CARRIER BASED PWM-VSI DRIVES IN THE OVERMODULATION REGION

By

Ahmet M. Hava

A dissertation submitted in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

(Electrical and Computer Engineering)

at the

UNIVERSITY OF WISCONSIN – MADISON

1998

Abstract

Pulse Width Modulated Voltage Source Inverters (PWM-VSI) are widely utilized in motor drive and other three-phase power conversion applications as voltage/current sources with controllable output frequency and magnitude. The choice of pulse width modulation method strongly affects the inverter energy efficiency, waveform quality, and voltage linearity. However, the dependence of these performance characteristics on the modulator type is not well understood.

This thesis attempts an in-depth analysis of switching loss, waveform quality, and voltage linearity characteristics of the modern PWM methods. The analytical results aid the development of simple, yet highly efficient modulation strategies and control algorithms. A Generalized Discontinuous PWM method (GDPWM) which minimizes the switching losses and provides a wide voltage linearity range has been developed. Algorithms which combine the superior performance characteristics of the GDPWM method with other high performance PWM methods have been established. Modulator voltage linearity characteristics have been thoroughly investigated. Both the per carrier cycle voltage linearity and per output voltage fundamental cycle voltage linearity characteristics have been analytically modeled. In the nonlinear modulation (overmodulation) range, the influence of the modulator nonlinearity on the drive steady state and dynamic performance has been thoroughly investigated. As a result high performance overmodulation algorithms could be developed for various drives and applications. With a strong emphasis on the overmodulation region performance of both open loop voltage feedforward controlled drives and closed loop current controlled drives, all the performance characteristics could be enhanced by employing the novel modulation methods and control algorithms. The theory has been supported with computer simulations and laboratory experiments and strong correlation has been obtained.

In addition to developing new modulation methods and control algorithms, this thesis establishes analytical and graphical methods for the study, performance evaluation, and design of the modern PWM methods. Also simple techniques for generating the modulation waves of the high performance PWM methods are described.

Acknowledgements

The ten years I spent at the University of Wisconsin-Madison as a graduate student were rather difficult. Many years of exhaustive search for a useful thesis research topic rendered me quite exhausted. I am indebted to my family and friends for all the support and encouragement they gave me throughout these years. Without them, I could not find the inner strength to survive these years.

I am grateful to the Turkish Republic and its people for the generous scholarship they provided me for many graduate school years. Without this scholarship, I would have never gotten the opportunity to attend the University of Wisconsin-Madison, a great place to seek knowledge and grow up.

I thank my advisor Professor Thomas A. Lipo and my final defense committee Professors Robert D. Lorenz, Deepak M. Divan, Richard S. Marleau, Donald W. Novotny of University of Wisconsin-Madison, and Dr. Russel J. Kerkman of Rockwell Automation-Allen Bradley Company.

My thesis research topic was developed in 1995 while I was working at Rockwell Automation-Allen Bradley Company as an intern student. Dr. Kerkman was my thesis research co-advisor. I am indebted to him for giving me the opportunity to work with his R&D group, and providing me significant support, guidance, and encouragement. I am grateful to Dr. Kerkman's R&D group members, especially to Mr. David W. Schlegel, for their help and friendliness.

Many thanks to Professor Novotny for those many great electric machines lectures. Special thanks to Dr. Luis J. Garcés of General Electric Company, who taught me a lot about drives and helped me with my thesis research, especially at the times I needed guidance most. Many thanks to Dr. Tsuneo Kume, my Supervisor at Yaskawa Electric America Inc., for his great help. It was very kind of him to allow me to complete the final pieces of my thesis at work. In addition, he has significantly contributed to my practical knowledge on drives.

Special thanks to the WEMPEC administrator, Kathleen Torok who has been a great friend and a perfect administrator. When I needed help, she was always there! Also thanks to many WEMPEC students, associates, and visitors for their help and friendliness.

My mother and maternal grandmother have been the two most influential people in my life. With their high morals and hard work, they have given me great guidance to success. Their love, care, and support has given me great inner strength to battle many years of hardship. Without their encouragement and efforts, I know I would not even make it to any engineering school. I am very grateful to them for everything they have given me. This work is dedicated to them.

Contents

Chapter 1

Introduction

The twentieth century is the most rapid technology advancement era in human civilization history. The substantial progress of the physical sciences in the preceding two centuries, in particular discoveries relating to electricity and magnetism, indicated devices operating with electric energy could offer significant advantages over human being's physical abilities. As a result, the twentieth century witnessed the invention of tremendous amount of devices most of which generate or utilize electric energy and provide service to the society. From food processing, textile, construction, metal industry etc. to transportation, communication, computer, education, entertainment etc. most necessities of today's society and environment involve electric energy and devices utilizing it.

In the early decades of the twentieth century the constant frequency constant voltage magnitude balanced three phase Alternating Current (AC) electric power source was found to be the most economical type for generation and transmission and was considered to be the most useful form of electric energy for many applications. Therefore, industrial loads have been supplied with three phase AC power sources and residential costumers with single phase AC power sources (by balanced distribution of the three phases among various residential areas) through large power grids and interties reaching even the most remote habitation areas of the globe. Until now, the constant frequency and magnitude AC power has remained generally superior to other forms for generation and transmission purposes. However, it has been long recognized that this form of power is not suitable for many industrial processes and residential applications. For example, many chemical processes require controllable Direct Current (DC) voltage source, and most AC motors require three phase AC voltage with controllable frequency and magnitude. In addition, many precision machines and strategically important devices require constant frequency constant magnitude AC voltage source with high reliability and continuous power flow regardless of the utility line unbalances and fault conditions. Therefore, in most of these applications the utility line power can not be directly utilized; interfaces and devices to convert the form of the line power are necessary. The strong demand for power conversion and conditioning devices to achieve these tasks has lead to the establishment of the power electronics field early this century. High performance semiconductor power switches, efficient power converter circuit topologies, and intelligent control algorithms have been invented. As a result of this evolution, today's many industrial and residential loads are connected to the AC power line through cost effective power converter circuits which enhance the overall performance, efficiency, and reliability.

Of all the modern power electronics converters, shown in Figure 1.1, the Voltage Source Inverter (VSI), is perhaps the most widely utilized device with power ratings ranging from fractions of a kilowatt to megawatt level. The VSI consists of six power semiconductor switches with anti-parallel feedback diodes. It converts a fixed DC voltage to three phase AC voltages with controllable frequency and magnitude. Since the VSI has discrete circuit modes for each set of switch states, generating an output voltage with correct frequency and magnitude requires an averaging approach. In the widely utilized Pulse Width Modulation (PWM) methods, the inverter output voltage approximates the reference value through high frequency switching. In AC motor drive applications, typically a rectifier device converts the AC three phase line voltages to DC voltage. Following the rectifier voltage passive filtering stage (typically capacitive filtering with/without DC reactor), the PWM-VSI interfaces the DC source with the AC motor to control the shaft speed/position/torque. In regenerative drive applications and AC-to-DC power conversion applications and also in Uninterruptible Power Supply (UPS) applications, the PWM-VSI provides reliable and high quality bidirectional power flow. When utilized in such applications, the device is often termed as converter (opposite of inverter), hence PWM-VSC. In all cases, power flow is controlled by the inverter switching device gate signals in a manner to obtain high performance, improved efficiency, and reliable operation.

Although its main circuit topology is quite simple, a modern PWM-VSI drive involves an overwhelming level of technology and intelligence. From the semiconductor power switching devices such as Insulated Gate Bipolar Transistors (IGBTs) operating at frequencies as high as many tens of kilohertz to

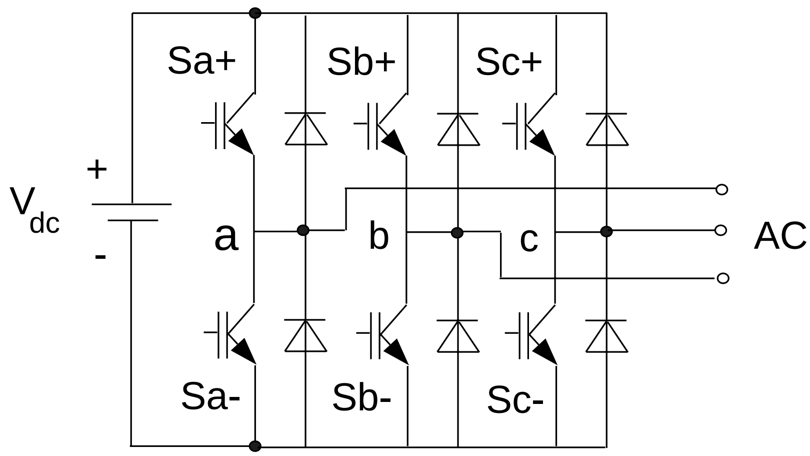

Figure 1.1: The main power structure of a VSI employing IGBT devices.

the microcontrollers and Digital Signal Processors (DSPs) that process the control signals at speeds beyond many tens of megahertz, most components of a state of the art PWM-VSI drive involve advanced technologies. The costumer's increasing demand for multifunctionality, precision performance, efficiency, reliability, and user friendliness has motivated engineers to build a significant amount of intelligence into the microcontrollers and DSPs of the PWM-VSI drives. Load parameter estimation, fault diagnostics, high performance vector control, observer based shaft encoderless speed control, energy efficiency optimization etc. algorithms have been developed and built into the modern PWM-VSI drives. With their global production rate above millions per year, the power ratings ranging from fractions of a kilowatt to megawatts, and the applications ranging from simple house applicances such as air-conditioning units to heavy industries such as steel mills, PWM-VSI drives are modern technology devices which have been experiencing a rapid progress over the last three decades. This rapid progress is partially due to the great effort of many academic and industrial researcher's attempts to respond to the costumers demand for increasing efficiency, reliability, and enhanced performance. And, it is partially due to the substantial progress in the enabling technologies, such as the semiconductor micro and macro electronics technology.

Although the global effort to enhance the performance and maximize the performance to cost and kilowatts to volume ratios of the PWM-VSI has resulted in remarkable progress and various technologically advanced products have been marketed and found large number of applications, the technology is far distant from a complete maturation stage. Several remaining fundamental issues are summarized in the following.

Perhaps shaft encoderless operation of AC motor drives (at/near zero stator frequency) and PWM-VSI size reduction issues (by employing intelligent power modules, reducing the filter components, integrating a motor with an inverter, etc.) are the two most challenging and globally recognized and investigated issues at the present time. Additionally, the electromagnetic compatibility and reliability issues of AC drives with high speed switching devices such as IGBT's (widely utilized in PWM-VSI drives) are significant and await feasible solutions. The academic and industrial research and development effort spent on these subjects over the last decade is substantial. However, performance issues involving the PWM techniques are as important and yet not fully understood and addressed.

Operating an inverter drive beyond the modulator voltage linearity limits, i.e. in the overmodulation region, is problematic. The voltage and current harmonics substantially increase and the dynamic performance is lost. Frequent overcurrent fault conditions occur and the drive performance and reliability degrade. Therefore, the operating range and power rating is constrained.

The linear modulation region switching loss and waveform quality characteristics of the conventional PWM methods are not well understood, and high performance controllers/modulators with implementation simplicity need be developed in order to increase the inverter efficiency and power quality.

Perhaps, the above several paragraphs summarize only a few of the many issues relating to the present state of the commercial PWM-VSI drives. Additionally, the ride-through performance, the unbalanced operating performance, switching device thermal performance, etc. all need be enhanced. It can be concluded from this discussion that the modern PWM-VSI drives have not completed their evolution and the opportunity to further enhance their performance is still vast.

