Investigation of Different Circuit Topologies For Multi-pulse STATCOM

by

Abdul Razib Dawood

A Thesis

submitted to the Faculty of Graduate Studies

in partial fulfilment of the requirements for the Degree of

Masters of Science

Department of Electrical and Computer Engineering

University of Manitoba

Winnipeg, Manitoba, CANADA.

© December, 1996

National Library of Canada
Acquisitions and Bibliographic Services Branch
395 Wellington Street
Ottawa, Ontario
K1A 0N4

Bibliothèque nationale du Canada
Direction des acquisitions et des services bibliographiques
395, rue Wellington
Ottawa (Ontario)
K1A 0N4

Your file Votre référence

Our file Notre référence

The author has granted an irrevocable non-exclusive licence allowing the National Library of Canada to reproduce, loan, distribute or sell copies of his/her thesis by any means and in any form or format, making this thesis available to interested persons.

L'auteur a accordé une licence irrévocable et non exclusive permettant à la Bibliothèque nationale du Canada de reproduire, prêter, distribuer ou vendre des copies de sa thèse de quelque manière et sous quelque forme que ce soit pour mettre des exemplaires de cette thèse à la disposition des personnes intéressées.

The author retains ownership of the copyright in his/her thesis. Neither the thesis nor substantial extracts from it may be printed or otherwise reproduced without his/her permission.

L'auteur conserve la propriété du droit d'auteur qui protège sa thèse. Ni la thèse ni des extraits substantiels de celle-ci ne doivent être imprimés ou autrement reproduits sans son autorisation.

ISBN 0-612-16119-6

Canada

Name ______________________________

Dissertation Abstracts International and *Masters Abstracts International* are arranged by broad, general subject categories. Please select the one subject which most nearly describes the content of your dissertation or thesis. Enter the corresponding four-digit code in the spaces provided.

Electronic and Electrical

SUBJECT TERM

0544

SUBJECT CODE

UMI

Subject Categories

THE HUMANITIES AND SOCIAL SCIENCES

COMMUNICATIONS AND THE ARTS
- Architecture 0729
- Art History 0377
- Cinema 0900
- Dance 0378
- Design and Decorative Arts 0389
- Fine Arts 0357
- Information Science 0723
- Journalism 0391
- Landscape Architecture 0390
- Library Science 0399
- Mass Communications 0708
- Music 0413
- Speech Communication 0459
- Theater 0465

EDUCATION
- General 0515
- Administration 0514
- Adult and Continuing 0516
- Agricultural 0517
- Art 0273
- Bilingual and Multicultural 0282
- Business 0688
- Community College 0275
- Curriculum and Instruction 0727
- Early Childhood 0518
- Elementary 0524
- Educational Psychology 0525
- Finance 0277
- Guidance and Counseling 0519
- Health 0680
- Higher 0745
- History of 0520
- Home Economics 0278
- Industrial 0521
- Language and Literature 0279
- Mathematics 0280
- Music 0522
- Philosophy of 0998
- Physical 0523
- Reading 0535
- Religious 0527
- Sciences 0714
- Secondary 0533
- Social Sciences 0534
- Sociology of 0340
- Special 0529
- Teacher Training 0530
- Technology 0710
- Tests and Measurements 0288
- Vocational 0747

LANGUAGE, LITERATURE AND LINGUISTICS
- Language
  - General 0679
  - Ancient 0289
  - Linguistics 0290
  - Modern 0291
  - Rhetoric and Composition 0681
- Literature
  - General 0401
  - Classical 0294
  - Comparative 0295
  - Medieval 0297
  - Modern 0298
  - African 0316
  - American 0591
  - Asian 0305
  - Canadian (English) 0352
  - Canadian (French) 0355
  - Caribbean 0360
  - English 0593
  - Germanic 0311
  - Latin American 0312
  - Middle Eastern 0315
  - Romance 0313
  - Slavic and East European 0314

PHILOSOPHY, RELIGION AND THEOLOGY
- Philosophy 0422
- Religion
  - General 0318
  - Biblical Studies 0321
  - Clergy 0319
  - History of 0320
  - Philosophy of 0322
- Theology 0469

SOCIAL SCIENCES
- American Studies 0323
- Anthropology
  - Archaeology 0324
  - Cultural 0326
  - Physical 0327
- Business Administration
  - General 0310
  - Accounting 0272
  - Banking 0770
  - Management 0454
  - Marketing 0338
- Canadian Studies 0385
- Economics
  - General 0501
  - Agricultural 0503
  - Commerce-Business 0505
  - Finance 0508
  - History 0509
  - Labor 0510
  - Theory 0511
- Folklore 0358
- Geography 0366
- Gerontology 0351
- History
  - General 0578
  - Ancient 0579
  - Medieval 0581
  - Modern 0582
  - Church 0330
  - Black 0328
  - African 0331
  - Asia, Australia and Oceania 0332
  - Canadian 0334
  - European 0335
  - Latin American 0336
  - Middle Eastern 0333
  - United States 0337
- History of Science 0585
- Law 0398
- Political Science
  - General 0615
  - International Law and Relations 0616
  - Public Administration 0617
- Recreation 0814
- Social Work 0452
- Sociology
  - General 0626
  - Criminology and Penology 0627
  - Demography 0938
  - Ethnic and Racial Studies 0631
  - Individual and Family Studies 0628
  - Industrial and Labor Relations 0629
  - Public and Social Welfare 0630
  - Social Structure and Development 0700
  - Theory and Methods 0344
- Transportation 0709
- Urban and Regional Planning 0999
- Women's Studies 0453

THE SCIENCES AND ENGINEERING

BIOLOGICAL SCIENCES
- Agriculture
  - General 0473
  - Agronomy 0285
  - Animal Culture and Nutrition 0475
  - Animal Pathology 0476
  - Fisheries and Aquaculture 0792
  - Food Science and Technology 0359
  - Forestry and Wildlife 0478
  - Plant Culture 0479
  - Plant Pathology 0480
  - Range Management 0777
  - Soil Science 0481
  - Wood Technology 0746
- Biology
  - General 0306
  - Anatomy 0287
  - Animal Physiology 0433
  - Biostatistics 0308
  - Botany 0309
  - Cell 0379
  - Ecology 0329
  - Entomology 0353
  - Genetics 0369
  - Limnology 0793
  - Microbiology 0410
  - Molecular 0307
  - Neuroscience 0317
  - Oceanography 0416
  - Plant Physiology 0817
  - Veterinary Science 0778
  - Zoology 0472
- Biophysics
  - General 0786
  - Medical 0760

EARTH SCIENCES
- Biogeochemistry 0425
- Geochemistry 0996
- Geodesy 0370
- Geology 0372
- Geophysics 0373
- Hydrology 0388
- Mineralogy 0411
- Paleobotany 0345
- Paleoecology 0426
- Paleontology 0418
- Paleozoology 0985
- Palynology 0427
- Physical Geography 0368
- Physical Oceanography 0415

HEALTH AND ENVIRONMENTAL SCIENCES
- Environmental Sciences 0768
- Health Sciences
  - General 0566
  - Audiology 0300
  - Dentistry 0567
  - Education 0350
  - Administration, Health Care 0769
  - Human Development 0758
  - Immunology 0982
  - Medicine and Surgery 0564
  - Mental Health 0347
  - Nursing 0569
  - Nutrition 0570
  - Obstetrics and Gynecology 0380
  - Occupational Health and Safety 0354
  - Oncology 0992
  - Ophthalmology 0381
  - Pathology 0571
  - Pharmacology 0419
  - Pharmacy 0572
  - Public Health 0573
  - Radiology 0574
  - Recreation 0575
  - Rehabilitaion and Therapy 0382
  - Speech Pathology 0460
  - Toxicology 0383
- Home Economics 0386

PHYSICAL SCIENCES

Pure Sciences
- Chemistry
  - General 0485
  - Agricultural 0749
  - Analytical 0486
  - Biochemistry 0487
  - Inorganic 0488
  - Nuclear 0738
  - Organic 0490
  - Pharmaceutical 0491
  - Physical 0494
  - Polymer 0495
  - Radiation 0754
- Mathematics 0405
- Physics
  - General 0605
  - Acoustics 0986
  - Astronomy and Astrophysics 0606
  - Atmospheric Science 0608
  - Atomic 0748
  - Condensed Matter 0611
  - Electricity and Magnetism 0607
  - Elementary Particles and High Energy 0798
  - Fluid and Plasma 0759
  - Molecular 0609
  - Nuclear 0610
  - Optics 0752
  - Radiation 0756
- Statistics 0463

Applied Sciences
- Applied Mechanics 0346
- Computer Science 0984
- Engineering
  - General 0537
  - Aerospace 0538
  - Agricultural 0539
  - Automotive 0540
  - Biomedical 0541
  - Chemical 0542
  - Civil 0543
  - Electronics and Electrical 0544
  - Environmental 0775
  - Industrial 0546
  - Marine and Ocean 0547
  - Materials Science 0794
  - Mechanical 0548
  - Metallurgy 0743
  - Mining 0551
  - Nuclear 0552
  - Packaging 0549
  - Petroleum 0765
  - Sanitary and Municipal 0554
  - System Science 0790
- Geotechnology 0428
- Operations Research 0796
- Plastics Technology 0795
- Textile Technology 0994

PSYCHOLOGY
- General 0621
- Behavioral 0384
- Clinical 0622
- Cognitive 0633
- Developmental 0620
- Experimental 0623
- Industrial 0624
- Personality 0625
- Physiological 0989
- Psychobiology 0349
- Psychometrics 0632
- Social 0451

THE UNIVERSITY OF MANITOBA

FACULTY OF GRADUATE STUDIES
*****

COPYRIGHT PERMISSION PAGE

INVESTIGATION OF DIFFERENT CIRCUIT TOPOLOGIES FOR MULTI-PULSE STATCOM

BY

ABDUL RAZIB DAWOOD

A Thesis/Practicum submitted to the Faculty of Graduate Studies of The University

of Manitoba in partial fulfillment of the requirements of the degree

of

MASTER OF SCIENCE

ABDUL RAZIB DAWOOD 1997 (c)

Permission has been granted to the Library of The University of Manitoba to lend or sell copies of this thesis/practicum, to the National Library of Canada to microfilm this thesis and to lend or sell copies of the film, and to Dissertations Abstracts International to publish an abstract of this thesis/practicum.

The author reserves other publication rights, and neither this thesis/practicum nor extensive extracts from it may be printed or otherwise reproduced without the author's written permission.

Acknowledgements

The encouragement, guide, support and incredible enthusiasm provided by Prof. A. M. Gole have been very crucial in making this thesis a reality. For that I am deeply grateful to him. I would also like to thank my employer, TNB Kuala Lumpur, for the financial and moral assistance provided throughout this period. To Mr. A Daneshpooy and all members of the Power Group, I certainly appreciate all generous help that you have given me. I also thank my family back home, especially my parents who have devoted most of their time and energy for the well being of their children.

Finally, I express my deep appreciation to my beloved wife whose love, understanding and endless support, were the essential ingredients in completing this work. To my eight months old daughter Syifaa Mardhiah, the tremendous joy of your presence has certainly given me an inspiration.

Abstract

An advanced static compensator or STATCOM is a reactive power source applied for the dynamic compensation in power transmission line to provide voltage support, increase transient stability and improve damping of power systems. The STATCOM uses a new solid-state (Gate-turn-off thyristor) converter approach to produce reactive power by operating as an ac voltage source behind a small coupling reactance. A problem that a basic STATCOM circuit has is the large amount of harmonics content in the output voltage that it produces. This thesis addresses the harmonic problem and suggests a multi-pulse converter method to improve the harmonic performances. The multi-pulse converter technique which provides a mechanism whereby harmonics are eliminated in pair is explained in the thesis. An additional merit of the multi-pulse converter is that the design is able to increase the STATCOM power rating. There are seven different multi-pulse circuit configurations that have been investigated. The simulation results indicate a large different in properties when they are analysed and compared. A clean power performance is shown by a 48-pulse STATCOM which almost approximate ideal STATCOM characteristics.

Table of Contents

List of Figures

List of Tables

CHAPTER 1

Introduction

1.1 BACKGROUND

In an ac power system the transmittable electric power is related to the transmission line voltage profile under steady state and dynamic conditions over a wide range of network contingencies. It is known that the voltage profile along the transmission line can be controlled in a more effective way by controlling the reactive power flow in the line. The application of the reactive power conditioner is a well established practice and it is termed as 'reactive power compensation'. The methods that have long been employed to increase the steady-state of the line are fixed or mechanically-switched capacitors and reactors. The reactors are installed in shunt at intervals along the line and large capacitors are connected in series. With the development of high power solid-state device i.e.

thyristor switches and electronic control, the reactive compensation is made rapidly variable. Hence, the devices called static var compensator (SVC) have emerged using thyristor-controlled reactors (TCRs) in combination with thyristor-switched capacitors (TSCs). During the last decade it has been convincingly demonstrated that both the transient and dynamic stability of the power system can be improved, and voltage collapse can be prevented [1] with rapid continuously variable control accomplished by solid state technology (i.e. thyristors). A few years ago gate turn-off thyristors (GTO's) have reached a power handling level comparable to that of the conventional thyristor. This has led to the development of self-commutated converter for reactive power sources. This new technology has resulted in equipment that is fundamentally different from the conventional thyristor-controlled static var compensator (SVC). The new equipment is called the Advanced Static Var Compensator or STATCOM. It has many technical advantages over the conventional SVC.

1.2 CONVENTIONAL STATIC VAR COMPENSATOR (SVC)

As opposed to mechanical switching the SVC uses the conventional thyristors (those having no intrinsic turn-off ability) to achieve a rapid and fine control of shunt connected capacitors and reactors. This overcomes the problems with mechanical switching which causes abrupt voltage and current transients. The single line diagram of a typical SVC [2] is given in Fig. 1.1 and its elements are:

I) The fixed capacitor (FC), providing a permanently connected generation of reactive power, designed also to act as a suitable harmonic filter.

II) The thyristor controlled reactor (TCR) consisting of anti-parallel thyristors in series with shunt reactors usually in delta configuration. These controlled reactors are used to absorb reactive power. The thyristors may be switched at any point over the half wave (90 to 180 electrical degree behind the voltage wave) to provide a fully adjustable control from 100 percent to zero of rated reactive power absorption.

III) The thyristor switched capacitor (TSC) has anti-parallel thyristors connecting shunt capacitors in a delta configuration. Switching on the TSC by firing the thyristors 90 degree ahead of the voltage wave, provides the generating capacity for reactive power. Thus a TSC is either fully on or fully off.

IV) Power transformer to connect to the high voltage busbar.

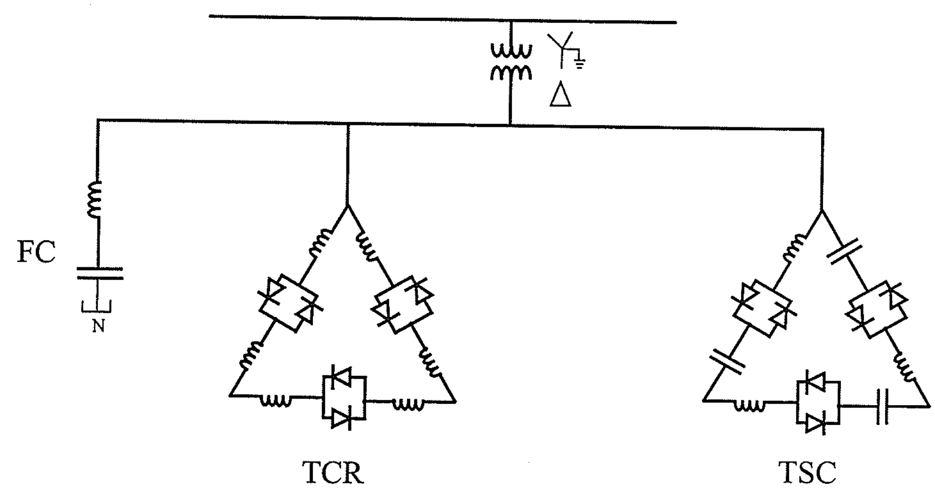


Fig. 1.1 Single-line Diagram of SVC

In essence, reactive power required for the compensation is generated or absorbed by traditional capacitor or reactor banks, and the thyristor switches are used only for the control of the combined reactive impedance these banks present to the system during successive periods of the applied voltage. As a result, conventional thyristor-controlled compensators present a variable reactive admittance to the transmission network and therefore generally change [3] the system impedance. Unlike breaker switched capacitors and indictors, the SVC has a continuous range of operation, primarily due to the continuous control on the TCR.

1.3 PRINCIPLES OF THE STATCOM

In contrast to SVC the functional operation of the STATCOM is more similar to that of the rotating synchronous condenser. The principles of the STATCOM will be explained after a brief look at how the rotating synchronous condenser works. A schematic diagram of a conventional rotating synchronous condenser is given in Fig. 1.2. It is simply a synchronous machine that is brought up to speed and synchronized to the power system. The three induced EMFs e_1, e_2 and e_3 of the machine are kept in phase with the system voltage V_1, V_2 and V_3 to achieve purely reactive power flow. The reactive power can be controlled by varying the amplitude E of the machines internal emf. This is done simply by controlling the excitation of the machine. Increasing E above the amplitude V of the system voltages causes leading (capacitive) current to be drawn from the AC system whereas decreasing E below V produces a lagging (inductive) load on the AC system.

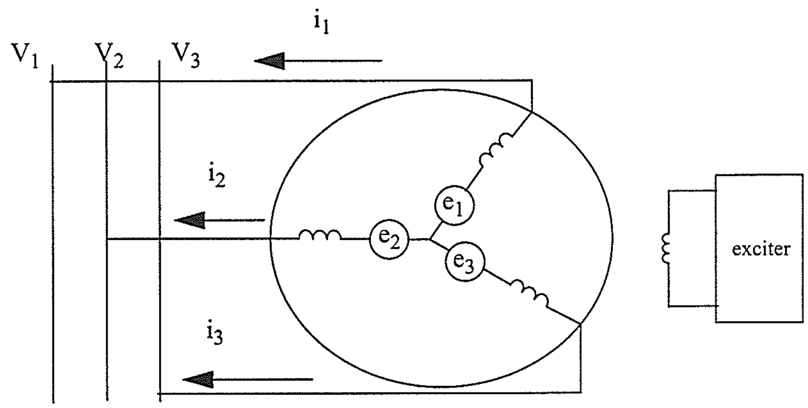


Fig. 1.2 Synchronous Generator

The STATCOM is based on a solid-state synchronous voltage source that is analogous to an ideal synchronous machine which generates a balanced set of (three) sinusoidal voltages, at the fundamental frequency, with controllable amplitude and phase angle. This ideal machine has no inertia, its response is practically instantaneous, it does not significantly alter [4] the existing system impedance, and it can internally generate reactive (both capacitive an inductive) power. Furthermore, it can dynamically exchange real power with the ac system if it is coupled to an appropriate energy source that can supply or absorb the power it supplies to, or absorbs from, the ac system.

The solid-state synchronous voltage source can be implemented by various switching power converters. However, a particular dc to ac switching power converter, the voltage-sourced converter, using gate turn-off (GTO) thyristors is presently considered the most practical for high power utility applications. The circuit analysis of the voltage-sourced converter is discussed in detail in the next chapter. The GTO converter (Fig. 1.3) produces a fundamental frequency voltage V_0 at the secondary of the step-down transformer and is isolated from the ac voltage through the transformer leakage. When the voltages V_0 and V_L are in phase the difference between the two will result in a reactive current through a 10% impedance which varies from full leading (capacitive mode) to full lagging (inductive mode) when the amplitude of V_0 changes by only ± 10%. If the output voltage is equal to the power system voltage, the reactive power exchange is zero. Similarly, the real power exchange between the inverter (having an appropriate dc energy storage device) and the power system can be controlled by phase-shifting the inverter output voltage with respect to the power system voltage. That is, the inverter from its dc energy storage supplies real power to the ac system if the inverter output voltage is made to lead the corresponding power system voltage. Conversely, the inverter absorbs real power from the power system for dc energy storage, if the inverter output voltage is made to lag the power system voltage.

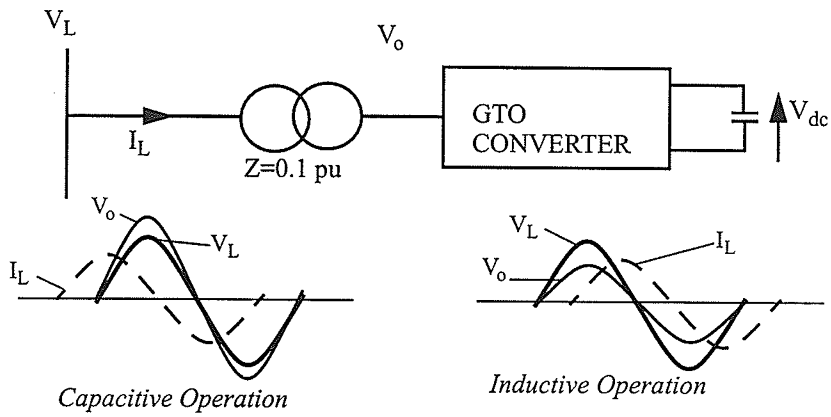


Fig. 1.3 GTO converter and its waveforms

1.4 ADVANTAGES OF STATCOM OVER SVC

The STATCOM offers several advantages over the SVC which include:

(a) The voltage source design is more compact and requires a small coupling reactance, usually the ac system transformer leakage and a single dc capacitor about one-eight of the size of the capacitor in a SVC of the same rating [3]. This leads to a significant reduction in equipment size and installation cost.

