ACTIVE POWER FILTER WITH AUTOMATIC CONTROL CIRCUIT FOR NEUTRAL CURRENT HARMONIC MINIMIZATION TECHNIQUE

by

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بسم الله الرحمن الرحيم

In the name of ALLAH, the most compassionate and the merciful.

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LIST OF SYMBOLS

i_R	Current for Phase R
i_Y	Current for Phase Y
i_B	Current for Phase B
I_{1m}	Amplitude of Fundamental Current
I_{nm}	Amplitude of n^{th} Harmonic Current
n	Harmonic Order
ϕ_1	Phase Angel of Fundamental Current
ϕ_n	Phase Angel of n^{th} Harmonic
f	Frequency of Fundamental Current
ω	Angular Speed
i_N	Neutral Current
I_{SC}	Short Circuit Current
IL	Load Current
Ihc	Harmonic Current
Is	Source Current
Vinj	Harmonic Voltage Injection
VL	Load Voltage
C_{bstrap}	Bootstrap Capacitor
Q_{Gate}	Total Gate Charge
V_{Gate}	Gate Voltage
t_d	Dead Time
j	Phase a,b and c
$i_{j.1}$	Fundamental component of the load current
$i_{j.h}$	The distorted current for phase j
$i_{j.h}^{+}$	Positive Sequence Harmonic
$i_{j.h}^{-}$	Negative Sequence Harmonic
$i_{j.h}^{0}$	Zero Sequence Harmonic

$i_{af.j}$	Active Power Filter Current
$i_{s.j}$	Supply Current
V_{on}	Voltage Across Power Switcher during ON Period
I_{sw}	Current Through Power Switcher during ON Period
P_{cond}	Conduction Loss
tr	Rise Time
tf	Fall time
V_d	Voltage Across Power Switcher during OFF period
E_{ON}	Energy Loss during Power Switcher during ON
t_{ON}	Turn-ON time
t_{OFF}	Turn-OFF time
E_{OFF}	Energy Loss during Power Switcher during OFF
E_{SW}	Total Energy Loss by Power Switcher
f_{SW}	Switching Frequency
P_{SW}	Average Power Loss by Power Switcher

LIST OF ABBREVIATION

EPR	Electric Power Research
THD	Total Harmonic Distortion
PCC	Point Common Coupling
THDi	Total Harmonic Current Distortion
CBEMA	Computer and Business Equipment Manufacturer Association
AC	Alternative Current
IEEE	Institute of Electrical and Electronic Engineers
APF	Active Power Filter
DC	Direct Current
PWM	Pulse Width Modulation
IGBT	Insulated Gate Bipolar Transistor
MOSFET	Metal Oxide Field Effect Transistor
rms	Root Mean Square
MCB	Miniature Circuit Breaker
UPS	Uninterruptible Power Supplies
PC	Personal Computer
TV	Television
MVA	Megavolt Ampere
emf	Electromotive Force
B	Flux Density
H	Magnetic Field Intensity
VAR	Static Apparent Power
TCRs	Thyristor Controlled Reactors
TSCs	Thyristor Switched Capacitor
Pf	Power Factor
Q	Quality Factor
R	Red
Y	Yellow
B	Blue
N	Neutral
HF	Harmonic Distortion Factor
WS	Weighted Sum
R’	Resistance
L	Inductance

C	Capacitance
IL	Load Current
Ihc	Harmonic current
Is	Source Current
Vinj	Harmonic Voltage Injection
VL	Load Voltage
VPCC	Point Common Coupling Voltage
CSI	Current Source Inverter
VSI	Voltage Source Inverter
GTO	Gate Turn OFF
ICM	Compensation Current
PQM	Power Quality Management
UPQC	Unified Power Quality Conditioner
SPWM	Sinusoidal Pulse Width Modulation
CT	Current Sensor
I_N	Neutral Current
TP	Test Point
EMI	Electromagnetic Interference
LED	Light Emitting Diode
DFB	Full Bridge Rectifier
TTL	Transistor-Transistor Logic
IC	Integrated Circuit
TR	Power Transistor
RY	Power Relay
CONT	Magnetic Contactor
NO	Normally Open
NC	Normally Closed
PESIM	Power Electronics Circuit Simulation
THDv	Total Harmonic Voltage Distortion
Lf	Link Reactor

LIST OF PUBLICATIONS & SEMINARS

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1. Izhar, M., Hadzer, C.M. and Syafrudin, M. (2003). Prelimenary of Closed Loop Harmonic Study Analysis in Under Load Variations for Power System. *IEEE Proceedings of the International Conference On Robotics, Vision, Information and Signal Processing.* 1. 675 – 682.
2. Izhar, M., Hadzer, C.M. and Syafrudin, M. (2003). Reduced Order Model of a Switched Capacitor Design. *IEEE Proceedings of the International Conference On Robotics, Vision, Information and Signal Processing.* 1. 683 – 689.
3. Izhar, M., Hadzer, C.M. and Syafrudin, M. (2003). An Analysis of the Harmonic Effect to Power Factor in the Power System. *IEEE Proceedings Engineering and Technology Conference.* 407 – 414.
4. Izhar, M., Hadzer, C.M. and Syafrudin, M. (2003). A Study of the Fundamental Principles to Power System Harmonics. *IEEE National Power Engineering Conference Proceedings.* 225 – 232.
5. Izhar, M., Hadzer, C.M. and Syafrudin M. (2003). An Investigation on Harmonic Level, Current & Voltage Distortion and Associated Power for Three Phase Four Wire Distribution System in a USM Electrical & Electronic Engineering Department Building. *IEEE National Power Engineering Conference Proceedings.* 371 – 378.
6. Izhar, M., Hadzer, C.M. and Syafrudin, M. (2004). Harmonics Reduction Performance of Passive and Active Power Filter in Distribution System. *Proceedings 6th Industrial Electronics Seminar, JICA-IEEE,* Oct. 42 – 46.
7. Izhar, M., Hadzer, C.M. and Syafrudin, M. (2004). An Analysis and Design of A Star Delta Transformer In Series With Active Power Filter for Current Harmonics Reduction. *IEEE National Power & Energy Conference,* Dec. 94 – 98.
8. Izhar, M., Hadzer, C.M. and Syafrudin, M. (2004). Performance for Passive and Active Power Filter in Reducing Harmonics in the Distribution System. *IEEE National Power & Energy Conference Proceedings,* Dec. 104 – 108.

