ANALYSIS OF HARMONICS CURRENT MINIMIZATION ON POWER DISTRIBUTION SYSTEM USING VOLTAGE PHASE SHIFTING CONCEPT

by

SURIADI

**Thesis submitted in fulfillment of the requirements
for the degree of
Master of Science**

June 2006

ACKNOWLEDGEMENTS

All praise due to Allah SWT, the Most Gracious and the most Merciful, for give me the strength, health and determination to complete my study project.

My utmost gratitude to my main supervisor, Dr. Ir. Syafrudin Masri, for his sincere and frank advise, constructive criticism and patient through out the study and during the preparation of this project. My great appreciation also goes to my second supervisor Associate Professor Dr. Che Mat Hadzer bin Mahmud for his precious and constructive critics that substantially improve this research.

The author would like to thank the Government of Nanggroe Aceh Darussalam, that had give me the financial support to pursue my study.

My deepest gratitude and love to my parent and wife (Imelda Chaidir) and my lovely son (Muhammad Harriz Danial) whom not only endured without any protest the loneliness while I prepared my thesis, but they also provided support, love and inspiration without which this research would have been never completed.

Finally, my thank goes to all the staffs and my friends at school of Electric and electronic Engineering USM that I can not mention their names one by one, for the supports and criticism for the further improvement of this research.

TABLE OF CONTENTS

		Page
ACKNOWLEDGEMENTS		ii
TABLE OF CONTENTS		iii
LIST OF TABLES		vi
LIST OF FIGURES		vii
LIST OF PLATES		ix
LIST OF SYMBOLS		x
LIST OF ABBREVIATION		xii
LIST OF APPENDICES		xiii
LIST OF PUBLICATIONS & SEMINARS		xiv
ABSTRAK		xv
ABSTRACT		xvii
CHAPTER I : INTRODUCTION		1
1.0	Background	1
1.1	Project Objective	5
1.2	Project Methodology	5
1.3	Thesis Outline	8
CHAPTER II : LITERATURE SURVEY		9
2.0	Introduction	9
2.1	Harmonic History	10
2.2	Source of Harmonics	10
2.3	Effect of Harmonic Distortion	10
	2.3.1 Effect of Harmonic on Rotating Machines	11
	2.3.2 Effect of Harmonic on Transformer	11
	2.3.3 Effect of Harmonic on Lines and Cable	12
	2.3.4 Effect of Harmonic on Converter Equipment	13
	2.3.5 Effect of Harmonic on Protective Relays	13
	2.3.6 Effect of Harmonic on Residential and Commercial Equipment	13
	2.3.7 Effect of Harmonic on Capacitor Bank	14

2.4 Three Phase Non-linear Load 15
2.5 Harmonic Minimization Method 16
2.5.1 L-C Filter 16
2.5.2 Active Power Filter 16
2.5.3 Phase Shifting 17
2.6 A Documented Case of Harmonic Resonance 18
2.6.1 Eurocan Pulp and Paper Mill Plant 18
2.6.2 Klockner Pentaplast Manufactures 19

CHAPTER III : HARMONIC ANALYSIS 20

3.0 Introduction 20
3.1 Fourier Series and Analysis 21
3.2 Root Means Square 24
3.3 Total Harmonic Distortion 26
3.4 Active Power 29
3.5 Effect of Harmonic on Power Distribution System 31
3.5.1 Power Factor 31
3.5.2 Resonance 32
3.5.3 Power Losses 33
3.5.3.1 Copper Losses 34
3.5.3.2 Eddy Current Losses 34
3.6 Phase Sequence of Harmonic Component 35
3.7 Standard of Harmonic 40

CHAPTER IV : THE VOLTAGE PHASE SHIFTING CONCEPT TO MINIMIZE HARMONIC CURRENT ON POWER DISTRIBUTION SYSTEM 41

4.0 Introduction 41
4.1 Current Harmonic Minimization Mechanism 42
4.2 Phase Shifting 52
4.2.1 Conventional Phase Shifting 52
4.2.2 Phase Shifting Modified 53

CHAPTER V : RESULTS AND DISCUSSION 58

5.0 Introduction 58
5.1 Experimentation Results 59

CHAPTER VI : CONCLUSION 68

6.0 Conclusion 68
6.1 Suggestion 69

BIBLIOGRAPHY 70

APPENDICES
Appendix A The Measurement Results Before Using Double Symmetric Zigzag Autotransformer Phase shifting 76

Appendix B The Measurement Results After Using Double Symmetric Zigzag Autotransformer Phase shifting 79

LIST OF TABLES

		Page
Table 3.1:	Categorizes the harmonics in terms of their respective sequence orders	39
Table 3.2:	The maximum current distortion limit by IEEE 519 -1992	40
Table 5.1:	Experiment results on the line current system using double symmetric zigzag autotransformer	60
Table A.1:	voltage and current rms on the branch of load A	76
Table A.2:	voltage and current rms on the branch of load B	77
Table A.3:	voltage and current rms on the line current system (PCC)	78
Table B.1:	voltage and current rms on the branch of load A	79
Table B.2:	voltage and current rms on the branch of load B	80
Table B.3:	voltage and current rms on the line current system (PCC)	81

LIST OF FIGURES

		Page
Figure 1.1:	The flow chart of harmonic current minimization on the three phase three wire power distribution system	7
Figure 2.1:	The effect of capacitor size on parallel resonant frequency (a) system with potential for problem parallel harmonic. (b) Equivalent circuit	14
Figure 2.2:	Three phase bridge diode rectifier	15
Figure 2.3:	Input line current and voltage waveform	16
Figure 3.1:	The current waveform distortions caused by odd harmonic component in three phases three wires power distribution system	23
Figure 3.2:	One line diagram power distribution system	29
Figure 3.3:	Phase sequence component	35
Figure 4.1:	Power distribution system with linear load	42
Figure 4.2:	Power distribution system with non-linear load	43
Figure 4.3:	The line current vector diagram of non phase shifting	46
Figure 4.4:	One line diagram of electrical power system distribution is using phase shifter	46
Figure 4.5:	The line current vector diagram use phase shifting (a) the current on the load side (b) the current on the line system (PCC)	48
Figure 4.6:	One line diagram of two branches load	49
Figure 4.7:	The phase shifting in cancellation of 5-th and 7-th harmonics current (a) shifted by -15^0 (b) shifted by $+15^0$	51
Figure 4.8:	The delta/Wye transformer phase shifting	52
Figure 4.9:	The phase shifting double symmetric zig-zag autotransformer configuration	54
Figure 4.10:	The phase shifting double symmetric zigzag autotransformer topology	55
Figure 4.11:	The Lamination core of double symmetric zigzag autotransformer	57