(b) The design offers fast continuous variation of reactive power generation during undervoltages. This ability to support the system voltage is much better than that obtained with a conventional SVC because the current in the capacitors falls in proportion to the voltage. The improvement in var output of the STATCOM under voltage conditions is illustrated in Fig. 1.4.

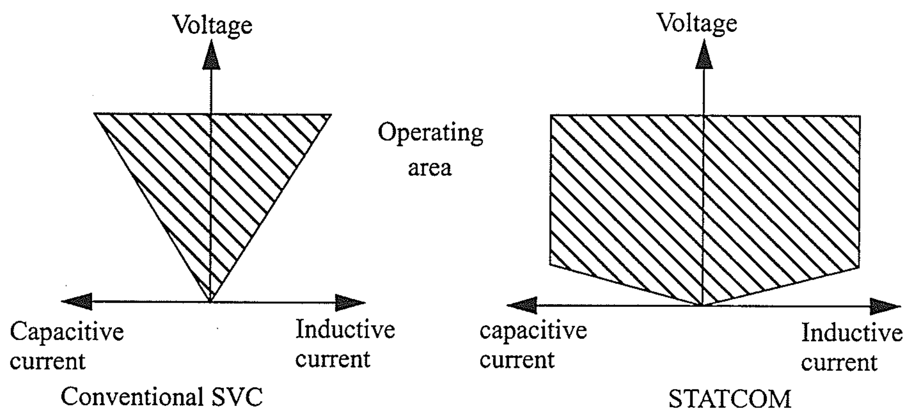


Fig. 1.4 Comparison of VAR output between Conventional SVC and STATCOM

(c) Better control stability [5] which translates to superior performance during major transients, and ultimately increased system transient stability and improved damping.

1.5 THE THESIS OBJECTIVES

There are many possible circuit configurations, which show very different properties, in realizing the practical multi-pulse typed STATCOM. This thesis will compare seven topologies of the multi-pulse STATCOM. Their harmonic performances will be the focal point of the investigation. The impact of multi-pulse connection on other STATCOM circuit parameters, such as capacitor and control, are to be analysed. Along the way, the important benefits of having multi-pule STATCOM are identified.The tool use in this investigation is the electromagnetic transient simulation program called PSCAD/EMTDC™ which is the product of Manitoba HVDC Research Centre, Canada [6].

CHAPTER 2

Basic Circuit Analysis

2.1 INTRODUCTION

The principle of a STATCOM has been introduced in the previous chapter. This chapter deals with the circuit analysis of a basic STATCOM. The basic circuit which employs a six-pulse voltage source converter (VSC) bridge represents the simplest realization of the STATCOM. The analysis of the basic three phase STATCOM gives an understanding of design parameters needed in the design of a large multi-pulse STATCOM. This chapter starts with the illustrations of the physical make up of the STATCOM. Then the basics of VSC are explained followed by a detailed discussion of the STATCOM operating principle and a definition of its control strategy. Finally, a report on the digital simulation applied to validate the STATCOM operation is presented.

2.2 COMPONENTS OF A STATCOM

The simplest implementation of a STATCOM is illustrated in Fig. 2.1. It shows the basic configuration of a three phase STATCOM with an elementary six-pulse voltage source converter (VSC). The major components of the STATCOM are a VSC and its switching control, a dc capacitor and a transformer to

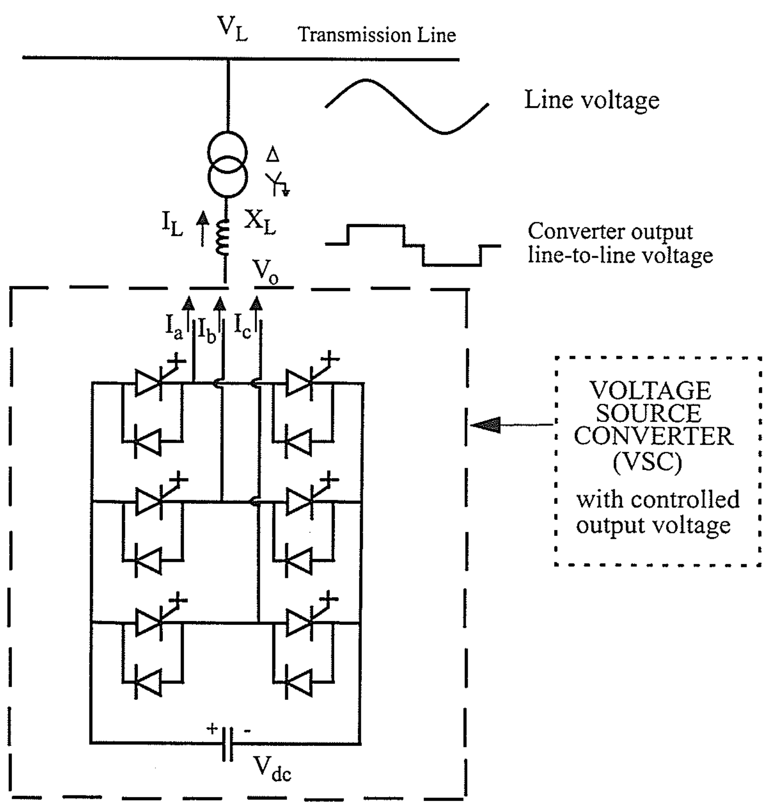


Fig. 2.1 Basic STATCOM with elementary six-pulse VSC

match the inverter to the line voltage. The voltage source converter, a basic electronic building block for the STATCOM, uses forced-commutated switching devices i.e. GTO thyristors. It consists of six GTO switches, each of which is shunted by a reverse-parallel connected diode. The VSC converts the dc voltage (V_{dc}) at its input terminals into a three-phase set of alternating output voltages (V_o) in phase with the ac line voltage (V_L). The step up transformer used for connection to the high voltage bus usually provides a relatively small reactance (X_L), from its per-phase leakage inductance.

2.3 VOLTAGE SOURCE CONVERTER (VSC) BASICS

As mentioned earlier, the three-phase voltage source converter (VSC) forms the basic building block of the STATCOM type of device. The type of VSC used in the STATCOM application, as shown in Fig. 2.1, is a three-phase full-bridge VSC. The basic form of the single-phase device [7] is as shown in Fig. 2.2(a). and it called a half-bridge single-phase VSC. The main switching devices T1 and T2 can be any self-commutated device such as a Gate-turn-off thyristor

(GTO) or an IGBT transistor (for lower ratings). The load terminal may be connected to the positive dc supply if GTO T1 is turned on, and to the negative supply

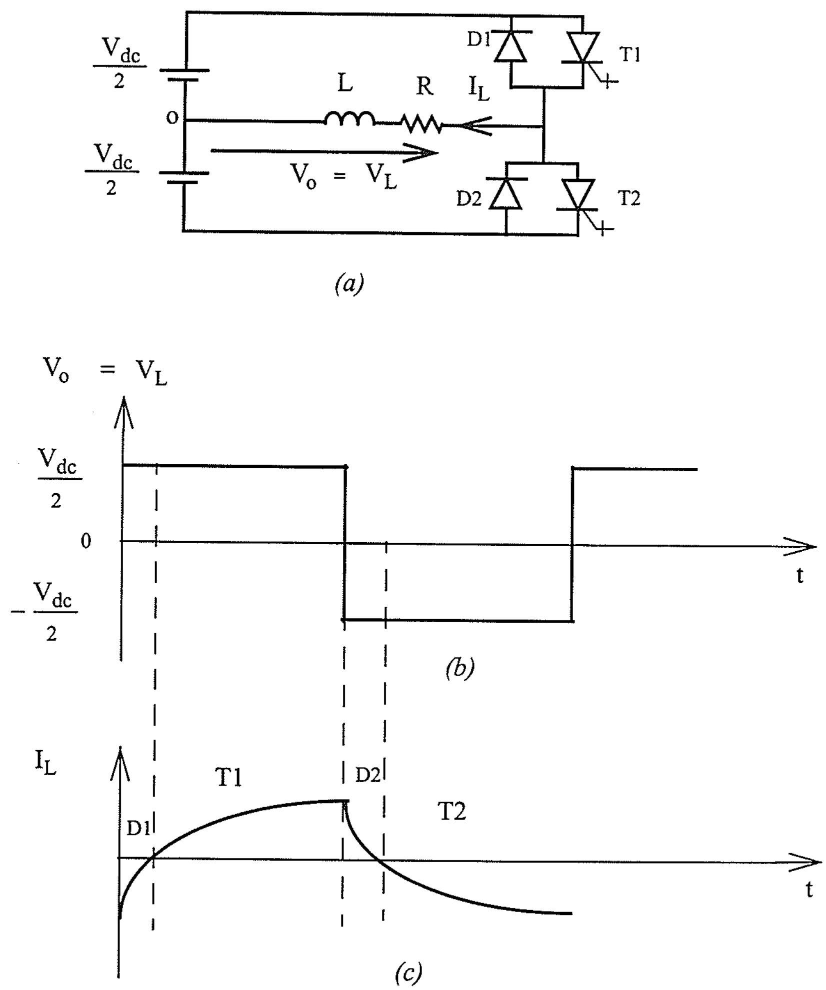


Fig. 2.2 Single-phase half-bridge VSC and its waveforms

if GTO T2 is turned on. The diodes handle negative polarity currents. For example, in Fig. 2.2(b) and (c), assume that T1 is on and $V_L=V_{dc}/2$, and that T1 is carrying the load current. To reverse the load voltage T1 is turned off, thereby forcing the load current through the diode D2 and thus applying a load voltage $V_L=-V_{dc}/2$. After a very small delay (to ensure that a short circuit is not applied across the battery with T1 and T2 both being on), T2 is given an on pulse which is maintained throughout its nominal firing interval. The negative voltage causes the current in the load to begin reversing and it eventually transfers from D2 to T2 on polarity reversal.

The instantaneous output voltage can be expressed in Fourier series as,

$$v_o = \sum_{n=1,3,5,\ldots}^{\infty} \frac{2V_{dc}}{n\pi} \sin(n\omega t) \qquad (2.1)$$

where $\omega = 2\pi f_o$ is the frequency of output voltage in rad/s. For n=1, Eq. (2.1) gives the rms value of fundamental component as,

$$V_1 = \frac{2V_{dc}}{\sqrt{2}\pi} \qquad (2.2)$$

A single-phase full-bridge version of VSC is shown in Fig.2.3(a). It has two switching branches. The full-bridge does not need a split dc voltage. This time the load terminal may be connected to the positive dc supply if GTOs T1 and T2are turned on simultaneously. The negative V_{dc} is applied to the load when T3

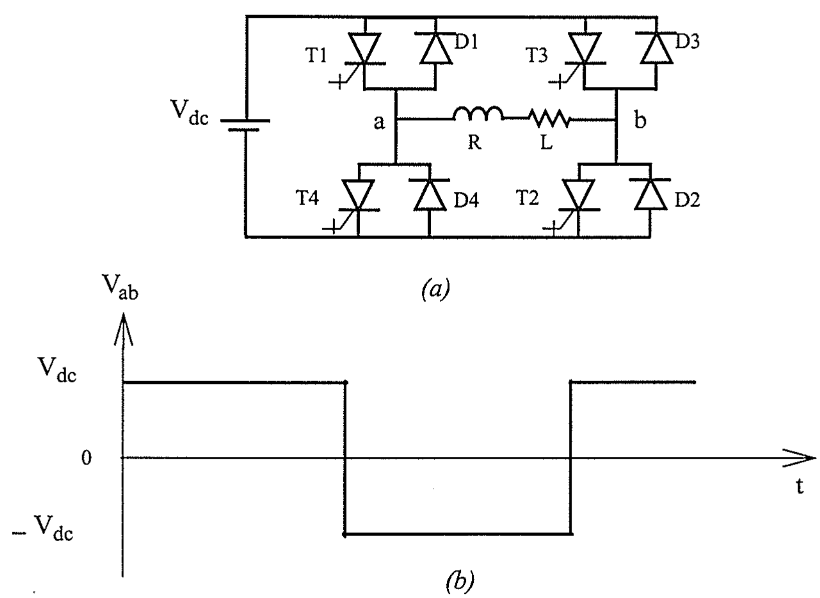


Fig. 2.3 Single-phase full-bridge VSC and voltage output waveform

and T4 are turned on. The output voltage waveform, shown in Fig. 2.3(b), can be expressed in Fourier series as,

$$v_o = \sum_{n=1,3,5,\ldots}^{\infty} \frac{4V_{dc}}{n\pi}\sin(n\omega t) \qquad (2.3)$$

The rms value of fundamental component is,

$$V_1 = \frac{4V_{dc}}{\sqrt{2}\pi} \qquad (2.4)$$

Clearly, the output voltage has a significant content of harmonics. One way of improving the harmonic performance is to use a technique called Single Pulse Width Modulation (PWM) [8], as shown in Fig. 2.4. The gating signals are generated by comparing a rectangular reference signal of amplitude Ar, with a triangular carrier wave of amplitude Ac. The pulse width δ, can be varied from 0 to 180° by varying Ar from 0 to Ac, thus controlling the VSC output voltage. The ratio of Ar and Ac is the control variable and defined as the modulation index. The Fourier series of output voltage is now,

$$v_o = \sum_{n=1,3,5,\ldots}^{\infty} \frac{4V_{dc}}{n\pi}\sin\frac{n\delta}{2}\sin(n\omega t) \qquad (2.5)$$

In single-pulse-width modulation, there is only one pulse per half-cycle. If multipulse were used, the output voltage will be more sinusoidal-looking waveform as some of the lower order voltage harmonics are reduced. However although the harmonic performance is improved, the switching losses do increase with this method.

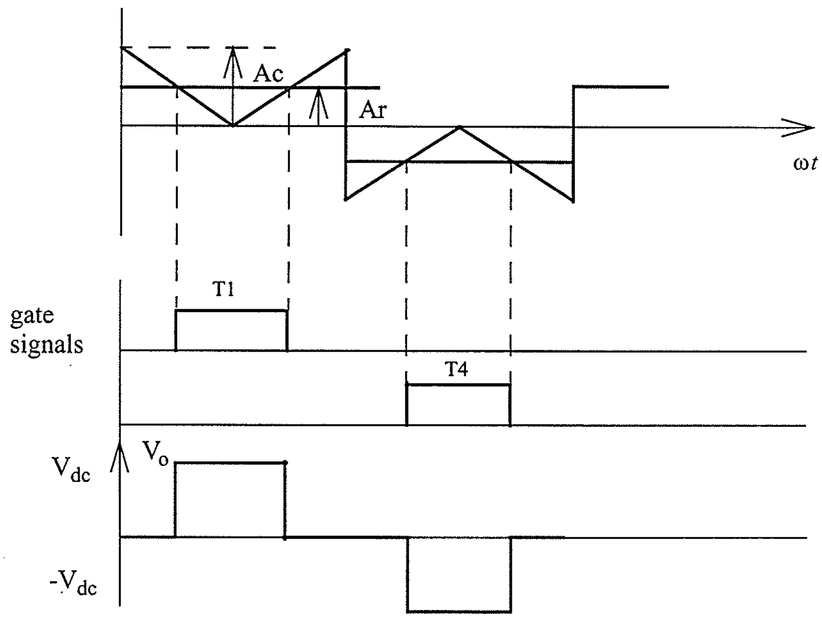


Fig. 2.4 Pulse Width Modulation technique

2.4 THREE PHASE VSC

In this thesis, a three-phase VSC is employed as the basic circuit in the STATCOM. The configuration is formed from six GTOs and six diodes as shown in Fig. 2.5(a). The GTOs are numbered in the sequence of gating the GTOs and each GTO conducts for 180°. The waveforms are shown in Fig. 2.5(b). When T1 is switched on, terminal a is connected to the positive terminal of the dc input voltage. When T4 is switched on, terminal a is brought to the negative terminal of the dc source. There are six modes of operation in a cycle and the duration of each mode is 60°. The instantaneous line-to-line voltages in Fig. 2.5(b) can be expressed in a Fourier series,

$$v_{ab} = \sum_{n=1,3,5,\ldots}^{\infty} \frac{4V_{dc}}{n\pi}\cos\frac{n\pi}{6}\sin n\left(\omega t+\frac{\pi}{6}\right) \tag{2.6}$$

$$v_{bc} = \sum_{n=1,3,5,\ldots}^{\infty} \frac{4V_{dc}}{n\pi}\cos\frac{n\pi}{6}\sin n\left(\omega t-\frac{\pi}{2}\right) \tag{2.7}$$

$$v_{ca} = \sum_{n=1,3,5,\ldots}^{\infty} \frac{4V_{dc}}{n\pi}\cos\frac{n\pi}{6}\sin n\left(\omega t-\frac{7\pi}{6}\right) \tag{2.8}$$

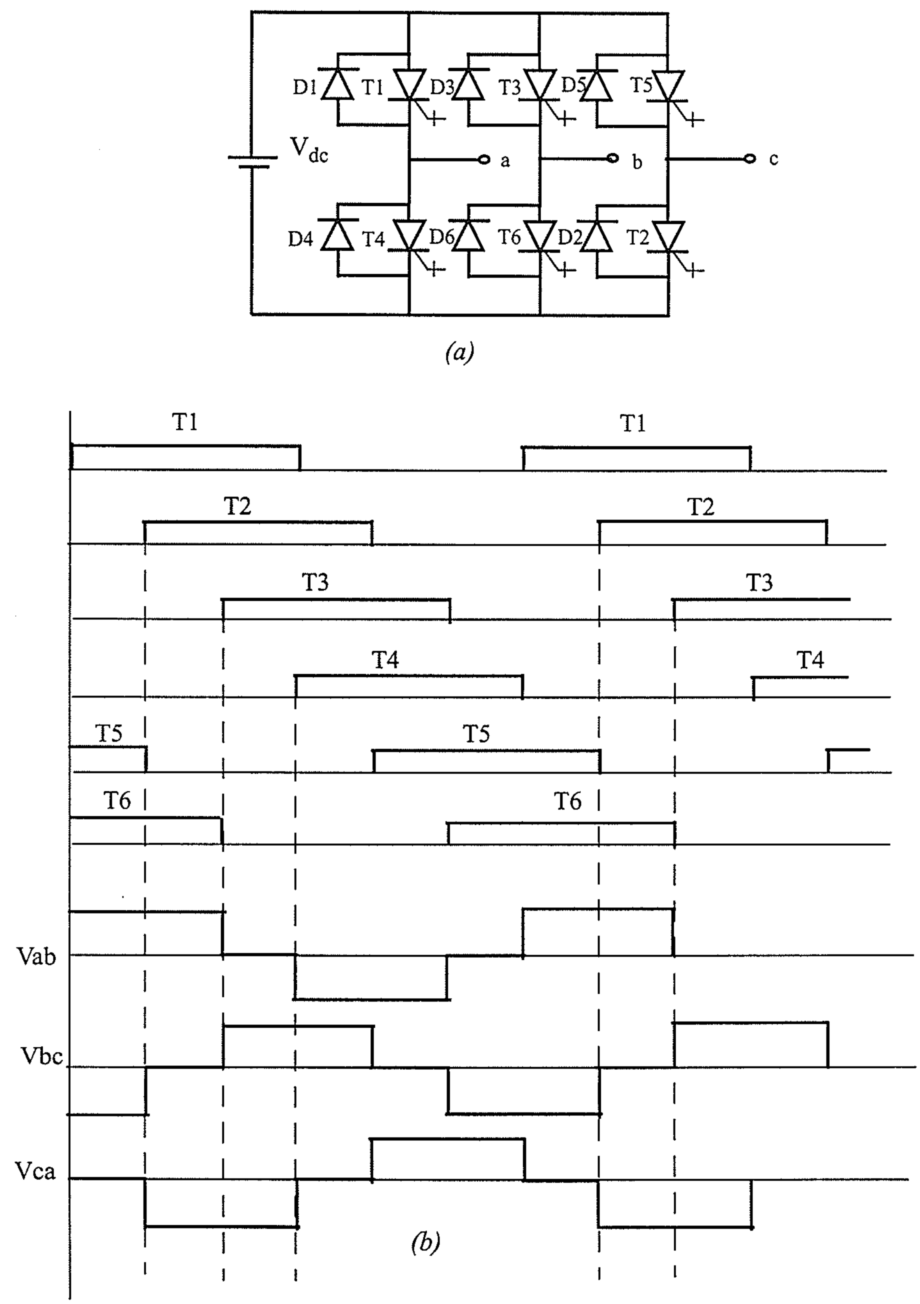


Fig 2.5 Three Phase VSC, gating signals and line voltages waveform

2.5 OPERATING PRINCIPLE OF THE STATCOM

The operating principle [9] of the STATCOM is best explained with the aid of the simplified model of the three phase STATCOM circuit shown in Fig. 2.6. Only the fundamental components are considered. From the simplified model diagram, the relationship that governs the reactive current I_L can be expressed as,

$$I_L = \frac{V_L - V_o}{\omega L} \quad (2.9)$$

It is clearly shown by Eq. 2.9 that the magnitude and sign of the reactive current I_L can be regulated by the amplitude of the variable converter voltage, V_o. When V_o and V_L are in phase and differ in amplitude, the line current I_L produced is always at 90^o to the V_L (i.e. reactive current) because of the reactive

