:

$$I_{rms} = \sqrt{I_1^2 + I_2^2 + I_3^2 + ... + I_n^2} \tag{2.10}$$

where I_1 is the fundamental current

I_2 is the second harmonic current

I_n is the nth harmonic current

Therefore, the effective value of the current has increased in the presence of harmonic. The same is true for harmonic voltages. To obtain the effective voltage for a system in which voltages of several frequencies are present, you must add the voltages in an rms fashion [10].

2.2 Power Measurement

The definitions of apparent power S, active power P, and reactive power Q in sinusoidal systems have been accepted by the Power Engineering Society for more than a century without reservation. Today, the increased use of power converter, adjustable speed drives, electronic devices, etc., contribute to the excessive distortion of voltage and current waveform due to harmonics. In general, the advancement and wide application of electronic device and microprocessors in many applications significantly contribute to the waveform distortion. This created the need for an accurate method for the measurement of the power components in the presence of harmonic distortion [14].

2.2.1 Power Components in Sinusoidal Condition

Power equation for a system was defined a long time ago. It mutually relates the active, reactive, and apparent power (P, Q, S) as

$$S^2 = P^2 + Q^2 \tag{2.11}$$

In addition, the instantaneous power *P(t)* has been defined as

$$P(t) = v(t) \cdot i(t) \tag{2.12}$$

where

$v(t)$ is the instantaneous voltage

$i(t)$ is the instantaneous current

Let the instantaneous voltage be

$$v(t) = V_m \cos(wt + \theta_v) \tag{2.13}$$

and the instantaneous current be given by

$$i(t) = I_m \cos(wt + \theta_i) \tag{2.14}$$

where

V_m is the amplitude of the voltage waveform

I_m is amplitude of the current waveform

w is the angular frequency in radian/s

θ_v is the phase of voltage waveform

θ_i is the phase of current waveform

Thus

$$P(t) = V_m I_m \cos(wt + \theta_v)\cos(wt + \theta_i) \tag{2.15}$$

It is informative to write Equation 2.15 in another form using the trigonometric identity.

$$\cos A \cos B = \frac{1}{2}\cos(A-B) + \frac{1}{2}\cos(A+B) \qquad (2.16)$$

which results in

$$P(t) = \frac{1}{2}V_m I_m \left[\cos(\theta_v - \theta_i) + \cos(2wt + \theta_v + \theta_i)\right]$$

$$= \frac{1}{2}V_m I_m \left\{\cos(\theta_v - \theta_i) + \cos\left[2(wt + \theta_v) - (\theta_v - \theta_i)\right]\right\}$$

$$= \frac{1}{2}V_m I_m \left[\cos(\theta_v - \theta_i) + \cos 2(wt + \theta_v)\cos(\theta_v - \theta_i)\right.$$

$$\left. + \sin(2wt + \theta_v)\sin(\theta_v - \theta_i)\right) \qquad (2.17)$$

The root-man-square (rms) value of *v(t)* is V_{rms} = $V_m / \sqrt{2}$ and the rms value of *i(t)* is I_{rms} = $I_m / \sqrt{2}$. Let $\theta = (\theta_v - \theta_i)$ [4]. The above equation, in terms of the rms values, is reduced to

$$P(t) = V_{rms} I_{rms} \cos\theta \left[1 + \cos(2wt + \theta_v)\right] + V_{rms} I_{rms} \sin\theta \sin 2(wt + \theta_v) \qquad (2.18)$$

where θ is the angle between voltage and current, or the impedance angle. The instantaneous power has been decomposed into two components [4]. The first components of Equation 2.18 is

$$p_R(t) = V_{rms} I_{rms} \cos\theta + V_{rms} I_{rms} \cos\theta \cos 2(wt + \theta_v) \qquad (2.19)$$

The second term in Equation 2.19, which has a frequency twice that of the source, accounts for the sinusoidal variation in the absorption of power by the resistive portion of the load [4]. Since the average value of this sinusoidal function is zero, the average power delivered to the load is given by

$$P = V_{rms} I_{rms} \cos\theta \qquad (2.20)$$

This is the power absorbed by the resistive component of the load and is also referred to as the active or real power. The product of the rms voltage value and rms current value $V_{rms}I_{rms}$ is called the apparent power and is measured in units of volt ampere. The product of the apparent power and cosine of the angle between voltage and current yields the real power. This is because $\cos\theta$ plays a key role in the determination of the average power, it is called power factor [4].