Figure 4.12: The double symmetric zigzag autotransformer phase shifting 57

Figure 5.1: The power distribution system three phase three wire using double symmetric zigzag autotransformer phase shifter 58

Figure 5.2: Fluke 41B power harmonics analyzer equipment 59

Figure 5.3: Before harmonic minimization : (a) The current and voltage waveform on the branch of load A; (b) The harmonic current spectrum on the branch of load A 61

Figure 5.4: Before harmonic minimization: (a) The current and voltage waveform on the branch of load B; (b) The harmonic current spectrum on the branch of load B 62

Figure 5.5: Before harmonic minimization: (a) The current and voltage waveform on the PCC; (b) The harmonic current spectrum on the PCC 63

Figure 5.6: After harmonic minimization: (a) The current and voltage waveform on the branch of load A shifted by $+15^0$; (b) The harmonic current spectrum on the branch of load A 65

Figure 5.7: After harmonic minimization: (a) The current and voltage waveform on the branch of load B shifted by -15^0; (b) The harmonic current spectrum on the branch of load B 66

Figure 5.8: After harmonic minimization: (a) The current and voltage waveform on the PCC; (b) The harmonic current spectrum on the PCC 67

LIST OF PLATES

		Page
1	The Lamination core of double symmetric zigzag autotransformer	57
2	The double symmetric zigzag autotransformer phase shifting	57
3	Fluke 41B power harmonics analyzer equipment	59

LIST OF SYMBOLS

			Page
1	I_{dc}	Direct current	15
2	V_{dc}	Direct voltage	15
3	v_{AS}	The instantaneous voltage component of phase A	15
4	v_{BS}	The instantaneous voltage component of phase B	15
5	v_{CS}	The instantaneous voltage component of phase C	15
6	i_A	Instantaneous current of phase A	15
7	i_B	Instantaneous current of phase B	15
8	i_C	Instantaneous current of phase C	15
9	$f(t)$	Non sinusoidal periodic function	21
10	a_0	Magnitude of DC component	21
11	$f_h(t)$	Periodic function of h-th harmonic	21
12	a_h	The event h-th order harmonic magnitude	22
13	b_h	The odd h-th order harmonic magnitude	22
14	F_0	DC Component	22
15	F_{mh}	the h-order harmonic component	22
16	ω	Angular angle	22
17	*t*	Time	22
18	ϕ	Voltage Angle phase shifting	22
19	*F*	The average value of $f(t)$	25
20	I_{smh}	Maximum value of the order h-th line current component	27
21	I_{sh}	rms value of harmonic *h-th* on the line current component	27
22	I_{dis}	The distortion component	28
23	*P*	Active power	30
24	*S*	Apparent power	31
25	*pf*	Power factor	32
26	X_L	Inductive Reactance	33
27	X_C	Capacitive Reactance	33
28	f_0	Frequency Resonance	33
29	P_l	Power losses	33
30	R	Resistance	33

31	P_t	Total edy current losses	34
32	i_{SC}	Maximum short circuit at PCC	40
33	$v_s(t)$	Instantaneous Voltage	42
34	$i_s(t)$	Instantaneous Current	42
35	V_{sm}	Maximum demand load voltage	44
36	I_{sm}	Maximum demand load current	44
37	α	Voltage angle phase shifting	46
38	N_A	The main winding of phase A	54
39	N_B	The main winding of phase B	54
40	N_C	The main winding of phase C	54
41	n_{a1}	Auxiliary winding of phase A1	54
42	n_{a2}	Auxiliary winding of phase A2	54
43	n_{a3}	Auxiliary winding of phase A3	54
44	n_{a4}	Auxiliary winding of phase A4	54
45	n_{b1}	Auxiliary winding of phase B1	54
45	n_{b2}	Auxiliary winding of phase B2	54
47	n_{b3}	Auxiliary winding of phase B3	54
48	n_{b4}	Auxiliary winding of phase B4	54
49	n_{c1}	Auxiliary winding of phase C1	54
50	n_{c2}	Auxiliary winding of phase C2	54
51	n_{c3}	Auxiliary winding of phase C3	54
52	n_{c4}	Auxiliary winding of phase C4	54

LIST OF ABBREVIATION

			Page
1	rms	Root Mean Square	24
2	THD	Total Harmonic Distortion	26
3	IEEE	The Institute of Electrical and Electronics Engineers	40
4	TDD	Total Demand Distortion	40
5	PCC	Point Common Couple	46
6	kVA	Kilo volt Ampere	53

LIST OF APPENDICES

		Page
Appendix A:	The Measurement Results Before Using Double Symmetric Zigzag Autotransformer Phase shifting	76
Appendix B:	The Measurement Results After Using Double Symmetric Zigzag Autotransformer Phase shifting	79

LIST OF PUBLICATIONS & SEMINARS

		Page
1.1	Suriadi, Syafrudin Masri. (2005). Minimization of harmonic current using double symmetric zigzag autotransformer Proceedings of the International Conference on Robotics, Vision, Information and Signal Processing ROVISP2005. Universiti Sains Malaysia, July 341-345	82

ANALISIS PENGURANGAN ARUS HARMONIK PADA SISTEM PENGAGIHAN ELEKTRIK KUASA MENGGUNAKAN KONSEP ANJAKAN SUDUT FASA VOLTAN

ABSTRAK

Beban tak linear seperti pembekal kuasa mod pensuisan dan pemacu kelajuan boleh kawal yang disambungkan kepada sistem pengagihan elektrik kuasa tiga fasa tiga dawai boleh menyebabkan arus talian sistem mengalami herotan yang menghasilkan komponen arus harmonik tertib ke-5 dan ke-7 yang sangat ketara.

Dengan meningkatnya kandungan arus harmonik pada sistem pengagihan elektrik kuasa dapat menurunkan prestasi sistem tersebut. Untuk mengurangkan kandungan harmonik arus pada sistem ini, perlu dilakukan pengurangan terhadap komponen arus harmonik peringkat ke-5 dan ke-7 tersebut. Pengurangan tersebut dilakukan dengan cara membagi beban tak linear menjadi dua bahagian cabang beban, dimana perbezaan sudut fasa voltan antara kedua cabang beban tersebut haruslah sebanyak 30^o. Disebabkan komponen arus harmonik tertib ke-5 mempunyai jujukan negatif dan komponen arus harmonik tertib ke-7 mempunyai jujukan positif, maka komponen-komponen arus harmonik ini pada talian sistem akan saling membatalkan. Berdasarkan konsep ini direkabentuk satu pengurang arus harmonik "**Double Symmetric Zig-zag Autotransformer**".