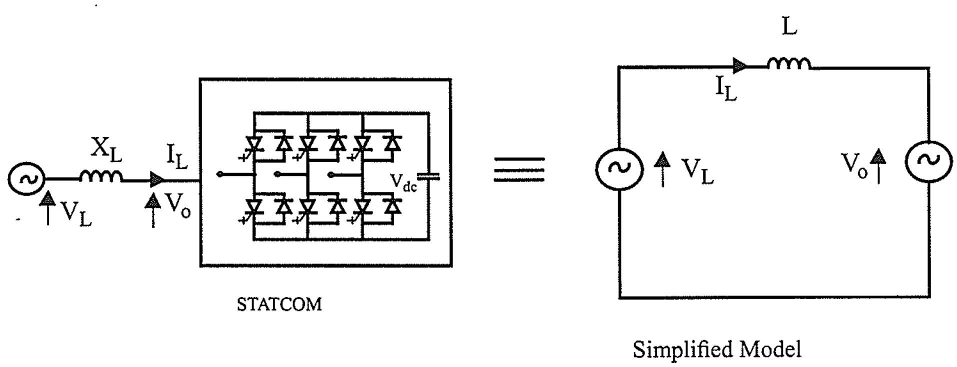


Fig. 2.6 Simplified model of a three phase STATCOM

coupling provided by the series reactance X_L, which is mainly the leakage reactance of the transformer. As mentioned at the beginning, the sign of I_L depends on the controllable converter output magnitude V_o. When V_o equals the line voltage i.e. $V_o = V_L$, the line current is zero (Fig. 2.7(b)). It means that there is no exchange of reactive power between the converter and the line. When V_o is higher

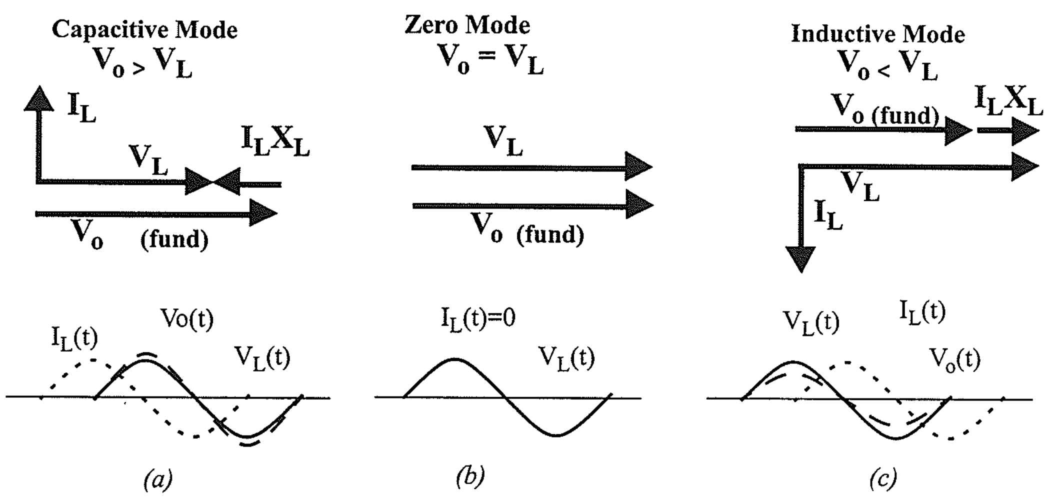


Fig. 2.7 Phasor diagrams and waveforms for the three modes of operation

than the line voltage i.e. $V_o > V_L$, leading reactive current is drawn from the line i.e. the capacitive current (Fig. 2.7(a)). It means that vars are generated. When V_o

is lower than the line voltage i.e. $V_o < V_L$, lagging reactive current (inductive) is drawn from the line i.e. vars are absorbed, (Fig. 2.7(c)). In conclusion, the type of reactive power produced by the STATCOM is determined by the values of V_o relative to V_L. The value of V_o, the converter output voltage, can be controlled in two different ways. The first method is by using PWM techniques which has already been described in Section 2.3. The other one is to control the phase displacement of V_o relative to V_L as to allow an exchange of active power between the line and STATCOM. As a result, the capacitor can be charged or discharged to raise or lower the dc voltage respectively. If for example [10], in the capacitive mode, when V_o is delayed by ϕ degree, the current flowing into the capacitor has a positive dc component as shown in Fig. 2.8(b). Consequently, the capacitor is charged up to raise the dc voltage, V_{dc}. Note that the phase difference between V_o and V_L is less than 90^o due to a small quantity of average real power flow from the ac system side into the converter. Fig. 2.8(a) shows the waveforms and phasor diagrams when the three phase STATCOM is in a steady state capacitive mode. To have an inductive current, V_o must smaller than V_L. This time V_o is made to lead V_L by a few degrees, in order for a small amount of active power start to flow out of the STATCOM. The next section will describe this in more detail.

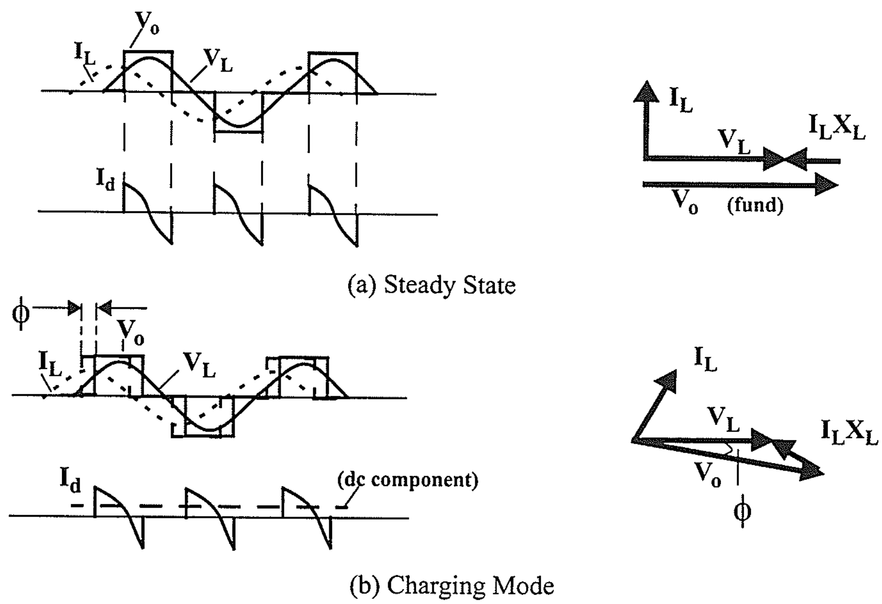


Fig. 2.8 Waveforms and phasor diagrams for steady state and charging capacitive mode.

2.6 TWO CONVERTER REPRESENTATION

A "two converter representation" [11] concept is useful in explaining how the phase difference between V_o and V_L affect the operation of the STATCOM. The single phase STATCOM shown in Fig 2.3(a) is inherently two converters connected in inverse parallel and can be redrawn as Fig. 2.9. There are two converters which operate in two different modes. Converter-1 operates in the inverter mode to allow the real power to flow from the dc side to ac side through

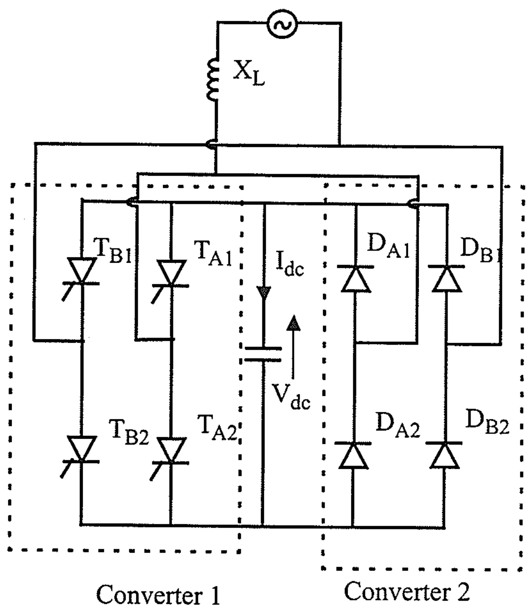


Fig. 2.9 Two converters representation of the single phase STATCOM

it. Converter-2 acts as an uncontrolled rectifier, where a small quantity of average real power flows from the ac side to the dc side (opposite to the converter-1). Initially, when converter-1 is not conducting, capacitor C is charged up to the peak value of the supply voltage through converter-2 and remains at that voltage as long as no real power transfer occurs between the circuit and the supply. If the switches of converter-1 are operated to obtain the fundamental of the STATCOM output voltage slightly leading the ac system voltage, converter-1 conducts for a longer period than the converter-2 causing a net real power flow from the dc side to the ac side. This in turn decrease the capacitor voltage and thus reactive power is absorbed by the STATCOM.

The converse is true when the STATCOM output voltage lags the system voltage by a few degrees, to give an increase in the capacitor voltage and hence the leading mode of operation. Thus, it may be concluded that the reactive power absorbed or generated by the STATCOM can be controlled by one parameter, i.e the phase angle between the fundamental of the STATCOM output (V_o) and the ac system voltage. The amount of reactive power being generated or absorbed depends on the magnitude of V_o.

2.7 THE ROLE OF THE CAPACITOR

Conventional shunt capacitors or shunt reactors cause leading (capacitive) current or lagging (inductive) current by the repetitive action [12] of accumulating the energy into the energy storage devices and releasing it to the line as shown in Fig. 2.10.

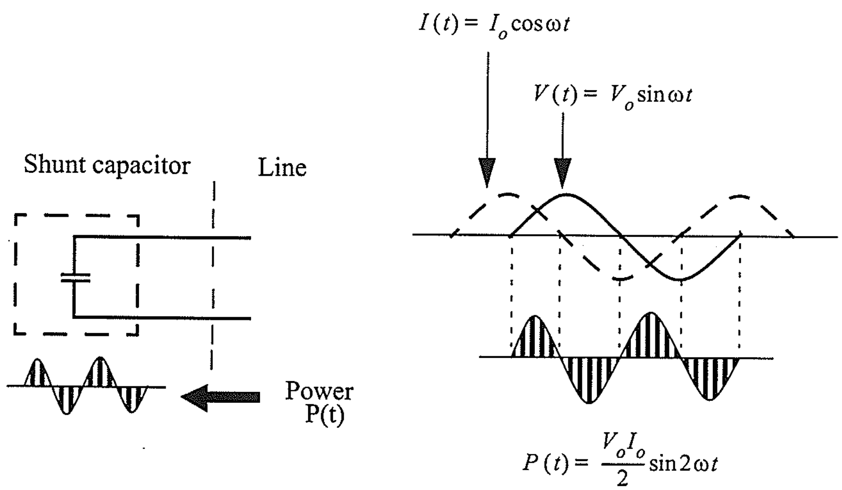
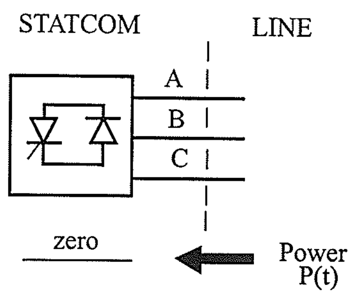


Fig. 2.10 Power flow between the line and shunt capacitor

In case of the three phase STATCOM, the sum of three phase powers which flows into the STATCOM from the line is zero at any instance while the three line voltages are balanced, as shown in Fig 2.11. In other words, the STATCOM which has no energy storage device can cause leading (capacitive) current or lagging (inductive) current, by circulating the energy among three phases at every instance.



$$V_A = V_o \sin(\omega t) \qquad I_A = I_o \cos(\omega t)$$

$$V_B = V_o \sin\left(\omega t - 120^0\right) \qquad I_B = I_o \cos\left(\omega t - 120^0\right)$$

$$V_C = V_o \sin\left(\omega t - 240^0\right) \qquad I_C = I_o \cos\left(\omega t - 240^0\right)$$

$$P(t) = V_A I_A + V_B I_B + V_C I_C = 0$$

Fig. 2.11 Power flow between the line and STATCOM

Therefore, the net instantaneous power at the ac output terminals of the STATCOM is zero. Since the net instantaneous power at the ac output terminals must always be equal to the net instantaneous power at the dc input terminals (neglecting the losses in the semiconductor devices), the real input power provided by the dc source (charged capacitor) must be zero. Hence, theoretically, the STATCOM does not need the energy storage device, i.e: the dc capacitor plays no part in the reactive power generation.

However, with a practical converter some amount of harmonics in the ac output are generated due to an imperfect sinewave of the converter output voltage waveform. For this reason, there is a small amount of fluctuating power at the ac terminals. To establish an equilibrium [4] between the instantaneous output and input power of the converter, the converter must have a corresponding ac “ripple” current flowing through the dc capacitor. In other words, the dc capacitor acts as a passive filter. The presence of the input ripple current components thus is entirely due to the ripple components of the output voltage, which are a function of the output waveform fabrication technique used. This current for a converter with high pulse number, under balanced ac output conditions is very small. However, under unbalanced conditions, which can result in significant fluctuating power at the ac terminals, a large ripple current would flow through the dc capacitor. In general the main factors in determining the size of the capacitor are:

1) The maximum capacitor ripple current due to the anticipated worst case unbalance.

2) The selected steady-state and allowed transient overvoltage across the capacitor.

So far in the discussion, the semiconductor switches of the converters are assumed lossless. In a practical STATCOM this is not the case. Therefore, during the discharging of the capacitor some of its energy is being used up to compensate the internal losses of the converter. During the steady state in both capacitive and inductive mode, the phase angle difference of V_L and I_L is less than 90^o and the converter absorbs it losses from the ac system. When the losses are compensated in this way, there is no continuous real power required from the dc source and no separate power supply is needed. Only a capacitor is required to maintain a smooth dc voltage (V_{dc}) while carrying the ripple current drawn by the converter.

2.8 GTO THYRISTOR SWITCH

The GTOs in the voltage source converter do not require reverse voltage blocking capability. They must block a forward voltage equal to the dc voltage plus overshoot due to stray inductance in the converter structure.The currents through the converter switches, each consisting of a GTO and a diode are shown for var generation in Fig. 2.12(a) and for var absorption in Fig. 2.12(b). Note that only the output phase a currents are shown and for clarity the currents are assumed to be pure sinewaves.With purely reactive loading, the GTOs and the anti-parallel connected free wheeling diodes each carry quarter wave segments of the fundamental current.When the converter is supplying vars to increase the line voltage, the GTOs must be capable of being turned off (commutated) at the peak of the current (see Fig. 2.12(a)). When the converter is absorbing vars to decrease the line voltage or compensate for capacitive loading, the GTOs are naturally commutated as the current passes through zero (see Fig. 2.12(b)). Therefore, the STATCOM can absorb vars transiently, well above its steady state rating. This feature is very effective in limiting overvoltage during load rejections.

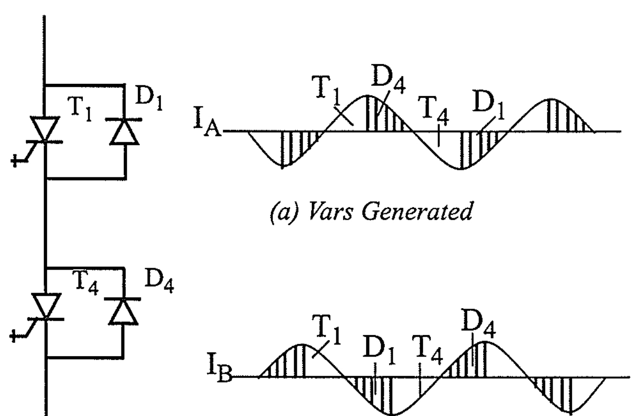


Fig. 2.12 Converter switch (GTO and diode) current

2.9 CHOICE OF FFM VERSUS PWM

As stated in the previous section, one of the ways to control the reactive current produced by the STATCOM is to control the phase angle difference between the fundamental of the converter output (V_o) and the ac system voltage. This technique is known as a "Fundamental Frequency Modulation" (FFM). Another possible technique is the Pulse Width Modulation (PWM). The PWM approach allows a direct adjustment of converter output voltage (V_o) without any phase shifting action between V_o and the ac system voltage. In the pulse-width modulation (PWM) technique, the GTOs switch several times per fundamental half -cycle to introduce notches in the voltage waveform. This technique can be used to control the amplitude of the fundamental inverter output voltage and provide reduction of harmonics at the ac terminals. While having the ability to vary the inverter voltage, PWM allows the dc bus voltage to be kept constant.

The multiple switching of the GTOs increase losses in the GTO devices and their snubber circuits. These extra losses reduce the efficiency of the converter. Consequently, at present PWM is less attractive for utility applications which require high efficiency and large power ratings. However, it has certain advantages such as faster response and capability for harmonic elimination, which could be exploited in future with semiconductor device improvements.

If a way can be found to get harmonic reduction and voltage control without the increase in losses, it would seem to be preferable. Hence, the FFM approach was chosen for the control circuit in this investigation. All of the GTOs are switched at a 60-Hz rate. No extra switching losses occur, and efficiency is maximized. Obtaining the control flexibility necessary for harmonic reduction and voltage control without extra switching requires many GTO devices and requires that they be gated at different times. This would at first appear to be a penalty, but in a rating as large as 10 MVA, many GTOs are required to carry the current. Present implementations of the STATCOM [3,12,15,17] typically employ fundamental frequency switching.

2.10 CONTROL STRATEGY

The control strategy adopted in this investigation is based on the fundamental frequency switching (FFM). As described in the preceding sections, the reactive output of the advanced static var compensator considered can be controlled by a single parameter: the phase angle between the output voltage of the inverter and the ac system voltage. This is because this phase angle controls the real power absorbed from, or supplied to, the dc storage capacitor, and the voltage of this capacitor determines the amplitude of the voltage produced by the inverter and thereby the reactive power generated for, or absorbed from the ac system.

There are two main tasks that the control scheme based on the above principle has to achieve. One is to establishes and maintain synchronism between the output voltage of the converter and the other is to control the phase angle between them. Fig. 2.13 shows the control loop [13] that was designed to perform the above tasks.The control loop relies on a phase-locked loop based firing system. A Voltage Controlled Oscillator (VCO) generates the angle information, the phase of which is compared with that of the bus voltage. The output of the reactive power PI controller (PI_p) represents the var demand signal. The var demand signal forces the Phase Locked Loop to produce the phase angle required for the converter output voltage (V_o) and either slightly lags or leads the line voltage (V_L).

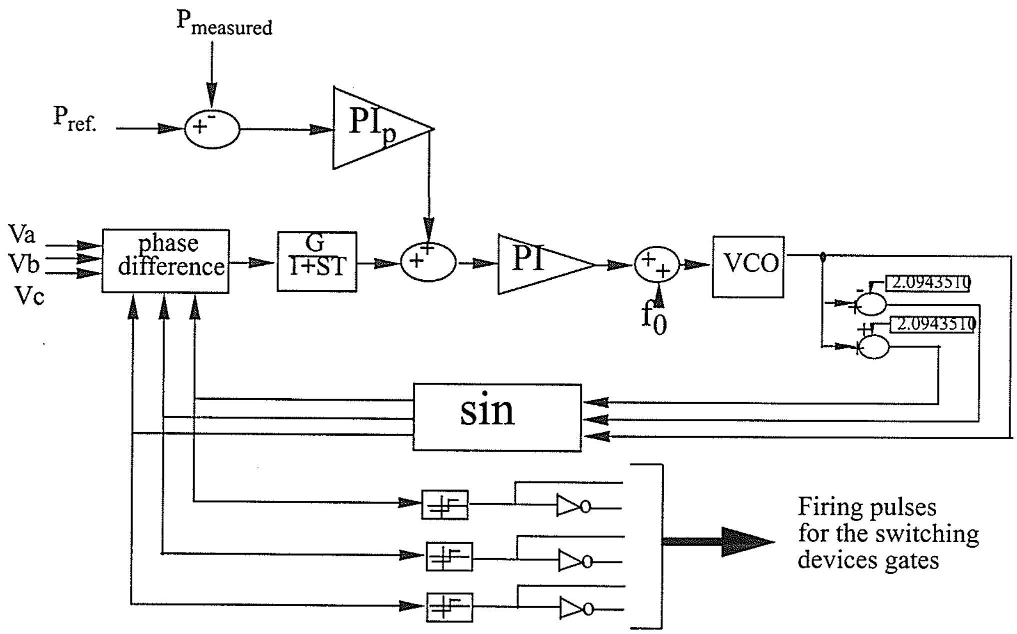


Figure 2.13 Phase lock loop for reactive power control

The control signal coming out from the PI_p output, together with the filtered phase error from the phase detector, is fed through a Proportional Integral block to change the VCO output frequency. The steady state is reached when the phase error has a value of zero, which indicates synchronism between the ac system and the VCO. The gate drive logic produces the proper gate signals needed to produce an output voltage in phase with the ac system voltage.

2.11 SIMULATION OF A BASIC SIX-PULSE STATCOM

Based on the principle and circuit analysis discussed in this chapter, a six-pulse STATCOM was digitally modelled to study and validate its operational performance. Simulation activities were carried out using the PSCAD/EMTDC program. PSCAD/EMTDC is an electromagnetic transient simulation program, with a graphical interface, for simulation of complex electrical power networks and the associated controls (Manitoba HVDC Centre [14]).