The second component of Equation 2.18

$$p_X(t) = V_{rms}I_{rms}\sin\theta\sin 2(wt+\theta_v) \quad (2.21)$$

pulsates with twice the frequency and has an average of value of zero. This component accounts for power oscillating into and out of the load because of its reactive element (inductive or capacitive). The amplitude of this pulsating power is called reactive power and is designated by Q [4].

$$Q = V_{rms}I_{rms}\sin\theta \quad (2.22)$$

Both P and Q have the same dimension. However, in order to distinguish between the real and the reactive power, the term 'var' is used for the reactive power [4].

2.2.2 Power Components in Non-sinusoidal Condition

Several attempts have been made to come up with accurate definitions of power system quantities in a non-sinusoidal condition. This section of research aims at formulating the power quantities from the basic definition of instantaneous power to define the power components at all harmonic frequencies [14].

2.2.2.1 Power Factor

Power factor PF, the ratio of active power to apparent power, is a familiar concept in power system management. It determines how much energy, both work producing (watts) and reactive (vars) is required to power a load. In sinusoidal condition, power factor is defined as

$$\text{PF} = \frac{P}{S}$$

$$= \frac{V_{rms} I_{rms} \cos\phi}{V_{rms} I_{rms}}$$

$$= \cos\phi \qquad (2.23)$$

However in the presence of harmonic, the definition of power factor in Equation 2.23 has to be modified to

$$PF = \frac{V_{rms1} I_{rms1} \cos\phi_1}{V_{rms} I_{rms}} \qquad (2.24)$$

If voltage is assumed an ideal sinusoidal waveform, Equation 2.24 become

$$PF = \frac{I_{rms1}}{I_{rms}} \cos\phi_1 \qquad (2.25)$$

where $\cos\phi_1$ = Displacement power factor (DPF)

PF = Total power factor

I_{rms1} = Fundamental rms current

I_{rms} = Total rms current

When active power is divided by apparent power in the presence of harmonics, the result is known as total power factor, PF. The component of power factor which does not contributed by harmonics is known as displacement power factor (DPF).

By using Equation 2.9, equation of power factor in term of THD_i level can also be created.

$$THD_i = \sqrt{\frac{I_2^2 + I_3^2 + I_4^2 + I_5^2 + \ldots}{I_1^2}}$$

$$= \sqrt{\frac{I_S^2 - I_1^2}{I_1^2}}$$

$$THD^2 I_1^2 = I_S^2 - I_1^2$$

$$(THD^2 + 1) I_1^2 = I_S^2$$

$$\frac{I_1}{I_S} = \frac{1}{\sqrt{1 + THD_i^2}} \qquad (2.26)$$

Thus,

$$PF = \frac{I_{rms1}}{I_{rms}} \cos\phi_1$$

$$= \frac{I_1}{I_S} \cos\phi_1$$

$$= \frac{1}{\sqrt{1 + THD_i^2}} \cos\phi_1 \qquad (2.27)$$

As shown in Equation 2.27, when the level of THD_i is increased, the value of PF will decrease. If a set of THD_i values are created to calculate the power factor PF values. The characteristic of the Equation 2.27 would be as shown in Figure 2.3. The figure shows the graph of true power factor, PF versus THD_i. Single-phase power electronic loads such as desktop computers and home entertainment equipment tend to have high current distortions, which is near to THD_i of 100%. Therefore, their true power factors are generally less than 0.707, even though their *displacement* power factors are near to unity [15]. For a THD_i of 140%, the true power factor can has a value as low as 0.58.