Hasil eksperimen terhadap pengurangan arus harmonic pada sistem pengagihan elektrik kuasa tiga fasa tiga dawai dengan menggunakan konsep anjakan sudut fasa voltan tersebut, menunjukkan kandungan arus harmonisa pada talian system dapat dikurangi daripada 30.03 % menjadi 10.2 %. Hasil ini memenuhui piawaian IEEE 159-1992 yang membolehkan kandungan arus harmonik pada talian sistem pengagih elektrik kuasa kurang daripada 20%.

Kelebihan konsep ini adalah mudah dan praktikal, kerana ia hanya terdiri dari litar elektromagnet yang tidak memerlukan suatu pengesan, pengawal dan komponen-komponen elektronik. Disamping itu, pengurang arus harmonik Double Symmetric Zig-zag Autotransformer ini mempunyai kadaran kVA yang rendah, bersaiz kecil, kehilangan kuasa yang rendah dan mempunyai kecekapan tinggi.

ANALYSIS OF HARMONICS CURRENT MINIMIZATION ON POWER DISTRIBUTION SYSTEM USING VOLTAGE PHASE SHIFTING CONCEPT

ABSTRACT

Non linear loads such as switch mode power supply and adjustable speed drive in three phase three wires power distribution system can causes line current system distorted. The non linear loads on three phases three wires power distribution system were produced dominantly 5-th and 7-th order harmonic currents.

Increasing of harmonics current on electric power distribution system leads to degradation of system performance. To reducing the harmonics current on power distribution system should be minimized the 5-th and 7-th order harmonics current components. The minimization process of harmonic current is accomplished by voltage phase angle shifting on the two branches of non-linear load system, where the different phase angle between both of branches should be 30^0. Because of 5-th order harmonic current component is negative sequence and 7-th order harmonic current component is positive sequence, therefore these harmonic current components on the line system are opposite each other. Base on this concept, the phase shifter designing to harmonic minimization is “**Double Symmetric Zig-zag Autotransformer**”.

The experimentation results for harmonic current minimization in three phase three wires power distribution system using this voltage phase angle shifting concept. It shows that the total current harmonic distortion on the line current system can be reduced from 30.03 % become 10.2 %. This value is fulfill the IEEE standard 519-1992 recommended, where the IEEE standard 519-1992 allows the maximum limits for total current harmonic distortion containing in power distribution system is bellow than 20 %.

The advantage of this concept is simply and practice, because it is only required electromagnetic circuit and does not require sensor and control and the electronic components. Beside this, The Double Symmetric Zig-zag Autotransformer harmonic reducer has low rating kVA, smaller size, low losses and higher efficiency.

CHAPTER I
INTRODUCTION

1.0 Background

Harmonics have existed in power systems for many years. In the past, most electrical equipment is using balance linear load. A linear load in a power system distribution is a component in which the current and voltage are perfect sinusoidal [Isokorpi, J.,et.al., 1999). Examples of linear loads are induction motor, heaters and incandescent lamps. But the rapid increase in the electronics device technology such as diode, thyristors, etc cause industrial loads to become non-linear. These components are called solid state electronic or non-linear load [Kevin, J. Tory., et.al., 1997]. The non-linear load connected to the power system distribution will generate harmonics current and voltage [Energyusernews, 2004].

Harmonics in power distribution system are current or voltage that are integer multiples of fundamental frequency. For example if the fundamental frequency 50 Hz, then the 2-nd harmonics is 100Hz, the 3-rd is 150Hz, etc [Robert D. Henderson et al., 1994]. A pure voltage or current sine wave has no distortion and no harmonics but non-sinusoidal wave has distortion and harmonics. To quantify the distortion, the term total harmonics distortion (THD) is used. The THD value is the effective value of all the harmonics current added together, compared with the value of the fundamental current [John H. Waggoner, 2001]. Wave form distortion can be analyzed using fourier analysis as a periodical oscillation at different frequency.

The harmonics current injected on power distribution system caused by non-linear load, and they can damage equipment overtime by sustained overheating or cause sudden failures due to resonant conditions [Subjak, J.S., et. Al., 1990]. In order to control harmonics, IEEE Standard 519, “Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems," was adopted. IEEE Standard 519 limitations on voltage and current harmonics in order to ensure that harmonic distortion levels throughout the entire electrical distribution system, from utility to consumer, will remain low enough for the system to function properly. Some of non linear load connected to the power system distribution is the three phase power electronics equipment. Generally, non-linear load using three phase-six pulse diode rectifier is used to covert alternating current (ac) become direct current (dc) need for power electronics equipment operation [Yacamini, R., 1996]. Due to three phase-six pulse diode rectifiers are non linear load, so the current waveform of power system distribution is distorted. Therefore, line current system is much contains 5-th and 7-th harmonics current order.

The harmonic current on three-phase three wires power distribution system are dominated by the 5-th and 7-th harmonics that are generated from the three phase bridge diode rectifiers [Hansen, S., et.al., 2003). The main problem of harmonics current on three phase distribution power system is harmonic resonance. The harmonic resonance is accurse in the 5-th and 7-th order harmonics frequency between power factor improvement capacitor and source inductance [Daniel, J.C., 2005]. Two forms of resonance which must be considered. Those are series resonance and parallel resonance. For the series resonance, the total impedance at the resonance frequency reduces to the resistance component only. For the case where this component is small, high current magnitudes at the exciting frequency will flow. It may lead to large oscillating currents and consequently high harmonics voltage. For the parallel resonance, frequency the impedance is very high and when excited from a source at this frequency, a high circulating current will flow in the capacitance-inductance loop [James, K.P., 1994]. Harmonic Resonance occurs when the capacitor reactance and the system reactance are equal. These currents will result in greater voltage distortion. This provides a higher voltage across the capacitor and potentially harmful currents through all capacitor equipment. Harmonic resonance may occur at any frequency but the 5-th, 7-th are the frequencies with most concerned [Kim, S., et.al., 1994]. Some indicators of resonance are overheating, frequent circuit breaker tripping, unexplained fuse operation, capacitor failure, electronic equipment malfunction, flicking lights and telephone interference.

In power distribution systems with more than 15%-20% of harmonic loads, a harmonic survey should be performed to indicate potential problem areas [Mack Grady, 2005]. Readings taken over changing load conditions at potential capacitor locations are most useful in determining the types of systems best employed to accomplish the ultimate harmonic suppression, power factor improvement, KVA reduction and other goals.