This thesis attempts to address several of the above indicated problems, in particular, those relating to the pulse width modulators. In a PWM-VSI drive, the drive control algorithm generates the voltage reference signals and the modulator programs the inverter switching device gate logic signals. When the logic signals are applied to the inverter switch gates, the switches commutate and an inverter output voltage which approaches the reference voltage over a predetermined carrier cycle is generated. As the gate logic signal source to the power semiconductor switching devices, the pulse width modulator forms the heart of an inverter drive. The choice of the switching sequence, number of switchings, the pulse widths etc. strongly affect the switching losses, inverter output voltage and current waveform quality, and the voltage linearity. Therefore, the modulator selection and design procedure of a high performance drive requires extreme care. On the other hand, choosing a modulator among a large variety is a challenging task. The modulator behavior is difficult to understand due to the nonlinear dependency of the modulator waveform quality, switching loss, and voltage linearity characteristics on several variables. With strong emphasis on voltage linearity characteristics, this thesis investigates the important modulator performance characteristics in detail, develops high performance modulation methods and provides modulator selection and design guidelines.

The fundamental contributions of this thesis are fourfold. First, modern modulators are grouped and characterized. A thorough investigation indicates the equivalency of various modulation methods. An attempt to unify the modern modulation methods successfully reduces their count and yields general rules for modulation signal generation. With the number of methods reduced to less than a handful, the characterization and comparison of their performance becomes a reasonable task. Establishing simple and accurate performance indices, the important modulator linear region performance characteristics (the waveform quality and switching losses) are rigorously analyzed. Graphic illustration of these characteristic functions aids visual learning and understanding the modulator behavior intuitively. In addition, the algebraic performance indices simplify the modulator comparison, selection, and design.

Second, a high performance Generalized Discontinuous PWM (GDPWM) method with on-line controllable characteristics has been developed and its characteristics analytically investigated. Simple to implement, GDPWM can be closed loop controlled to maintain high performance (reduced switching losses and waveform distortion etc.) as opposed to the conventional modulators with predefined performance characteristics.

The third important contribution involves the overmodulation region performance investigation of voltage feedforward controlled open loop constant volts per hertz ($\frac{V}{f}$) drives. Detailed fundamental component voltage gain and waveform quality characterization of all modern modulators reveals the advantageous nature of a discontinuous PWM method in the linear high modulation and overmodulation regions. The inverter blanking time and the minimum pulse width constraints are shown to have substantial effect on the modulator linearity and the degradation is shown to be minimal with the discontinuous PWM methods.

The fourth important contribution of this thesis involves the dynamic overmodulation region behavior of closed loop current controlled high performance AC drives such as field oriented AC motor drives and PWM-VSC drives. The detailed theoretical and experimental investigations show the strong interaction between the modulator and current controller can lead to drive instability and failure. The degree of instability is shown to strongly depend on the modulator type. Therefore the dynamic overmodulation characteristics should be considered in the modulator design process. Also steady state overmodulation in current controlled drives is studied and the performance issues discussed. The studies of this section aid the closed loop controlled high performance drive modulator design and control algorithm development process. High performance algorithms enhance the drive power output capability and the drive dynamic performance.

Overall, this thesis attempts an in-depth modulator analysis and the study yields precise design rules and high performance control algorithms for modern PWM-VSI drives. The emphasis of the thesis is on the overmodulation region. However, during the thesis evolution stage, a substantial effort was spent towards understanding the linear modulation region behavior. This effort yielded several important contributions to the linear modulation subject. Therefore, a substantial portion of the thesis also involves the linear modulation region behavior analysis and performance enhancement. The thesis clarifies most of the common misconceptions about PWM and simplifies the design and performance prediction task. With the novel high performance modulator and control algorithms, it enhances the PWM-VSI drive performance. As a result, the modern PWM-VSI drives advance one step closer towards becoming ideal power electronic converter devices.

The organization of this thesis is in the following order. In the second chapter, a detailed literature survey and state of the art assessment is provided. The in-depth survey reveals the importance of several neglected publications and illustrates some common misconceptions about modulators. The linear modulation and overmodulation region performance issues of the state of the art PWM-VSI drives are discussed in detail. A broad survey of the overmodulation operating region performance issues prepares the reader to recognizing the difficulty involved in operating in the overmodulation region.

The third chapter classifies the modern PWM methods, develops efficient methods to generate their modulation waves, and analytically investigates their waveform quality and switching loss performances with simple performance indices. The chapter also involves development and performance analysis of the GDPWM method. The superiority of this method over conventional modulators is illustrated both by theory and laboratory experiments.

The fourth chapter involves the overmodulation region characteristics of open loop voltage feedforward controlled drives. The fundamental component voltage gain characteristics are analytically derived and waveform quality investigated. The narrow pulse problems are discussed and finally performance comparison and modulator design are discussed.

The fifth chapter addresses the dynamic overmodulation region performance issues of closed loop current controlled drives such as the high performance field oriented motor drives. Following the modulator per carrier cycle dynamic behavior analysis, an intuitive explanation supported with computer simulations and experimental work illustrate the performance issues of several popular PWM methods and solutions to the problem are investigated. The steady state overmodulation performance issues of current controlled drives are also studied and detailed computer simulations illustrate the performance limitations of such drives.

The sixth and final chapter summarizes the research results and recommends further investigations on subjects related to this thesis.

Since this thesis has contributions in various weakly related areas of modulation and drive technologies, the experimental investigations are discussed at the relevant stages of the associated chapters instead of being discussed all together in a separate chapter. Therefore, experimental work of each subject is discussed in the associated sections immediately after establishment of the theory.

Chapter 2

Literature Review and State Of The Art Assessment

2.1 Introduction

The one and a half century of progress in the electric machines field, about three quarters of a century of progress in the power electronics field, and about half a century of progress in the micro-electronics/macro-electronics and control fields are inherited in the state of the art PWM-VSI drives. Mostly occurring at different time frames, the breakthroughs experienced in each field have strongly and positively influenced the evolution of today's various types of cost effective, efficient, compact, and reliable high performance PWM-VSI drives. Since they involve various disciplines of engineering and there has always been a strong demand for them in the market, PWM-VSI drives have continuously drawn the attention of many researchers all around the world. Therefore, in parallel with this progress, a substantial amount of literature relating to electric drives has been accumulated. In particular, the literature involving the PWM methods and drive control algorithms has surpassed thousands. Following a brief review of the early drives history, state of the art PWM-VSI drives will be described and the fundamental contributions to the area will be discussed in detail in this section.

2.2 A Brief History of Inverter Drives

Following the discoveries of electricity and magnetism laws in the preceding two centuries, the nineteenth century witnessed the invention of the DC machine, synchronous machine, the induction machine (1885 Ferraris, 1887 Tesla [7]) and the squirrel cage rotor induction machine (1890, Dobrowolsky). In particular, the last two inventions recently have found wide range of applications and the induction machine has become the workhorse of industry. From the early period to the present time the electric machines field experienced a continuous progress. Machines with improved structure and performance characteristics could be manufactured at reduced cost. As the machine characteristics have been investigated in detail and better understood, high performance control methods could be developed.

DC machine speed regulation by armature voltage control was established by Ward Leonard in 1891 [153], and in the following years high performance speed/position/torque control of DC machine methods were established. The constant $\frac{V}{f}$ operation principle of voltage feedforward controlled open loop AC induction motor drives was established in the first half of the twentieth century. High performance induction machine control methods, however, were not developed until late 1960's. Since the induction machine dynamic behavior is more involved than the DC machine, mathematical methods were needed for understanding the dynamics and establishing high performance control methods. Following the establishment of the space vector theory in the 1950's [108], the Field Orientation Control (FOC) method was established by Hasse [61] and Blaschke [15, 16] in the late 1960's for high performance induction motor control. Since the FOC induction machine drive could approach or outperform a high performance DC machine drive, and offer cost reduction and ruggedness, it could replace DC drives in most applications. Permanent Magnet (PM) AC machines have recently emerged as a superior solution (to the DC machine predecessors) for high performance servo drive applications due to their high energy density, high efficiency, and reliability [183]. With the increasing energy cost, the PM machines are also becoming attractive for many industrial drive applications. Also, observer based shaft encoderless motion control methods for AC machines have been under development since the late 1970's. Therefore, the progress in the field of electric machines and their control has been continuous and at an increasing rate. However, all the advanced control methods require involved controllers and more importantly power sources with controllable characteristics, i.e. power electronic converters. Therefore, the developments in the electric machines area have generally been in parallel to the power electronics, control theory, and analog/digital microelectronics fields.

The power electronics field was established early in the twentieth century. By the middle of the century, power converters such as the mercury valve rectifiers, thyratrons, metal tank rectifiers, cycloconverters, load commutated inverters, current source and voltage source inverters, etc. were invented. Capable of controlling the flow rate and the form of electric energy, these power converters could regulate the electric machine motion and could control processes requiring electric power in AC or DC form. In particular, the invention of the three phase VSI was significant as it proved to be a high performance and cost effective device. The early development years of power converters (including the VSI), have been discussed in detail in [13, 128, 152, 154, 204]. Owen reviews the history of inverters and credits D. Prince for the invention of the earliest inverter device in 1925 [152]. He suggests the name "inverter" was given to this device for its operating characteristics are the reverse of the rectifiers; instead of AC to DC voltage transformation, DC to AC. The first practical application of three phase inverters is claimed to be in textiles [154]. However, inverters did not find widespread applications until the development of the modern power electronic switches.

Perhaps, the modern power electronics era began with the invention of the thyristor device in 1957. Overcoming the size, cost, efficiency, reliability, and performance deficiencies of the previous power converter switching devices, the solid state semiconductor made thyristor gained immediate acceptance. In particular, its application in power converter circuits with inherent natural commutation characteristics such as cycloconverters, phase controlled rectifiers, reactive power compensators, etc. has been the most practical solution to the present date. However, lacking self commutation capability, the thyristor would require involved commutation circuits in forced commutation applications, rendering the drive bulky, expensive, and complex. Therefore, its utilization in forced commutation power electronic converters, in particular in the VSI applications, was limited and become obsolete with the invention of gate-turn-off solid state semiconductor devices such as the Bipolar Junction Transistor (BJT), Metal Oxide Silicon Field Effect Transistor (MOSFET), Insulated Gate Bipolar Transistor (IGBT), and at high power the Gate Turn Off (GTO) thyristor. In particular, the IGBT switches have become the most widely utilized devices and have revolutionized the PWM-VSI drives.

The switching frequency of the early power electronic converters was typically low. For example a VSI would operate in the six-step mode, yielding a switching frequency equal to the output voltage fundamental frequency. The intelligence involved in generating the gate signals was not significant and the control could be implemented with analog circuits. However, the low switching frequency would result in large amount of low frequency harmonic voltages/currents and therefore large amount of motor harmonic losses, torque ripple, etc. would be generated. With the continuously increasing switching frequency capability of the solid state semiconductor devices, the power electronic converters could transfer energy to the load in small and controlled quantities such that the harmonics and their detrimental effects are substantially reduced. For example, in the VSI the output voltage could be synthesized of controlled width pulses such that the low frequency harmonics are substantially reduced. Therefore, large number of intelligent power electronic switching algorithms, most of which could be classified as PWM methods and on-off principle based current control, have been developed in parallel with the semiconductor device and control theory developments. Beginning in the early 1960's, the PWM field has been exhaustively investigated, and many methods have been developed for various types of converters and various applications. Although the early implementations involved analog circuits, with the increasing pulse pattern complexity and the demand to reduce the control circuit size and cost have lead to the development of the cost effective fully digital controllers which employ high performance microcontrollers, DSPs, and Application Specific Integrated Circuits (ASICs). Large volume production of these microelectronic chips with advanced manufacturing techniques continuously reduced the cost and the performance has been continuously enhanced with the clock speeds surpassing tens of megahertz.

As the historical review indicates the PWM-VSI drives are the product of nearly one and a half century of progress. They first become practical with the availability of the semiconductor switching devices thyristor and BJT, and the progress in the last three decades in the switching device, digital microcontroller and the control methods has lead to today's modern PWM-VSI drives. In the following, we describe the state of the art PWM-VSI drives and discuss the progress made over the last three decades, i.e. in the modern drives era.