TEKNIK PENURAS KUASA AKTIF DENGAN LITAR KAWAL AUTOMATIK UNTUK MEMINIMUMKAN HARMONIK ARUS NEUTRAL

ABSTRAK

Disertasi ini bertujuan untuk membangun penuras kuasa aktif yang cekap dan boleh dipercayai bagi meminimumkan lebihan harmonik arus neutral dan juga masalah harmonik di dalam talian neutral untuk sistem tiga fasa empat dawai. Arus neutral ini pada umumnya mengandungi tertib harmonik ' triplen' seperti ke-3, ke-9, ke-15 dan lain-lain yang dijanakan oleh beban tidak lelurus. Arus harmonik ke-3 adalah harmonik dominan. Untuk mengatasi masalah ini, disertasi ini mencadangkan skema penuras kuasa aktif bersama aplikasi pengubah bintang-delta bagi membatalkan harmonik arus neutral dalam talian neutral. Kajian ini mencadangkan penuras kuasa aktif terdiri daripada pensuis kuasa yang dimodulasikan berdasarkan teknik pensuisan baru dengan menggunakan aras duaan gelombang segitiga dan gelombang sinus tunggal. Dalam mempertingkatkan lagi pengurangan arus harmonik, litar baru kawal automatik untuk isyarat keluaran-mengekor adalah diperkenalkan. Ini untuk membolehkan pemodulatan lebar denyut yang dijanakan dengan penuras kuasa aktif adalah selaras dengan tidak ketetapan magnitud arus neutral. Kajian ini juga mencadangkan pendekatan baru untuk perlindungan dalam sistem operasi bagi membolehkan sistem dalam mod terbuka secara automatik disebabkan arus lampaun atau litar pintas. Prestasi keputusan keseluruhan menunjukkan bahawa pengurangan arus neutral dengan menggunakan penuras kuasa aktif dengan litar kawal automatik ialah 68.4%, berbanding kepada litar tanpa kawal automatik iaitu 61.9%. Peningkatan pengurangan arus neutral ialah 6.5%. Keputusan juga menunjukkan bahawa purata pengurangan arus harmonik untuk ke-3, ke-9 dan ke-15 masing-masing bertambah daripada 60.1% kepada 65.8%, 67.7% kepada 74.9% dan 71.1% kepada 75.9%. Kajian mengenai kesan dari penuras kuasa aktif ke atas sistem talian elektrik pengagihan kuasa juga dijalankan. Purata keputusan menunjukkan bahawa jumlah kandungan arus harmonik berkurangan daripada 83.6% kepada 62.3%. Sementara itu, faktor kuasa bertambah daripada 0.54 kepada 0.76. Perihal sah keputusan ditunjukkan dengan simulasi dan ujikaji.

ACTIVE POWER FILTER WITH AUTOMATIC CONTROL CIRCUIT FOR NEUTRAL CURRENT HARMONIC MINIMIZATION TECHNIQUE

ABSTRACT

The aim of this thesis is to develop an efficient and reliable active power filter in order to minimize the excessive neutral current as well as harmonic problem in the neutral line for three phase four wire system. This neutral current generally consists of triplen harmonics order such as 3rd, 9th, 15th and etc., which are generated by nonlinear load. The dominant harmonic is 3rd harmonic current. In response to this problem, this thesis proposes an active power filter scheme along with star-delta transformer application to cancel neutral current harmonic in neutral line. The development of active power filter, consisting of power switcher, which is modulated based on new switching technique by using dual level triangular waveform and single sinusoidal, is proposed. In order to further improve the harmonic current reduction, the new automatic control circuit for output-following signal is introduced. This is to enable the pulse width modulation to be generated by active power filter that is synchronized with magnitude of neutral current inconsistency. The research also proposes a new approach for the protection in operating system that enables the system to be in turn-OFF mode automatically due to over current or short circuit. The overall performance results showed that the neutral current reduction by using active power filter with automatic control circuit was 68.4% as compared to without automatic control circuit, which was 61.9%. The improvement of neutral current reduction was 6.5%. The results also showed that the average of harmonic current reduction for 3rd, 9th, and 15th increased from 60.1% to 65.8%, 67.7% to 74.9%, and 71.1% to 75.9% respectively. A study on the effects of active power filter on the electrical power line distribution system was also carried out. The overall result showed that the Total Harmonic Current Distortion decreased from 83.6% to 62.3%. Meanwhile, the Power Factor increased from 0.54 to 0.76. The validity of results is demonstrated by simulation and experiment.

CHAPTER 1
INTRODUCTION

1.1 Background

In a three phase four wire distribution systems have been widely employed to deliver electric power at low voltage levels. A typical low voltage of three phase four wire system in the Malaysian consists of a 415/240V in distributing electric energy to several office buildings and manufacturing plants. Therefore, the operating conditions have changed dramatically because of the rapid growth of advanced power conversion devices, electronics equipments, computers, office automation, air-conditioning systems, adjustable speed heating ventilation and etc. [Kevin, J.T. and Rich, P., 1997]. According to the Electric Power Research (EPR) in 1995, 35-40% of all electric power flows through electronic converters. This is expected to increase to 70% by the year 2000 [Roger, C.D., *et.al.*, 1996]. All these devices are namely as nonlinear loads and become sources of harmonics. Harmonics is considered as one of the most essential problems in electrical power systems.

Harmonics in power distribution system are current or voltage that are integer multiples of fundamental frequency. For example if the fundamental frequency 50Hz, then 3rd is 150Hz, 5th is 250Hz [Robert, D.H. and Patrick, J., 1994]. Ideally, voltage and current waveforms are perfect sinusoids. However, because of the increased popularity of electronic and non linear loads, these waveforms become distorted. This deviation from a perfect sine wave can be represented by harmonic components having a frequency that is an integral multiple of the fundamental frequency. Thus, a pure voltage or current sine wave has no distortion and no harmonics and a non sinusoidal wave has distortion and harmonics. In order to quantify the distortion, the term of 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.W., 2001].

The simple block diagram in Figure 1.1 illustrates the distortion problem due to harmonic at low voltage levels.