2.11.1 EMTDC Model

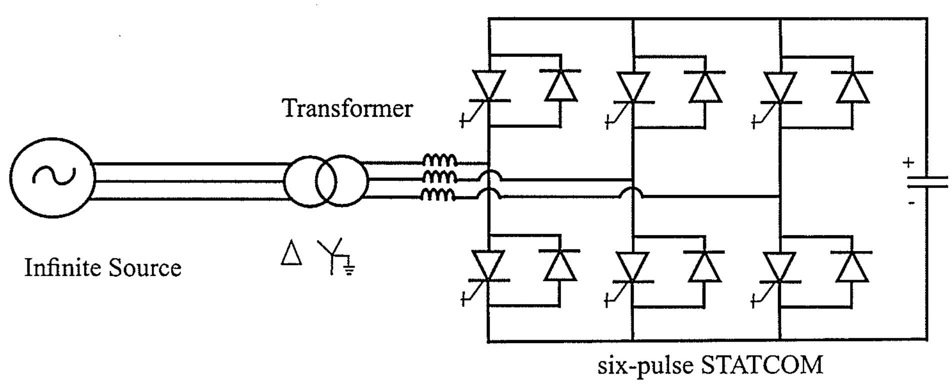


Fig. 2.14 The simulation circuit

A simple system, shown in Fig. 2.14, comprising of an infinite source, a transformer with leakage inductance and a six pulse STATCOM was simulated. The rating of the system is given in appendix A. As suggested in the control strategy, a phase locked loop (PLL) is the control loop used in the EMTDC control circuit model. A Phase Locked Loop locked to the system frequency was used to obtain the phase angle i.e. angle difference between converter output and ac system voltage. The phase angle controls the reactive power transfer between the STATCOM and the system. The firing signals corresponding to FFM mode of operation were obtained using the PLL output and the EMTDC discrete logic components. Harmonic analysis of the circuit was done with the aid of the Fourier analysis tools provided in the program. To study the performance of the STATCOM, a VAr demand signal was incorporated in the PLL. This signal was changed manually to study the dynamic response of the STATCOM.

2.11.2 STATCOM Operations in Leading and Lagging Mode

This simulation was conducted in both full leading and full lagging mode STATCOM operations. Fully leading and fully lagging correspond to -100 MVAr capacitive and +100 MVAr inductive respectively. Fig. 2.15 shows voltage and current waveforms for the line and converter (ac and dc sides) when the STATCOM was operating at fully leading mode. Similar sets of waveforms for fully lagging operation are shown in Fig. 2.16. As can be seen from Fig. 2.15(a) and (b), V_o is bigger than V_L and the line current is leading the voltage. It means

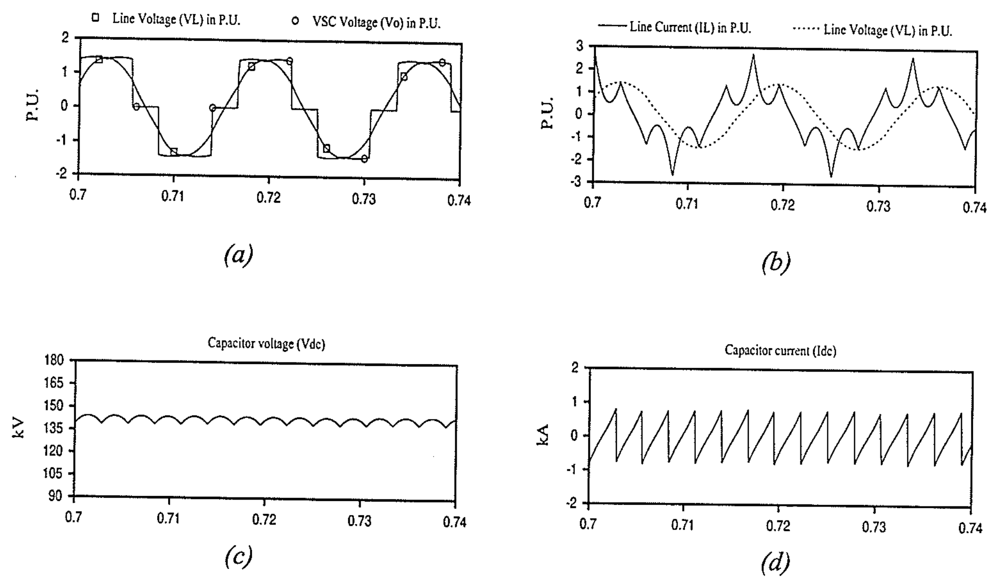


Fig. 2.15 Waveforms for leading mode of operation

that the STATCOM is generating the reactive power. The converse is true for the STATCOM operating in the inductive region and absorbs reactive power. The waveforms are shown in Fig. 2.16. The staircase waveshape of voltage for both the lagging and leading reactive currents can clearly be seen. It is obvious that the line currents are not sinusoidal. On the dc side of the converter, both capacitor voltage and current demonstrate a ripple as shown in Fig. 2.15(c)-(d) and Fig. 2.16(c)-(d). The spectrum of the line current and capacitor dc current are given in Fig. 2.17 and Fig. 2.18 for leading and lagging operation respectively. The presence of a large 5th and 7th harmonics in the line current is unacceptable. Conse-

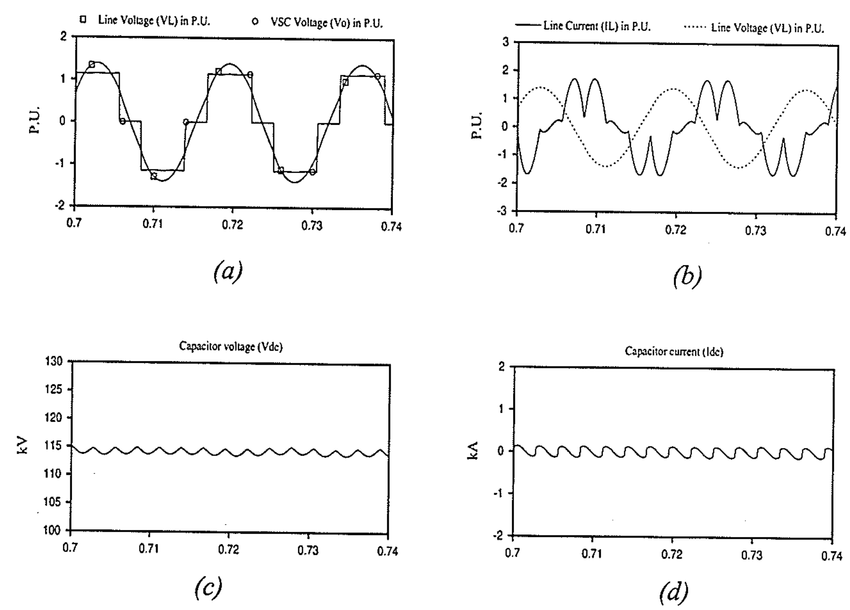


Fig. 2.16 Waveforms for lagging mode of operation

quently, the basic six-pulse STATCOM is not suitable for practical application in high voltage power systems. It is evident that the STATCOM is a source of voltage and current harmonics. The harmonic distortion of the inverter voltage in turn causes a distortion in the line current.The DC-capacitor gets a ripple current, which leads to a small ripple in the DC- voltage depending on the capacitance.For this type of STATCOM, the line current contains harmonic components of frequency $(6n \pm 1)f$, where f is the frequency and n=1,2,3. etc.

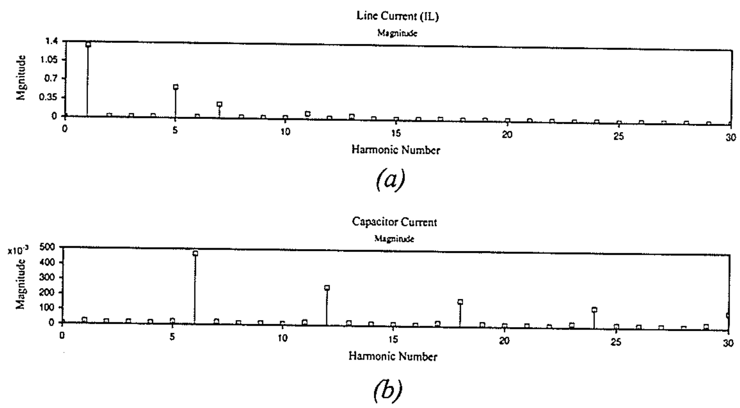


Fig. 2.17 Harmonic spectrum for leading mode

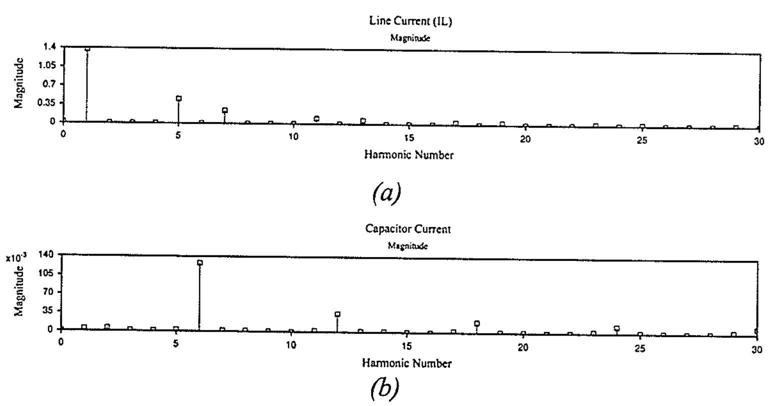


Fig. 2.18 Harmonic spectrum for lagging mode

2.11.3 Dynamic Operations

To illustrate the dynamic response of the STATCOM, Fig. 2.19 shows its response to the step change of the reactive power demand.The figure indicates that the phase locked loop and proportional-integral controller available in the EMTDC program can respond to reactive power changes from fully leading to fully lagging within two and half cycles of the system frequency (60 Hz). This demonstrates that FFM gives good dynamic response. However, there may be advantages in using PWM techniques to improve the response speed.

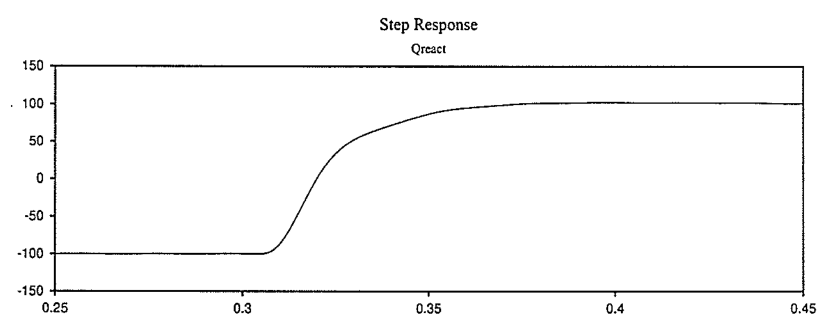
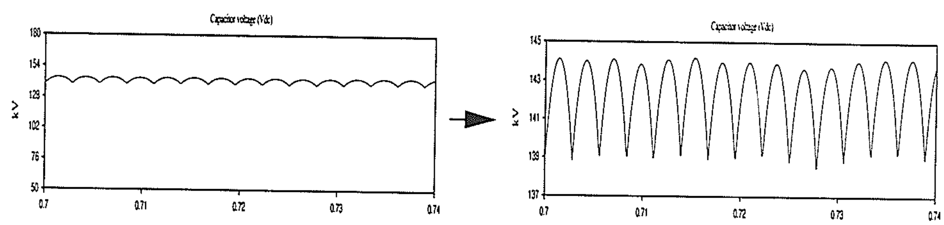


Fig 2.19 Dynamic response of the STATCOM

2.11.4 The Effects of Capacitor Size

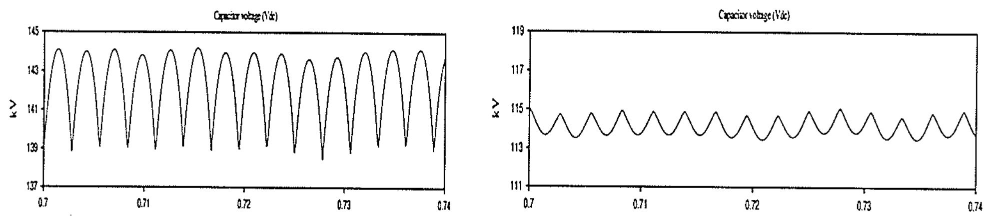
The first part of this studies is to compare the values of the ripple between the two operational modes. Previously, Fig. 2.15(c) has displayed a ripple



(a) *(b)*

Fig. 2.20 DC capacitor voltage ripple for full leading mode of operation

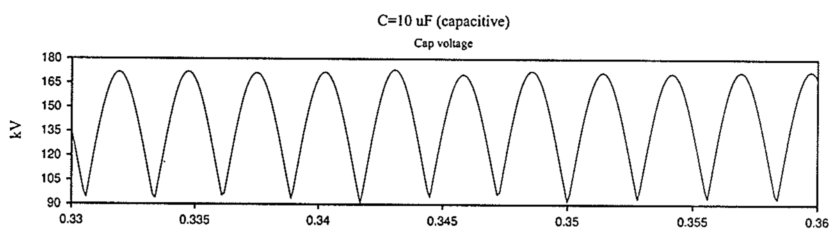
in the capacitor voltage. To emphasize this point, a zoomed in waveform of capacitor voltage is shown again in Fig. 2.20(b). Fig. 2.21 shows a comparison of the ripple presence in the capacitor voltage between the two modes of operations. It is obvious that the peak to peak ripple is worst in the capacitive mode, as shown in Fig. 2.21(a). This is because the value of the dc capacitor voltage is maximum at fully leading operation.



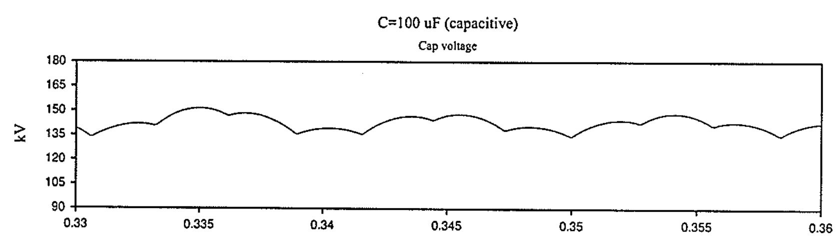
(a) *(b)*

Fig. 2.21 Comparison of voltage ripple between full capacitive and full inductive

The effect of capacitor size on the ripple was also investigated.Two extreme values of capacitance were chosen i.e. C=10 and C= 100 μF The wave-form corresponding to C=10 μF, shown in Fig 2.22(a), has much worse peak to



(a)



(b)

Fig. 2.22 DC capacitor voltage ripple for difference values of capacitance peak ripple compared to C=100 μF in Fig. 2.22(b). Hence, the capacitor can limit the ripple on the dc-voltage. The simulation was also conducted to determine the influence of the capacitor size to the dynamic response of the STATCOM. The MVAr demand was set to dynamically change from fully leading to fully lagging, then back to fully leading.The results are shown in Fig. 2.23 for C=10 μF and Fig. 2.24 for C=100 μF. The controller gains have been optimized to give a fast response. The big value of capacitance has a large oveshoot i.e. 20% and takes longer time than small capacitance to come close to the demand MVAr. With the small capacitor, response to the demand MVAr within two third of the cycle. It takes almost seven cycles for the big capacitor to settle to within ± 5 % of the demand MVAr. It can be concluded that the big capacitor value shows in general a more sluggish response to the dynamic change. Stemmler [16] has attributed this dynamic response to energy interchange between the capacitor and the transformer inductance.

The main purpose of this studies is to investigate several operating topologies of STATCOMS. The selection of the capacitor is a design problem. The value of 100 μF chosen is probably unrealistically large, but does not have a bearing on the essential arguments.

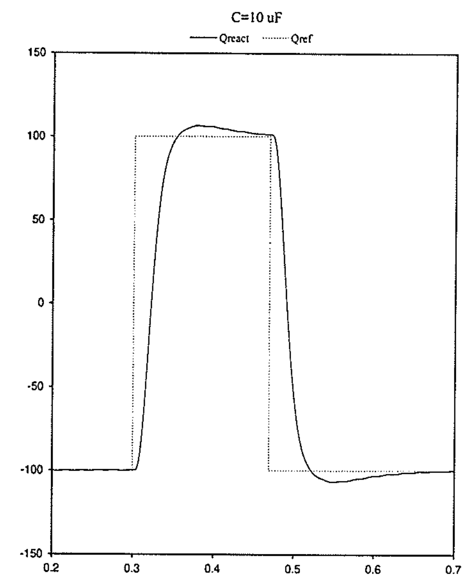


Fig. 2.23 Dynamic response when capacitor is 10 uF

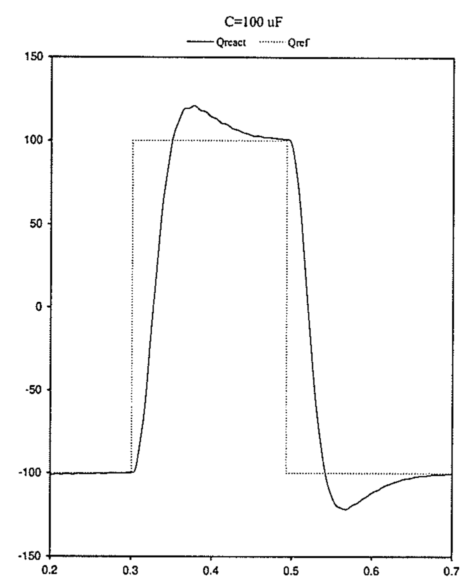


Fig. 2.24 Dynamic response when capacitor is 100 uF

2.11.5 Other Feature

Fig. 2.25 shows the result of reactive power output versus DC voltage. The reactive power output as a function of DC voltage shows a linear relationship.

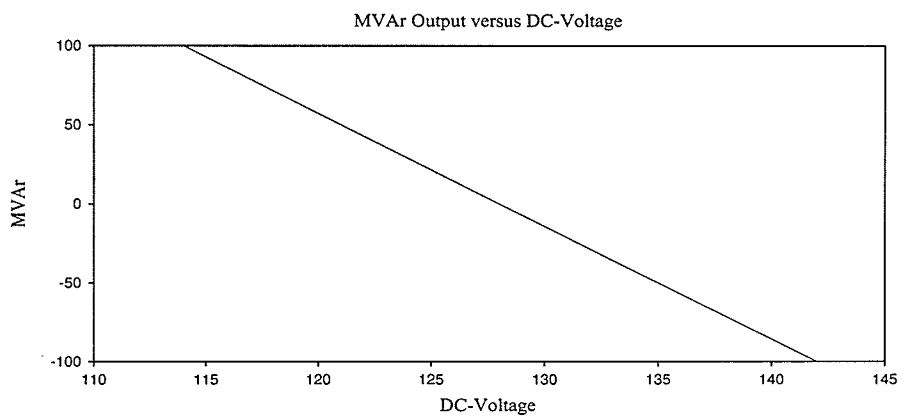


Fig. 2.25 Reactive power output versus DC-Voltage

CHAPTER 3

Topologies for 12-pulse STATCOM

3.1 INTRODUCTION

A large line current harmonics produced by the basic 6-pulse STATCOM illustrated in the previous chapter would make it impractical for high power application. A more complex circuit is needed to improve the harmonics performance without resorting to a large filtering device in order to meet the harmonic requirement. This chapter will look at how the basic circuit can be combined to form a twelve pulse structure. There are four different circuit topologies of 12-pulse STATCOM being compared here. Their harmonic performance is the main subject of this analysis.

3.2 BENEFITS OF HIGH PULSE STATCOM

(a) Increased Power Rating

Compensators for utility applications require ratings from 10s to 100s of MVAr [5]. With 4.5kV/3kA GTOs, the basic six-pulse STATCOM allows a maximum DC-voltage of 3kV and a line current of 1.3kA (rms-values). This means a reactive power of 3.9MVAr in the inductive and capacitive mode. Hence, by adding one or more converters into the basic structure the power rating of the STATCOM is increased.

(b) Improved Harmonic Performance

With the basic six-pulse STATCOM the corresponding harmonic components that appear in the line current are normally intolerable and have to be reduced by costly parallel filter banks on the power system side. The extended circuit, twelve or higher pulse number, a multi-pulse method is used to improve the harmonic performance of the STATCOM. The multi-pulse methods involves multiple converters connected so that the harmonics generated by one converter are cancelled by harmonics produced by other converters.This technique is well known in conventional thyristor rectifiers to increase the pulse number of the DC-current and reducing the distortion of the line current. The same principle can be applied to the STATCOM. This concept will be discussed in the following section.

3.3 TRUE AND QUASI MULTI-PULSE METHODS

In the true multi-pulse methods [14], phase-shifting transformers are an essential ingredient in providing the mechanism for complete cancellation of harmonic current pairs, for example, the 5th and 7th harmonics, or the 11th and 13th and so on. For the quasi multi-pulse [15], firing control is operated as to have the same phase displacement effect like in the phase shifting transformer by firing each component bridge at a different firing angle. This is done at the expense of an incomplete cancellation of harmonic current pairs and hence the word quasi is originated.