2.3 State Of The Art Modern PWM-VSI Drives

2.3.1 The Power Circuit Structure

Modern PWM-VSI drives have a wide range of residential and industrial applications. Since the power rating, performance, cost, size, etc. criteria of each application is different, the inverter drive design and control philosophies of different applications significantly vary. Therefore, a variety of PWM-VSI drives exists.

Generally, the voltage and current ratings required by the application of a PWM-VSI determine its power circuit design. The power circuit topology, type of the switching devices and passive filtering components, the cooling method, etc. are selected based on the drive voltage and current ratings. The higher the power rating, the more emphasis on efficiency, the more the auxiliary circuits and the more complex the cooling requirements. The voltage and current ratings also determine the drive hardware protection circuit complexity. The higher the power the more sophisticated protection circuitry. Finally, the controller and sensor choice is influenced by the performance requirements of the application. The higher the dynamic performance (bandwidth), the higher the controller complexity and the higher the sensor count, bandwidth, and resolution. Therefore, as the power rating and the bandwidth requirements increase, the overall complexity increases.

With the cost being the driving factor, general purpose PWM-VSI drives with low kilowatt ratings (fractional to several tens of kilowatts) are generally designed with minimum component count and complexity. In AC motor drive applications, shown in Fig. 2.1 (a) a single/three phase diode bridge circuit rectifies the AC input voltage and a DC link capacitor filters the rectified voltage forming a stiff DC voltage source. The PWM-VSI converts the DC voltage to three-phase AC voltages with controllable magnitude and frequency via a PWM method. Below about hundred volts MOSFETs and at higher voltages IGBT power semiconductor switching devices are utilized in the VSI, and the switching frequency can be as high as many tens of kilohertz. The power circuit may also contain a DC link capacitor pre-charging circuit, a small EMI filter, and transient voltage suppression devices.

With the AC utility line power quality regulations becoming more stringent, at power ratings higher than several tens of kilowatts the input rectifier device performance becomes important. As shown in Fig. 2.1 (b), an inductor (DC reactor) is inserted in series with the rectifier in order to reduce the harmonic content on both the AC line and the DC link capacitor. Alternatively, a three phase reactor may be inserted in series with the AC line to suppress the harmonics. Also a dynamic brake formed by a resistor and a gate turn-off switch is connected across the DC bus capacitor in order to limit the DC bus voltage under transients and during regeneration (Fig. 2.1 (c)). In regenerative applications with emphasis on energy efficiency back-to-back connected thyristor bridges or more commonly a PWM-VSC can be utilized (Fig. 2.1 (d)). However, with the PWM-VSC a relatively large and therefore expensive three phase reactor is required. Therefore, this solution is the most expensive approach. Up to near a megawatt the switching device choice remains to be IGBT due to its cost and performance advantages.

In higher power non-regenerative applications 12-pulse rectifiers together with input transformers with star primary and star-delta secondary windings are frequently utilized to reduce the input current harmonic distortion. In the megawatt power range, the PWM-VSI may be formed from parallel inverters, inverters with parallel devices, or more complex inverter device structures such as the three level VSI [79, 113, 140]. In regenerative applications back-to-back connected thyristor bridges may be utilized or a GTO based PWM-VSC can be utilized. The power semiconductor devices can be IGBT's, GTO's or some of the recently developed high voltage IGBT's and other new devices [188]. Due to the switching losses and the thermal issues associated with them, the switching frequency of the PWM-VSI decreases from tens of kilohertz at lower tens of kilowatts level to less than a kilohertz at the megawatt level. At increasing power levels, typically snubber circuits are added to reduce the commutation losses and the peak stresses on the devices.

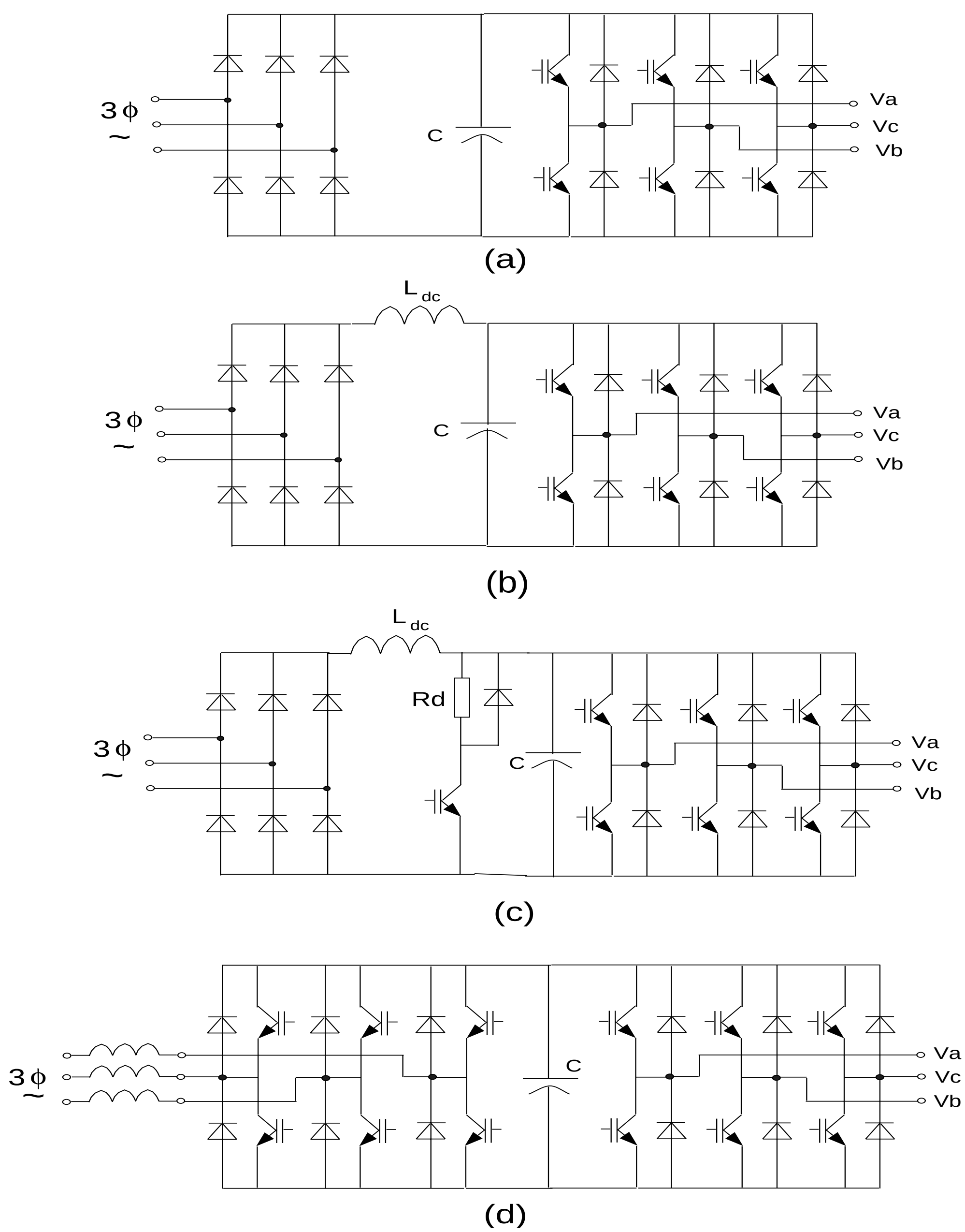

Figure 2.1: The power converter structure of various PWM-VSI drives.

The DC link structure is also application dependent. In applications such as the electric vehicle drives or UPS systems a stiff DC voltage source (battery etc.) is employed, hence no large DC link filter capacitor is required. The UPS application also differs from the motor drive application with the demanding filtering requirements in the AC output. Relatively large L-C-R filter elements are connected between the inverter outputs and the output terminals of the UPS.

From the simplest low power PWM-VSI drives to the most sophisticated high power VSI drives, all inverter drives employ hardware inverter overcurrent detector, DC link overvoltage detector, switching device saturation voltage detector, ground fault detector, heat sink temperature detector, and line voltage surge suppressor. With the increasing power rating, additional protection devices and sensors are involved. To rapidly interrupt the drive and protect both the load and the PWM-VSI after a fault condition, all the protection is normally implemented in hardware. Additional intelligent software protection and diagnosis algorithms can also be employed to enhance the reliability.

As the above summary indicates, the PWM-VSI hardware structure may significantly vary depending on the application. However, the main functionality of all the PWM-VSI drives remain the same; generating three phase voltages with controllable magnitude and frequency from a DC voltage source. Therefore, the switching device gate pulse pattern generation method determines the performance of a VSI. Discussed in the following, various PWM and control methods result in unique drive types with advantageous performance characteristics.

2.3.2 The Drive Type

The controller choice of a PWM-VSI drive is determined by the requirements of the application. Low dynamic performance AC motor speed control applications may employ a simple control algorithm while high performance AC motor drives and utility interfaces may employ involved vector control algorithms. Although the control algorithms of various drive types are generally different, for the same power ratings, their power converter structure varies only slightly. Therefore, it is typical to design a common power structure for all applications and select the controller type, the sensors, and interfaces depending on its application. It is possible to integrate the sensor, interfaces, and controllers of all possible applications in one drive and allow the user to configure a control method suitable to the application. However, this approach has only recently become practical and in the traditional approach the commercial PWM-VSI drives were generally offered in various types mainly based on the controller functionality. In the following these drive types are briefly reviewed.

a)Constant Volts Per Hertz Control

The largest application area of PWM-VSI drives is AC motor control. Three phase AC induction machines, permanent magnet or wound field synchronous machines, synchronous reluctance machines, etc. can be driven from a PWM-VSI to obtain torque, speed, and/or position regulation. Similar to Ward Leonard's method of DC motor speed regulation by armature voltage control, the constant volts per hertz ($\frac{V}{f}$) method is an effective method for AC motor drive speed regulation. In this method, the inverter output voltage is varied proportionally to the reference frequency such that constant stator flux is maintained. In particular in an induction motor drive, this operating mode results in shunt speed-torque characteristics (linear portion of the torque-speed curve), yielding low slip frequency and therefore high energy efficiency and good speed regulation. Therefore, the method gained wide acceptance in many industrial and residential induction motor drive speed regulation applications. The early applications of $\frac{V}{f}$ controlled VSI drives were reported in [26, 133, 134] and the feasibility of such drives proven by the late 1960s. These drives have had a large share of inverter drives market. However, the $\frac{V}{f}$ method is seldom implemented in its naive form, and additional algorithms and control loops are included in the control algorithm to enhance its performance. Slip frequency compensation methods to improve the load overhaul characteristics, voltage boost methods to compensate for the resistive voltage drop at low speed, and frequency skipping techniques to avoid the unstable operating regions are widely established and utilized [110, 135, 138].

State of the art $\frac{V}{f}$ inverter drives perform satisfactorily in a wide speed range (from $1 : 20$ to better than $1 : 40$) with 5% or better speed accuracy [44] and higher resolution can be obtained with shaft encoder feedback. However they exhibit limited speed response (less than a couple of hertz bandwidth), poor load torque disturbance characteristic, and inferior low speed characteristics (they can not perform well below several hertz). Also, they have unstable voltage-frequency operating regions which should be avoided by carefully designing the $\frac{V}{f}$ curve. Typical application areas of $\frac{V}{f}$ drives are pumps, ventilation systems, etc. which have passive torque-speed characteristics (with inherent damping) and no precise speed regulation requirement.

b) Vector Controlled Drives

Many high performance motion control applications require precise position, speed or torque regulation. In elevator drives start-up, acceleration, constant speed vertical travel, and deceleration must be smooth for a comfortable ride. Motion quality must be retained regardless the mechanical or electrical disturbances to the system [137]. In printing press and winding machines precise tension control is mandatory. Pick and place type applications such as packaging require precise positioning. Spindle tools require a wide speed operating range with rapid acceleration characteristics. High precision machining processes require high servo performance with very high resolution position control. In these and many other demanding applications the performance of $\frac{V}{f}$ drives is not satisfactory. Although installing a shaft encoder feedback enhances the steady state speed regulation, the encoder feedback does not cure the dynamic performance notably, neither does it provide precision position control.