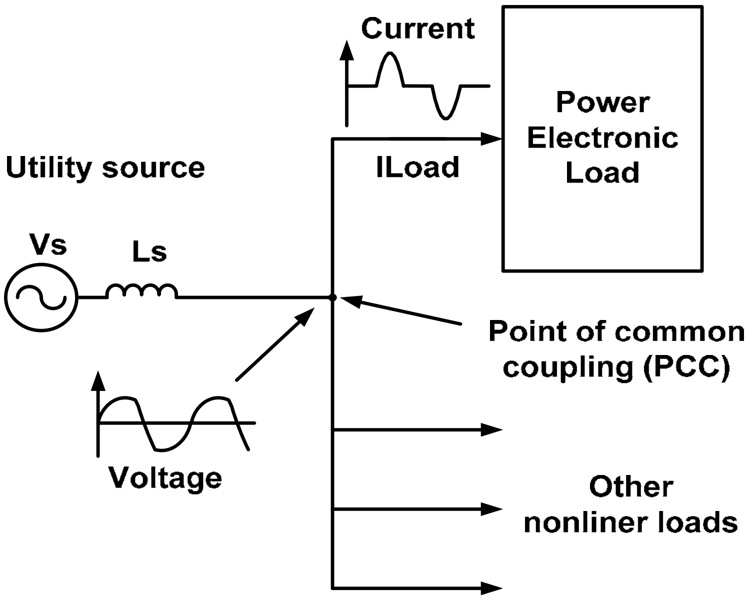

Figure 1.1: Harmonic distortions at PCC

The voltage waveform at the Point Common Coupling (PCC) is distorted due to harmonic current generated by the power electronic or nonlinear load. This result will effects on the line currents distortion is increased, malfunction of sensitive electronic equipment, increased losses and contributes to inefficient use of electric energy [Takeda, M., *et.al.*, 1987, Juan, C.M. and Samra, A.H., 1998].

In a three phase four wire distribution systems, under normal operating conditions with the loads are balanced, the current in the neutral current conductor is expected to be small, typically is not to exceed 20% of the normal load current in the phase [Choy, A.L., 1989]. However, the problem of excessive neutral current in three phase four wire systems is arised due to rapid growth of advanced nonlinear loads.

The neutral currents are basically zero sequence current harmonics, which is mostly, consists of triplen current harmonics. The zero sequence current harmonics, especially the 3rd and other odd triplens 9th, 15th, 21st, 27th and etc. will be accumulated in the neutral wire, thus results in overloading of the neutral conductor and the distribution transformer. The most dominant harmonic current is 3rd harmonic. Due to that, the neutral current magnitudes are higher than compared with phase currents. A survey results for 146 computers by Gruzs is indicated that 23% had neutral currents exceeding the phase currents and their Total Harmonic Current Distortion (THDi) is more than 100% [Gruzs, T.M., 1990]. Inductive ballast also inject considerable harmonics in neutral conductors, fire has been reported due to such overloading incident [Liew, A.C., 1989]. These results also founded by Computer and Business Equipment Manufacturer Association (CBEMA). CBEMA recently reported that a shared neutral conductor in building may carry increased harmonic currents and result in wiring failures [CBEMA, 2001]. The potential problems related to the excessive zero sequence current harmonics in the neutral conductor are [Pekik, A.D., *et.al*., 1997].

i. The risk of wiring failure due to improper sizing of the neutral conductor
ii. Transformer overheating due to harmonic currents
iii. Excessive neutral current to ground voltage due to a voltage drop caused by neutral current

There are standards that determine the maximum allowable level for each harmonic in the Alternative Current (AC) system [IEEE Std. 519, 1981]. When excessive harmonic voltage and current are generated, filters are usually installed to reduce the harmonic distortion [Fang, Z.P., *et.al.*, 1990, Fang, Z.P., *et.al.*, 1993, Mark, M.G. 2003, Hugh, R., *et.al.*, 2003, Helga, S., 2004]. There are two functions to connect harmonic filter at line distribution systems as listed below.

i. To reduce the harmonic voltage and current in the AC system below the permitted levels
ii. To provide some of the reactive power absorbed by the converter system [IEEE Std. 519, 1981]

Conventionally, passive filters have been used to eliminate harmonic problems. This filter mainly consists of common devices such as inductance and capacitance. These devices tuned to the frequency of the harmonic to be removed. However it has the following limitation.

i. A separate filter is necessary for each harmonic frequency
ii. As both the harmonic current and the fundamental frequency current flow into the filter, the capacity of the filter must be decided by taking into account both currents
iii. The filter will be overloaded when the content of the harmonic in the AC line increases

Other methods of harmonic reduction is considered such as current injected by Active Power Filter (APF) to overcome the above limitation [Charles, A.G. and James, R.J., 1999, El-Habrouk, M., *et.al*., 2000, Sangsun, K. and Parasad, N.E., 2001, Ambra, S., *et.al.*, 2003]. The APF filter concepts are used power electronic switching to generate harmonics components to cancel the harmonic components of the nonlinear loads. It means that in these devices, Direct Current (DC) is converted to form the harmonic currents out of phase of the load which is then injected into AC line, thereby preventing the harmonics currents flowing into the supply [Arrilaga, J., *et.al.*, 2003].

The suitable device in developing the APF is utilizing Pulse Width Modulation (PWM) inverter by using power semiconductors devices such as Insulated Gate Bipolar

Transistor (IGBT) or Metal Oxide Field Effect Transistor (MOSFET) [Philip, J.A., *et.al*., 1997]. The PWM is used because it can be easily adjusted in order to control amplitude harmonic current injection and frequency switching.

Following are the reasons APF had been used to minimize harmonic pollution in the distribution line system compared with passive filter.

i. All the harmonics presented in AC line system can be compensated by using one equipment
ii. The maximum order of harmonic to be suppressed has no limitation and is determined by PWM switching
iii. Even the existing harmonic components change in magnitude and frequency in line it can be accommodated by control adjustment by triangular and voltage reference circuit rather than equipment changes from time to time
iv. It is not designed to filter out one harmonic component only, but is intended to attenuate several harmonics in one time

Compared with passive filter methods, the harmonic current injection into the power network by applied a high frequency switching inverter able to offers suppress harmonic as much as possible adequate with low cost had been reported [Nakajima, *et.al*., 1988].

In this thesis APF is proposed to minimize the zero sequence current harmonic current as well as to reduce neutral currents magnitudes in three phase four wire systems. Both simulation and experimental works are performed in order to validate the results.

1.2 Objectives

The main objectives of this research are to develop and design APF to reduce the excessive neutral current as well as harmonic currents in neutral wire for three phase four wire distribution systems. The main proposed APF can be outlined as follows:

i. Development of a new switching strategy control by using single sinusoidal via dual level triangular waveform
ii. Development of a new automatic control circuit for output-following signal in order the harmonic cancellation is synchronize appropriately with neutral current in neutral conductor
iii. Development of a new safety precaution for APF
iv. Complete design, test and prototype for APF modular
v. Comparison results of the proposed APF between simulation and experimental work

1.3 Project Methodology

At the moment APF is focused for the harmonic current compensation for single and three phase systems [Akagi, H., 1994, Akagi, H., 1996]. It is clearly understood that the development of APF is very complicated. Meanwhile the ABB Company takes initiative to develop APF for three phases from year 1995 till 2004 for commercial purposes but not three phase four wire system [Olivier, S[1]. and Olivier, S[2]., 2004].