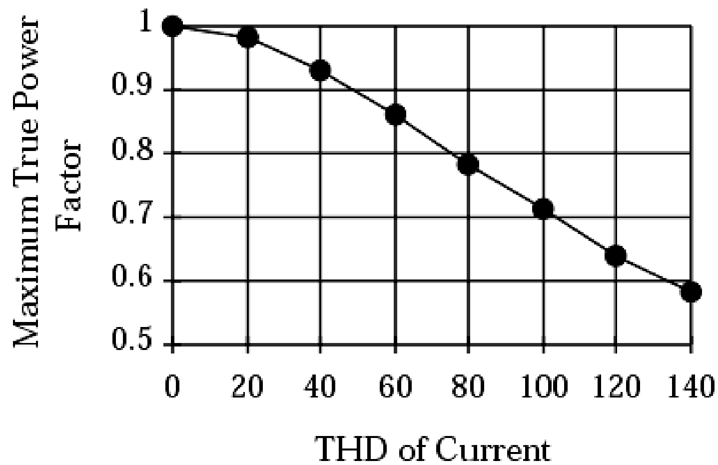

Figure 2.3: Maximum true power factor versus THD_i

2.2.2.2 Derivation of Power Components

The voltage waveform for M harmonics can be written as

$$v(t) = \sum_{m=1}^{M} \sqrt{2} V_m \cos(mwt + \alpha_m) \tag{2.28}$$

Similarly, the current waveform for N harmonics is

$$i(t) = \sum_{n=1}^{N} \sqrt{2} I_n \cos(nwt + \alpha_n + \theta_n) \tag{2.29}$$

Thus, the instantaneous power is

Error! Bookmark not defined. $p(t) = v(t) \cdot i(t)$

(2.30)

or

$$p(t) = \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} 2 V_m I_n \cos(mwt + \alpha_m) \cdot \cos(nwt + \alpha_n + \theta_n) \tag{2.31}$$

Equation 2.31 can be expanded as follows:

Error! Bookmark not defined.Error! Bookmark not

defined. $p(t) = \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} 2 V_m I_n \cos(mwt + \alpha_m) \cdot \{\cos(nwt + \alpha_n) \cos\theta_n - \sin(nwt + \alpha_n) \sin\theta_n\}$

(2.32)

or

$$p(t)=\sum_{m=1}^{\infty}\ 2V_m I_m\cos^2(mwt+\alpha_m)\cos\theta_m-2V_m I_m\cos(mwt+\alpha_m)\sin(mwt+\alpha_m)\sin\theta_m$$

$$-\sum_{m=1}^{\infty}\sum_{n=1}^{\infty}2V_m I_n\cos(mwt+\alpha_m)\cdot\{\cos(nwt+\alpha_n)\cos\theta_n-\sin(nwt+\alpha_n)\sin\theta_n\}$$

(2.33)

Therefore, the final expression for the instantaneous power can be expressed as

$$p(t)=\sum_{m=1}^{\infty}V_m I_m\cos\theta_m(1+\cos(2mwt+2\alpha_m))-V_m I_m\sin\theta_m\sin(2mwt+2\alpha_m)$$

$$+\sum_{m=1}^{\infty}\sum_{n=1}^{\infty}V_m I_n\cos\theta_n\{\cos((m-n)wt+(\alpha_m-\alpha_n))+\cos((m+n)wt+(\alpha_m+\alpha_n))\}$$

$$-\sum_{m=1}^{\infty}\sum_{n=1}^{\infty}V_m I_n\sin\theta_n\{\sin((m+n)wt+(\alpha_m+\alpha_n))-\sin((m-n)wt+(\alpha_m-\alpha_n))\}$$

(2.34)

Equation 2.34 indicates that the instantaneous power can be separated into four components. One of the components is the average component, and the two other components rotate with twice the frequency and are orthogonal to each other. These two components are called the rotating real power and the quadrature power. The last component is called the residual power. The rotating real power is a cosinusoidal function that results from a combined even voltage and current harmonic components. In other words, m+n and m-n must be even numbers. Similarly, the quadrature power is a sinusoidal function that results from a combined even voltage and current harmonic components (i.e., m+n and m-n must be odd numbers). Therefore, each of the four components described above can be written as follows [14]:

measured power or average component

$$P_{dc}=\sum_{m=1}^{\infty}V_m I_m\cos\theta_m \tag{2.35}$$

rotating real power

$$\Pr^{(t)} = \sum_{m=1}^{\infty} V_m I_m \cos\theta_m (\cos 2mwt + 2\alpha_m) + n\sum_{m=1}^{\infty}\sum_{n=1}^{\infty} V_m I_n \cos\theta_n \{\cos((m-n)wt$$
$$+ (\alpha_m - \alpha_n)) + \cos((m+n)wt + (\alpha_m + \alpha_n))\} \tag{2.36}$$