Such applications traditionally have employed DC machines with shaft encoder. However, the continuous progress in AC machine control theory, power electronics, and digital microelectronic controllers yielded the modern vector controlled AC machine drives which can match or surpass the performance and reliability characteristics of DC drives and cost less.

Modern vector controlled AC induction motor (typically squirrel cage rotor type) and synchronous motor (typically below hundreds of kilowatts surface mount or interior permanent magnet machines and at higher power ratings wound field machines) drives meet the demanding performance criteria of most high performance motion control applications. Although high performance control method of the wound field synchronous motors which is based on the vector control principle was established in the 1930s [6, 144], the concept could not be easily extended to induction motors. Due to the coupling between the stator and rotor circuits, the induction machine formed a complex system with difficult to manipulate dynamic transients. However, with the aid of vector coordinate transformations and intuitive modeling, the machine behavior could be better understood and lead to the development of the vector control theory based Field Orientation Control (FOC) method which most modern high performance induction motors employ [145].

The principles of high performance induction motor control were established about 25 years ago. The Indirect Field Orientation Control (IFOC) method was developed by Hasse [61] and employs a shaft encoder to close the speed loop. The Direct FOC (DFOC) method was developed by Blaschke [15, 16] and it employs flux sensors/observers. In FOC, the magnetizing flux and torque producing components of the stator currents are properly and independently distributed both during steady state and dynamic conditions. Independently regulating each component with a high performance current controller, the drive torque can be controlled in the same precise manner as the DC machine [145].

Since installing flux sensors in the stator or the airgap of a machine is difficult, and the operation is not reliable, the DFOC method is practically rarely employed in its original form. Employing flux observers, the DFOC method provides high performance torque control, in particular in the high speed region where the stator resistance voltage drop is small compared to the stator EMF and the stator flux observer is highly accurate. The stator flux oriented DFOC method is attractive for traction, spindle tool etc. applications which require operation in a wide field weakening region. However, near zero speed the stator flux observer estimator error becomes substantial due to the dominance of the stator resistive voltage component over the nearly zero EMF and the DFOC method looses performance.

In a large number of applications requiring high performance in the low speed operating region the rotor flux oriented IFOC method is utilized. Since the rotor flux oriented IFOC method utilizes the rotor time constant to build the rotor flux observer, the method is sensitive to the rotor resistance and inductance variations and a suitable parameter adaptation method is employed [51, 176].

With accurate parameter adaptation, the IFOC based induction machine drives can provide servo performance in a wide speed region, and only in very wide field weakening applications their performance at high speed becomes unacceptable. In such very wide operating region applications, hybridization of the DFOC and IFOC methods has proven to yield an overall superior performance, however at the cost of increasing controller complexity. The combined algorithms established by Jansen et al. transition from IFOC at low speed to DFOC at high speed seamlessly, yielding precise motion control [84].

Modern permanent magnet synchronous machine drives employ the same vector control principle as in FOC. However, in this case the controller axis is precisely aligned with the rotor magnet or magnetic reluctance axis. Therefore, with the rotor position measured or estimated accurately, the control method is straightforward. In surface-mount permanent magnet rotor synchronous machines the stator current flux producing component (the direct axis current) is normally zero, and the torque is proportional to the stator current. In the buried (internal) and inset magnet rotor synchronous machines and in the synchronous reluctance machines both direct and quadrature axis currents exist and must be properly controlled to obtain high torque per ampere, superior dynamics, and wide speed range. The surface-mount magnet synchronous machines are widely utilized as AC servo drives, while the buried and inset magnet PM machines are utilized in wider speed range applications due to their superior field weakening capability. Also synchronous reluctance machine drives have been developed for integral horsepower lower cost applications.

Since the torque regulation quality of an FOC induction motor drive or vector controlled synchronous machine drive is mainly dependent on the current controller accuracy and bandwidth, high performance motion control requires high performance current regulators. Of the various current control algorithms, the Synchronous Frame Current Regulator (SFCR) [174] and its stationary frame equivalent [166, 167] have superior steady state and dynamic performance and they have been widely employed in high performance AC motor drives and also in UPS and PWM-VSC applications. In these controllers the proportional and integral components operate on the current errors and generate voltage references in which are translated to switching signals by a PWM method. The hysteresis type current controllers which have superior dynamic performance have not gained acceptance in motor drives due to the difficulty in controlling their switching frequency and significant waveform distortion.

Employing high switching frequency IGBT devices and high performance digital signal processors or microprocessors, high performance current controlled drives provide high torque/speed bandwidth, hence high motion quality. As a result, the state of the art FOC induction motor drives and vector controlled PM motor drives perform quite satisfactorily. High performance FOC drives have been successfully employed in industrial and servo drive applications for more than a decade [109]. The evolution of FOC drives from concept to industrial products and successful applications has been summarized by Leonhard in [119, 120] in detail. The speed range of state of the art FOC drives surpasses 1 : 3000 and the speed regulation is better than 1 %. With a speed bandwidth as high as 100 Hz, high start-up torque capability, and wide range of field weakening capability, state of the art FOC induction machine drives exhibit servo performance and continue to replace the DC drives. Vector controlled synchronous PM machines are widely employed in high performance servo drives and their application range continues to expand due to their superior energy efficiency and high power density.

c) Shaft Encoderless High Performance AC Drives

Since the IFOC method requires an encoder and its associated cabling and interface circuits, its utilization in many medium performance applications is cost prohibitive. Furthermore, in certain applications the operating environment is hostile and the encoder, its cabling, and connectors may fail due to extreme stress rendering the drive fault prone. In such applications, various types of shaft encoderless AC motor speed control algorithms which perform between $\frac{V}{f}$ and FOC drives, emerge.

Following the early attempts to enhance the performance of $\frac{V}{f}$ drives and the recognition of their performance limitations [2, 3], the pioneering work in the shaft encoderless motor speed control area was reported by Jötten and Maeder in 1983 [87]. They employed the induction motor fundamental model to estimate the slip frequency and the back emf of the machine and provided a closed loop controller to regulate the slip such that superior dynamic performance could be obtained in a wide speed region, including the field weakening region. Although a large variety of shaft encoderless control methods have been reported from that time to the present date, only a few found practical applications [67, 78]. Of these, the Direct Torque Control (DTC) method and several other state estimation methods which employ the fundamental model of the induction machine and the vector control principle to estimate the stator/rotor flux, velocity, and position, and often termed as "open loop flux vector" methods have been fully developed (in particular for induction motor drives), commercialized and employed in a wide range of applications.

As the name suggests, the DTC method regulates the motor torque and flux directly. The direct torque control principle was established in the early 1980's by Török [195] and further developed by Takahashi and Noguchi [190] and Depenbrock [43]. In the DTC approach, the torque reference is compared to the estimated motor torque and the reference stator flux is compared to the estimated stator flux, both employing hysteresis controllers. The torque and flux hysteresis controller output logic signals are evaluated in an optimal switching logic table to generate the inverter switching device gate signals. Both the estimated torque and stator flux are calculated from the machine model and measured motor currents, reference voltages, and the DC bus voltage. The method has recently been employed in various industrial applications and its viability proven [34, 123, 143, 193, 194]. With their rapid torque response, and wide band spread switching frequency harmonics (white noise) characteristics, the DTC drives exhibit notable performance differences from the conventional drives.

Several popular state estimation based induction motor control methods employ the fundamental model of the induction machine and provide a parameter adaptation method to account for the parameter variations of the machine. Several methods employ a rotor flux oriented IFOC model in order to approach a FOC drive performance [86, 150, 151]. These methods employ a reference model of the induction machine and the actual rotor flux axis of the machine and the flux axis of the controller are locked so that FO condition is attained. The motor phase currents/voltages (measured and/or predicted) are utilized in the reference model and any misalignment between these axes is minimized by the controller, yielding superior speed regulation. The choice of observer variables depend on the method, and the performance of each method is dependent on how accurate the reference model parameters represent the actual system. The method by Okuyama et al. [151] utilizes the torque current error, $i_{qe}^{*} - i_{qe}$, to calculate the correction angle and a voltage feedforward controller programs the reference voltages that operate the drive under IFOC condition. The method by Ohtani [150] employs the torque current error also, however it involves a rapid current controller and has superior accuracy and dynamic performance. The method by Kerkman et al. [94, 168] employs the direct axis voltage error and with accurately measured voltages, it can provide superior angle correction yielding superior performance, in particular in the lower speed region. All the practical methods also employ adaption algorithms to account for machine parameter variations [173]. However, all these methods have limited performance near zero speed. This fundamental limitation has lead to the investigation of alternative methods [17, 41, 56, 82, 83, 179] which may be combined with the above methods to provide a wider operating range.

The DTC and open loop flux vector methods have recently been successfully employed in many industrial applications with no stringent near zero speed performance requirements. With their superior load and DC bus voltage disturbance rejection capability, they provide high quality motion control. Impact loads and load overhaul condition are better manipulated than $\frac{V}{f}$ drives. They provide high accuracy speed regulation and sufficient dynamic response in a wide speed range. State of the art open loop flux vector controlled induction motor drives can provide as wide as a 1:1000 speed range, a speed loop electrical bandwidth as high as 15 Hz, a speed regulation better than 0.1% and can supply more than 150 % starting torque in wide power range from fractions of a kilowatt to several hundred kilowatts [44, 130, 150, 173].

In addition to induction machines, PM synchronous machines (in particular, machines with large magnetic saliency) have also been successfully operated without speed sensor down to zero speed [164].

d) Multi-purpose, Universal, and Integrated Drives

Many modern inverter drives have the capability of operation with any of the above discussed three different drive control methods. In such user configurable drives the motor can be controlled in any of the above modes by simply selecting the desirable mode through the user interface. The interface, controller memory size, and current/voltage sensor requirements of such drives are designed for the highest performance IFOC operating conditions. Therefore the component cost is higher than all above. However, the modularity and multi-functionality, reduced design and assembly cost and reduced hardware cost of these drives yield better performance to cost ratio and therefore these drives have gained wide acceptance. Such drives have been advertized as universal drives, general purpose drives, multi-purpose drives [201] and have found wide range of applications.

In addition to modularizing the control board of inverter drives, the switching devices are also modularized and intelligent power modules with enhanced reliability and reduced hardware requirements have been developed. Furthermore, the integration of motors and inverter drives has resulted in additional space and cost reduction. In particular, the fractional and integral horsepower range integrated induction motor and inverter drives have been offered as compact and low cost drives with superior performance [11, 55].

Many industrial processes have been employing programmable logic devices to program the motion required for an industrial process. Several recent inverter drives are built with such capabilities and they eliminate the additional wiring and device cost/maintenance. As this and all the above examples illustrate, the strong influence of the digital microelectronic technology on inverter drives has been continuing at an increasing rate.

e) Voltage Source Converters and UPS Applications

In addition to being utilized in motor control applications, PWM-VSI drives are also employed in AC/DC power conversion applications such as regenerative motion systems, UPS and utility interface of DC voltage loads. Although several important design differences and performance requirements exist, generally these drives employ vector control principles in order to achieve high performance voltage/current/power quality and robustness against disturbances [124].

Back to back VSIs are increasingly being utilized in applications such as elevators which frequently operate in regenerative mode. While the load side VSI provides high performance motion control, the line side VSI provides high power quality and high energy efficiency. Additionally, the DC link capacitor of such drives can be made significantly smaller than the diode rectifiers [5, 170].