This thesis studies the current injected active AC power filter utilizing power semiconductors to cancel excessive neutral current harmonics. A new simple technique in developing a half bridge inverter is the heart of APF had been introduced out. Also a new switching technique, using single sinusoidal waveform via dual level frequencies carrier for strategic control of two switches PWM controlled APF has been developed. In addition to that the new approached automatic control circuit for output-following signal to improve harmonic cancellation is carried out. Besides that, the new approached of safety precaution for APF is presented. In this research the star delta transformer is employed with APF for application in three phase four wire system.

The performances of the simple APF and new strategy control are investigated by simulation and experiments. Using these results of simulation and experiments, it is possible to optimize the operation of the APF for three phase four wire distribution system.

The new proposed of important aspects in project methodology for neutral current reduction of three phase four wire distribution systems as follows:

i. Literature review and find the information on APF, nonlinear loads characteristics, current waveform distortion and total harmonic distortion
ii. Model three phase four wire distribution systems, under normal operating conditions with the nonlinear loads reasonably balanced in order to determine the harmonic currents and excessive neutral current in neutral conductor
iii. Design and develop the PWM switching strategy control by using single sinusoidal via dual level triangular waveform to cancel triplen harmonics (3^{rd}, 9^{th} ,15^{th}, etc.) in neutral line
iv. Design and develop the automatic control circuit for output following signal to synchronize between harmonic cancellation with neutral current magnitude in neutral conductor, therefore the reduction of harmonic will be furthered improved
v. Design and develop the safety precaution circuit so that the whole systems are free from hazards

vi. To perform simulation and experimental work for data collection of excessive neutral current minimization.

vii. Analyse the simulation and experimental results

The block diagram for the project methodology can be represented in Figure 1.2.

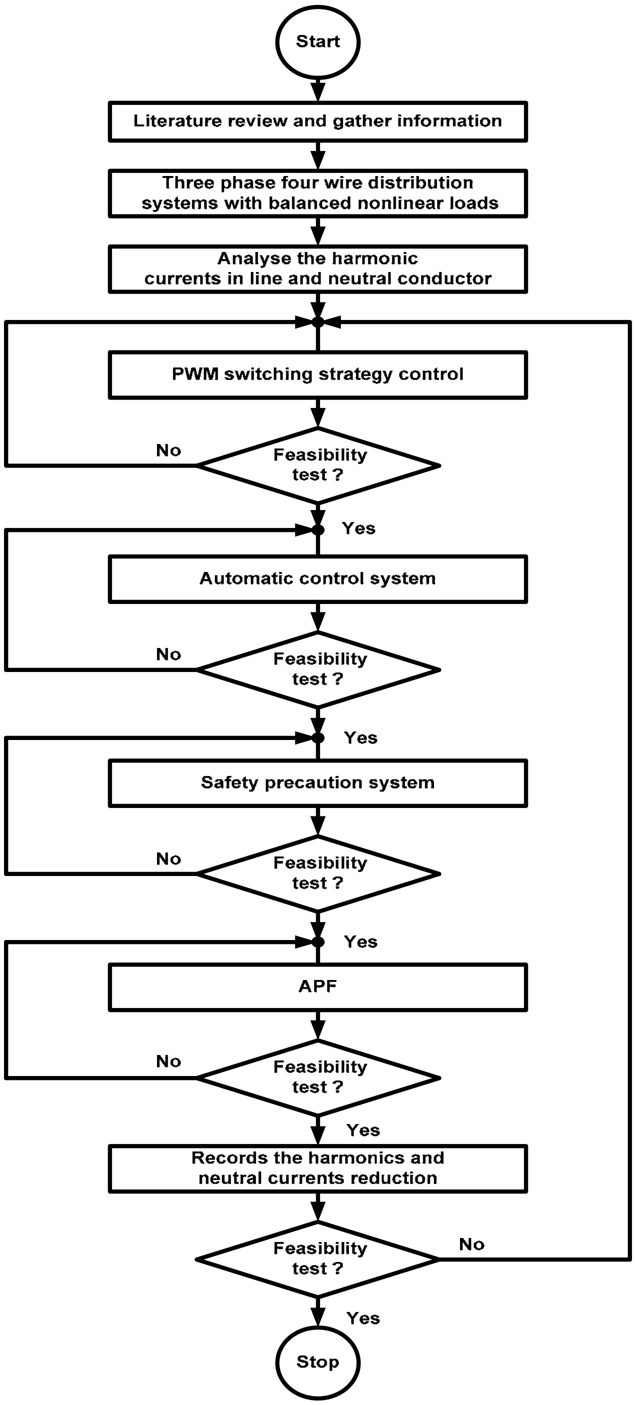

Figure 1.2: Flowchart for Project Methodology

1.4 Scopes and Contributions

This thesis is a contribution to the design and implementation technique for APF in minimizing harmonics currents in neutral conductor for three phase four wire distribution systems. An experimental APF unit rated 1kVA was developed and used for testing and validation purposes. The main scopes of works can be outlined as follows:

i. The power circuit for APF is a force commutated sinusoidal pulse width modulated voltage source inverter based on half bridge configuration. A new simple circuit, low cost and reliable new switching strategy control are proposed in order to turn-ON and OFF power circuit for APF. The approached implementation uses dual level triangular wave compared with single sinusoidal to generate sharpen sinusoidal pulse width modulation with lower dead time. It is achieved by using high precision voltage comparator and high speed integrators

ii. The new switching strategy controls along with automatic control circuit for output-following signal are implemented. The proposed implementation uses a new simple and low cost circuit such as light emitting diode and photoresistor technique that allows the operation of switching is synchronized with magnitude neutral current in neutral line in order to achieve better harmonic current cancellation

iii. The protections in operating system technique are implemented in order to avoid hazard to humans, offers protection from short circuit and over neutral current in neutral line. The proposed implementation uses a simple and low cost controllers such as relay, driver and magnetic contactor

The specific contributions as follows:

i. A detail design and techniques to develop a new approached APF is presented
ii. The root mean square (rms) neutral current and harmonic current can be minimized by using a new approached techniques for APF were developed
iii. The THDi phase currents were reduced
iv. The power factor in distribution system were improved
v. Based on the new switching strategy control the periods of life time power switchers is longer and switching power losses is lower. Also, no requires additional circuit for dead time control in order to avoid overlapping gating signal during power switchers turn-ON and OFF. Beside that no short-through problems between upper and lower of power switchers
vi. Due to automatic control circuit the harmonic current reduction can be furthered improved
vii. The safety precaution circuits were developed in APF instead of Miniature Circuit Breaker (MCB) to protect the potential hazards to humans and electrical circuit from damage caused by electrical faults in power systems
viii. The sized and weight of APF is less compared to the passive filter