The concept of true multi-pulse is considered first by referring to the circuit shown in Fig. 3.1. Here two separate loads are fed from two converters, each having its own supply transformer. Converter #2 is fed through a wye/delta transformer that produces a three-phase set of secondary voltages shifted by 30^{o} with respect to the primary voltage. Converter #1 is fed by secondary voltages, from wye/wye transformer, which has no phase shift. Since the two converter operate with the same control angle, the fundamental frequency currents on the ac side of the two transformers are in phase with one another. The symmetry between two converter current waveforms can be seen in Fig. 3.2(a). However, some of the harmonic currents are differently phased because of the transformer action. For discussion purpose in this example, let us consider only the 5th and 7th harmonics. As shown in Fig. 3.2(c), the 5th and 7th harmonic are shifted to 180° in the

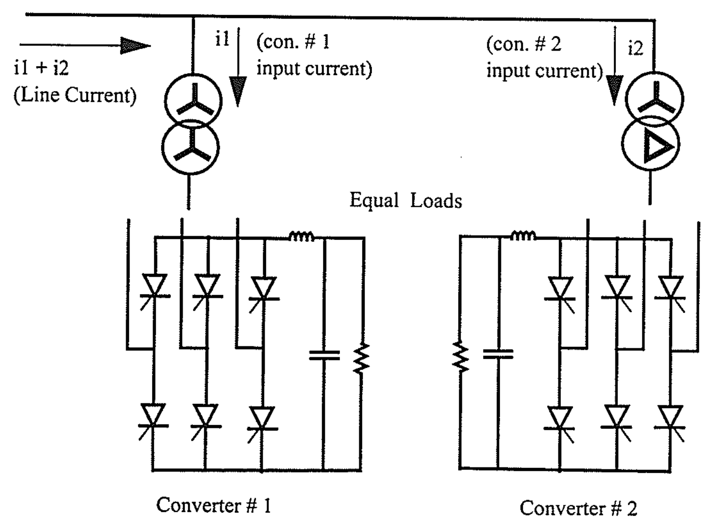


Fig. 3.1 Two separate converters with equal load and different transformers

converter #2 input current. Fig. 3.2(b) shows the phase of harmonic for converter #1 input current where the 5th and 7th are at 0°. Hence, the 5th and 7th harmonic currents are in phase opposition which will be diminished in the resultant line current as illustrated in Fig. 3.2(d). Also shown in Fig. 3.3 are the harmonic spectrum i.e. magnitudes of both converters currents. These phase relationships can be indicated in the expressions for ac currents fed to each converter as follows:

$$i1 = a_1 \sin(\theta) + a_5 \sin(5\theta + \lambda_5) + a_7 \sin(7\theta + \lambda_7) + \ldots \qquad (3.1)$$

and

$$i2 = a_1 \sin(\theta) + a_5 \sin(5\theta + \lambda_5 - \pi) + a_7 \sin(7\theta + \lambda_7 - \pi) + \ldots \qquad (3.2)$$

thus,

$$i1 + i2 = 2a_1 \sin(\theta) + 2a_{11} \sin(11\theta + \lambda_{11}) + 2a_{13} \sin(13\theta + \lambda_{13}) + \ldots \qquad (3.3)$$

Derivation of these series is given in the appendix A. Thus, it can be said that some of the harmonic currents required by one converter are supplied by another. The phase shift provided by the transformer must be appropriate for the number of converter. In general, the minimum phase shift required for cancellation of current harmonics in a converter with 6-pulse waveform is,

$$\text{phase shift}^{\circ} = (60 / \text{number of converters}) \qquad (3.4)$$

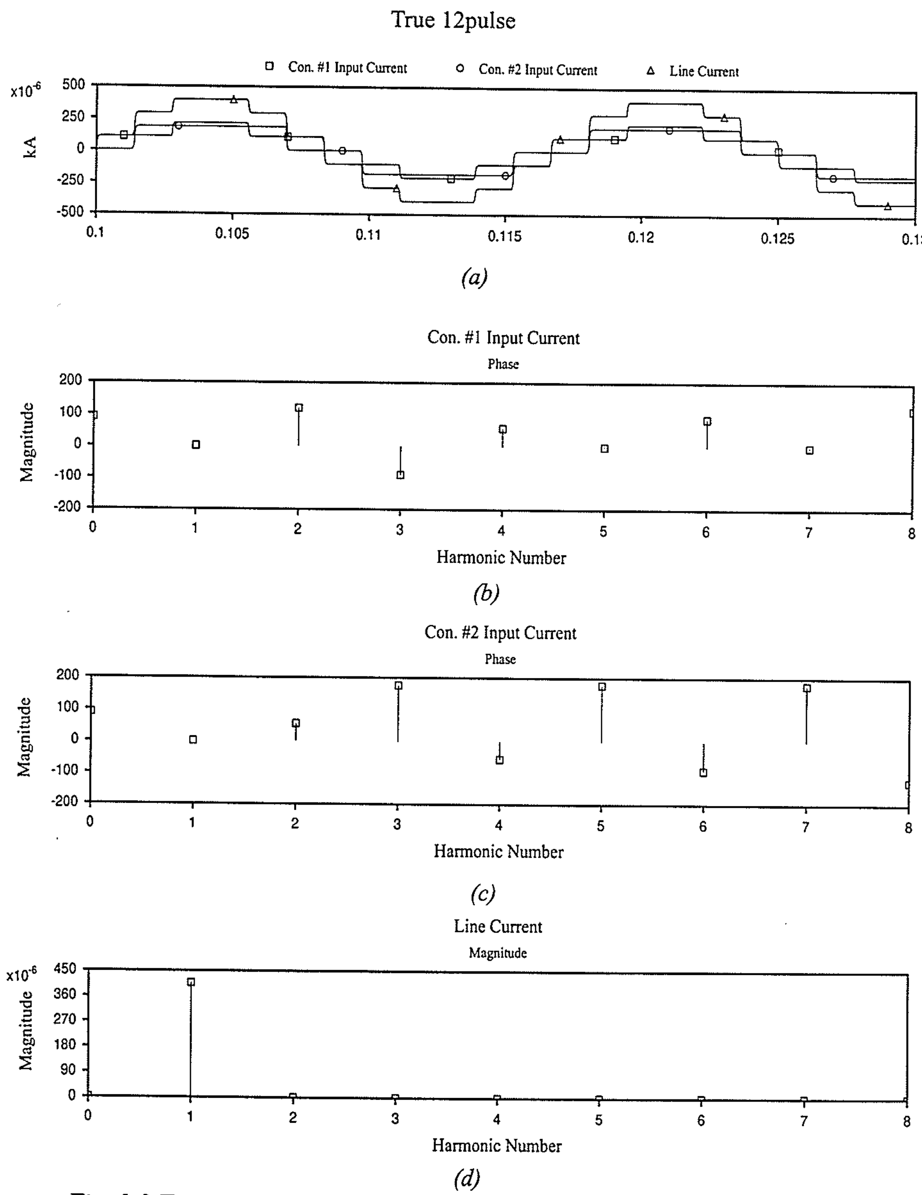


Fig. 3.2 True 12-pulse converter current waveforms and its spectrum

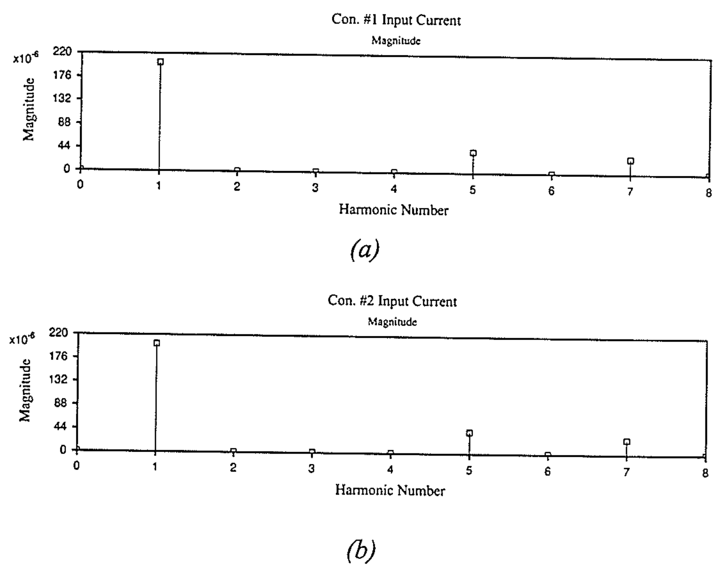


Fig. 3.3 Harmonic spectrum (magnitude) for both converters currents.

Quasi multi-pulse methods do not use phase shifting transformers. As stated earlier, the phase displacement is achieved by mean of the firing control mechanism. Consider the circuit shown in Fig. 3.4. Both converters have the same wye/wye transformers which provide no phase shift but they operate with different control angle. Converter #2 is operated to have a 30° control angle delay with respect to converter #1. The input current waveforms for both converters are no

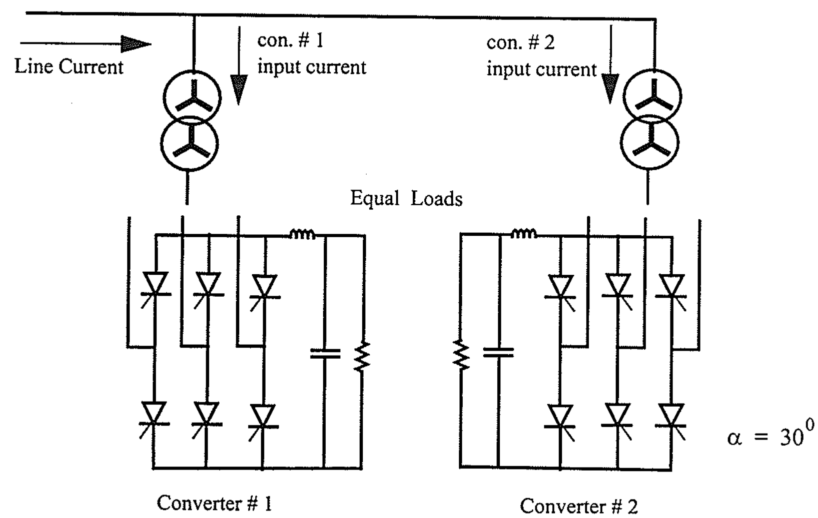


Fig. 3.4 Two separate converters with equal load and same transformers

longer in phase as shown in Fig. 3.5(a). The effect of 30° firing delay to the 5th harmonic current input of converter #2 is to shift it from 0° to -150° and the 7th harmonic to +150°as shown in Fig. 3.5(c). Fig 3.6 shows the magnitude of harmonic currents for both converters.

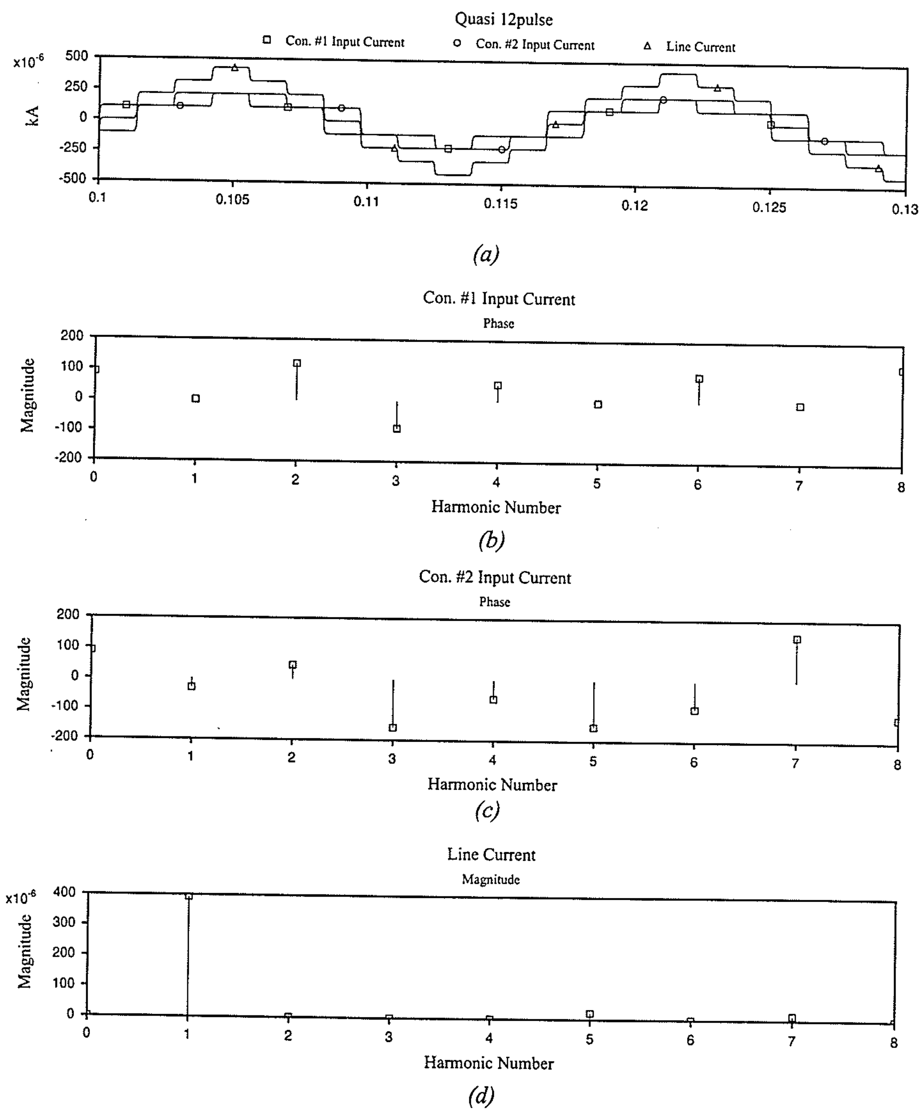


Fig. 3.5 Quasi 12-pulse converter current waveforms and its spectrum

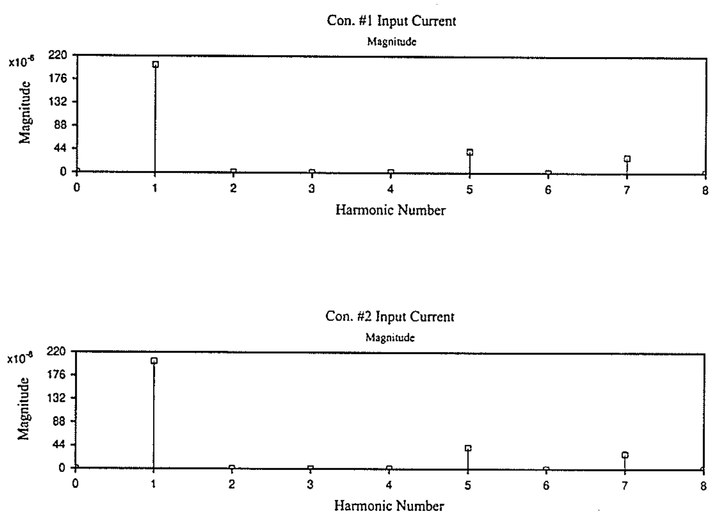


Fig. 3.6 Harmonic spectrum (magnitude) for both converters currents.

A conclusion that can be made from these results is some of the harmonic current pairs are not exactly in phase opposition. This is due to the different overlap angles in each bridge. Hence their cancellation is incomplete and they appear to some degree in the line current as shown in Fig. 3.5 (d).

3.4 CIRCUIT TOPOLOGIES FOR 12-PULSE STATCOM

There are four different circuit topologies [16] of 12-pulse STATCOM that have been considered in this investigation; the difference lies in the way the phase shifting transformers are arranged to connect the two converter bridges together. Both true and quasi multi-pulse methods have been applied.

3.4.1 Basic Quasi 12-Pulse Circuit

The circuit diagram is shown in Fig. 3.7. The circuit uses the quasi technique to form a 12-pulse STATCOM. The secondary windings are three separate isolated windings and it referred to as open wye transformer. Only one phase of connection is shown in the circuit diagram. The voltage across the secondary winding is the difference of the converter voltages. A phasor diagram in Fig. 3.7 shows the phase angles of the upper (V_{c1}) and lower (V_{c2}) converter voltages with respect to the line voltage as being α_1 and α_2 respectively. For a full harmonic control, α_1 and α_2 are the same and equal to 0.26 rad.

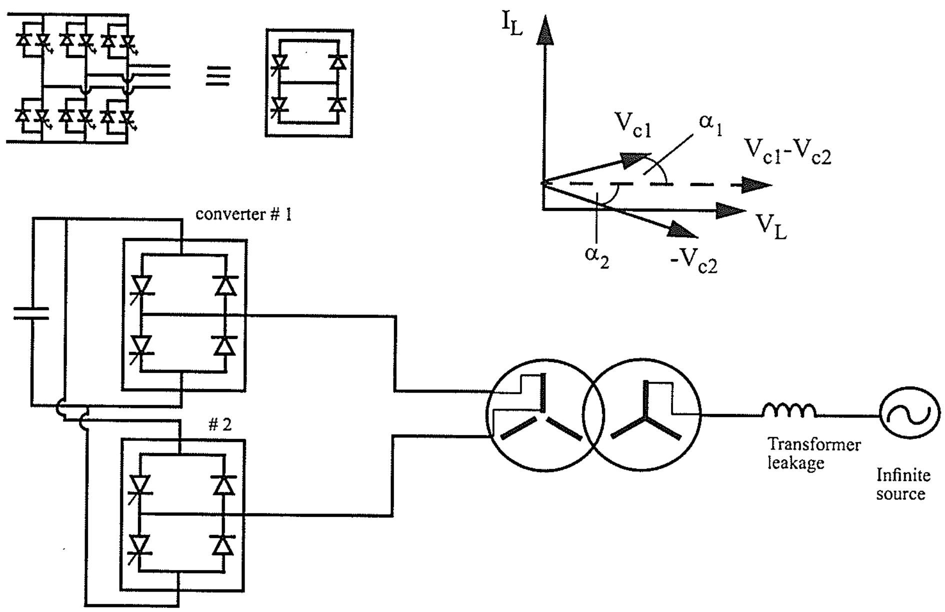


Fig. 3.7 Basic Quasi 12-Pulse circuit and phasor diagram

3.4.2 True 12-Pulse With Simplified Transformer Connection

The circuit diagram is shown in Fig. 3.8. A phase shifting transformer is used in this design. Both wye-delta transformer winding have the same rating. The wye configured winding is an open wye transformer. The delta winding is connected across the output of the lower six-pulse converter. In the upper bridge the phase connection from the GTO valves is to the open wye part of the transformer phase, the other terminal of that phase being connected to the ac bus.The converters are operated as such their voltage outputs are separated by 30^{o} but have the same amplitude, as illustrate in phasor diagram Fig. 3.8. The phase-shifted fundamental voltage induced in each winding from the upper inverter falls directly in phase with the fundamental voltage produced by the lower inverter. This results in a true 12-pulse output having twice the fundamental amplitude produced by each six-pulse inverter.

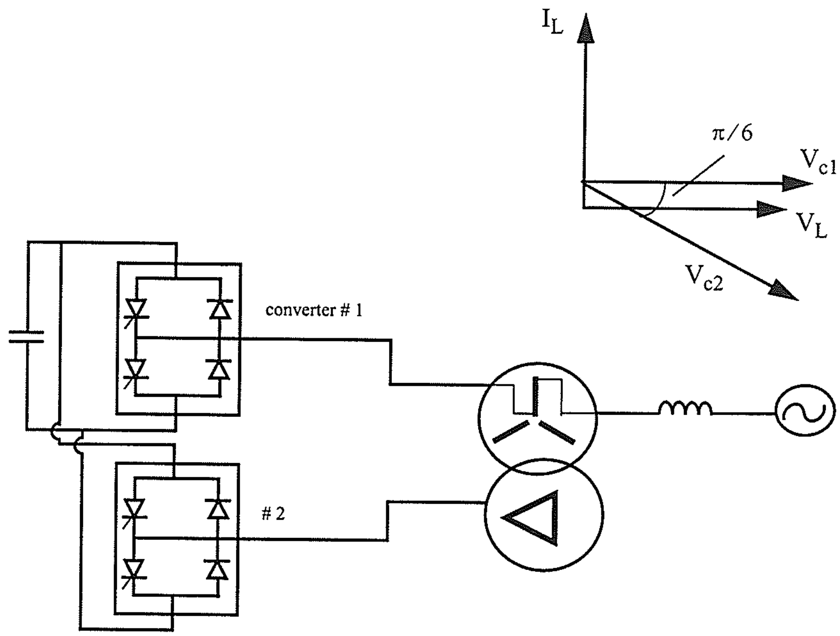


Fig. 3.8 True 12-pulse circuit with simplified transformer and phasor diagram

3.43 True 12-Pulse With Multi-winding Transformer

The circuit diagram is shown in Fig. 3.9. There are two secondary windings, one in star and the other one in delta. The converters are being connected in parallel. This is again a true 12-pulse since it employed the phase shifting transformers. The same operational arrangement is applied to this circuit as it does to the previous one. The phasor diagram in Fig. 3.9 illustrates this fact.

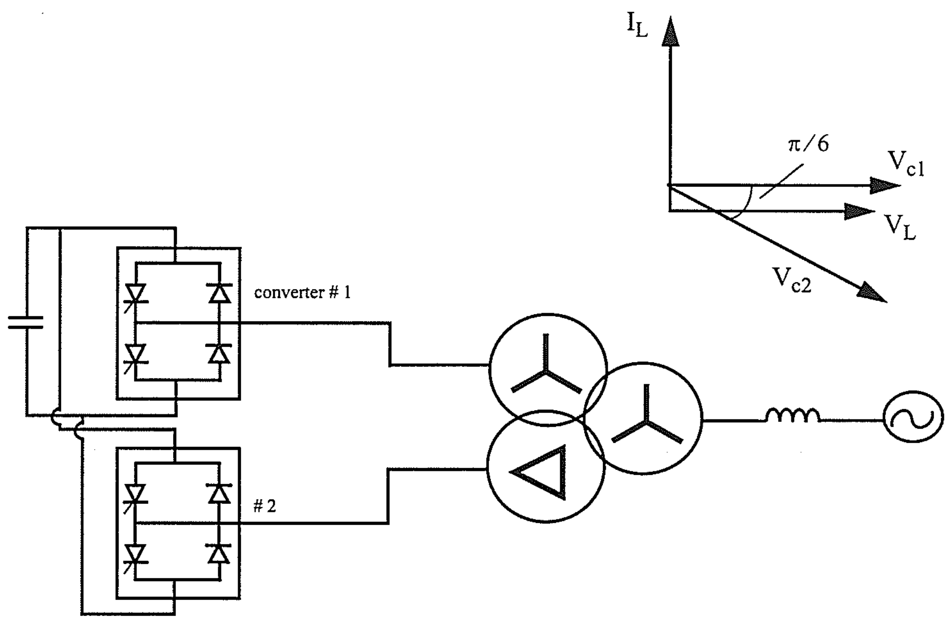


Fig. 3.9 True 12-pulse circuit with multi-winding transformer and phasor diagram

3.44 True 12-pulse With Series Connected Primary Winding

The circuit diagram is shown in Fig.3.10. There are two transformers in this circuit. The primary windings are connected in series. Again, the same operational arrangement as in the previous circuit. This is shown by the phasor diagram in Fig. 3.10.