Today, a number of methods have been proposed to address this phenomenon. One conventional method is the application of LC passive filter. However, LC passive filter has disadvantages: The designing form is large and weight to filter low frequency harmonic current order. The LC filter which to filter harmonic current needs specific value of LC for each order harmonic. Beside this, The LC filter has a problem formulation due to the system impedance variation and resonance condition. The other method in reducing harmonic is Active Power Filter (AFP). The active power filter is a PWM inverter current source. Therefore, it is very difficult used for high capacity and more expensive. The other disadvantage of PWM inverter is that it generate high order harmonic current which can distorted the telecommunication systems, audio and video [Peng, at. al.,1993).

In this thesis explains the total harmonic minimization in three-phase three wires power distribution system. The method of THD_i minimization is used voltage phase angle shifting in branch loads system. With voltage angle phase shifting in branch loads as well as the harmonic current component phase angle were occurred. The value and direction of harmonic current phase angle is depended order and phase sequence. The specified voltage phase angle shifting can obtain the specified 5-th and 7-th harmonic current component phase angle shifting in branch loads. It is shifted angle phase by 30^0. Due to specified harmonic current component phase angle shifting cause the 5-th and 7-th harmonic current component in two branch loads is opposite. Therefore, the superposition of 5-th and 7-th harmonic current component in branch loads will be canceled. Hence, the line system did not contain 5-th and 7-th harmonic current component. It mean that the THD_i can be minimized.

1.1 Project Objective

The Objective of this thesis is to obtain a new concept and analysis for odd harmonic current minimization which dominantly on three phases three wires power distribution system, and to design voltage phase angle shifting that has special phase angle to minimize 5-th and 7-th order harmonic current .

1.2 Project Methodology

The methodology used in the research base on analysis and experimentation approach. The important aspects in the study of harmonic minimization for three phase three wires power system distribution are given as follows:

A. Literature review. From the literature study determine non linear load characteristic, voltage and current wave form.

B. The summery of literature review is to obtain a formulation that has correlation to minimize 5-th and 7-th harmonic current component which domination on three phase three wires power system distribution

C. Conducting harmonic reducing analysis on three phase three wires power system distribution by voltage phase angle shifting on the load branches

D. Designing double symmetric zigzag autotransformer as voltage phase angle shifter

E. Analyzing of six pulse three phases diode rectifier as non linear load

F. To measure the harmonics current and voltage caused by six pulse three phases diode rectifier using fluke 41B Power Harmonic Analyzer.

G. To perform experiment and data collection of harmonic minimization on three phase three wires power system distribution use double symmetric zigzag autotransformer phase shifting. The systems required in balance load.

H. Analysis and investigation on experimentation results.

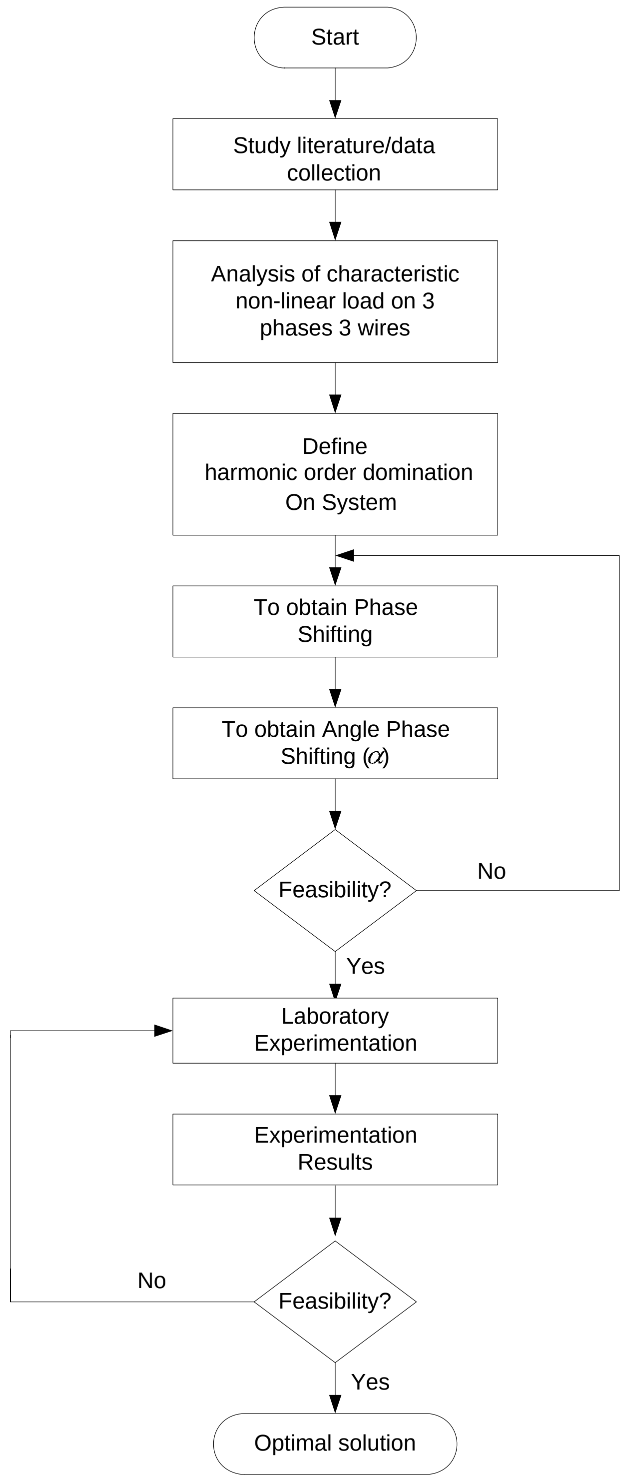

Figure 1.1: The flow chart of harmonic current minimization on the three phase three wire power distribution system.

1.3 Thesis Outline

Chapter 2 covers a literature survey of this thesis. The main topics discussed here are harmonics history, sources of harmonic, effect of harmonic distortion, three phase non-linear load, Harmonic minimization method, A documented case of harmonic resonance.

Chapter 3 provides a quantitative discussion of harmonics. Distorted waveform are analyzed and presented using Fourier series. The calculation of rms values and distortion measures are developed. The limit of allowable voltage and current harmonic distortion set by IEEE-159-1994 standard are presented.

Chapter 4 present the mechanism of current harmonic minimization on the three phase three wires line current system by voltage phase shifting. The analytical design equations are presented to facilitate the design of phase shifting component and design of configurations of phase shifting autotransformer.