Research work in this thesis has produced several publications in various conferences as follows:

i. Izhar, M., Hadzer, C.M. and Syafrudin, M. (2003). Prelimenary of Closed Loop Harmonic Study Analysis in Under Load Variations for Power

System. *IEEE Proceedings of the International Conference On Robotics, Vision, Information and Signal Processing.* 1. 675 – 682.

ii. Izhar, M., Hadzer, C.M. and Syafrudin, M. (2003). Reduced Order Model of a Switched Capacitor Design. *IEEE Proceedings of the International Conference On Robotics, Vision, Information and Signal Processing.* 1. 683 – 689.

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vi. Izhar, M., Hadzer, C.M. and Syafrudin, M. (2004). Harmonics Reduction Performance of Passive and Active Power Filter in Distribution System. *Proceedings 6th Industrial Electronics Seminar, JICA-IEEE,* Oct. 42 – 46.

vii. Izhar, M., Hadzer, C.M. and Syafrudin, M. (2004). An Analysis and Design of A Star Delta Transformer In Series With Active Power Filter for Current Harmonics Reduction. *IEEE National Power & Energy Conference,* Dec. 94 – 98.

viii. Izhar, M., Hadzer, C.M. and Syafrudin, M. (2004). Performance for Passive and Active Power Filter in Reducing Harmonics in the Distribution System. *IEEE National Power & Energy Conference Proceedings,* Dec. 104 – 108.

1.5 Thesis outline

This thesis is organized as follows:

Chapter 2 covers the background and literature reviews. In this Chapter also describes the harmonics as a power quality problem such as sources and effect harmonics in the power systems, harmonic reduction technique, includes survey of the active filtering technique is discussed.

Chapter 3 describes and discusses in detail on the design and implementation circuit technique in order to develop APF to reduce rms neutral current as well as harmonic currents in neutral conductor for three phase four wire distribution system. Also, the simulation results are examined to validate the design proposed

Chapter 4 explains on the experiment results and discusses from the beginning to the end of development for APF. Both simulation and practical results are demonstrated to verify the proposed approach

Chapter 5 concludes the thesis and identifies some area for future research work

At the end of the thesis, a list of relevant references and appendices are given.

CHAPTER 2
BACKGROUND AND LITERATURE REVIEW

2.1 Introduction

Ideally, all power utilities should provide their customers with a quality supply which has constant magnitude and frequency of sinusoidal voltage. Unfortunately is a hard task to maintain this quality supply for constant magnitude and frequency of sinusoidal voltage. In reality the supply waveforms are always got distorted resulting in supply or not purely sine wave due to nonlinear load. The common nonlinear loads nowadays such as variable speed drivers, rectifiers, Uninterruptible Power Supplies (UPS), Personal computers (PC), Television (TV) sets etc. These loads draw current from the sources which do not follow the voltage shape and hence introduce harmonic [Bachry, A., *et.al.,* 2000, Power Notes-Power System Harmonics, 2003]. 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 2nd harmonics is 100Hz, the 3rd is 150Hz etc. [Robert, D.H., *et.al*., 1994]. These harmonics are growing problem for both electricity suppliers and users [Tom, S., *et.al*., 1995, Mansoor, A. and Grady, W.M., 1998, Grady, W.M., *et.al.,* 2002].

Harmonics are usually defined as sinusoids of any frequency other than the AC power system fundamental frequency. There are two types of harmonics that can be encountered in a power system [IEEE Std. 100-1988].

i. Synchronous harmonics
ii. Asynchronous harmonics

Synchronous harmonics are sinusoids with frequencies which are multiples of the fundamental frequency. The multiplication factor is often referred to as the harmonic number. The synchronous harmonics can be subdivided into two categories.

i. Subharmonic when the harmonic number is less than one
ii. Superharmonic when the harmonic number is greater than one

For example, the line current contains both subharmonic and superharmonic such as cycloconverters and line commutated three phase thyristor based rectifiers. These waveforms are considered as distortion [Leon, M.T., *et.al.*, 2003, Chang, G., *et.al.*, 2004].

Asynchronous harmonics are those sinusoids which do not maintain a frequency relationship with the fundamental frequency sinusoid. These sinusoids never exhibit a constant harmonic number and similarly do not maintain a stationary phase relationship with the fundamental frequency sinusoid.

Harmonics as a power quality problem which is perturbed in the power systems is first discussed in Section 2.1. Sections 2.2 and 2.3 highlight the causes and the impact of the harmonic problems. The limits of harmonic and overview on harmonic mitigation techniques, with emphasis on the APF filtering solution is given in Section 2.4 and 2.5 respectively. Meanwhile, Section 2.6 will further discuss on the literature review on APF.

2.2 Harmonics as a Power Quality Problem

Harmonics are qualitatively defined as sinusoidal waveforms having frequencies that are integer multiples of the power line frequency. In power system engineering, the term harmonics is widely used to describe the distortion for voltage or current waveforms. The harmonic problem is not a new phenomenon in power system. It was detected as early as the 1920s and 30s [IEEE Working Group On Power System Harmonic: An Overview, 1983, Hirofumi, A., 1994]. At the time, the primary sources of harmonics were the transformers and the main problem was inductive interference telephone systems. Some early investigation work on harmonic filtering in distribution feeders was performed around that time.

Harmonic distortion can have detrimental effects on electrical distribution systems. It can waste energy and lower the capacity of an electrical system [Heydt, G.T., *et.al*., 1994]. Understanding the problems associated with sources and effects of harmonics as well as the methods to reduce the harmonic will increase the overall efficiency of the distribution system [Kassakian, J.G., *et.al*., 1991, Kendall, P.G., 1992].

2.3 Sources of Harmonics

Figure 2.1 illustrate the different sources of harmonics in power distribution system. The different sources of harmonics namely from three main areas as listed below.

i. From the fast switching associated of power electronic devices
ii. From the conventional sources such as electrical rotating machines and transformers
iii. From modern electronic equipments

2.3.1 Harmonics from Fast Switching of Power Electronic Devices

Nowadays, due to the applications advanced technologies in industrial sectors such as power semiconductor systems which are designed using phase controlled or uncontrolled rectifiers, inverters, AC voltage controllers, cycloconverter and converters.