2.4 Voltage and Current Regulators

The position, speed, torque, DC bus voltage etc. control loops of all the previously discussed PWM-VSI drives generate voltage or current references that must be matched by the inverter. High performance voltage and current regulators are critical parts of an inverter drive that achieve this task. Depending on the performance requirements, the regulator types vary. Constant $\frac{V}{f}$ drives employ voltage feedforward, while all the other high performance drives employ closed loop voltage/current regulators. As an exception the DTC method employs torque and flux regulation and the voltages and currents are not directly controlled. High performance FOC induction and synchronous motors and PWM-VSC applications employ current regulators. Within two decades the current regulator technology evolved from the simplest on-off principle based AC current regulator to the present day industry standard high performance synchronous frame current regulators.

The three phase current regulators can be grouped into two classes; on-off principle based (memory-less) regulators and linear control principle based regulators employing carrier based PWM methods. The hysteresis and delta current regulators are the two established on-off principle based current regulators. In the delta current regulators the phase current errors are periodically sampled and the phase current error polarity determines the switch state of the associated inverter leg [186]. If the error is positive the upper device, otherwise the lower device of the inverter leg associated with the regulated phase is turned on. In the hysteresis current regulator the phase current errors are continuously monitored and if the current errors become larger than a predefined tolerance band, commutation takes place in the same manner as the delta regulator. Hysteresis current regulators can be built for each phase individually (scalar method) or in vector coordinates (vector method) with the latter being superior.

The historical development of the on-off principle based current regulators is as follows. Plunkett showed that current regulated drives could have more stable behavior than $\frac{V}{f}$ drives, and implemented a scalar hysteresis current regulator [159]. Brod and Novotny studied the coupling of the scalar method and illustrated its limit cycle behavior [28]. McMurray analyzed the switching frequency characteristics of hysteresis current regulators and illustrated the phase and load parameter dependency of the switching frequency [127].

The on-line predictive method developed by Holtz et al. [76], the table based predictive method developed by Nabae et al. [139], and the synchronous frame based hysteresis current regulator with rectangular tolerance band by Bube et al. [74, 96] are all high performance vector hysteresis current control methods. Intelligently selecting the adjacent inverter states, these regulators provide lower distortion per switching than the scalar method. With these methods a small performance enhancement comes at the expense of significant controller complexity [122, 172]. Both vector and scalar hysteresis methods have poorer waveform quality than the linear control methods employing PWM. In addition to the poor waveform quality, the methods have operating condition dependent switching frequency variation and the output waveform contains significant magnitudes of white noise harmonic spectrum (an inherent feature in on-off principle based regulators) unacceptable in many applications. Therefore, these methods have found limited applications.

As previously discussed, the DTC method employs vector hysteresis controller and the waveform characteristics of DTC controlled VSI are the same as vector hysteresis current controllers. However, the control variables of DTC are the torque and flux, instead of the currents. Although the method has superior torque response characteristic, its waveform quality characteristics are not acceptable in many applications. Therefore, the vector hysteresis flux and torque controller, and the DTC method which utilizes this principle have limited applications.

Most state of the art high performance PWM-VSI drives employ linear current controllers with Proportional and Integral (PI) structure which have superior steady state performance compared to on-off principle based methods. In these methods, the current errors are evaluated in the PI controllers, hence the current errors are translated to voltage references. Voltage feedforward and cross-coupling decoupling terms are added to the reference voltages in order to enhance the controller performance. A PWM method processes the reference voltages to generate the switching signals. In the scalar method, the phase current errors are fed to the PI controllers of the associated phases and the output of each controller forms its voltage reference. In the vector method, the currents are transformed to the controller coordinates (typically the synchronous frame). The direct and quadrature axes PI controllers process the errors and add voltage feedforward and cross-coupling decoupling terms to generate the reference voltage vector. The reference voltage vector is transformed to the stationary frame and this vector is either directly utilized to compute the device duty cycles, or it is transformed to abc variables and fed to a modulator to generate the switching signals.

Schauder and Cody showed that the vector PI current regulator behavior is dependent on the reference frame it is implemented in [174]. They developed the SFCR method which has zero steady state error and high dynamic performance. Hence, superior performance compared to the stationary frame per phase current regulators. Rowan and Kerkman showed that SFCR can be implemented in stationary frame which allowed a simplified hardware implementation [167]. In addition they provided analytical comparison between stationary and synchronous frame regulator performance and illustrated the superiority of SFCR through the regulator gain versus frequency plots. Shown in Fig. 2.2 both SFCR and its stationary equivalent implementation have been widely utilized due to their high performance characteristics. State of the art SFCRs typically employ additional voltage feedforward and cross-coupling decoupling control to increase the dynamic performance of the drive [50, 93, 118, 121, 160]. References [50, 148] describe the design of high performance SFCRs with sufficient detail. In particular, [50] discusses practical approaches to obtain very high bandwidth current controller performance. The SFCR stationary equivalent structure does not have cross-coupling components and need only voltage feedforward components to obtain high performance. With careful design, the analog implementation of this regulator can yield very high bandwidth. Also recently a complex vector

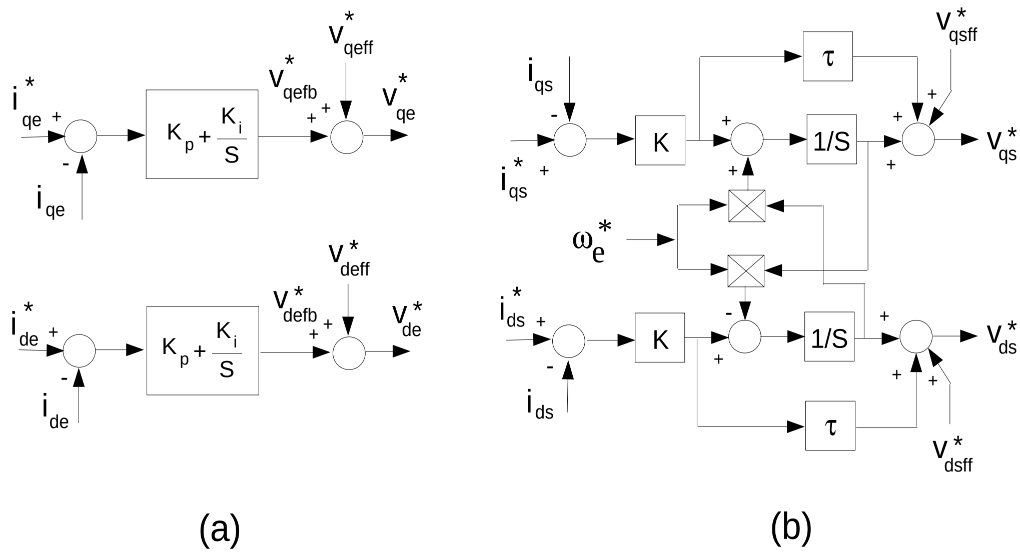

Figure 2.2: Synchronous frame current regulator (a), and its stationary frame equivalent (b). In both regulators the coordinate transformation operators are not shown.

SFCR method was established by Briz and Lorenz [27]. In the modulator linearity range, this controller is exhibits quite similar performance characteristics to SFCR.

Early current regulators were implemented with analog hardware circuits. The SFCR and its stationary equivalent both involved analog/digital hardware circuits that were bulky and expensive. With the development of low cost high performance DSP and microcontrollers the digital implementations rendered the analog controllers obsolete. The early experimental work by Gabriel et al. illustrated the feasibility of microprocessor controlled FOC drives with analog current loops [49]. This study hinted the future trends in implementing the AC drive controllers. As the microelectronics technology advanced and the signal processing speed increased with the cost decreasing, the fast current loops could also be implemented on a digital platform. Pollmann illustrated the feasibility of fully digital AC drives employing digital SFCR [160]. Although the analog current controllers involved continuous feedback and control signals, the digital implementations involved discrete feedback signals, hence the feedback current sampling issues were important.

In the "synchronous sampling" method, the feedback currents are periodically sampled at the carrier frequency rate. Sampling the feedback currents at the positive and/or negative peak values of the triangular carrier wave (where the switching frequency harmonic currents are negligible) would yield a "switching frequency harmonic free" measurement. The synchronous sampling method has become the industry standard and is widely employed in most fully digital drives [206]. Matsui et al. discussed the feedback current sampling issues in digital current loops and proposed an averaging method which improves the feedback current measurement accuracy [126]. Further improvements on feedback current sampling, signal conditioning, and accurate measurement have been reported in [12, 39, 73, 184].

As a result of this progress, the microprocessor and DSP based digital drive controllers today, are more cost effective and provide better performance than the analog/digital hardware based designs. Design of application specific digital controllers, such as the recently developed VECON and TMS320F240 chips (fast DSP for control, low cost microcontroller for communications and low priority level tasks, PWM generator, blanking time generator, etc. integrated in one chip) at low cost is expected to accelerate this trend even further [97, 115, 141, 155].

2.5 Modulation Methods

In the on-off current controlled drives and torque/flux regulated DTC drives, the switching signals are available immediately at the controller outputs. However, in PI controller based (linear) current regulated drives, and voltage feedforward controlled drives the switching signals are determined in an additional block termed as the "modulation" block. In this block the reference voltages are evaluated and proper switching device gate logic signals are generated for all the three inverter legs.

Since voltage source inverters employ switching devices with finite turn-on time and turn-off time characteristics, inverter switching losses are inevitable. Because the switching losses strongly affect the energy efficiency, size and reliability of an inverter, a modulation method with high performance is desirable. Therefore, the modulation method choice is significantly important. Of the variety of modulation methods, the carrier based PWM methods and the programmed pulse modulation method are the two most recognized methods.

In the programmed pulse modulation methods the switching patterns are precalculated for a given performance optimization criteria and the commutation angles are stored in a memory array. During operation the memory array is accessed on-line through the drive controller to generate the inverter gating signals for a given reference voltage phase and magnitude value. Various performance optimization criteria have been considered in generating the commutation angle table. A harmonic elimination method which totally eliminates certain harmonics from the output waveform (typically the unwanted harmonics are the 5th, 7th, 11th, 13th etc.) was first developed by Turnbull [200] and later further investigated by Patel and Hoft [156, 157]. Following this work, Buja and Indri proposed an output current THD minimization criteria for optimizing the pulse pattern [33]. Efficiency optimized pulse patterns [208], and torque ripple minimized pulse pattern [209] have also been characterized. Utilizing such optimal switching patterns as a template, Holtz et al. developed trajectory tracking methods which improve the dynamic performance of voltage feedforward drives [70, 71, 73].

All the programmed pulse methods require large computer memory space and in most methods the number of pulses per fundamental cycle is limited to a small number, typically less than five switchings per phase and per quarter cycle. In particular, in the high voltage utilization range, the optimal angles near the peak of the fundamental component of the voltage become significantly close, with no sufficient room left for commutation or blanking time. Due to this fundamental limitation, the programmed modulation methods can not operate with high switching frequency. Therefore, they can not provide output waveforms with very low harmonic distortion waveform. The application of the programmed pulse methods is usually limited to very high power drives with power ratings above a megawatt level where low switching frequency is selected for low switching losses.