Chapter 5 presents the results and discussion of the preceding chapters. The values of the harmonics component of non linear loads (three phase diode bridge rectifier as source of harmonics) are presented. The results of the measured in the each load branch and line current system before and after reducing harmonic current by double symmetric zigzag autotransformer phase shifting are shown.

Lastly, Chapter 6 gives the conclusion to the research work. Some conclusive remarks are presented in this chapter as well. Apart from that, suggestion for improvement is also given at the end of this chapter.

CHAPTER II
LITERATURE SURVEY

2.0 Introduction

The increasing of electronic devices in power distribution system cause the quality of the power becomes degradation. Traditional electrical power distribution system design has very little need to deal with harmonics because the loads typically designed for were linear in nature. With the proliferation of variable speed drives, electronic device need to be adjusted because amounts of 5-th and 7-th order harmonic currents are being injected in to power distribution system. Over the years, essentially approaches evolved and became widely used to minimize of 5-th and 7-th order harmonic current is phase-shifting transformers of different configurations[Philip J.A, 2004]. It used for decades in industrial, typically treat harmonics current produced by non- linear loads and connected phase to phase e.g. 5-th, 7-th order .

2.1 Harmonic history

Before twentieth century, the predominant use of electricity for business and industry was power motors, lights and heating devices. These uses have little effect on the fundamental frequency. They are called linear loads, because the current rises and falls in proportion to the voltage wave.

In recent years, few industries use devices such as rectifiers or converters, power supplies and other device to improve product quality [Rice, et.al, 1986]. All of these make the current sinusoidal waveform distorted, because the current flow was not directly proportional to the voltage. These loads are called non-linear loads.

Non-linear loads cause waveforms that are multiples of the fundamental frequency sine wave to be superimposed on the base waveform. These multiples are called harmonics, like the frequency of the second harmonic is two times the fundamental; the third harmonic is three times the fundamental. The combination of the sine wave with all the harmonics creates a new non sinusoidal wave of entirely different shape is called harmonic distortion.

2.2 Source of Harmonic

The main source of the harmonics is any non-linear loads that produce the voltage harmonics and current harmonics. This occurs because the resistance of the device is not a constant. The resistance in fact, changes during each sine wave. So, non linear device is one in which the current is not proportional to the applied voltage. Some examples of common sources of power distribution system harmonics cause serious problems are [Arrillaga, J., 1987]:

1. Fluorescent lighting
2. Computer switch mode power supplies
3. Static VAR compensators
4. Variable frequency motor drives (VFD)
5. DC-DC converters
6. Inverters
7. Television power supplies.

2.3 Effects of Harmonic Distortion

The effect of current distortion on power distribution systems can be serious, primarily because of the increased current flowing in the system. In other words, because the harmonic current doesn't deliver any power, its presence simply uses up system capacity and reduces the number of loads that can be powered [Murotani, K., 1982]. Harmonic current occur in a facility’s electrical system can cause equipment malfunction, data distortion, transformer and motor insulation failure, overheating of neutral buses, tripping of circuit breakers, and solid-state component breakdown. The cost of these problems can be enormous.

Harmonic currents also increase heat losses in transformers and wiring. Since transformer impedance is frequency dependent, increasing with harmonic number, the impedance at the 5th harmonic is five times that of the fundamental frequency. So each ampere of 5th harmonic current causes five times as much heating as an ampere of fundamental current [Michael Z. Lowenstein, 2002]. More specifically, the effects of the harmonics can be observed in many sections of electrical equipment and a lot machines and motors. These effects can be described in more details as follows:

2.3.1 Effects of Harmonics on Rotating Machines

For both the synchronous and the induction machines, the main problems of the harmonics are increasing on the iron and copper losses, and heating by result of the high current caused by harmonics as a result reducing the efficiency. The harmonics can be a one reason as an introduction of oscillating motor torque. Also, the high current can cause high noise level in these machines [Roger C. Dugan, 1999].

2.3.2 Effects of Harmonics on Transformers

Transformers are designed to deliver the required power to the connected loads with minimum losses at fundamental frequency. Harmonic distortion of the current, in particular, as well as the voltage will contribute significantly to additional heating. There are three effects that result in increased transformer heating when the load current includes harmonic components [Sewan Choi, et.al., 1996]:

1. **rms current**. If the transformer is sized only for the KVA requirements of the load, harmonic currents may result in the transformer rms current being higher than its capacity. The increased total rms current results increase conductor losses.

2. **Eddy-current losses**. These are induced currents in the transformer caused by the magnetic fluxes. These induced currents flow in the windings, in the core, and in the other connecting bodies subjected to the magnetic field of the transformer and cause additional heating. This component of the transformer losses increases with the square of the frequency of the current causing the eddy current. Therefore, this becomes a very important component of transformer losses for harmonic heating.

3. **Core losses**. The increase in core losses in the presence of the harmonics will be dependent on the effect of the harmonics on the applied voltage and the design of the transformer core. Increasing the voltage distortion may increase the eddy currents in the core laminations [Szabados, et.al., 1981]. The net impact that this will have depends on the thickness of the core laminations and the quality of the core steel. The increase in these losses due to harmonics is generally not as critical as the previous two.

2.3.3 Effects of Harmonics on Lines and Cables

The main problems associated with harmonics are: increased losses and heating, serious damages in the dielectric for capacitor banks and cables, appearance of the corona (the amount of the ionization of the air around the conductor or the transmission line) due to higher peak voltages and corrosion in aluminum cables due to DC current.

2.3.4 Effects of Harmonics on Converter Equipments

These equipments can be expressed as switches or On-Off equipment because of the switching the current and voltage by some devices such as diodes and thyristors [Palethorpe, et.al., 2000]. These converters can switch the current so, creating notches in voltage waveforms, which may effect the synchronizing of the other converter equipment. These voltage notches cause misfiring of the thyristors and creating unarranged other firing instances of the other thyristors in the equipment.

2.3.5 Effects of Harmonics on Protective Relays

The protective devices such as circuit breakers and fuses are designed to trip out in specific current and voltage and through very specific short time. The presence of the harmonics causes the difference on the voltage and current [Sankaran, C., 2001]. So, this can cause failing tripping of these protective equipment. Also, the harmonics can let the relays to operate slower and/or at higher pickup values. Over current and over voltage can cause improper operation for relays. However, this cause the unsuitable tripping time so, causing some serious damages as far as fire occurs.

2.3.6 Effects of Harmonics on Residential and Commercial Equipment

These effects can be observed for some specific important types of equipment. For instance:

- Computers: sensitive to threshold voltages of digital circuit. Manufactures impose limits on supply-voltage harmonics distortion.
- Television: distorted waveforms cause fluctuations in TV picture size and brightness.
- Converters (rectifiers, inverters…etc): are sensitive to voltage so, misfiring angles for these converters.