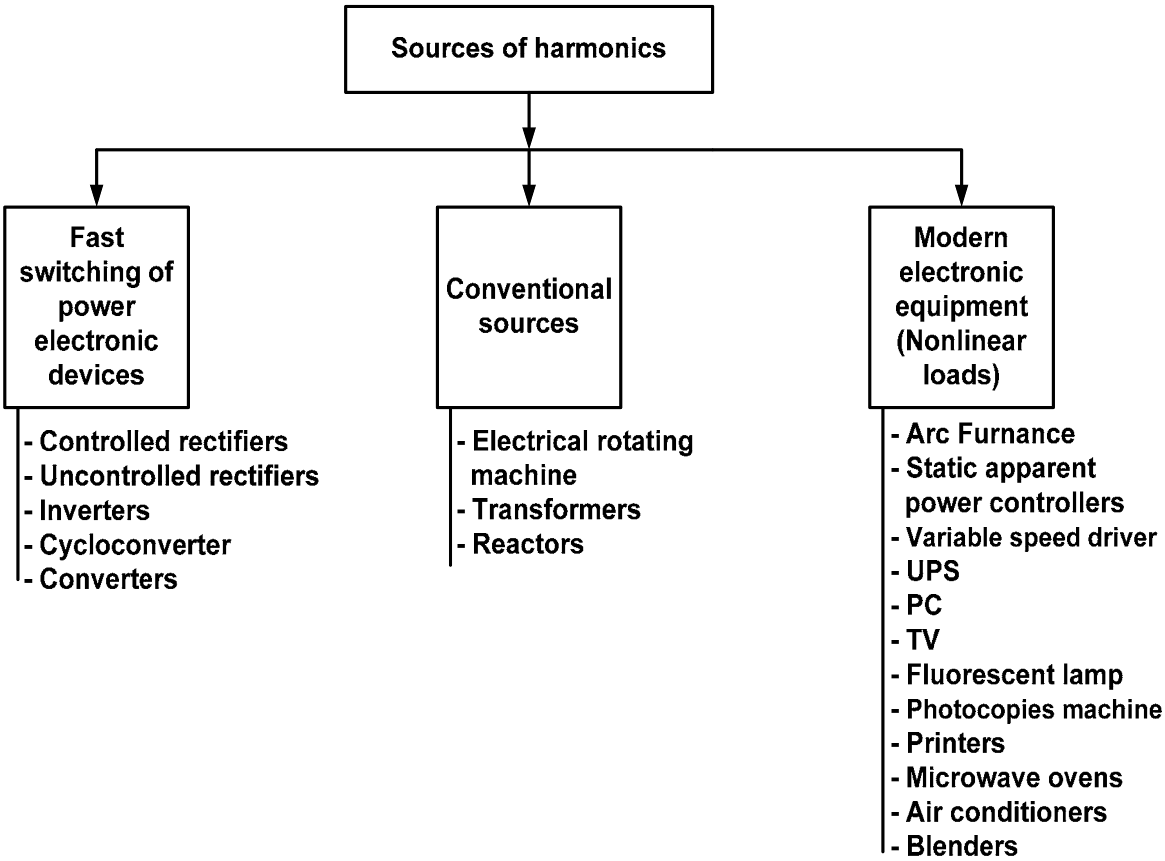


Figure 2.1: The Sources of Harmonics In Power Distribution System

In single phase full wave controlled rectifiers the harmonic generated are more significant at lower frequency compared with higher frequency [Dubey, *et.al.*, 1986, Ned, M., *et.al.*, 1995, Yasuyuki, N., *et.al.,* 1997]. Meanwhile, the three phase controlled rectifiers is used for high power with large Mega Volt Ampere (MVA) rating [Farhad, N. and Patel, H.S., 1988, Karshenas, H.R., *et.al.,* 1995] it produces large harmonics currents on 3^{rd}, 5^{th}, 7^{th}, 9^{th}, 11^{th}, 13^{th}, 15^{th}, 17^{th} and 19^{th} harmonics [Philips, J.K., *et.al.,* 1991]. Others applications of thyristor controlled rectifiers such as:

i. To control the acceleration and deceleration of electric engine can cause current distortion including order 3^{rd}, 5^{th} and 7^{th} harmonic currents is directly injected into utility [Zhongming, Y., *et.al.*, 2000, Shoofeng, X., *et.al.,* 2003]

ii. To control the speed of portable hand tool driver. The 3rd harmonics is dominant harmonic which contributed to the power distribution systems [Mack, G. and Santoso, S., 2001]

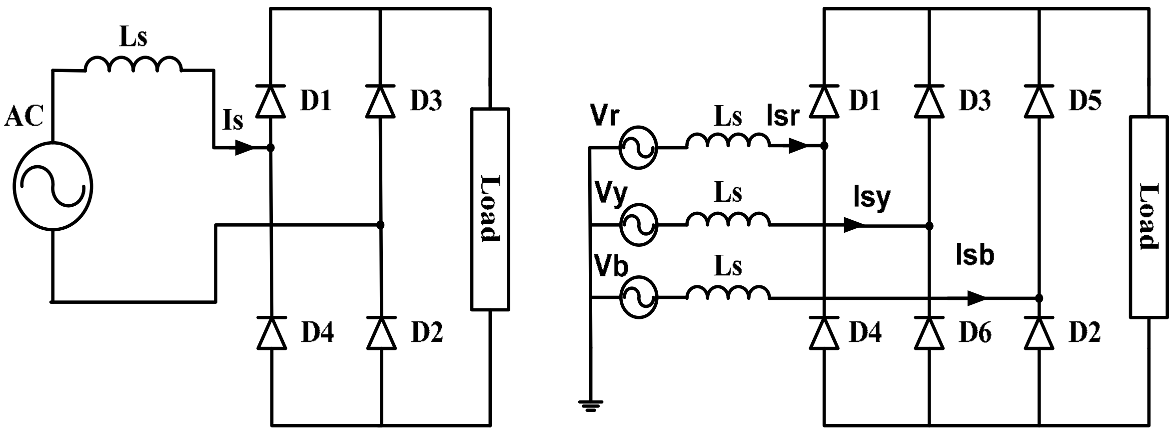
iii. To establish a voltage level in providing the gate current to turn on and off the thyristor for home and industry applications such as light dimmer and induction motor. The 3rd harmonics is dominant harmonic into power distribution system [Emanuel, A.E., *et.al*, 1980, Daniel, W.H., 1997]