quadrature power

$$qr^{(t)} = -\sum_{m=1}^{\infty} V_m I_m \sin\theta_m \sin(2mwt + 2\alpha_m) - \sum_{m=1}^{\infty}\sum_{n=1}^{\infty} V_m I_n \sin\theta_n \{\sin((m-n)wt$$
$$+ (\alpha_m - \alpha_n)) - \sin((m+n)wt + (\alpha_m + \alpha_n))\} \tag{2.37}$$

residual power

$$d(t) = \sum_{m=1}^{\infty}\sum_{n=1}^{\infty} [V_m I_n \cos\theta_n \{\cos((m-n)wt + (\alpha_m - \alpha_n)) + \cos((m+n)wt + (\alpha_m + \alpha_n))\}$$
$$+ V_m I_n \sin\theta_n \{\sin((m-n)wt + (\alpha_m - \alpha_n)) - \sin((m+n)wt + (\alpha_m + \alpha_n))\}] \tag{2.38}$$

Equations 2.35 to Equation 2.38 define the four power components. These equations are general and can be applied for common or uncommon harmonics with no reservations [14]. If Equation 2.34 is compared with the Equation 2.18 in Subtitle 2.2.1, average component and rotating real power can be defined as active power P. As for quadrate power, this component can be categorized as reactive power Q. Thus,

$$P = P_{dc} + \Pr^{(t)} \tag{2.39}$$

$$Q = qr^{(t)} \tag{2.40}$$

If the level of harmonic is increased, the value of true power factor, $\cos\theta_m$ will decrease as discussed in Subtitle 2.2.2.1. Thus, active power, P would decrease. On the other hand, reactive power, Q would increase because value of $\sin\theta_m$ increases in the presence of harmonic. A new power quantity called distortion power or residual power is created in non-sinusoidal condition. This distortion power is defined as

$$D = d(t) \tag{2.41}$$

2.3 Non-linear Load

A linear element in a power system is a component in which the current is proportional to the voltage. In general, this means that the current waveform will be the same as the voltage as shown in Figure 2.4. Typical examples of linear loads include motors, heaters and incandescent lamps [11].

On the other hand, the current waveform on a nonlinear load is not the same as the voltage as shown in Figure 2.5. Typical examples of non-linear loads include rectifiers (power supplies, UPS units, discharge lighting), adjustable speed motor drives, ferromagnetic devices, DC motor drives and arcing equipment. The current drawn by non-linear loads is not sinusoidal but periodic, meaning that the current waveform looks the same from cycle to cycle [11].