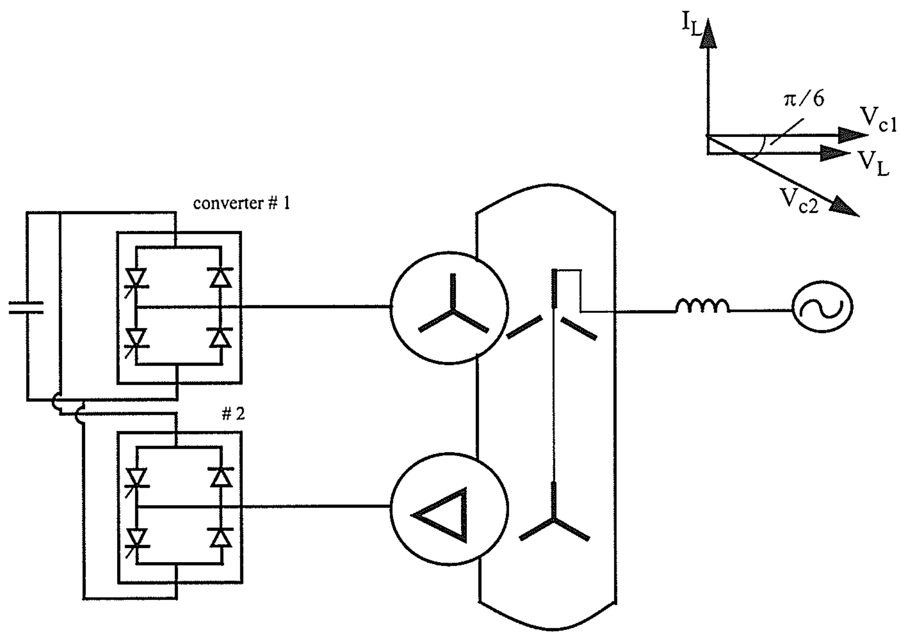


Fig. 3.10 True 12-pulse circuit with series connected primary and phasor diagram

3.5 RESULTS OF SIMULATIONS AND DISCUSSIONS

All circuit topologies were operated at full leading mode in the simulation. Table 1 summarizes the analysis concluded from the simulation results.

Important characteristic waveforms with their spectra are illustrated in Fig. 3.11 through Fig. 3.14 for every circuit configuration. Focus is made primarily on the line current harmonic content.

The STATCOM output voltages presented are actually the STATCOM resultant voltage behind leakage impedance. This point is actually not accessible in a real transformer. On the dc side of the circuit, the peak to peak ripple voltage gives a feel for the quality of the capacitor voltage. Following comments only highlight the significant difference of an individual circuit compared to others in term of the harmonic performance. Similar conclusions are seen with full lagging performance but are not shown in this report. The following table shows a summary of results for a full leading operation of each STATCOM configuration.

Circuit configurations	AC Side		DC Side		I_L, THD (%)
	Primary	Secondary	capacitor current harmonics eliminated	capacitor voltage ripple (%)	
	Eliminated Line current harmonics, I_L	Eliminated Inverter current harmonics			
Basic 12-pulse quasi	(5/7), (17/19)	(5/7), (17/19)	(6), (8)	5.0	12.6
True 12-pulse with simplified transformer	5/7, 17/19	5/7, 17/19	6, 8	3.2	6.7
True 12-pulse with multi-winding transformer	5/7, 17/19	-	6, 8	4.1	6.7
True 12-pulse with series connected primary	5/7, 17/19	5/7, 17/19	6, 8	1.2	6.7

Table 1 Summary of the results

note: (5/7), (17/19), (6) and (8) harmonic numbers shown in parentheses means minimized but not eliminated.
Only harmonics up to 19th order are considered

3.51 Basic Quasi 12-Pulse Circuit

The characteristic waveforms and related harmonic spectra are shown in Fig. 3.11. The quasi multi-pulse method is used to minimize the 5th and 7th harmonic in the line current. The minimization also influences the 17th and 19th and the corresponding components (6th, 18th) in the dc circuit. Its line current total harmonic distortion (THD) is 12.6%, which shows a great reduction form 48.5% THD in basic 6-pulse circuit. The 5% peak to peak ripple in capacitor voltage is the worst compared to other circuits. An interesting observation from all these results is the ability to improve the harmonic performance without acquiring the phase shifting transformer. This gives a simplification to the transformer design.

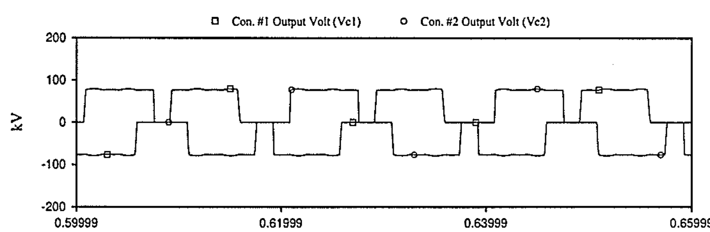


Fig. 3.11(i) Converter #1 & #2 output voltages

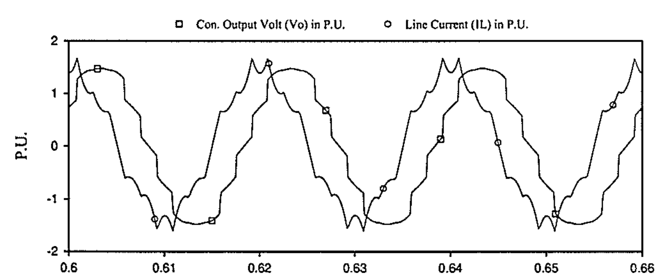


Fig. 3.11(ii) STATCOM resultant voltage behind leakage impedance and line current

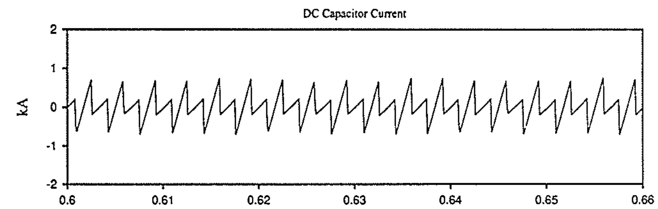


Fig. 3.11(iii) Capacitor current

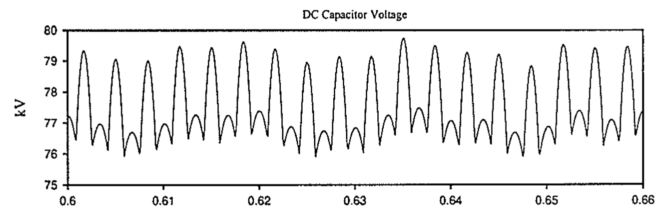


Fig. 3.11(iv) Capacitor voltage

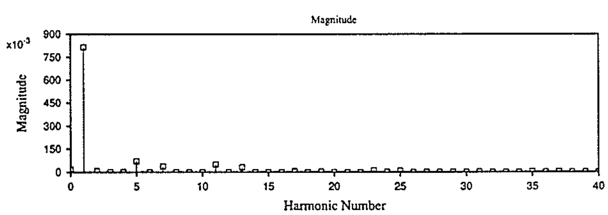


Fig. 3.11(v) AC-Line current harmonic spectrum

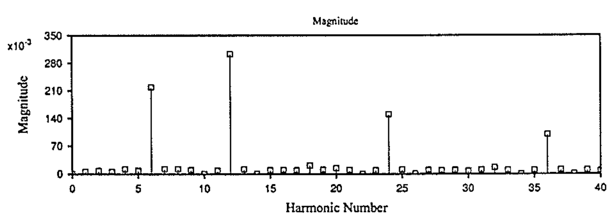


Fig. 3.11(vi) DC-Capacitor current harmonic spectrum

3.52 True 12-Pulse With Simplified Transformer Connection

The characteristic waveforms and related harmonic spectra are shown in Fig. 3.12. On the ac circuit, harmonic contents in line current and converter current are the same. It appear that this circuit has the same harmonic performance as in the true 12-pulse with series connected primary winding. This is not the case on the dc side. It has bigger ripple in capacitor voltage. The circuit certainly provides a simple transformer design. However, the stepping up or down of voltage is not possible for this transformer.

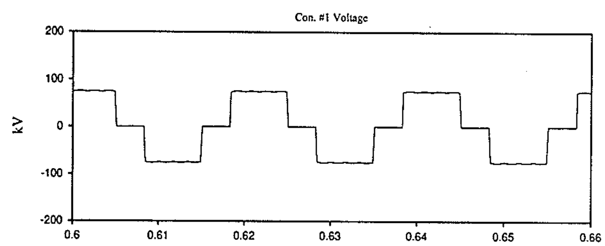


Fig. 3.12 (i) Converter #1 output voltage

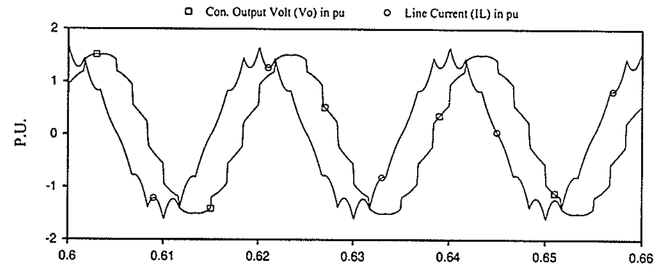


Fig. 3.12(ii) STATCOM output voltage and line current

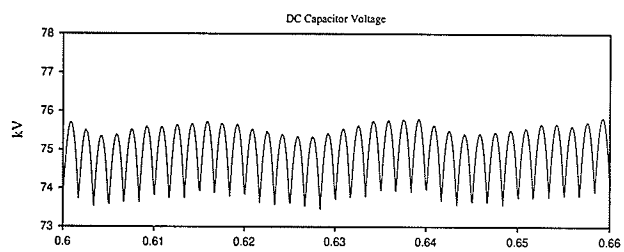


Fig. 3.12(iii) Capacitor voltage ripple

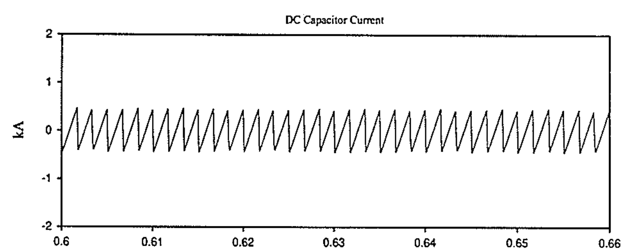


Fig. 3.12 (iv) Capacitor current

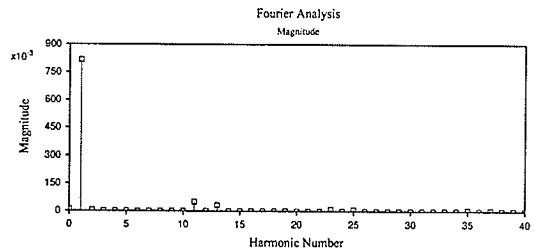


Fig. 3.12 (v) AC-Line current harmonic spectrum

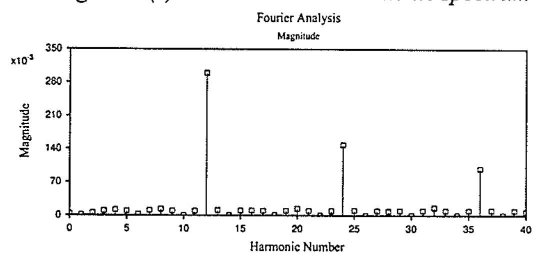


Fig. 3.12 (vi) DC-Capacitor current harmonic spectrum

3.53 True 12-Pulse With Multi-winding Transformer

The characteristic waveforms and related harmonic spectra are shown in Fig. 3.13. There is a difference in harmonic content between voltages on primary i.e. the STATCOM output voltage and secondary sides of the coupling transformer. In the STATCOM output voltage only the 11th and 13th and 23rd and 25th etc. harmonics appear. However, on the secondary side of the transformer still all harmonics are present as shown in Fig. 3.13(i). In other words, current is more distorted on the converter side than on the line side. However, the system is partially redundant because it can operate with just one converter at half of the nominal power with degraded harmonic performance. Compared to the previous circuit, this transformer allows a step up or down voltage operations but more complicated windings.

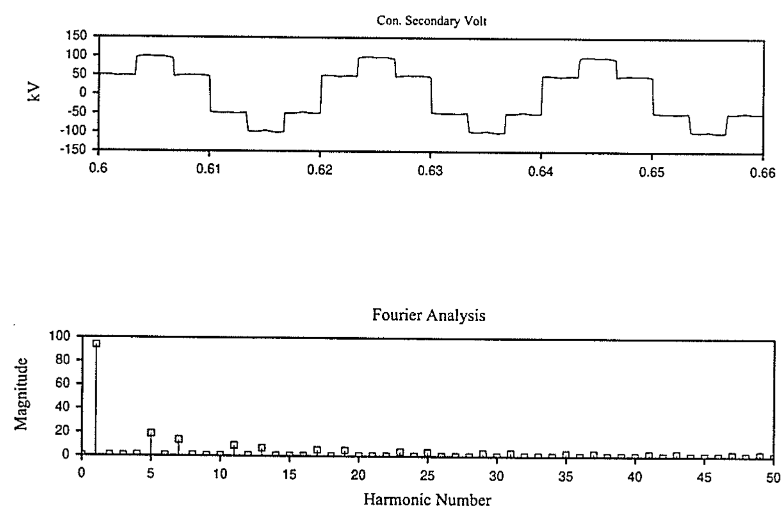


Fig. 3.13(i) Converter secondary voltage and its spectrum

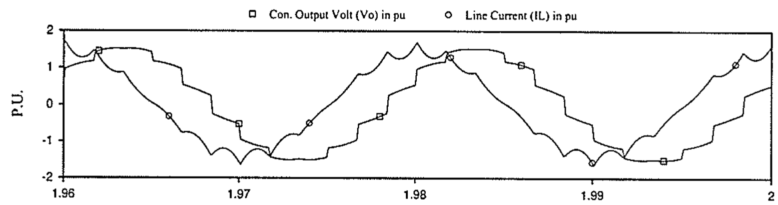


Fig 3.13 (ii) STATCOM Converter output voltage and line current

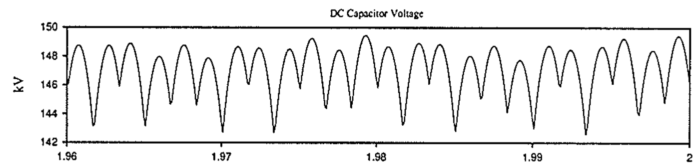


Fig. 3.13 (iii) Capacitor voltage ripple

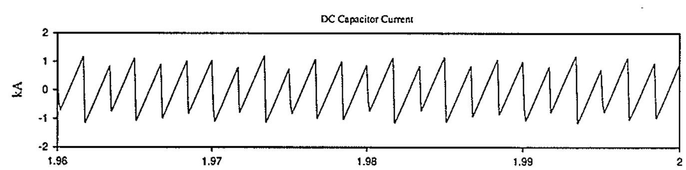


Fig. 3.13 (iv) Capacitor current

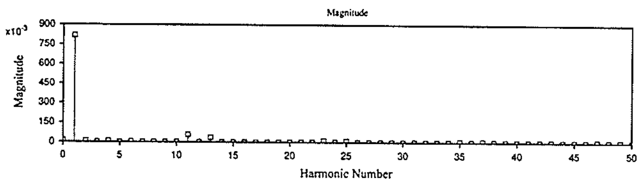


Fig. 3.13 (v) AC-Line current harmonic spectrum

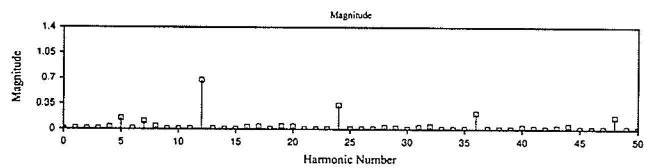


Fig. 3.13(vi) DC-Capacitor current harmonic spectrum

3.54 True 12-pulse With Series Connected Primary Winding

The characteristic waveforms and related harmonic spectrum are shown in Fig. 3.14. Unlike the previous circuit, the 5th and 7th harmonic currents components are eliminated on both sides of the transformers. This achievement is very important since it means strongly reduced peak currents in the converter. The design of the converter depends closely on this peak value and a reduction of it allows a higher rms value and, therefore, a larger STATCOM power rating. Furthermore, this circuit has the lowest peak to peak capacitor voltage ripple compared to the rest of the circuits. However, the transformer arrangement requires the largest number of windings but lesser rating than any of the earlier discussed option

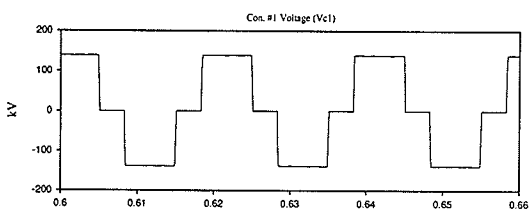


Fig. 3.14 (i) Converter #1output voltage

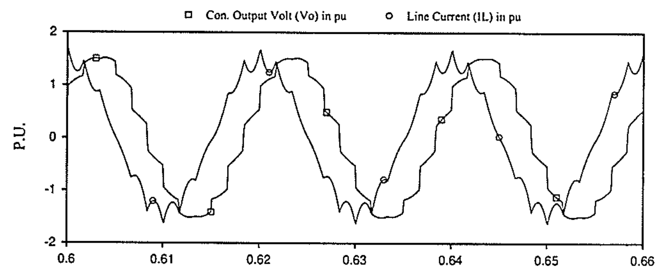


Fig. 3.14 (ii) STATCOM output voltage and line current

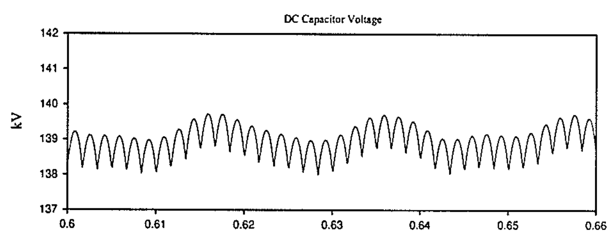


Fig. 3.14(iii) Capacitor voltage

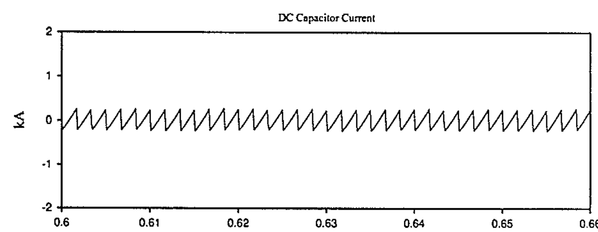


Fig. 3.14(iii) Capacitor current

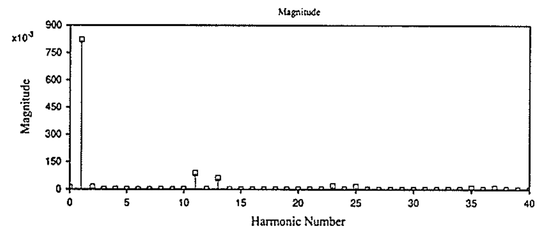


Fig. 3.14(v) AC-Line current harmonic spectrum

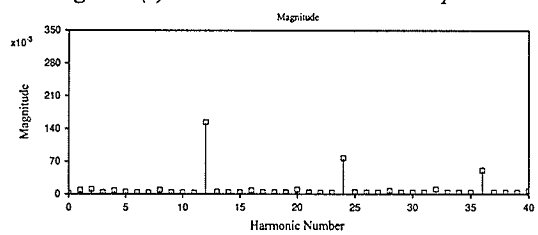


Fig. 3.14 (vi) DC-Capacitor current harmonic spectrum

CHAPTER 4

High-Pulse Number STATCOMS

4.1 INTRODUCTION

The previous chapter has introduced the concepts of the multi-pulse STATCOM. In that chapter we looked at different connections of two converter bridges so as to provide full or partial harmonic cancellation. This chapter extends further the concepts to a higher pulse STATCOM. For transmission line applications, a pulse number of 24 or higher is required [15] to achieve adequate waveform quality without the use of passive filters. The pulse number chosen for these studies is 48. Three different topologies of 48-pulse STATCOM are analysed and compared through the computer simulations performed to validate the circuits performance. The important characteristic waveforms and their spectra are presented. Their merits, based mainly on harmonics performance are highlighted.

4.2 GENERAL CONCEPTS OF THE 48-PULSE STATCOM

A high number pulse STATCOM is presently considered the most practical [17] for high power utility applications. Using the concept of multipulse methods, the input and output of *n* basic six-pulse STATCOMS (which are operated with appropriate relative phase displacement) can be combined so as to obtain an overall P=6*n* highpulse STATCOM structure. On the ac-side of this P-pulse STATCOM, the frequencies of the harmonics present is [Pk±1]f and the amplitude of number kth harmonic is inversely proportional to [Pk±1]. Variable f is the fundamental output frequency and k=1,2,3,.... On the dc-side, the frequencies of the harmonics present is Pkf and the amplitude of number kth harmonic is inversely proportional to Pk. It is clear that the harmonic spectrum improves rapidly with increasing pulse number.