iv. To control mine winders, draglines, electrical shoves, electrochemical and metallurgical plants. It founds that the almost harmonic current is 5th, 7th and 11th harmonics. It's rare to find the 3rd, 9th, or 15th harmonics [A Gold Mine of Troubleshooting, 2003, Pacific Gas and Electric Company,2003]

v. To control variable speed motor drives. Effects from this phenomenon will be served the main contributor harmonic distortion in supply system is 3rd, 5th and 7th harmonic currents [Sadeq, A.H., 1997]

vi. To vary the AC voltage controller for lighting control, variable transformer by using taps changing, heather, industrial heating and induction motor. By controlling the phase delay of the thyristor the load currents are varied within desired limits. This result will effect in distorted input current and simultaneously significant harmonic current such as 3rd, 5th, 7th , 9th and 11th is generated and injected into the supply system [Abou-Elela M. and Alolah A.I., 1994, Czarneccki, L.S and Tan, O.T., 1994, Grady, W.M., *et. al.,* 1994, Kamath, G., *et.al*., 1995, Grady, W.M., *et. al.* 2002, Hashem, G.M. and Darwish, M.K., 2004].

An identically the constructions circuits for uncontrolled rectifiers of single phase and three phase were similar with controlled rectifiers. The different is that diodes are used for uncontrolled rectifiers compared with thyristor for phase controlled rectifiers. The circuit is shown in Figure 2.2



(a) (b)

Figure 2.2: Uncontrolled Rectifiers (a) Single Phase (b) Three Phase

These rectifiers are mainly used in DC power supplies. Most the above configuration circuits are used to convert AC supply to DC supply. This DC supply is used for internally circuits. Both single phase and three phase diode rectifiers injects large amounts of harmonic currents into the utility system. It means that this is the major contributors of harmonic in the supply system [Ned, M. *et.al.,* 1995].

The single and three phase inverters are commonly used to convert DC to AC power at some desired output voltage and frequency. The output voltage, current and frequency of inverter can be controlled by control strategies of inverters [Lai, J.S.*, et.al*., 1994, Von, J., *et.al*., 1995, Akira, N., *et.al*., 1996, Evon, S.T and Oakes, B., 1999, Vazquez, N., *et.al*., 1999, Ahmad, F.R. and Omar, A.M., 2005]. However, in practically inverters outputs contain certain harmonics. With the availability of high speed power semiconductors devices, the harmonic contents of the output voltage and current can be minimized significantly by switching technique and additional passive filters to be used [Liang, T.J., *et.al*., 1997].

AC-AC conversion such as cycloconverter can be used to control the low speed of induction motor and AC motor drives in the range up to 15kW with frequencies from 0 to 50Hz. It is shown that this application suitable for low speed and very large horsepower applications. It is shown that this application suitable for low speed and very large horsepower applications. The harmonics currents on 3^{rd}, 5^{th}, 7^{th} and 11^{th} including interharmonics from cycloconverters are injected into power network and caused the current distortions [Muhammad, H.R., 1993, Ned, M. *et.al.,* 1995, Jiang, J. and Xie, W. 2000, Pontt, J., *et.a*l., 2003].

Next, the converters are mainly consists of power electronics devices and widely used in the industry to convert one type of signal to another form. The summary for type's converters and their functions are tabulated in Table 2.1. The alternating current drawn from the main supply by a converter, theoretically contain harmonics are represented by (mk±1), where m is the pulse number (number of pulses of current that pass through the load circuit during one cycle of the source voltage) and k is any integer. It means that a 6 pulses thyristor controlled converter will theoretically contains 3^{rd}, 5^{th}, 7^{th}, 11^{th}, 13^{th},…etc. harmonics, 12 pulse converter will theoretically contains the 11^{th}, 13^{th}, 23^{rd}, 25^{th},…etc. harmonics and 24 pulse converter will theoretically contains the 23^{th}, 25^{th}, 47^{th} , 49^{th}…etc. harmonics [IEEE Std. 519, 1981].

Hence, the fast switching of power electronics were created significant amount of harmonic pollution in the power distribution systems is greater than compared with the conventional sources. It is predicted that in future more than 60% of the industrial loads will be controlled by power electronics [Lamarre, L., 1991].

Table 2.1: Types and functions of converter

No.	System	Function
1.	Rectifiers i. Controlled ii. Uncontrolled	 Fixed voltage AC supplied to variable voltage DC Fixed voltage AC supplied to fixed voltage DC
2.	Inverters i. Controlled ii. Uncontrolled	 Fixed voltage DC supplied to fixed voltage AC Fixed voltage DC supplied to variable voltage AC
3.	AC voltage controllers	Fixed voltage AC supplied to variable voltage AC
4.	Cycloconverters	Fixed frequency AC to variable frequency and variable voltage AC
5.	DC / DC Converter (Chopper)	Fixed voltage DC supplied to variable voltage DC

2.3.2 Harmonic from Conventional Sources

Over the past decade, some electric power facility such as electrical rotating machine, transformer and reactor will be injected harmonic current into power distribution system. Effect from this the electric current drawn by these devices is non sinusoidal which contain a lot of harmonics. Therefore, this harmonics current can produce problems such as vibration and overheated to that device respectively [Bishop, M.T., *et.al*., 1996].

A basically an electrical rotating machines are injected harmonic into power system. The generated harmonic by electrical rotating machines can be discussed as follows.

i. Non-Symmetrical voltage supply

If a balanced three phase voltages are applied to the stator of induction and synchronous motor, a rotating magnetic flux is produced. This flux passes through air gap, rotor surface and cutting rotor conductors to produce rotation. The rotation of rotor can be forward and backward based on the method how three phase voltage terminal is connected [Theraja, B.L., 1984), Theodore, R.B., 1997]. Furthermore, by using the symmetrical components technique, the performance of unbalanced three phase voltage and currents from unbalanced faults can be analysed [Hadi, S.,1999]. Any vectors of unbalanced three phase system can be resolved into three sequences. Firstly, a positive sequence, secondly, a negative sequence and lastly a zero sequence voltage in order to relate harmonic in the three phase system [Barners R., 1989].