2.3.7 Effects of Harmonics on Capacitor Banks

Resonance due capacitor banks can magnify the harmonic problems. Capacitors used by both electricity suppliers and customers to improve there power factor. There is an intermediate range of frequencies where the capacitive and inductive effects can combine to give very high impedance. A small harmonic current within this frequency range can give a very high and undesirable harmonic voltage. This is the condition, which is called resonance [Gonzalez,D.A., 1987]. At harmonic frequencies, from the perspective of harmonic sources, shunt capacitors appear to be in parallel with the equivalent system inductance as shown in the equivalent circuit in Figure 2.1 PCC is the nearest point that the additional installation might be added. At the frequency where capacitor reactance Xc and the total system reactance are equal, the apparent impedance of the parallel combination of inductance and capacitance becomes very large. This results in the typical parallel resonance condition.

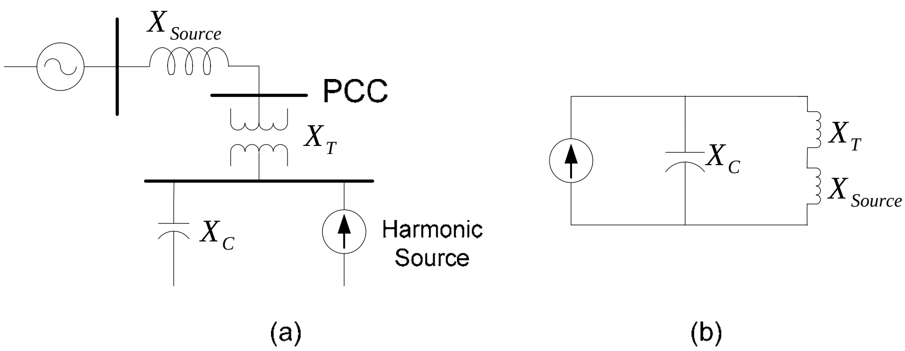

Figure 2.1: The effect of capacitor size on parallel resonant frequency

(a) System with potential for problem parallel harmonic (b) Equivalent circuit

2.4 Three Phase Non- Linear Load

In fact, the non linear load is the source of the harmonic. A three phase electrical power system distribution has high capacity non-linear load such as converter for electric motor control use to power drive in industries, factories, LRT power supply and direct current transmission system [Hansen, S., et.al., 2003]. In general, this non-linear load base on three phase bridge diode rectifier, also known as the six pulse bridge because it is six pulses per cycle on the DC out put. It is shown in Figure (2.2). The diodes are numbered in order of conduction sequence and each are conduct for 120^0. A three phase bridge diode rectifier is a circuit that converts an ac signal in to a dc signal. The six pulse bridge produces harmonics at order 6n+1 and 6n-1, at one more and one less than each multiple of six [Stratford, et.al., 1990]. In theory, the magnitude of each harmonic number is the reciprocal of the harmonic order, so there would be 20% fifth harmonic and 9% eleventh harmonic [Tolbert, L.M., 1996].

To assume that three phase bridge diode rectifier is ideal, therefore no ripple of instantaneous output current. The input current of three phase bridge rectifier is square wave perform. It is shown in Figure (2.3).

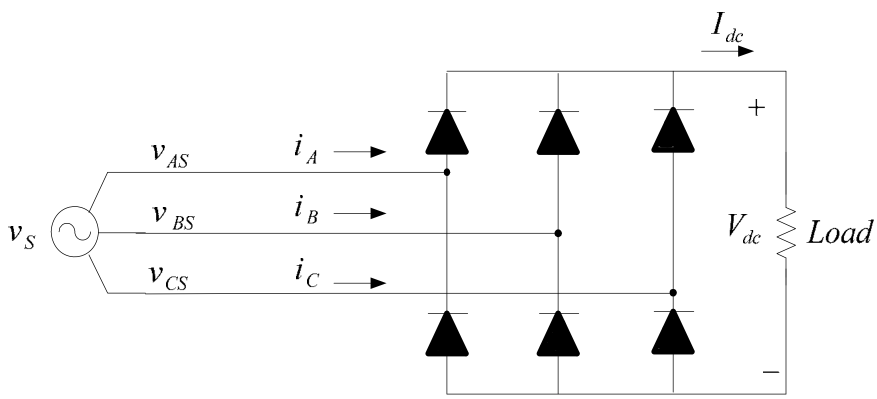

Figure 2.2: Three phase bridge diode rectifier

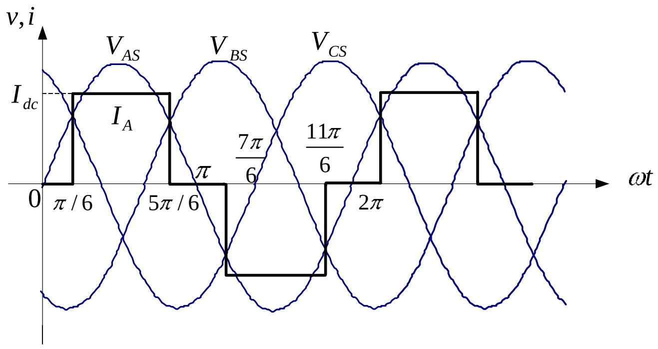

Figure 2.3: Input line current and voltage wave form

2.5 Harmonic Minimization Methods

In order to ensure the highest "Power Quality" on the line current power system distribution, it is necessary to minimize harmonics. Harmonic minimization can be performed by methods as bellow:

2.5.1 L-C Filter

An L-C filter consists of a capacitor bank and an induction coil. The filter is designed or tuned to the predetermined non-linear load and to filter a predetermined harmonic frequency range. This is connected in parallel to the non-linear load with the objective of filtering the major harmonics generated by the non-linear load. This application is mostly used when specified for a UPS or variable frequency drive motor in a manufacturing plant [Key, T.S., et. al., 1998].

2.5.2 Active Power Filter

The active power filter (AFP) is a device that is connected in system to cancels the reactive and harmonic currents from a group of nonlinear loads so that the resulting total current drawn from the ac main is sinusoidal [Grady, W.M, et. al., 1993]. Ideally, the APF needs to generate just enough reactive and harmonic current to compensate the nonlinear loads in the line, thus it handles only a fraction of the total power to the load. The performance of this active power filter depends on the inverter topologies and the PWM control method [Akagi, H, 1996]. Therefore, the suitable device in developing the AFP is “Pulse Width Modulated (PWM)” inverter by using IGBT or MOSFET devices. There are two kinds for active power filter such as series and shunt filters.