Unlike the programmed pulse modulation methods, the carrier based PWM methods can operate with high switching frequency and they offer high waveform quality and implementation advantages. Carrier based PWM methods employ the per carrier cycle volt-second balancing principle to program a desirable inverter output voltage waveform. The first important contribution in the carrier based PWM area was done by Schönung and Stemmler [177] in 1964 with the development of the sinusoidal PWM (SPWM) method. As shown in Fig. 2.3, in this method the sinusoidal reference waveform (the modulation wave) of each phase and a periodic triangular carrier wave are compared and the intersection points determine the commutation instants of the associated inverter leg switches. The well established modulation theory indicates that for sufficiently high carrier frequency to modulation wave fundamental frequency ratio, the modulation waveform fundamental component magnitude and the inverter output voltage fundamental component magnitude are linearly related until the modulation wave magnitude becomes large and the sine and triangle intersections begin to disappear [10, 14]. Within the linear modulation range, the sinusoidal PWM method sub-carrier frequency harmonic content is significantly low, and the switching frequency is fixed. Due to its simplicity and its well defined harmonic spectrum which is concentrated at the carrier frequency, its sidebands, and its multiples with their sidebands, the SPWM method has been utilized in a wide range of AC drive applications. However, the method has

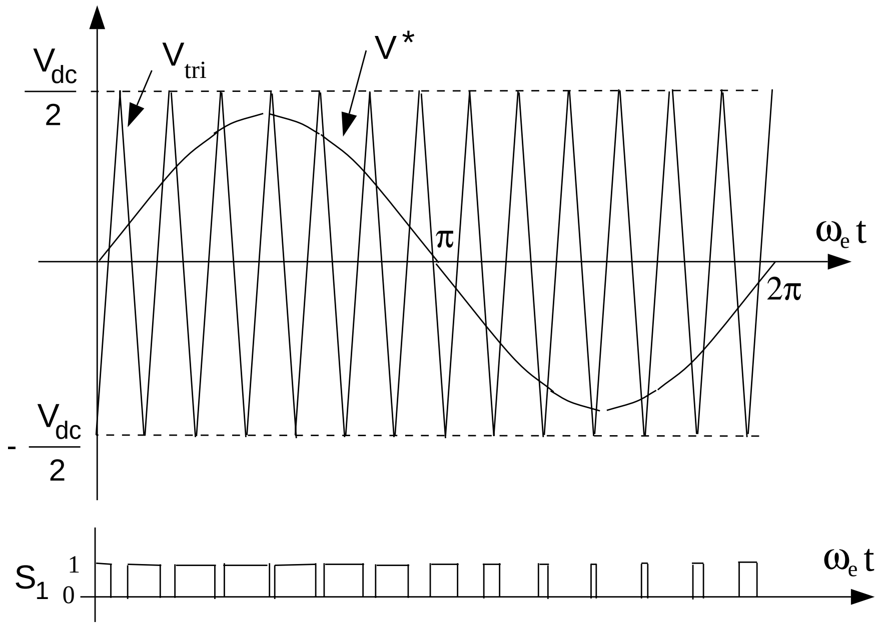

Figure 2.3: Sinusoidal PWM method. The intersection points of the modulation wave and carrier wave define the switching instants.

a poor voltage linearity range, which is at most 78.5 % of the six-step voltage fundamental component value, hence poor voltage utilization. Therefore, the zero sequence signal injection techniques that extend the SPWM linearity range have been introduced for isolated neutral load applications which comprise the large majority of AC loads [32, 101].

In most three phase AC motor drive and utility interface applications the neutral point is isolated and no neutral current path exists. In such applications in the triangle intersection implementations any zero sequence signal can be injected to the reference modulation waves. K. G. King was possibly the first researcher to utilize this concept in a voltage source inverter, and his zero sequence signal choice which will be discussed in the next chapter in detail, remains to be one of the most popular choices [101]. King realized that a three phase diode rectifier circuit shown in Fig. 2.4 could be utilized to generate a zero sequence signal. His choice of scale which was based on the linearity maximization criteria allowed the converter to extend its linearity range from 78.5% to 90.7% of the six-step voltage. This important invention has been neglected for a long time. This modulation method was later re-invented employing the space vector theory [29, 158]. Since the method in these publications was termed "Space Vector PWM" (SVPWM), in this thesis this name is also adopted for King's method. In addition to developing a digital implementation for SVPWM, Van Der Broeck et al. illustrated the SVPWM method has superior waveform quality compared to SPWM in particular in the high modulation region [29]. Since this implementation involves a vector controlled drive and the reference voltage vector information is directly translated to inverter switch duty cycle information, this method is often termed "direct digital implementation technique," while the implementation involving modulation waves is termed "the triangle intersection technique."

A recent publication re-introduced King's configuration as a new analog hardware SVPWM implementation [66]. Perhaps, the neglect has been due to the difficulty in distinguishing the valuable literature among a large volume as well as the difficulty in understanding his article. However, various other zero sequence signal injection methods with advantageous performance characteristics have been invented between the 1970's and the present time.

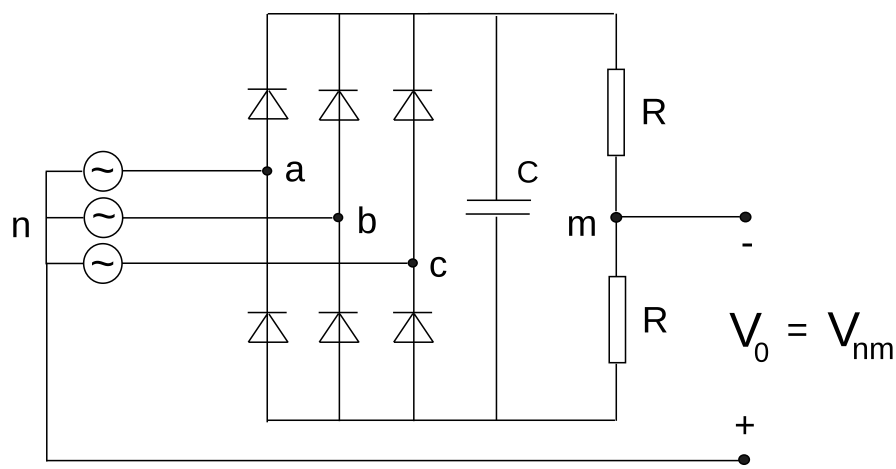

Figure 2.4: King's zero sequence signal generating circuit.

The third harmonic injection PWM method was developed by Buja and Indri [32]. It was shown a triplen harmonic with a magnitude equal to one-sixth of the fundamental component modulation wave would provide maximum inverter voltage utilization. Similar to King's invention, this invention has not gained attention and the method was re-reported many years later with no recognition of the original work [77]. However in this case a digital implementation was described. Bowes and Midoun attempted to compute a modulation wave with minimum RMS harmonic distortion by computer simulations and numerical approaches. They concluded that a third harmonic injection with a magnitude equal to one-fourth of the fundamental component is a numerical optimum value [24]. With the performance optimization criteria being the output waveform harmonic distortion RMS value minimization, Kolar et al. analytically verified this argument [105, 106]. However, the performance advantage was shown to be only in the high voltage utilization range. Moreover, the advantage over SVPWM and the other methods was shown to be insignificant. Both methods discussed in this paragraphs are constrained to a pure third harmonic signal injection, while King's SVPWM approach naturally included additional triplen harmonics and yielded superior performance. Furthermore, many years before such academic exercises were published, it was well understood that in the high modulation range the above discussed methods were inferior to a special group of modulation signals.

Perhaps, the invention of various Discontinuous PWM (DPWM) methods has been the third most important modulator invention following the invention of SPWM and SVPWM. In the DPWM methods, a zero sequence signal which brings one of the three modulation signals to the same level with the positive or negative peak of the triangular carrier wave is selected. Since the switching in the corresponding inverter leg ceases, the switching losses are eliminated so long as this condition persists. Therefore, the inverter switching losses can be controlled with the zero sequence signal. This fact was first was recognized by Schörner [178]. In his work, Schörner aimed to extend the linearity of SPWM by injecting a zero sequence signal to the sinusoidal modulation wave. However, his choice of zero sequence signal was significantly different than the previously reported. Of the three phase modulation signals, he selected the one with the maximum magnitude for generating his zero sequence signal. Therefore, the top and bottom 60° portion of each sinusoidal modulation signal would be processed to obtain a zero sequence signal. He generated a zero sequence signal by calculating the difference between the peak value of the sinusoidal modulation signal and its instantaneous value within the associated 60° section. Injecting this zero sequence signal to the sinusoidal references, modulation signals with two 60° flat top segments could be obtained. For modulation depth smaller than 91 % of the six step voltage fundamental component value, the modulation signals are contained within the triangular carrier wave boundaries. However at this end point, the top and bottom segments become equal to $\frac{V_{dc}}{2}$. Therefore, at this operating point, the particular phase ceases switching. Therefore switching discontinues and no switching losses are generated.

In the following years, Depenbrock established a method which provides discontinuous modulation throughout the modulation region and also proposed a simple analog hardware implementation [42]. Similar to King's SVPWM circuit, Depenbrock's DPWM circuit employed a diode bridge rectifier to generate the zero sequence signal. However, additional analog switches were required. The modulation waves of Schörner's method and Depenbrock's method are identical at 90.7 % voltage utilization. However, the latter ceases switching at least for the two 60° segments regardless of the voltage utilization level. Depenbrock quantitatively investigated the switching loss reduction, voltage linearity, and waveform quality characteristics of this DPWM method. He illustrated the performance superiority of this method over SPWM in particular in the high voltage utilization region. As the attributes of this methods were recognized, it has found applications in motor drives and PWM-VSC applications [46, 124, 142].

Since in this method only two phases modulated at a time, the method has been termed as "two phase modulation." Since in this and the following methods modulation of each phase ceases for a certain portion of the fundamental cycle, the methods are more often termed as "Discontinuous PWM" (DPWM) methods. The latter term will be adopted in this thesis. Also, The DPWM method which is described above will be abbreviated with the DPWM1 symbol throughout this thesis.

Although clamping the two center 60° portions of the modulation waves reduces the number of commutations per fundamental cycle and the switching losses (by at least 33 %), depending on the load power factor, the quantitative value of the switching loss reduction may be different than the commutation numbers. Since in a typical semiconductor device the switching losses are proportional to the commutated current, under unity power factor condition DPWM1 has the lowest switching losses compared to different power factor conditions. Ogasawara et al. recognized this fact and developed a modulator suitable for induction motor loads [146] which typically operate near 30° lagging power factor condition. Instead of ceasing modulation at the center portions, they proposed a 30° phase delayed DPWM such that the portion that modulation ceases coincides with the largest phase current. Since it provides significant switching loss reduction compared to DPWM1, this method gained recognition and found wide range of industrial applications. This method will be abbreviated with the DPWM2 symbol throughout this thesis.

The work by Ogasawara et al. utilized the space vector coordinates for analysis and illustration of the effectiveness of the method. The direct digital implementation was utilized and the superiority shown with solid theory and experimental work. The publication by Vukosavic and Stefanovic is another example of re-invention for it repeats the work of Ogasawara et al. with no improvements and no recognition of the original invention [187]. Furthermore, Trzynadlowski and Legowski re-invented the same method for the second time [199].

In addition to establishing the $30°$ leading DPWM method (opposite to DPWM2), which provides minimum switching loss for $30°$ leading power factor loads, Kenjo developed an intuitive approach to describe the modulator behavior. Describing the inverter switch duty cycles in the three dimensional Cartesian coordinates, he illustrated the trajectories of different PWM methods, and the projection on a normal plane would correspond to the reference voltage vector in the inverter hexagon [90]. This method was later utilized in [181] for theoretical analysis of certain modulator characteristics.

In addition to the above described methods, several other methods with marginal improvement have been reported in the literature and several survey publications discuss these methods [68, 197]. The method by Kume et al. which provides controllable harmonic spectrum and reduces the carrier frequency sideband harmonics [111], the DPWM method by Taniguchi et al. which has a single $120°$ clamped segment (as opposed to $2 \times 60°$ clamped segments) [191], the DPWM method by Kolar et al. which has minimum harmonic distortion [107], and the carrier frequency modulation method by Holtz and Beyer [72] are worth mentioning. Following the invention of SPWM, SVPWM, and DPWM methods the next natural step involved their implementation issues.