Let a three phase alternator which identical phases winding Red, Yellow and Blue in which harmonics are generated. The three phase current will be represented in phase sequence by the following equations [Theraja, B.L., 1984, Pejovic, P. and Janda, Z., 1999].

$$i_R(t) = I_{1m}\sin(\omega t + \phi_1) + I_{3m}\sin(3\omega t + \phi_3) + I_{5m}\sin(5\omega t + \phi_5) + \dots \quad (2.1)$$

$$i_Y(t) = I_{1m}\sin\left(\omega t - \frac{2\pi}{3} + \phi_1\right) + I_{3m}\sin\left[3\left(\omega t - \frac{2\pi}{3}\right) + \phi_3\right] + I_{5m}\sin\left[5\left(\omega t - \frac{2\pi}{3}\right) + \phi_5\right] + \dots \quad (2.2)$$

$$i_B(t) = I_{1m}\sin\left(\omega t - \frac{4\pi}{3} + \phi_1\right) + I_{3m}\sin\left[3\left(\omega t - \frac{4\pi}{3}\right) + \phi_3\right] + I_{5m}\sin\left[5\left(\omega t - \frac{4\pi}{3}\right) + \phi_5\right] + \dots \quad (2.3)$$

where,

i_R is the current for phase R

i_Y is the current for phase Y

i_B is the current for phase B

I_{1m} is the amplitude of fundamental current

I_{nm} is the amplitude of n^{th} harmonic current

ϕ_1 is the phase angel of fundamental current

ϕ_n is the phase angel of n^{th} harmonic

$f = \dfrac{\omega}{2\pi}$ is the frequency of fundamental current

Simplified Equation (2.2) and Equation (2.3) become

$$i_Y(t) = I_{1m}\sin\left(\omega t - \frac{2\pi}{3} + \phi_1\right) + I_{3m}\sin(3\omega t + \phi_3) + I_{5m}\sin\left[5\left(\omega t - \frac{4\pi}{3}\right) + \phi_5\right] + \ldots\ldots \quad (2.4)$$

$$i_B(t) = I_{1m}\sin\left(\omega t - \frac{4\pi}{3} + \phi_1\right) + I_{3m}\sin(3\omega t + \phi_3) + I_{5m}\sin\left[5\left(\omega t - \frac{2\pi}{3}\right) + \phi_5\right] + \ldots\ldots \quad (2.5)$$

It can be seen from Equation (2.1), (2.4) and (2.5) that all third harmonics are equal in all phase. The fifth harmonics have a backward rotating, in nature as a negative sequence. Further, all harmonics which are not multiples of three have phase displacement of 120°. Therefore, the harmonic sequence is tabulated in Table 2.2.

Table 2.2: Harmonics phase sequences for three phase power system

Harmonic Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Harmonic Sequence	+	-	0	+	-	0	+	-	0	+	-	0	+	-	0

In general it can be shown that the positive sequence current is related to the $(3k+1)^{th}$ harmonic, negative sequence current is related to the $(3k-1)^{th}$ harmonic and zero sequence current is 3k harmonic, where k is any integer. In the same way it can be shown that:

1. All triple-n harmonics are in phase i.e 3^{rd}, 9^{th}, 15^{th}, etc
2. The 7^{th}, 13^{th} and 19^{th} harmonics have a positive phase sequence
3. The 5^{th}, 11^{th}, and 17^{th} harmonics have a negative phase sequence

ii. Unequal loading in three phase

If three phases are not equally loaded (unbalanced system), negative and zero sequence currents will be generated which are related to the $(3k-1)^{th}$ and 3k harmonics [Modern Rectifiers and Power System Harmonics, 2004].

iii. Anomalies in machine specifications

In general the rotors of AC machines have defects such as on their couple unbalance, angular misalignment, bad shaft, misalignment bearing, mechanical looseness, sleeve bearing wear, rotor & stator rub, cleanness problems and winding surface is not efficient. All these anomalies criteria's can be caused in generating harmonic for electrical machines [Vibration Diagnostics Chart, 2003].

iv. Non sinusoidal distribution of the flux in the air gap.

In principal all machine are controlled by voltage or current source inverters. The machines currents are therefore nonsinusoidal. It will flows through winding of a phase. As a result the Electromotive Force (e.m.f) produced is non sinusoidally and simultaneously distributed in the air gap between rotor and stator. This air gap flux, therefore, consists of fundamental and harmonic components of fluxes. This phenomenon will increase the pollution of harmonic in the power system [Paresh, C.S., 1997, Charles, H. 2004].

The nonlinear load characteristics of the iron core transformer generate odd current harmonics due to nonlinear character of the Flux Density (B) and Magnetic Field Intensity, (H). (B-H curve) and hysteresis loop in the excitation current is shown in Figure 2.3.

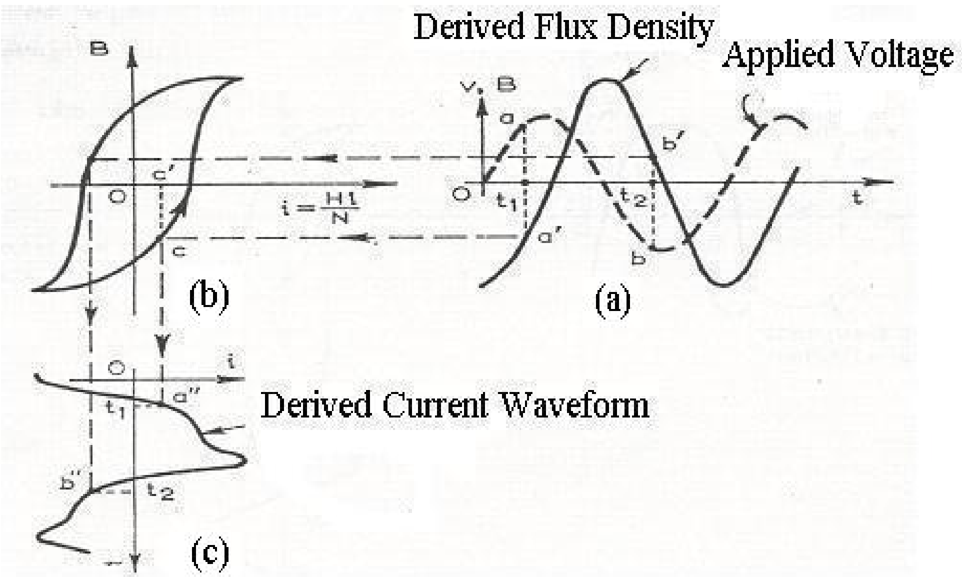


Figure 2.3: Waveforms in Iron Cored Transformer (a) Applied voltage (b) B-H Curve (Hysteresis loop) (c) Current through an iron cored transformer

It is seen that the current curve has identical positive and negative half cycles, so that it contains no even harmonics [Paresh, C.S., 1997, Calvert, J.B., 2001]. The measurement shows that the 3rd (72%) harmonic currents are dominates for excitation current compared with others harmonics order 5th (45%), 7th (25%), 9th (12%), 11th (5%), 13th (2%) of a distribution transformer [Ahsan, H., *et.al.,* 1999].