A 48-pulse STATCOM composed of eight basic six-pulse converters, each with an appropriate phase shift, are combined to produce a multi-pulse voltage waveform which approximates sufficiently well the desired sine-wave. A variety of circuit arrangements, using different magnetic circuits, are possible to implement the 48 -pulse STATCOM. The approach that has been taken in this studies is to use a coupling transformer. The coupling transformer is split into eight of series-connected, uncoupled transformers, one for each three-phase converter with an appropriately phase shifted secondary winding.

4.3 A TRUE 48-PULSE STATCOM

According to Eq. 3.4, the phase shift required for 48-pulse STATCOM is 7.5^{o}. To comply with true multipulse principles, a phase shifting transformer that can deliver the desired shifting effect has to be employed in this configuration. These uncommon phase angles shift needs a special transformer. Hence, the zig-zag transformer [18] is employed. The zig-zag windings on the secondary side of the coupling transformers are designed to give an appropriate phase shift to each converter voltage waveform.

4.3.1 Principle of Zigzag Transformer

The term "zigzag" refers to the manner in which output voltages are formed from segments of different voltage vectors. With a three-phase supply, there are in affect six ways for the voltage vectors to zig and zag. These depend upon selection of one of three angles and one of two polarities (directions).

An example of zigzag transformer giving a phase shift of Φ between primary and secondary of line to neutral voltage is shown in Fig. 4.1. The primary transformer has a normal wye winding. There are six secondary windings which are interconnected to form the output zigzag winding as shown in Fig. 4.1. The corresponding vector diagram is also shown in Fig. 4.1. Since the schematic physical diagram of the windings conform to the vector diagram, we can deduce a relationship between Φ and voltages in zigzag windings as,

$$\frac{V_{bn}}{\sin\left(120^{o}\right)} = \frac{V_{bs}}{\sin\left(\Phi\right)} = \frac{V_{bl}}{\sin\left(60^{o} - \Phi\right)} \tag{4.1}$$

Thus, given the line to neutral voltage of zigzag output and choice of phase shift Φ, we can determine the appropriate turns ratio between the long winding (V_{bl}) and the short winding (V_{bs}) in the zigzag transformer which will give us the desired phase shift.

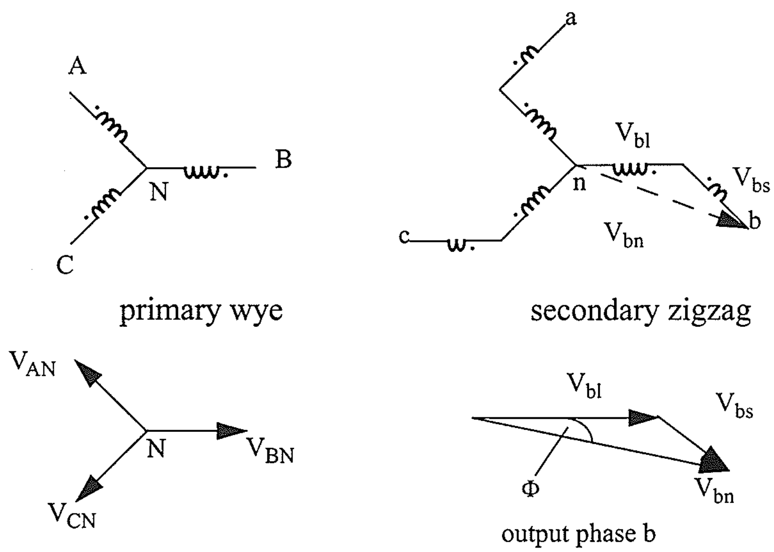


Fig. 4.1 Schematic and vector diagram of a zigzag transformer

4.3.2 Structural and Operational Arrangement

The STATCOM consists of eight unit converters as shown in Fig. 4.2. The converters are operated from a common dc capacitor voltage with a successive 7.5^{o} phase-displacement. Each of the generated output voltage waveform is shifted by a transformer with zig-zag secondary winding configuration to cancel the phase-displacement of the converters. Starting from converter #1 through #8,

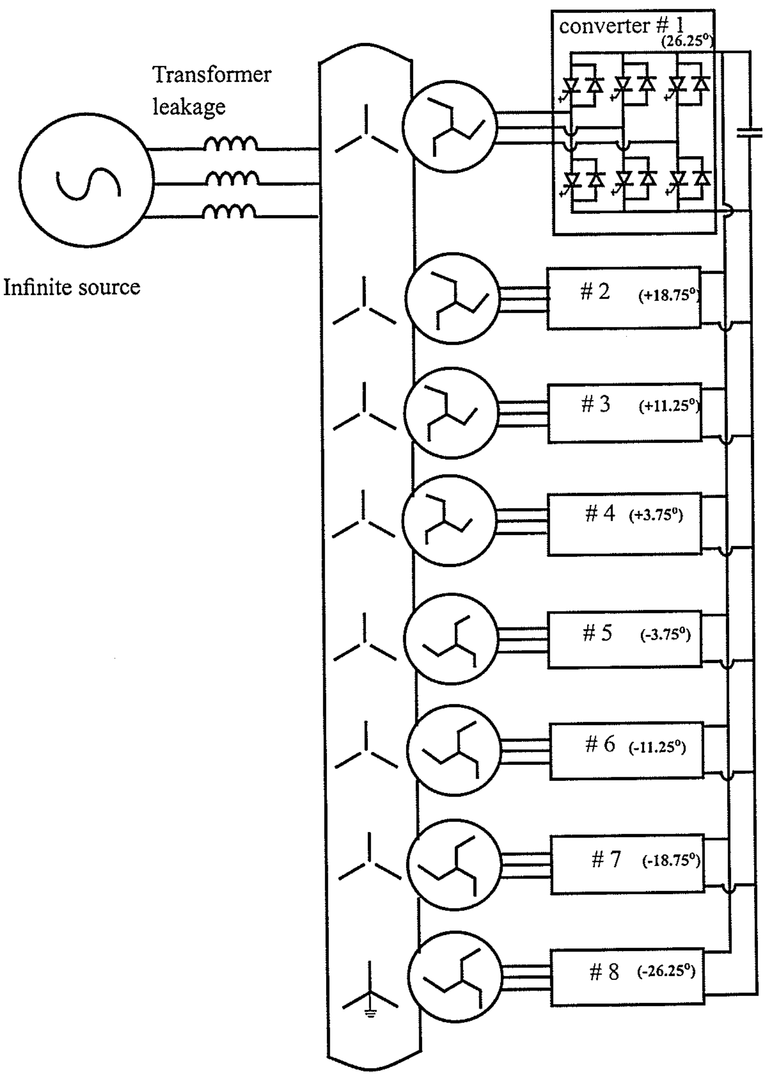


Fig. 4.2 A 48-pulse STATCOM with zig-zag coupling transformers

the zig-zag secondary windings are designed to give phase shift of +26.25°, +18.75°, +11.25°, +3.75°, -3.75°, -11.25°, -18.75° and -26.25° respectively. This results in only four transformer types among the eight transformers employed. The transformed outputs of all converters (which are in phase) are summed by the series connection of all corresponding primary windings. Each transformer is rated at 1/8 of the total VA output.

4.3.2 Results of Simulations and Discussions

The main purpose of this studies is to investigate several operating of STATCOM topologies. The selection of the capacitor is a design problem. The value of 100 μF chosen is probably unrealistically large, but does not have a bearing on the essential arguments.

In the simulation, the STATCOM was set to operate at full leading mode. Fig. 4.3 shows the output voltage waveform of the STATCOM. It can be seen that the STATCOM output voltage waveform has a 48-pulse staircase waveshape. Although this waveform does not have the perfect sinusoidal shape, the current that the STATCOM drawn through its leakage impedance almost looks

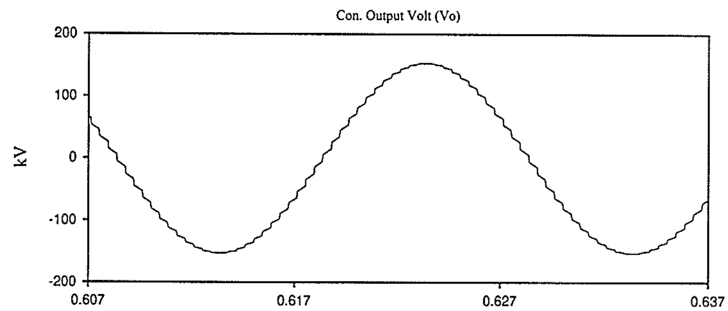


Fig. 4.3 A true 48-pulse STATCOM output voltage

like a sinusoidal shape as shown in Fig. 4.4. As can be seen from the line current harmonic spectrum shown in Fig. 4.5, the lowest harmonic component is the 47th. and it presence is not significant as far as it amplitude is concerned. The line current THD is calculated as 1.2%. Hence, this 48-pulse STATCOM can be installed without passive filter. Passive filters can cause additional dynamic response that may degrade overall system performance. Additional resonances may occur in the system employing the passive filters. Furthermore, it may increase the cost. However, this circuit requires that the voltage shared by each unit transformer be uniform by the adoption of the same value for the leakage impedance of each unit transformer. In the simulation, the zigzag transformer leakage values have been made purposely very small to avoid voltage imbalance problem.

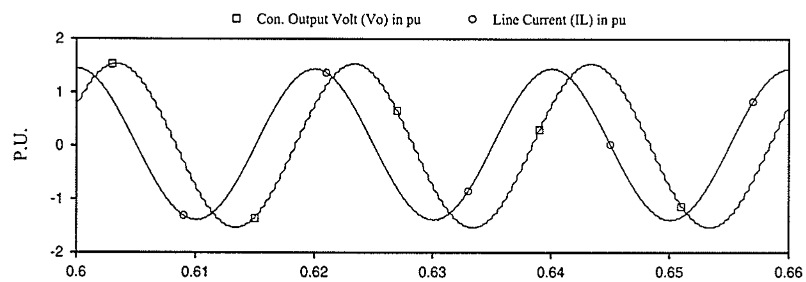


Fig. 4.4 Line current and STATCOM output voltage

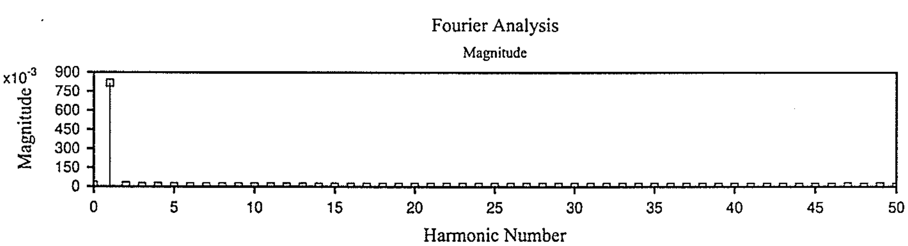
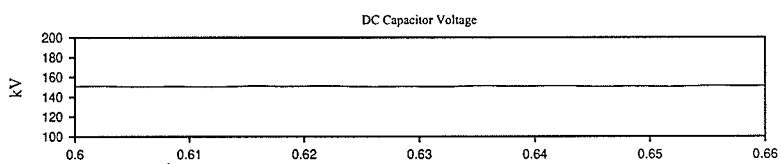
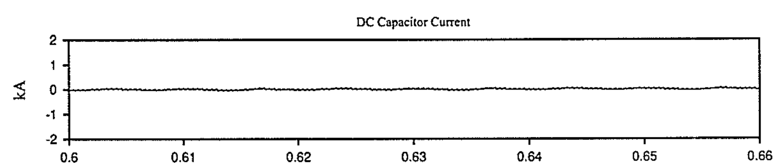


Fig. 4.5 Line current harmonic spectrum

On the dc part of the STATCOM circuit, a similar clean waveform quality is manifested. Fig. 4.6(a) illustrates almost a constant zero dc current. The Fourier analysis of the dc current is shown in Fig. 4.7 on the next page. The peak-to-peak ripple on the dc voltage is only 0.5%. Hence, it can be said that the capacitor is able to maintain nearly a constant dc value without showing any significant fluctuation.



(a)



(b)

Fig. 4.6 DC-capacitor current and voltage

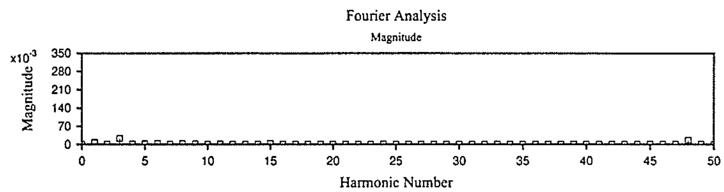


Fig. 4.7 DC-capacitor current harmonic spectrum

4.4 A QUASI 48-PULSE STATCOM

As explained in chapter 3, a quasi multipulse method does not use a phase shifting transformer as in the previous circuit. Hence, the problem of leakage balancing can be avoided. This quasi 48-pulse STATCOM circuit elegantly exploits the conventional wye/delta transformer to form a true 12-pulse converter as a basic building. Then, a number of these basic building blocks called module are assembled to form a quasi 48-pulse STATCOM.

4.4.1 Structural and Operational Arrangement

For a 48-pulse STATCOM, four identical modules are used. These

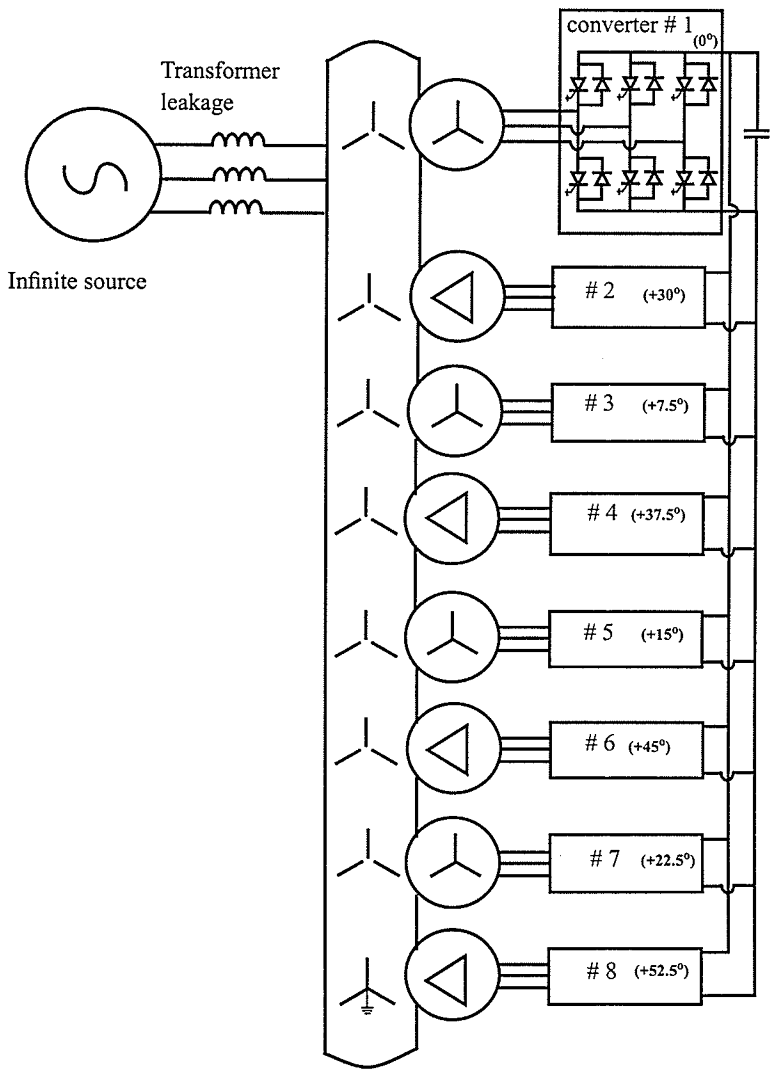


Fig. 4.8 A quasi 48-pulse STATCOM with conventional transformers

modules are combined by connecting the corresponding primary windings of all transformer in series as shown in Fig. 4.8. A module incorporates two six-pulse converters, one operated from a wye to wye, and the other from a wye to delta transformer. The converters in any unit module are operated as a true 12-pulse STATCOM i.e. with 30^{o} phase displacement. In addition, each module is operated with successive 7.5^{o} phase displacement using electronic phase delay (quasi).

4.4.2 Results of Simulations and Discussions

The first small difference between this circuit and the previous one can be spotted in the converter output voltage waveshape. The quasi 48-pulse STAT-

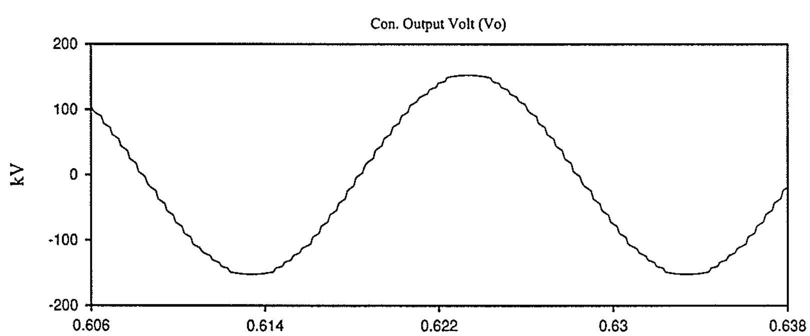
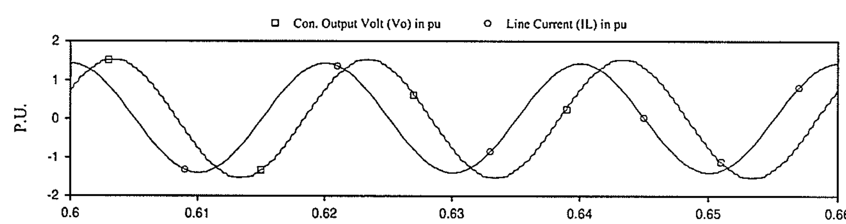


Fig. 4.8 A quasi 48-pulse STATCOM output voltage

COM output voltage does not have equal 48-pulse staircase waveshape as in the true 48-pulse STATCOM. As shown by Fig. 4.9, the waveshape has less than 48-pulse staircases. Another difference performance is the presence of residual 12-pulse harmonic in the line current. The line current and its spectrum, shown in Fig 4.10, illustrates the present of 11th, 13th, 23, 25th etc. harmonics. However, their amplitudes are very small as demonstrated by the 1.6% THD number. Hence, it can be said that the quasi 48-pulse STATCOM could approximate the line current harmonic performance as in the true 48-pulse STATCOM.

(a)



(b)

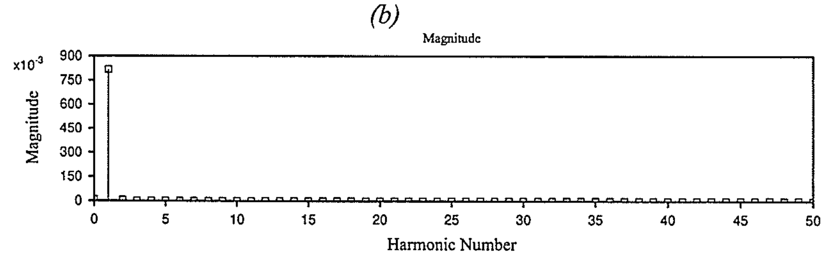
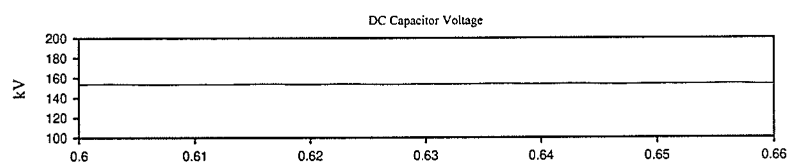
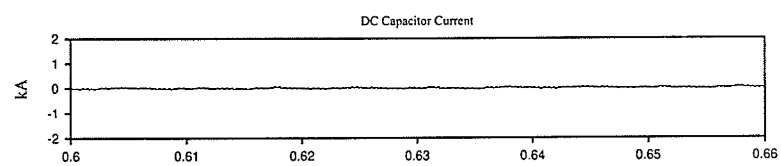


Fig. 4.10 Line current, STATCOM output voltage and line current harmonic spectrum

On the dc side of the circuit, the capacitor dc current (Fig. 4.11(a)) and voltage ripple (Fig 4.11(b)) are almost agreeable as in the true 48-pulse. The harmonic spectrum for the capacitor dc current is given in Fig 4.12. The magnetic circuit could be further optimized by using a common iron structure reducing overall MVA windings; but is beyond the scope of this thesis.



(a)



(b)

Fig 4.11 DC capacitor voltage and current

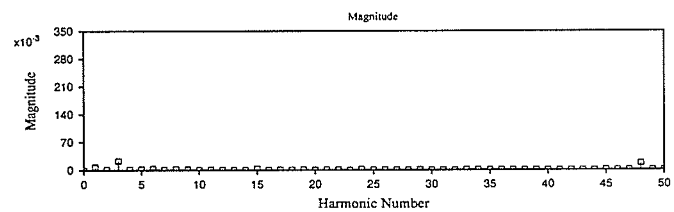


Fig. 4.12 DC current harmonic spectrum

4.5 A QUASI 48-PULSE WITH UNIFORM TRANSFORMERS

The concept of this circuit is similar to the previous circuit. The modification is made on the coupling transformers. Now the transformer configuration is divided into two separate structures. One is called the uniform wye transformers and the other is the main step-up transformer, as illustrated in Fig. 4.13. The converters are grouped into two 24-pulse module STATCOM. The top and bottom groups are called the wye and the delta converter groups respectively, corresponding to the type of winding which they are connected to at the main transformer.