The early implementations largely involved analog hardware modulation signal generators and triangular carrier wave generators. In the early development years of the microprocessor technology several of the above modulation signals were often approximated with trapezoid etc. functions such that these signals could be successfully generated with the limited capability microprocessors of that time [23, 24, 25, 149, 198]. These methods could be implemented with the high performance microprocessors and electronic circuits available, and their superior performance was illustrated. However, cost and complexity were prohibitive in most practical applications [22, 129, 171]. However, the rapid progress in the microelectronics technology yielded high performance low cost microcontrollers, DSPs, and ASICs that could implement the high performance modulation methods with high precision [163]. Not only the modulation signal could be generated inside the IC chip, but also digital PWM counters/comparators could be integrated to it, rendering the analog triangular wave generator obsolete. As a result, the recent drives have incorporated high performance low cost digital microelectronic chips and with the implementation of the above discussed modulators superior performance could be obtained [29, 97, 141, 155]. Furthermore, more than two modulators could be incorporated into a single processor and intelligent modulator selection could yield superior performance. For example, in AC motor drive applications, in the low speed region SPWM and in the high speed region a DPWM method could be employed and seamless transition from one modulation algorithm to another would yield an overall enhanced drive performance.

Although SPWM by Schönung and Stemmler, SVPWM by King, and DPWM1 by Depenbrock utilized simple rules to generate the modulation waves, the direct digital implementation methods have appeared more complex until recently. The calculations involved selection of an inverter hexagon sector, calculating the inverter active state time intervals, and converting to duty cycles. However, recently it has become obvious the earlier approach by King and Depenbrock were superior and have been preferred [50, 62, 63, 98].

In the early implementations, especially at power ratings in the order of tens of kilowatts and above, synchronization between the carrier and modulation signals was mandatory to achieve high waveform quality with the limited switching frequency capability of the inverters. However, the advent of BJT and IGBT devices allowed switching frequencies to become in the order of kilohertz and higher. Therefore, asynchronous PWM became acceptable in most drives except for high power drives and very high speed drives. With this constraint removed, the modulator implementation complexity of most drives has significantly reduced.

With the development of digital modulation methods, the discretization of the modulation signal resulted in a slightly different harmonic spectrum than the analog (natural) sampling characteristic of analog triangle intersection implementation. These differences were investigated in detail and it was recognized the regular sampling characteristic of the discrete time modulation signals would yield a slightly less harmonic distortion [23, 24]. The performance characteristics of various modulators have also been recently investigated by employing analytical or numerical approaches. Thus, better understanding of the waveform characteristics, switching and conduction loss characteristics, voltage linearity characteristics, peak current stress characteristics, etc. has become possible [30, 31, 63, 68, 69, 107].

At the high power end, alternative to the programmed pulse modulation methods, synchronous PWM methods have been developed to eliminate the sub-fundamental frequency harmonic voltages which cause subsynchronous resonance problems at high power. Zubek et al. developed methods that can dynamically vary the carrier frequency in order to be able to operate in a wide modulation range and achieve smooth transition when changing the carrier to fundamental frequency ratio (also called gear changing)[211]. Utilizing synchronous PWM, they showed that the gear changing has to be at well defined points with respect to the fundamental component waveform in order to avoid unwanted transients. Stanke and Nyland recognized the performance superiority of pulse programmed modulation methods over the synchronous SPWM method in the high modulation region and developed an algorithm which selects SPWM in the low speed region and pulse programming method in the high modulation region. They demonstrated the transition between the two methods could be achieved with minimum disturbance with the transition points being the peak of the modulation wave fundamental component peak values [185]. Further details were discussed in the publication by Richter [165]. High performance microprocessor implementation of the synchronous SVPWM method on a high power drive was reported in the late 1980s [112]. High performance DSPs and microcontrollers have been widely utilized in high power drives. The present high power drives benefit more from the advanced digital microelectronic technology than the medium and low power drives due to the significant performance to cost ratio levels achieved in high power drives.

As the above summary indicates, the PWM literature is rich and the large variety of methods and their performance characteristics are difficult to completely understand, evaluate and compare. Although the zero sequence signal injection principle is well understood and various high performance zero sequence signals have been developed, interpreting the differences and similarities between various methods has been substantially difficult. With many modulator re-invention examples illustrated in this chapter, the lack of global understanding has been solidly proven. Perhaps, the source of this difficulty lies in the fact that the number of modulators is large, and the waveform quality and switching loss characteristics of each modulator are multivariable functions.

One of the aims of this thesis is to simplify the modulator study task through grouping the methods and methodically analyzing and illustrating their important performance characteristics such as the switching loss, waveform quality, and linearity. With the aid of rigorous analytical derivations (with simple results) and detailed graphics, the modulator characteristics will be better understood and recognition of the similarities and differences between various PWM methods will lead to a global vision of PWM. Perhaps, this approach will also aid the reader recognize the importance of the not-well-recognized early literature both from the future applications and historical perspective. Developing all the modulator characteristics and definitions with a coherent terminology will also simplify the analytical derivations involved in the remainder of this thesis. Although similar analytical and graphic methods were pursued by various researchers until the present time and the fundamental approach in modeling such characteristics has been established for more than a decade ago [29, 30, 31, 42, 146], lack of coherence and completeness have been a main deficiency [4, 37, 40, 62, 103, 104, 105, 106, 107, 114, 189]. Detailed comparative evaluation and intuitive illustration of the multivariable modulator characteristics through graphics has also not been provided. Therefore, in the modulator review and performance analysis chapter of this thesis, the emphasis will be on the principles and interpreting the results, not on illustrating the details of exhausting algebraic manipulations required for formula derivation.

Since the above discussed conventional modulators have predetermined performance characteristics, selecting a modulator and utilizing it over an operating range generally yields less than optimal characteristics. On the other hand, a modulator with controllable, rather than fixed characteristics would be preferable. This thesis pursues this issue also, and a novel high performance DPWM method with superior performance characteristics is reported in the third and fourth chapter.

As a result of the above summarized exhaustive research in the PWM area, high performance modulation methods have been developed and todays AC drives widely utilize these matured modulation techniques. However, most of these modulation methods exhibit poor performance in the very high modulation range. For carrier based modulators, the region between the end point of linear modulation region, and the six-step operating point, which is defined as the overmodulation range, exhibits a complex nonlinear behavior. Since the maturation stage of the linear modulation technology, interest has recently been shifted towards understanding the modulator and drive behavior in the overmodulation region, and towards enhancing the drive performance in this region [54, 75, 93]. Being the focus of this thesis, the overmodulation subject will be surveyed and reviewed in the following separate section.

2.6 Inverter Overmodulation

Since the DC link voltage of a PWM-VSI drive has a finite value, the voltage linearity of a modulator is confined to a limited voltage range. Therefore, the reference voltage-output voltage relation of a PWM-VSI drive is linear until the reference voltage magnitude exceeds the modulator linearity limit. As shown in Fig. 2.5, for SPWM, when the reference voltage magnitude exceeds $\frac{V_{dc}}{2}$, or equivalently 78.5 % of the six-step voltage fundamental component value, the sine-triangle intersections begin to disappear, and voltage pulses are dropped. Although during these intervals the corresponding upper switch operates with 100% duty cycle, it can not match the reference voltage and nonlinear relations result between the reference and output waveforms. The same condition repeats during the negative half of the cycle, and the large negative reference signal can not be matched by the inverter. The term "overmodulation" is adopted to distinguish this nonlinearity of a modulator and the "overmodulation region" is the voltage range beginning from where the nonlinearity begins and ending at the six-step operating point. Similar to SPWM, the other conventional modulators also have nonlinear gain relations in their overmodulation region. Although the range of linearity is wider for the popular zero sequence signal injection modulators, their linear voltage gain relations eventually ends at 90.7 % of the six-step voltage value. As a result, the controller reference voltage $|V^*|$ and the PWM-VSI output voltage $|V|$ are not equal in the overmodulation range of operation for all the conventional carrier based modulators. In addition to this fundamental component gain nonlinearity, the reference voltage and output voltage phase angles are nonlinearly related also. The implication of the phase and magnitude errors can be different and depend on the drive type.

In voltage feedforward controlled constant $\frac{V}{f}$ drives, entrance into the overmodulation region results in waveform quality degradation and voltage gain loss. As a result, the harmonic losses and the current/voltage stress on the VSI active and passive components increase. While in this region, the drive control

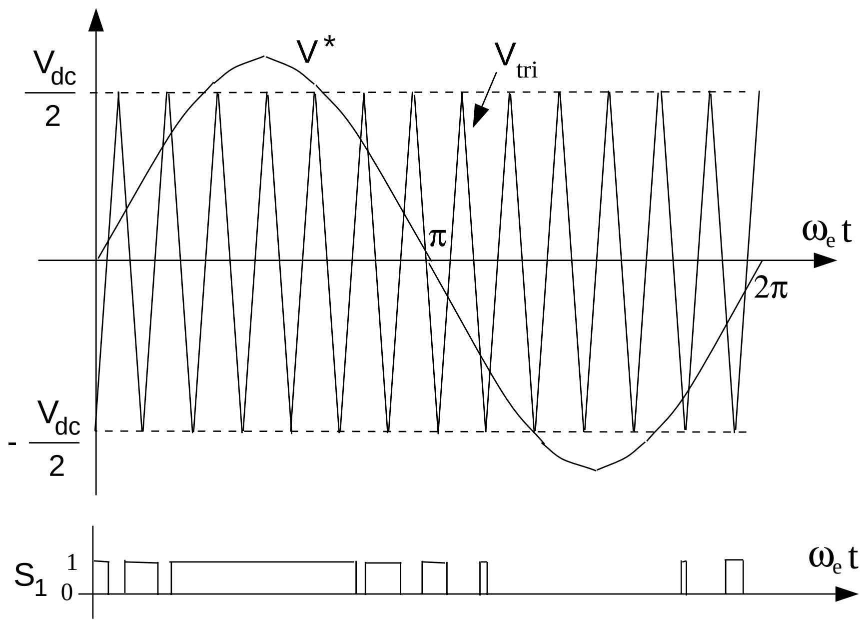

Figure 2.5: Voltage overmodulation mode modulator waveforms and switch signals in sinusoidal PWM.

linearity is lost and due to incorrect motor flux control ($\frac{V}{f}$ value deviates from $\frac{V*}{f}$) poor performance results. In addition, rapid transition to/from the six-step operating mode results in large transients and frequent overcurrent fault conditions occur. In AC drives with large commutation time, eliminating narrow pulses in the overmodulation region can also cause substantial current transients and lead to drive failure [53]. Although the load side dynamics can be reduced by selecting the drive maximum acceleration/deceleration rate conservatively, DC link voltage disturbances such as line voltage sag conditions in a diode rectifier front end type PWM-VSI drives can not be predicted and avoided. If they occur, they result in transients and poor performance [93].

In current regulated drives, in the overmodulation region the drive torque and/or speed and/or position loop bandwidth is lost, the current waveform quality degrades more significantly than the voltage feedforward controlled drives, and poor and oscillatory performance results [12, 54]. Both on-off principle based and classical PI current controller based drives exhibit poor performance in this region. In an SFCR, the integral controller signals of the d and/or q channels may become significantly large (wind-up) and large settling times and significant overshoots deteriorate the performance. Furthermore, a drive overcurrent failure may occur. The performance can be only partially retained by employing anti-windup controllers. Therefore, operation in the overmodulation region is problematic. However, in current controller drives, operation in this region is inevitable. Since current controlled drives are required to provide precise performance under both mechanical load and AC line disturbances, their overmodulation region performance requires more attention than the voltage feedforward drives. Furthermore, in high dynamic performance applications the overmodulation region is intentionally utilized in order to obtain maximum acceleration. In particular, at high speeds, where the machine back emf voltage is high and a little voltage margin remains for torque control, utilizing the overmodulation region voltage becomes significantly important. Therefore, the subject needs immediate attention.