2.5.3 Phase Shifting

A harmonic minimizing using transformer is a new power quality product for minimizing harmonic problems in electrical distribution systems. This type of transformer has patented built-in electromagnetic technology designed to remove the most harmful harmonics from the 3rd through 21st. The technique used in these transformers is call phase shifting [Victor A. Ramos JR 1999]. These transformers can be used to reduce existing harmonics in line current system. This same application can be designed into new construction to prevent future harmonics problems.

In the new electrical environment, the engineers should be familiarized with the concept of the phase shifting. By using phase shifting in the line current system is given good performance under condition of balance load. This is due to the 120^0 between the phases, when one phase is in the positive the two other phases act to cancel it. If a system is 30^0 shifted to the primary line (Delta/Wye transformer) the 5-th and 7-th order harmonic should largely be reduced on the primary line by another system that is phase shifted 0^0 to that line [Jean-Guy Boudrias 2004]. This is due to the fact that when a system 5-th harmonic is on the positive sequence of the sinusoid the other system 7-th is on the negative side.

2.6 A Documented Case of Harmonic Resonance

The harmonic resonance occurs in a power system when the power system natural frequency corresponds to the frequency of a source of harmonic current. The following expression two documents case of power system harmonic resonance.

2.6.1 Eurocan Pulp and Paper Mill Plant

On 24 June 1986 the Eurocan Pulp & Paper mill located at Kitimat, B.C, Canada, experienced a major failure of its standby incoming 13.8 kV utility tie circuit breaker [Guy Lemieux, 1988]. The circuit breaker failure resulted in fire and complete destruction of the unit. The possibility of harmonic resonance was considered since the mill power factor was corrected by large bank 13.8 kV capacitors. The mill has approximately 8 MW of paper machine thyristor drives which are generators of 5-th, 7-th, 11-th, 13-th, 17-th, etc. harmonics.

During a resonant condition, the 13.8 kV bus capacitors combine with the system reactance to form a tank circuit, resulting in amplified currents of the resonant frequency flowing from the capacitor bank to the system reactance. The amplification factor of source current to the tank circuit current is given by the system X/R ratio times the harmonic order. Also during resonance, the tank circuit appears as a high impedance anti-resonant circuit to the resonant current source. Since thyristor drive harmonic currents tend to be high impedance current sources, significant harmonic resonant voltage can result. The system resonant impedance looking outward from the resonance current source is approximately equal to the system X/R ratio times the capacitor reactance.

2.6.2 Klockner Pentaplast manufactures

Klockner Pentaplast manufactures heavy duty plastic film. The process uses calendars which are driven by dc motor drives. As a result, there is significant harmonic current generation and the plant power factor without compensation is quite low. Shunt capacitors can be added to partially correct the power factor but this can cause harmonic problems due to resonance conditions and transient problems during capacitor switching by the utility [Grebe, T.E., et.al., 1992]. Klockner Pentaplast is building a new facility in Rural Retreat to manufacture plastic film. This facility will include two calendar lines similar to lines at their existing facility in Gordonsville. Measurements performed at the Gordonsville facility are used to characterize these dc drive loads and additional analysis is described to determine power factor correction for the new facility. Klockner would like to correct the power factor to 0.95 with power factor correction equipment (capacitors). However, the power factor correction must take into account the potential for resonance which could magnify the harmonic currents generated by the dc drive loads. This results in a need for harmonic filters to reduce the harmonic current components injected on to the utility system. The plant electrical system consists of two sets of 480 Volt switch gear fed from a common 480 Volt bus. A 3750 kVA transformer steps down from a 34.5 kV distribution line for the entire facility.

CHAPTER III
HARMONIC ANAYSIS

3.0 Introduction

Harmonics current are created by non-linear loads that generate non-sinusoidal current on distribution power system. However, because of the increased popularity of electronic and other non-linear loads, the current waveform quite often became distorted. To understand the distortion phenomena, it is necessary to analyze the distorted waveform by a process called harmonic analysis [Lehtonen, M., 1993]. It allows us to express the distorted waveform as a sum of dc component, fundamental sine wave of the distorted waveform and a series of pure sine waves. These sine waves have different magnitudes and their frequencies are integer multiple of the fundamental distorted waveform. In this chapter provides a quantities discussion of harmonics analysis. Distorted waveform, effective value, Total Harmonics Distortion (THD), effect of harmonic for power and power factor are analyzed and presented using Fourier series. Characteristic of symmetrical component and their relation with sequence of harmonic on three phase distribution system are also presented in this chapter. The end of this chapter is describe current harmonic generation by three phase rectifier.

Harmonics are usually defined as periodic steady state distortions of voltage and current waveforms in power system [Gary W. Chang, 2001]. The purpose of this chapter is to present basic harmonic theory. Initially, the Fourier Series and analysis method that can be used to interpret waveform phenomenon are reviewed. The general harmonics theory, the definitions of harmonic quantities, harmonic indices in common use, and power system response are then described.

3.1 Fourier Series and Analysis

The theory of the Fourier series was first introduced by the French physicist and mathematician, Joseph Fourier, in his article 'Analytic Theory of Heat' which was published in 1882. It proves that any non-sinusoidal periodic function *f(t)* in an interval of time *T* could be represented by the sum of a fundamental and a series of higher orders of harmonic components at frequencies which are integral multiples of the fundamental component. The series establishes a relationship between the function in time and frequency domains. This expression is called *Fourier series* representation.

A distorted waveform can be analyzed using *Fourier series* representation given as the following equation

$$f(t) = F_o + \sum_{h=1}^{\infty} f_h(t) = \frac{1}{2}a_o + \sum_{h=1}^{\infty}\{a_h \cos(h\omega t) + b_h \sin(h\omega t)\} \tag{3.1}$$

where:

f(t) is called non sinusoidal periodic of the function

$F_o = \frac{1}{2}a_o$ is average value of the function *f(t)*

$$a_o = \frac{1}{2\pi}\int_0^{2\pi} f(t)d(\omega t)$$

which $\omega = \frac{2\pi}{T}$ and *T* is periodic of the function *f(t)* and $T = \frac{1}{f}$

f = frequency

a_h and b_h is series coefficient that can be determined as follow:

$$a_h = \frac{1}{\pi}\int_0^{2\pi} f(t)\cos(h\omega t)d(\omega t) \qquad ; h=1,2,3,\ldots$$

$$b_h = \frac{1}{\pi}\int_0^{2\pi} f(t)\sin(h\omega t)d(\omega t) \qquad ; h=1,2,3,\ldots \tag{3.2}$$