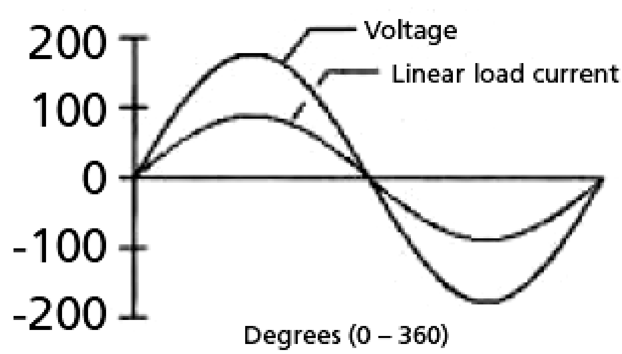

Figure 2.4: Voltage and current waveforms for linear loads

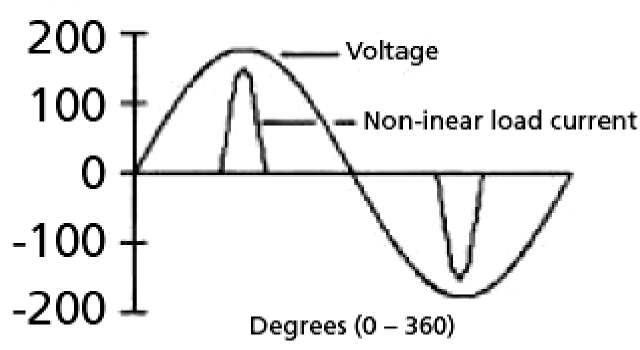

Figure 2.5: Voltage and current waveforms for non-linear loads

The sinusoidal components are integer multiples of the fundamental where the fundamental, in Malaysia, is 50 Hz. The only way to measure a voltage or current that contains harmonics is to use a true-rms reading meter. If an averaging meter is used, which is the most common type, the error can be significant. Each term in the series is referred to as a harmonic of the fundamental. The third harmonic would have a frequency of three times 50 Hz or 150 Hz. Symmetrical waves contain only odd harmonics and unsymmetrical waves contain even and odd harmonics. A symmetrical wave is one in which the positive portion of the wave is identical to the negative portion of the wave. An unsymmetrical wave contains a DC component (or offset) or the load is such that the positive portion of the wave is different from the negative portion. An example of unsymmetrical wave would be a half-wave rectifier [11].

Most power system elements are symmetrical. They produce only odd harmonics and have no DC offset. There are exceptions, of course, and normally symmetrical devices may produce even harmonics due to component mismatches or failures. Arc furnaces are another common source of even harmonics, and they are notorious for producing both even and odd harmonics at different stages of the process [11].

2.3.1 Converter as Non-linear Load

The AC-DC converter used in the switching type power supplies found in most personal computers and peripheral equipment, such as printers, is an example of a non-linear load. While they offer many benefits in size, weight and cost, the large increase of equipment using this type of power supply over the past fifteen years is largely responsible for the increased attention to harmonics. Figure 2.6 shows how the first stage of a switching-type power supply works. The AC voltage is converted into a DC voltage, which is further converted into other voltages that the equipment needs to run. The rectifier consists of semi-conductor devices such as diodes that only conduct current in one direction. In order to do so, the voltage on the one end must be greater than the other end. These devices feed current into a capacitor, where the voltage value on the capacitor at any time depends on how much energy is being taken out by the rest of the power supply [12].

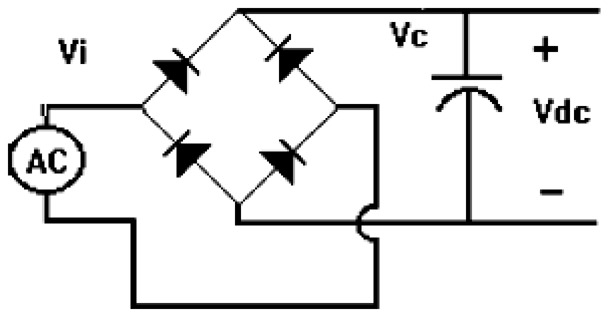

Figure 2.6: Typical AC-DC converter

When the input voltage (Vi) is higher than voltage on the capacitor (Vc), the diode will conduct current through it. This results in a current waveform as shown in Figure 2.7. Obviously, this is not a pure sinusoidal waveform with only a 50 Hz frequency component [12]. In non-linear load, current is drawn for a fraction of the entire cycle, causing the generation of harmonics on the input current [13].

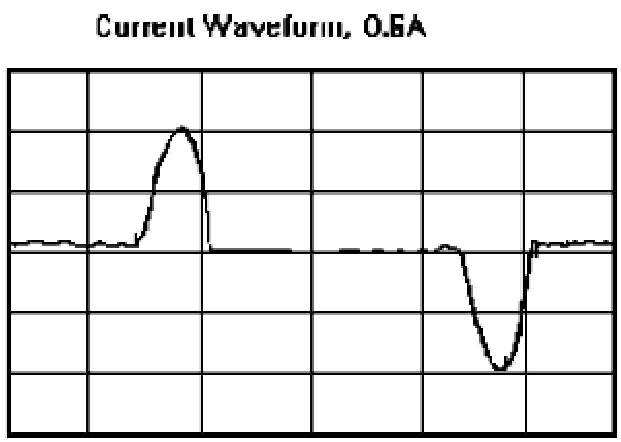

Figure 2.7: Distorted current waveform

If the rectifier had only been a half-wave rectifier, the waveform would only have every other current pulse, and the harmonic spectrum would be different. Whereas the above harmonic spectrum contains only odd harmonics for current, the spectrum for the current of a half wave rectified circuit would only have even harmonics [12].