4.5.1 Structural and Operational Arrangement

The uniform wye transformer structure consist of wye/wye windings with series connection on the primary.The wye and delta converter groups have identical uniform wye structure. However, they are differ in firing angle control, as indicated in Fig. 4.13. The main transformer is a single step down having wye and delta secondary.

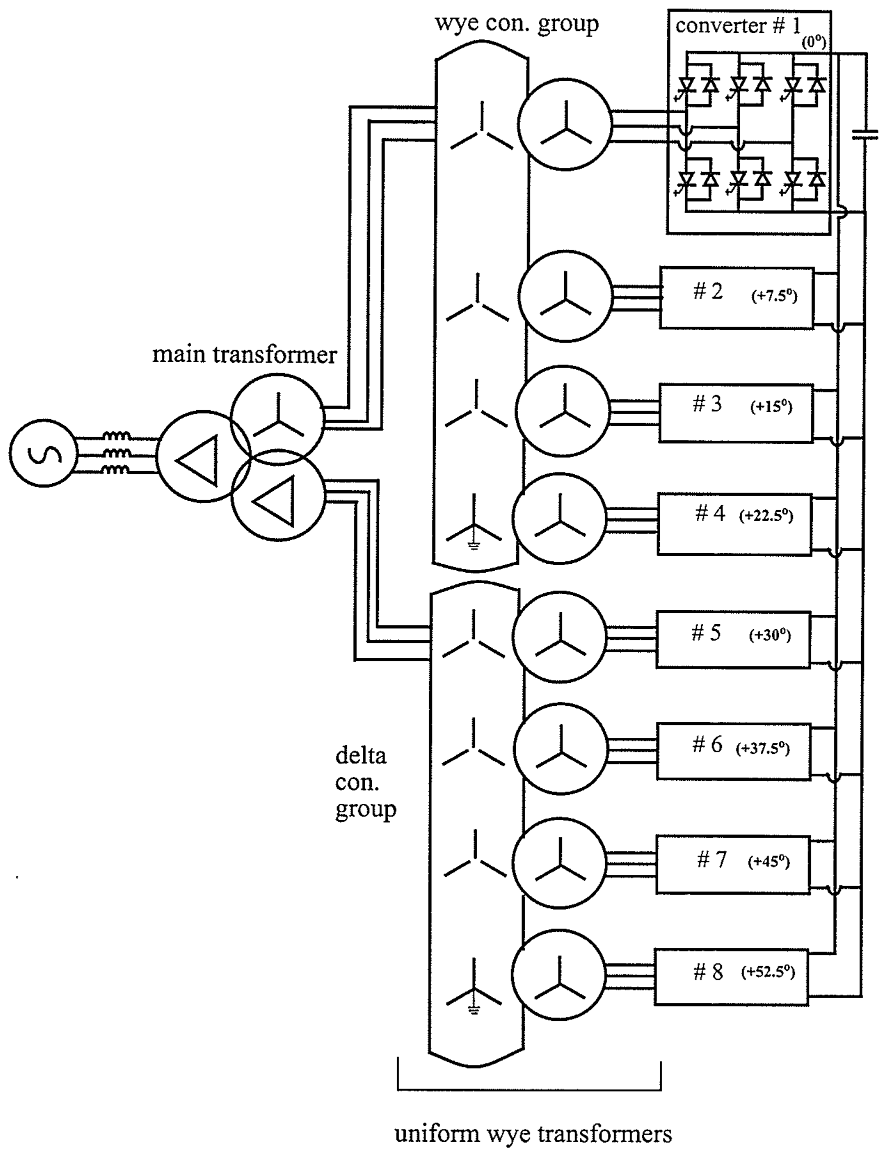


Fig. 4.31 A quasi 48-pulse STATCOM with uniform wye transformers

4.5.2 Results of Simulations and Discussion

Fig. 4.14(a) is the output voltage of the top wye converter group. It has small residual of 6-pulse harmonic as shown in Fig. 4.14(b). However, these har-

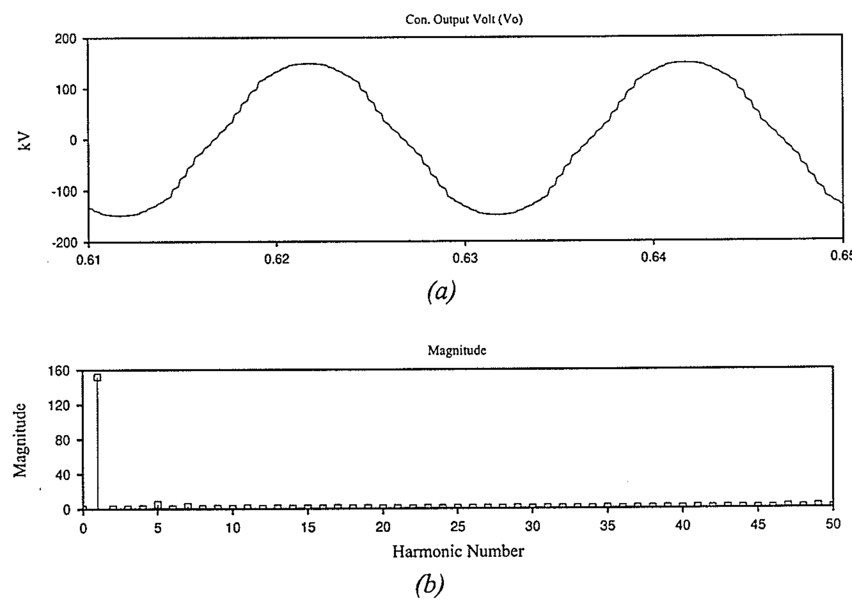


Fig. 4.14 The top converter group output voltage and its harmonic spectrum

monics do not exist in the final STATCOM output voltage which exhibits much better waveshape as shown in Fig. 4.15. The line current and its harmonic spectrum illustrated in Fig. 4.16 confirm the similar characteristics of this circuit, on the line side, with the previous circuit. However, due to the small presence of residual 6-pulse harmonics in the converter side the capacitor current shows a slightly more ripple than then in previous circuit (Fig. 4.17(b) and 4.18). The same can also be said to the capacitor voltage (Fig.4.17(b)). Having mentioned all these,

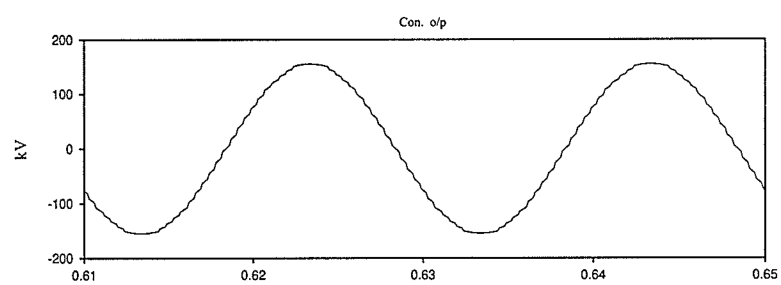


Fig. 4.15 The STATCOM output voltage

this circuit is certainly comparable to the other two options discussed earlier especially the final output voltage that it produced. The uniformity of the wye windings transformer is a plus point to this circuit. The transformers may be cheaper and lighter.

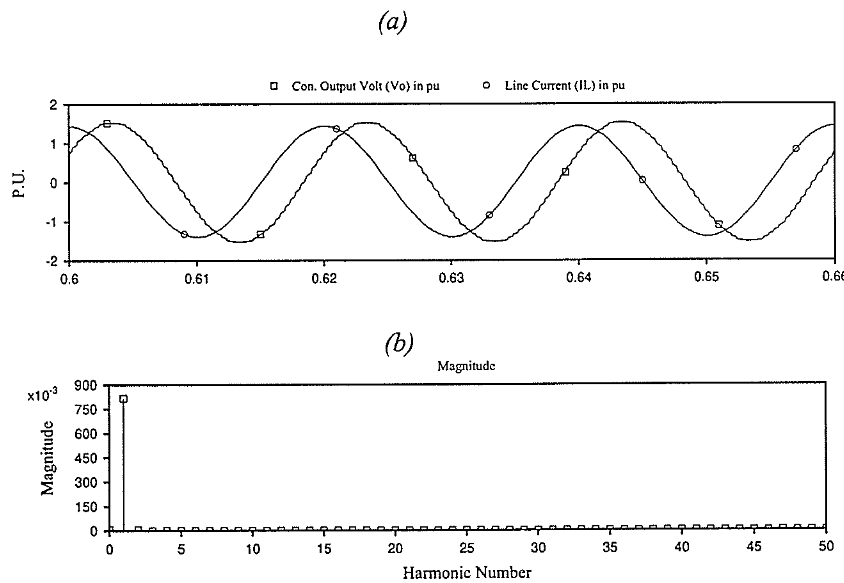


Fig. 4.16 Line current, STATCOM output voltage and line current harmonic spectrum

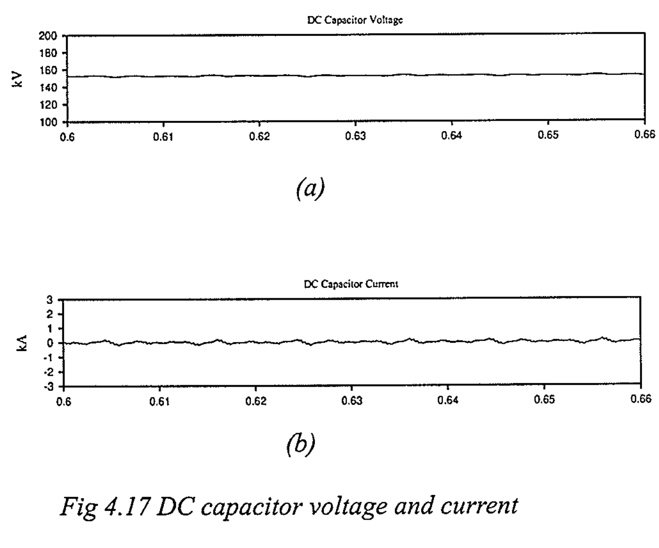


Fig 4.17 DC capacitor voltage and current

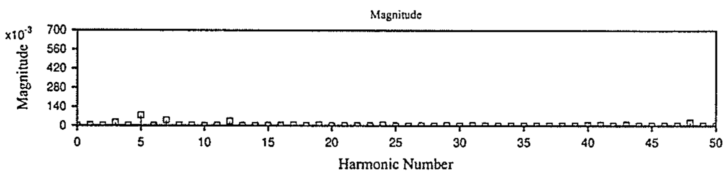


Fig. 4.18 DC current harmonic spectrum

CHAPTER 5

Conclusions

5.1 CONCLUSIONS

There are many possible circuit configurations for multi-pulse type STATCOMS. A number of them have been introduced and compared in this study. They have shown a fairly large difference in harmonic performance. Therefore, the choice of a circuit for a certain application has to be made very carefully. The main benefit of the multi-pulse connection is the improvements in the harmonic performance. As the number of pulses increase further reduction in harmonics is achieved. The power rating is also increased when a STATCOM has more basic converter bridges in its structure. However, increasing the pulse numbers would add more transformers and complicate the winding arrangements.

In this thesis, a total of eight topologies of basic 6-pulse, 12-pulse and 48-pulse STATCOM have been modelled and evaluated to verify their performance. The basic 6-pulse STATCOM has large low order harmonics in the output voltage and corresponding components in the line current. Therefore, this simple circuit is impractical for high power applications.

Multi-pulse methods have been applied to the STATCOM circuit design for improvement in its harmonic performance. There are various possible circuit arrangements, using different magnetic devices, to implement a multi-pulse STATCOM. The 12-pulse is the basic multi-pulse STATCOM. Four different transformer arrangements of 12-pulse STATCOM have been presented which show a different harmonic performances.

The basic quasi 12-pulse circuit only minimizes the 5th and 7th harmonic components while the true 12-pulse configurations have eliminated them completely. The true 12-pulse circuit with only a wye/delta transformer represents the simplest transformer arrangement. However, the transformer ratio is confined to only one to one ratio. The next circuit considered is the one which used multiple secondary winding. This circuit requires larger MVA capacity as a result of partial harmonic elimination on the converter side. The last 12-pulse circuit used the largest number of windings but lower rating. However, it has the best harmonic performances among all. Despite the improved harmonic performances shown by the 12-pulse STATCOM, a passive filter is still required. Circuit (a) requires the largest passive filter since it implement a quasi multi-pulse method where harmonic cancellation is incomplete.

The perfect STATCOM would generate sinusoidal output voltage and draw a pure dc input current without harmonics. All the 48-pulse STATCOM topologies studied in this thesis have been shown to be able to approximate satisfactorily this ideal condition. However, the zigzag transformer used in the true 48-pulse circuit has a leakage balancing problem. The quasi 48-pulse with conventional wye/delta transformer can avoid the leakage problem. It is clear that 48-pulse STATCOM could achieve adequate waveform quality without a passive filter. It has also been shown that the STATCOM with smaller capacitance value would react faster to the dynamic change in reactive power demand. A slight fluctuation of dc current in the of 48-pulse STATCOM allows an employment of a small size capacitor in the circuit. Hence, one of the advantage of having a 48-pulse connection is the faster response to the dynamic change. The quasi multi-pulse behave just like the true multipulse when the pulse number is as high as 48. Consequently, the choice has to be for the quasi multipulse arrangements since it offers uniformity in transformer design by using the conventional wye/delta winding. The quasi 48-pulse with uniform wye winding transformers separates the coupling transformer into two parts. The selection of this circuit for the 48-pulse STATCOM depends very much on achievement to reduce the weight of the transformer and the manufacturing cost.

5.2 RECOMMENDATIONS FOR FURTHER WORKS

For a true evaluation, the following points should be given the considerations:

a) Compared with a multi-level technique of improving the harmonic performances.

b) Optimization of the magnetic structure.

c) More work have to be done on the dynamic response of the device when connected to a transmission line.

d) Design of capacitor, transformer etc.

e) Fault studies.

References

[1] I.A.Erinmez, Ed., “Static Var Compensator,” Working Group 38-01, Task Force No. 2 on SVC, CIGRE 1986.

[2] R.R.Wood et. al., “FACTS Overview, Draft No. 2,” Working Group 14.14, CIGRE 1994.

[3] C.W.Edwards, K.E.Mattern, E.J.Stacey, P.R.Nannery, J.Gubernick, “Advanced Static Var Generator employing GTO Thyristors,” IEEE Transcations on Power Delivery, vol.3, no. 4, October 1988, pp. 1622-1627.

[4] L.Gyugyi, “Dynamic Compensation of AC Transmission Lines by Solid-State Synchronous Voltage Sources,” IEEE Transactions on Power Delivery, vol. 9, no. 2, April 1994, pp. 904-911.

[5] E.Larsen, N.Miller, S.Nilsson, S.Lindgren, “Benefits of GTO-Based Compensation Systems for Electric Utility Application,” IEEE Transactions on Power Delivery, vol. 7, no. 4, October 1992, pp.2056-2064.

[6] Manitoba HVdc Research Centre : *PSCAD/EMTDC User Manuals*, Copyright © 1986 1988 Manitoba HVdc Research Centre, Winnipeg, Manitoba.

[7] A.M.Gole, A.R.Dawood,"New Circuit Concepts for HVDC", Working Group 14.22, 36th CIGRE SESSION, Paris 1996.

[8] Rashid,"*Power Electronics*" (book), Prentice Hall 1988.

[9] D.Wuest,"An Improved PWM Optimization for a Reactive Power Compensator with Self-Commutated Inverter", Power Electronic Specialists Conf., Cambridge MA1991, pp. 763-768.

[10] S.Mori, K.Matsuno, T. Hasegawa, S.Ohnishi, M.Takeda, M.Seto, S.Murakami, F.Ishiguro, "Development of a large Static Var Generator using Self-Commutated Inverters for Improving Power System Stability," IEEE Transactions on Power System, vol. 8, no. 1, February 1993, pp. 371-377.

[11] N.Jenkins, Ekanayake, "A Three-level Advanced StaticVar Compensator", IEEE Transactions on Power Delivery, Vol.11, No. 1, January1996, pp. 540-545.

[12] Y.Sumi, Y.Harumoto, T.Hasegawa, M.Yano, K.Ikeda, "New Static Var Control using Force-Commutated Inverter," IEEE Transactions on Power Apparatus and Systems, vol. 100, no. 9, September 1981, pp. 4216-4224.

[13] A.M.Gole, V.K.Sood, L.Mootoosamy, "Validation and Analysis of a Grid Control System using d-q-z Transformer for Static Compensator System", Canadian Conference on Electrical & Computer Engineering, Montreal, September 1989, pp 745-748.

[14] D.A.Paice, "*Power Electronic Converter Harmonic: Multipulse Methods*" (book), IEEE Press 1996.

[15] L.Gyugyi, N.G.Hingorani, P.R.Nannery, N.Tai, "Advanced Static Var Compensator Using Gate Turn-Off Thyristors for Utility Applications," paper no. 23-203, CIGRE 1990.

[16] D.Wuest, H.Stemmler, G.Scheuer, "A Comparisons of Different Circuit Configurations for an Advanced Static Var Compensator", Power Electronic Specialist Conf. 1992, pp. 521-529.

[17] C.Schuder, M.Gerhardt, E.Stacey, T.Lemak, L.Gyugyi, T.W.Cease, A.Edris, "Development of a 100 MVAR Static Condenser for Voltage Control of Transmission Systems,"IEEE Transactions on Power Delivery, vol. 10,no. 3, July 1995, pp. 1486-1496.

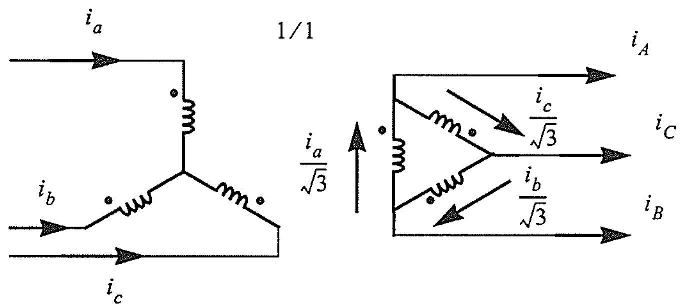
[18] L.Walker, "10-MW GTO Converter for Battery Peaking Service," IEEE Transcations of Industry Applications, vol. 26, No. 1, Jan'Feb 1990, pp.63-72.

STATCOM Rating (Primary side)

Rated capacity	100 MVA
Rated voltage	100 kV
Rated current	577.4 A
Rated frequency	60 Hz
Phase	3 phases

Converter Rating

Rated capacity	100 MVA
Rated DC voltage (Vdc)	128.56 kV
Rated AC voltage	100 kV
Rated AC current	577.4 A
Pulse number	6



$$i_A = \frac{i_a - i_c}{\sqrt{3}}$$

$$i_B = \frac{i_b - i_a}{\sqrt{3}}$$

$$i_a + i_b + i_c = 0$$

$$i_A = a_1 \sin(\theta) + a_5 \sin(5\theta + \lambda_5) + a_7 \sin(7\theta + \lambda_7) + a_{11} \sin(11\theta + \lambda_{11}) + \ldots$$

$$i_B = a_1 \sin\left(\theta - \frac{2\pi}{3}\right) + a_5 \sin\left(5\theta + \lambda_5 + \frac{2\pi}{3}\right) + a_7 \sin\left(7\theta + \lambda_7 - \frac{2\pi}{3}\right) + a_{11} \sin\left(11\theta + \lambda_{11} + \frac{2\pi}{3}\right) + \ldots$$

Note: $\sin x - \sin\left(x - \frac{2\pi}{3}\right) = \sqrt{3}\sin\left(x + \frac{\pi}{6}\right)$ and

$$\sin x - \sin\left(x + \frac{2\pi}{3}\right) = \sqrt{3}\sin\left(x - \frac{\pi}{6}\right)$$

thus,

$$\frac{i_A - i_B}{\sqrt{3}} = a_1 \sin\left(\theta + \frac{\pi}{6}\right) + a_5 \sin\left(5\theta + \lambda_5 - \frac{\pi}{6}\right) + a_7 \sin\left(7\theta + \lambda_7 + \frac{\pi}{6}\right) + \ldots$$

Let,

$$i_a = i_{a\Delta}$$

Hence,

$$i_{a\Delta} = a_1 \sin\left(\theta + \frac{\pi}{6}\right) + a_5 \sin\left(5\theta + \lambda_5 - \frac{\pi}{6}\right) + a_7 \sin\left(7\theta + \lambda_7 + \frac{\pi}{6}\right) + \ldots$$

If θ is referred to the wye bridge, then we must replace θ with $\theta - \frac{\pi}{6}$

thus, $$i_{a\Delta} = a_1 \sin(\theta) + a_5 \sin\left(5\theta + \lambda_5 - \frac{5\pi}{6} - \frac{\pi}{6}\right) + a_7 \sin\left(7\theta + \lambda_7 - \frac{7\pi}{6} - \frac{\pi}{6}\right) + \ldots$$

Since,

$$i_{ay} = a_1 \sin(\theta) + a_5 \sin(5\theta + \lambda_5) + a_7 \sin(7\theta + \lambda_7) + a_{11} \sin(11\theta + \lambda_{11}) + \ldots$$

Therefore,

$$i_{a\Delta} + i_{ay} = 2a_1 \sin(\theta) + 2a_{11} \sin(11\theta + \lambda_{11}) + \ldots$$