Therefore, the Fourier series in Equation 3.1 can be expressed as:

$$f(t) = F_o + F_{m1}\sin(\omega t + \varphi_1) + F_{m2}\sin(2\omega t + \varphi_2) + F_{m3}\sin(3\omega t + \varphi_3) + \ldots$$
$$+ F_{mh}\sin(h\omega t + \varphi_h) \tag{3.3}$$

where :

F_o	*is dc component*
F_{m1}	*is the maximum value of the fundamental component*
F_{m2}	*is the maximum value of the 2-nd harmonic order*
F_{m3}	*is the maximum value of the 3-rd harmonic order*
F_{mh}	*is the h order harmonic component*
ω	*is angular angle*
π	*is constantan (=3.14)*
t	*is time*
φ_1	*is the phase shift of fundamental component*
φ_2	*is the phase shift of 2-nd harmonic order component*
φ_3	*is the phase shift of 3-rd harmonic order component*

The Fourier expression is an infinite series. In this equation,F_0 represents the constant or the DC component of the waveform. $F_{m1}, F_{m2}, F_{m3} \ldots F_{mh}$ are the peak values of the successive terms of the expression. The terms are known as the harmonics of the periodic waveform. The fundamental (first harmonic) frequency has a frequency of *f*, the fifth harmonic has a frequency of (5 × *f*), the seventh harmonic has a frequency of (7 x *f*) and the n-th harmonic has a frequency of (n x *f*). If the fundamental frequency is

50 Hz, the fifth harmonic frequency is 250 Hz, and the seventh harmonic frequency is 350 Hz. The ability to express a non sinusoidal waveform as a sum of sinusoidal waves can use the more common mathematical expressions and formulas to solve power distribution system problems [John Cherney, 2003].

The harmonic current on the three phases power distribution system is defined as frequency components which is an integer multiple of the fundamental frequency. A pure sine wave not contains harmonic. When a wave becomes distorted, it means harmonics current are present in this distorted waveform. The harmonics current generated by three phase converter in three phases three wires power distribution system are 5-th, 7-th, 11-th, 13-th, 19-th and so on. The following is shown the current waveform distorted $i_s(t)$ caused by the three phases converter connected to power distribution system. Figure 3.1 illustrates how individual harmonics that are sinusoidal can be added to form a non sinusoidal waveform. The current distorted waveform in Figure 3.1 is the summation of fundamental frequency and 5^{th}, 7^{th},11^{th}, 13^{th}, 17^{th}, 19^{th} harmonics.

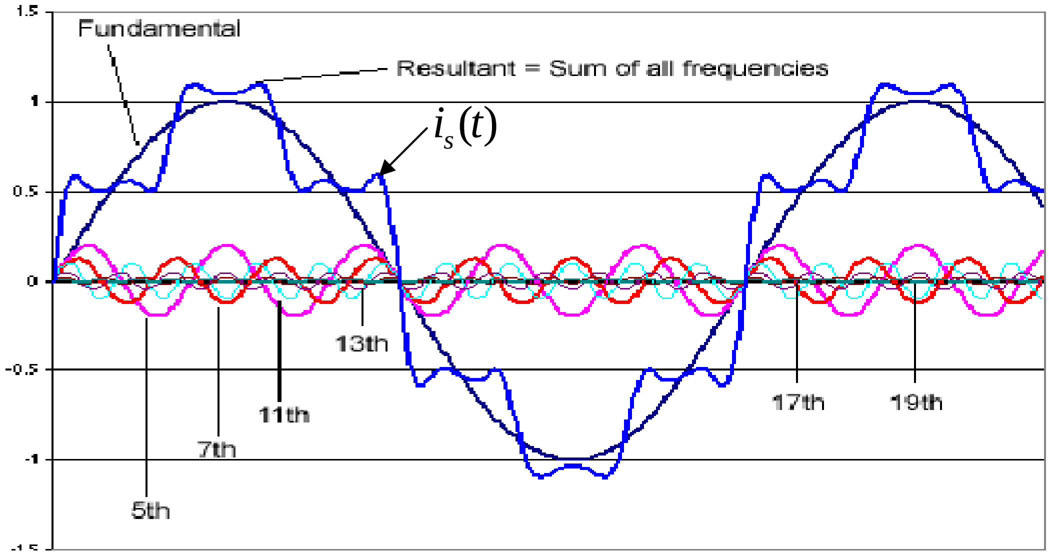

Figure 3.1: The current waveform distortions caused by odd harmonic component in three phases three wires power distribution system

3.2 Root Mean Square

The root mean square (rms) value also known as the effective value. It is the true measure of electrical parameters. The rms of a Fourier series function *f(t)* is defined as:

$$f(t)^2 = [F_0{}^2] + [F_{m1}\sin(\omega t+\phi_1) + F_{m2}\sin(2\omega t+\phi_2) + F_{m3}\sin(3\omega t+\phi_3) + ...]^2 \qquad (3.4)$$

or

$$\begin{aligned} f(t)^2 = [F_0{}^2] + [&F_{m1}{}^2\sin^2(\omega t+\phi_1) + F_{m2}{}^2\sin^2(2\omega t+\phi_2) + F_{m3}{}^2\sin^2(3\omega t+\phi_1) + ... \\ &+ F_{mh}{}^2\sin^2(h\omega t+\phi_h) + 2F_{m1}F_{m2}\sin(\omega t+\phi_1)\sin(2\omega t+\phi_2) + \qquad (3.5) \\ &2F_{m1}F_{m3}\sin(\omega t+\phi_1)\sin(3\omega t+\phi_3) + ...] \end{aligned}$$

To analyzing all root mean square of function *f(t),* part of contains sinusoidal function in Equation (3.5) is grouped in to two kinds of harmonic order multiplying part, as follow

- The same harmonic order multiplying part is given as

  $F_{mh}{}^2\sin^2(h\omega t+\phi_h)$

- The different of harmonic order multiplying part is given as

  $2F_{mh}F_{mK}\sin(h\omega t+\phi_h)\sin(k\omega t+\phi_k)$

where

h and k is integer value (1,2,3,……….) and k $\neq h$

The average value of $[F_{mh}{}^2\sin^2(h\omega t+\phi_h)]$ is:

$$= \frac{1}{2\pi}\int_0^{2\pi} F_{mh}{}^2\sin^2(h\omega t+\phi_h)d(\omega t) \qquad ;\text{ for } \omega t=\theta\text{, then}$$

$$= \frac{F_{mh}{}^2}{2\pi}\int_0^{2\pi}\sin^2(h\theta+\phi_h)d(\theta)$$