Figure 2.8 shows the harmonic current spectrum for an AC to DC converter. The converter has a THD_i of 136% and a distortion factor DF of 59%. 3^{rd} harmonic has the highest amplitude of harmonic, which is about 91% of fundamental amplitude. However, the amplitude of the harmonic is decreasing as the order of the harmonic is increasing. Harmonic order which more than 11^{th} harmonic give less influent on the total harmonic distortion level.

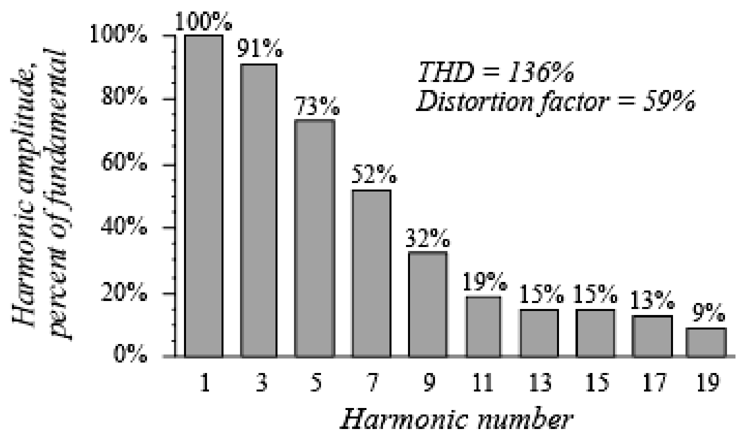

Figure 2.8: Harmonic current spectrum for AC-DC converter

2.3.2 Simulation of Single Phase Full Wave Rectifier (Converter) as Non-linear Load in PSIM Program

Single phase bridge rectifier can convert ac voltage to dc voltage. Figure 2.9 shows a rectifier circuit which is connected to a voltage source of 240V, 50Hz and load of resistor and capacitor. During the positive half cycle of the input voltage, the power is applied to the load through diodes D1 and D2. During the negative cycle, diodes D3 and D4 conduct.

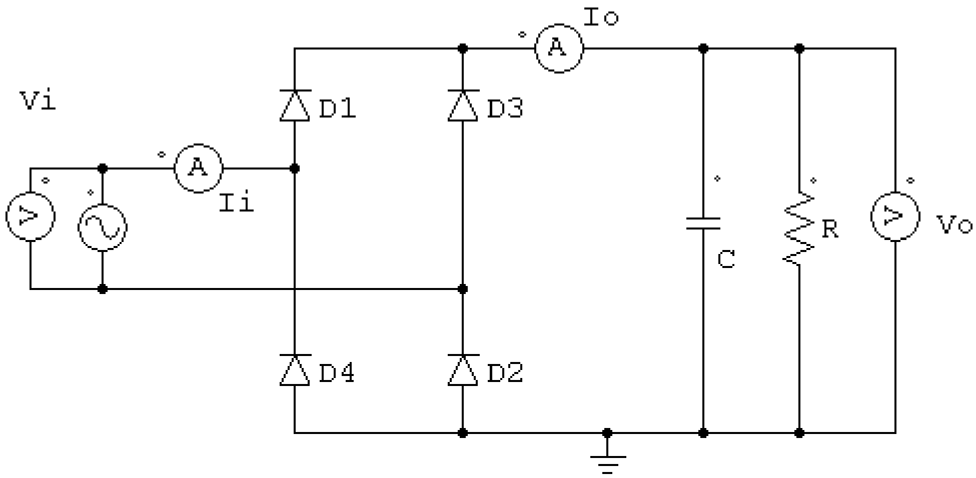

Figure 2.9: Single phase bridge rectifier circuit

As the circuit of Figure 2.9 is simulated in PSIM software program with a load of 5Ω resistor only (capacitor load is not connected), the waveforms of input voltage and current are as shown in Figure 2.10(a) while the waveforms of output voltage and current are shown in Figure 2.10(b). Figure 2.10(a) shows that both input voltage and current give the sinusoidal waveforms.