To avoid undesirable operating conditions under disturbances, to obtain high steady state performance in the overmodulation range, and to obtain high dynamic performance during rapid acceleration/deceleration, the overmodulation range behavior must be well understood, and proper measures must be taken. If possible, from zero voltage to the six-step voltage the full voltage range should be available with maximum performance. However, the present drives do not have such capabilities, and their operating voltage range is constrained due to significant performance loss in the overmodulation range. Although most PWM issues have been significantly researched and reported over the last three decades, the overmodulation region performance issues have not been well recognized and the literature on this subject is scarce. Perhaps, this is due to the difficulty in modeling and understanding the overmodulation nonlinearity of the modulators. However, with the increasing demand for performance and following the maturization of the PWM technology (mainly, the linear mode) attention has recently been focused on the overmodulation subject. The relevant literature is discussed in detail in the following.

Following the recognition of the linearity limits of SPWM and the zero sequence signal injection principle based modulators [20, 101], the problematic behavior of the modulators in the overmodulation region was immediately recognized [53, 102]. Kliman and Plunkett recognized the waveform distortion of SPWM in the overmodulation range and introduced a modification to the modulation waves to improve the current waveform quality [102]. Grant investigated the problems in operating the constant $\frac{V}{f}$ drives in the overmodulation range. He illustrated that abrupt pulse dropping in the overmodulation region could induce significant current transients. He developed a pulse limiting method where the narrowing voltage pulses are held at a minimum value and shifted to the sides of the modulation wave such that the adverse effects of the narrow pulses could be reduced [53].

Rowan et al. investigated the SPWM modulator nonlinearity and utilized the fundamental component voltage gain formula to analyze the current controlled drive overmodulation region behavior [169]. They utilized the SPWM gain function [147] to evaluate the performance of the stationary PI current regulator and SFCR to predict the drive behavior in the overmodulation range. They demonstrated that associated with the gain loss, both current regulators exhibited degraded performance. However, the stationary regulator performed poorly compared to SFCR in the overmodulation range.

Xu and Novotny studied the overmodulation issues by simulating several current regulator structures in the high modulation range and indicated that on-off current regulators which operate on an instantaneous basis provide less voltage utilization than those that modulate by accounting for the full fundamental cycle [205]. Through experiments and simulation studies, they showed that the on-off regulators have significant phase delay and magnitude error. They indicated increasing the switching frequency of an on-off current regulator increases bus utilization. They also recognized the influence of the induced EMF voltage on the current regulator performance, and suggested that for carrier based PWM, the feedforward command increases the bus utilization.

Holtz et al. developed a space vector based feedforward PWM method for the overmodulation operating range [75]. The method divides the overmodulation region into two sub regions, each of which has a unique overmodulation characteristic (space vector trajectory). Similar to [169], the work focuses on the per fundamental cycle characteristic. Therefore, the fundamental component gain concept is implied. In this modulation method the reference voltage vector is pre-processed through a look-up table based gain and/or angle adjuster. In the first overmodulation region, only the magnitude of the reference vector is modified and it is multiplied by a gain and the resulting vector is processed by the conventional space vector modulator. In the second region both the angle and magnitude of the reference are modified by the pre-processor and then the resulting vector is processed by the conventional modulator. The method is computationally complex, requires a mode selection loop and relatively large look-up tables. Essentially being a fundamental component gain adjuster, the method has dynamic performance limitations, therefore it is not suitable for current controlled drive applications. However, the space vector approach is very attractive from the perspective of vectorially illustrating the overmodulation range behavior of VSIs. Through vector diagrams, the voltage limit of the inverter becomes geometrically visible, and intuition can be gained on the overmodulation range behavior.

Recognition of SVPWM as a superior modulation method which fully utilizes the inverter voltage hexagon [29] has been followed by the development of several space vector overmodulation methods. Gaining intuition from the inverter hexagon geometry, several researchers developed various overmodulation methods for both voltage feedforward and current controlled drives.

The vector space based overmodulation method developed by Habetler et al. selects the largest voltage vector that is aligned with the reference vector (minimum angle error method) [57, 58] and it was utilized in a dead beat current controlled drive. Another intuitive approach developed by Mochikawa et al. selects the voltage vector that is vectorially closest to the reference (minimum magnitude error method) [131] by projecting the reference voltage vector tip point on the closest inverter hexagon side. The one step optimal control characteristic of this approach was later recognized by Seidl et al. [181], and the authors developed a neural network hardware implementation as opposed to the original implementation which involved computation of the algebraic exact equations by numeric approximation. While the minimum angle error method is limited in voltage capability (its output voltage is less than 95 % of the six-step voltage), the minimum magnitude error method requires additional neural network hardware circuit or a high performance signal processor.

Jul-Ki and Sul compared the above discussed two graphic methods and developed a method with superior performance characteristics [88]. In this method, the vector formed by the superposition of the feedforward voltage vector and the PI current controller output vector is intersected with the hexagon side. The intersection point of the PI controller vector with the hexagon side defines the tip point of the modified reference voltage vector. In an induction motor application, this approach typically yields a vector which is located in between the minimum magnitude error vector and minimum angle error vector. The method has better performance than the other methods. However, it is complex and its performance improvement over the previous two is not significant.

Another intuitive method which was proposed by Tenti et al. [192], projects the reference vector tip point on the inverter voltage vector closer to the reference vector. The point on the hexagon side which the projection line intersects is selected to be the modified reference vector. The method is inferior to the one step optimal method and its implementation difficulty is comparable.

Kerkman et al. utilized the nonlinear inverter gain function model to remove the adverse effect of the nonlinear gain on the regulator performance by multiplying the inverter gain by its exact inverse which is calculated from the gain formula and stored in a look up table [91, 93]. They applied this principle to voltage feedforward type regulators and to the feedforward channel of the current regulators. They illustrated that the gain compensation method enhances the DC bus voltage disturbance characteristics and improves the overmodulation region performance. They showed that the modulator would have similar switching patterns to the pattern of the feedforward method suggested by Holtz et al. [75].

Similar to some of the developments of this thesis, a couple most recent publications investigate the modulator overmodulation characteristics [59, 60, 161]. The work by Pop and Kelemen investigates the harmonic characteristics and the narrow pulse issues of DPWM methods and compare to other methods [161]. However, no in depth analysis is provided. Haras also recognizes this issue [59, 60], and also focuses on the space vector overmodulation method developed in [75]. However, this work also has limited focus and in particular the influence of the modulator characteristics on the drive performance has not been recognized, and the modulator characterization study is superficial.

Recently in Europe several studies on the high modulation range (including overmodulation range) performance issues of high power traction drives have been investigated in detail [8, 48, 185]. In such drives in the low speed range synchronous SPWM or SVPWM method is utilized. As the speed sufficiently increases transition to pulse programmed optimal PWM methods, and as the speed further increases transition to the six-step mode follows. Since in such drives the switching frequency is limited, typically transition from one method or one voltage level to the next may result in large current spikes and oscillatory behavior. Therefore, sophisticated transitioning methods have been established and relatively smooth transition to/from six-step mode of such drives has been achieved [8, 48, 185]. In most such methods transition is allowed to occur at specific angles with respect to the inverter hexagon, hence the dynamic performance is constrained. The fundamental component current measurement is an issue and involved estimation methods are employed to calculate its value for closed loop current control [48, 70, 71, 73, 185]. Although the current control loop bandwidth is low due to the measurement/estimation delays, it is sufficient in FOC controlled high power drive traction applications with no stringent dynamic performance requirements [47, 48, 185]. However, these methods are not suitable for industrial and servo drives with demanding dynamic performance characteristics and stringent controller cost and performance limitations.

In addition to the above summarized important publications, there have been several other publications involving overmodulation. Employing the complex variable Fourier analysis, Bolognani and Zigliotti analytically re-investigated the voltage vector overmodulation characteristics [18, 19] previously reported in [75] and utilized numerical data to characterize the modulator phase and magnitude functions. Another similar approach was recently reported in [116]. Yasuda et al. re-invented the SPWM voltage gain characteristic [207] and gain compensation method which was reported in [93, 91]. Assuming the overmodulation nonlinearity is a difficult to model complex function, a fuzzy overmodulation control algorithm was developed in [95].

The above summary of the overmodulation literature indicates continuous and rapid progress in this area. Most of the discussed literature involves the modulator steady state voltage gain characteristics which is generally meaningful for voltage feedforward controlled drives. In particular, the complex plane (space vector) illustration has been widely utilized to analyze the modulator characteristics and to invent new overmodulation methods. However, the overmodulation characteristics of modern triangle intersection PWM methods have not been well understood (with the exception of SPWM). The waveform quality and the fundamental component voltage gain characteristics are not thoroughly analyzed and the behavior is not well understood.

In most of the above summarized publications overmodulation in current controlled drives has not been considered. The overmodulation range performance degradation of current controlled drives has been recognized [205, 169]. However, the literature involving performance study of such drives and techniques to enhance the performance is limited. Voltage margin control methods have been proposed for FOC drives so that overmodulation is avoided as much as possible during field/flux weakening [99, 100, 180]. In these methods the synchronous frame d and q axis voltages are partitioned in a manner to maintain current controller performance. Accounting for the load back emf, these methods allocate a direct axis voltage margin for maintaining the torque producing current controllability and maximize the torque output of vector controlled drives. They also improve the disturbance rejection characteristics of FOC drives[180]. However, rapid acceleration and abrupt DC bus and load torque disturbances often result in entrance to the overmodulation region.

The overmodulation region behavior of FOC based induction motor drives employing the minimum magnitude error and minimum phase error PWM methods was studied, and a superior overmodulation method was reported in [88, 182]. Also two overmodulation region current control methods with superior performance have recently been developed by Choi and Sul [35, 36]. The minimum time current controller involves a transient time minimization algorithm with given inverter voltage and current boundaries recognized. Involved computations yield the optimal d and q axis voltage references which are on the inverter hexagon boundary[36]. In the cross-coupling current controller, during overmodulation the q axis current error of the SFCR is subtracted from the d axis current reference in order to maintain the torque capability of the drive [35]. In an induction motor application this approach yields dynamic field weakening, and performance is retained as much as possible during transients.

The recently reported and above summarized current controlled drive overmodulation studies are limited in scope, and many performance and implementation issues are open to detailed investigations. In the modern triangle-intersection PWM methods, the interaction between the current controller and the modulator has not been recognized or investigated in detail. The steady state and dynamic overmodulation performance characteristics of current controlled drives are not well understood. Therefore, the investigation of such characteristics and development of advanced methods is mandatory. The overmodulation chapters of this thesis will attempt to address these and the previously described issues of open loop voltage feedforward controlled drives with rigorous theoretical study and detailed experimental work.

2.7 Summary

This chapter provided a detailed literature survey of inverter drives with emphasis on the modulators and control methods. It has become obvious the inverter drives technology has gone through several major breakthroughs and revolutionized the industrial processes with magnificent performance advancements. With a lot more than a handful of books including at least a sizable chapter on PWM and drives [21, 85, 89, 90, 108, 118, 132, 136, 196, 202, 203], and thousands of articles on PWM and drives in existence, the subject has still not reached a full maturation stage. Due to the significant flexibility in controlling the inverter switches, large number of switching algorithms were developed and some of these have gained wide acceptance and fully developed. However, the performance of modern drives utilizing the modern modulation and control methods is limited. In particular, the overmodulation region performance is poor and further progress is inevitable.

This thesis develops advanced modulation methods and control algorithms with superior energy efficiency, low harmonic distortion, and high dynamic performance. In particular, the overmodulation region performance is investigated in detail.

Before establishing the advanced PWM methods and control algorithms, a detailed review of carrier based PWM methods is provided in the following chapter. This review intends to prepare the reader to the following chapters which involve detailed knowledge of the important PWM methods and their performance characteristics. A novel high performance DPWM method is also introduced in the chapter.