CHAPTER 2

LITERATURE SURVEY

2.1 INTRODUCTION

This chapter presents a literature review, which aims at providing the backgrounds of the research and the topic. Modulation is the process of switching the power electronic device in a power converter from one state to another. Many new modulation techniques have been developed to cater the growing number of MI topologies. They are aimed at generating a stepped switched waveform that best approximates an arbitrary reference signal with adjustable amplitude, frequency, and phase fundamental component that is usually a sinusoid in steady state. Since the modulation scheme is intended to be used in high-power converters, the main figures of merit pursued are high power quality and minimum switching frequency. These two requirements compete with each other, and therefore, it is considered one of the major challenges in MC technology. MI systems have been compared on the basis of overall performance, with little attempt being made to adapt the best modulation strategy for one topology to other structures. The existing modulations suitable for CMI are reviewed based on switching loss reduction, DC-link capacitor voltage balancing, and harmonic performance improvements.

2.2 GENERAL CONSIDERATIONS

Multilevel modulations are meant to produce an average output voltage proportional to the reference given by some external algorithm. The high number of switches composing a MI may lead to the conclusion that complex algorithms are necessary. Fortunately, all the modulations used for standard two-level converters can be easily adapted to MI.

Multilevel modulation algorithm should be designed to fulfil the following requirements (Naumanen et al 2009):

- Voltage quality should be good.
- Modular design.
- Simultaneous switching of multiple voltage levels is not allowed.
- Module switching frequency should be minimized.
- Switching frequency of power devices should be minimized.
- The power modules should share the load equally.
- The control algorithm should be simple to implement with low cost.

The modulation algorithm used to drive the MI has to be aimed to give the voltage level required for each leg; the translation in the proper switch configurations are done by other algorithms which can be hardware or software implemented. It is generally accepted that performance of an inverter, with any switching strategy is closely associated to the harmonic contents of its output voltage.

2.3 MULTILEVEL MODULATION CLASSIFICATION

There are several ways to classify modulation techniques; in (Rodriguez et al 2005) and (Du et al 2008), two possible ways are presented. The switching frequency can subdivide multilevel modulations into two classes; fundamental, and high switching frequency. Fundamental switching frequency modulations produce switch commutations at output fundamental frequency and can be aimed to cancel some particular low frequency harmonics. In this class, there are Space Vector Control (SVC) and Selective Harmonic Elimination (SHE). In SVC, the complex plain is divided in several hexagonal zones defining the proximity of the reference to the nearest generable vector which is definitely applied. In SHE, the output is a staircase wave with steps duration optimized to cancel the specified harmonics; however the number of harmonics which can be eliminated at the same time is proportional to the number of converter levels.

High switching frequency modulations are the adaptations of standard PWM to multilevel and they are meant to switch at very high frequency, about 10 to 20 kHz. Among them, there is Phase Shifted Carrier (PSC) PWM and a subclass called level shifted PWM. The carriers can be arranged with shifts in amplitude relating each carrier with each possible output voltage level generated by the inverter. This strategy is known as Level Shifted PWM (LSPWM), and depending on the disposition of the carriers, they can be in Phase Disposition (PD), Phase Opposition Disposition (POD), and Alternate Phase Opposition Disposition (APOD) (McGrath and Holmes 2002).

LSPWM methods can be implemented for any MI topology; however, they are more suited for the NPC, since each carrier signal can be easily related to each power device. Particularly, LSPWM methods are not very attractive for CMI, since the vertical shifts relate each carrier and output level to a particular cell, producing an uneven power distribution among the cells. This power unbalance disables the input current harmonic mitigation that can be achieved with the multi-pulse input isolation transformer, reducing the power quality. In addition to these modulations, Single Carrier Sinusoidal

Modulation (SCSM) and Carrier Based Space Vector Modulations (CBSVM) are reviewed for CMI.

In general, low switching frequency methods are preferred for high power applications due to the reduction of switching losses, while the better output power quality and higher bandwidth of high switching frequency algorithms are more suitable for high dynamic range applications.

2.4 SPACE VECTOR CONTROL

SVC can be used to approximate the reference voltage at the fundamental frequency by choosing the closest generable vectors since MI with a high number of voltage levels provide a high number of voltage vectors (Rodriguez et al 2002). SVC with the natural fundamental switching frequency results in reduced switching losses for high-power application. Moreover, the switching frequency of each switch is equal to the fundamental, meaning reduced commutation losses and the possibility to apply this modulation even to slow devices like Gate Turn-Off (GTO) thyristors for high power applications.

The time-domain version of SVC is the nearest level control, which in essence is the same principle but considering the closest voltage level that can be generated by the inverter instead of the closest vector. Both methods are suitable for inverters with a high number of levels, since the operating principle is based on an approximation and not a modulation with a time average of the reference; also, due to the low and variable switching frequency, they present higher Total Harmonic Distortion (THD) for inverters with a lower number of levels and also for low modulation indexes.

It is a vector modulation technique in which the possible vectors are available with vertices of a triangular grid in the complex plain. Surely the vector will lay in one of the hexagonal regions determining, in this way, its closest generable vector which has to be applied to the output. In a period of time, as in PWM cycle, SVC does not produce an output vector with the same DC value of the reference. This determines an error which is not compensated, but the aim of the modulation is to choose among all the generable vectors, the one which minimizes it. If the reference is a vector rotating at a constant angular speed, the output voltage waveform will be a symmetric staircase.

This kind of modulation is particularly suited for MI with a higher number of levels because the error made is getting smaller and smaller increasing the levels. So it is unnecessary to use a more complex modulation scheme involving the three vectors adjacent to the reference due to the high density of vectors the MI present when their number of levels is quite high. Evidently, SVC is definitely unreliable when it is applied to a three-level and five-level inverters because the ripple on the output voltage becomes unacceptable.

2.5 SELECTIVE HARMONIC ELIMINATION

As an alternative, SHE can be applied to MI for high-power applications due to the reduction in the switching losses (Li et al 2000). The principle of the SHE is one in which switching levels in order to form step-shaped waveform close as possible to sinusoidal, using only one pulse of each switch within whole output voltage period. The flexibility of the multiple voltage levels allows the synthesis of a sinusoid to be achieved by simple staircase control, whereby each voltage level is applied across the load at the optimal electrical angle in the cycle. The switching angles for the voltage levels are calculated to cancel the low-order harmonics.

Chiasson et al (2004) have extended their theory of resultants to SHE angle computation for CMI. SHE can be applied to CMI using two approaches. The first one is to consider one commutation angle per inverter; thus, the number of harmonics that can be eliminated is N − 1. To ensure the desired spectral quality and output amplitude, the angles at which each voltage level is applied need to be selected. In order to compute these angles, a set of simultaneous equations can be derived and solved similar to two-level SHE (Du et al 2006). Numeric mathematical methods used to solve these equations are Newton's method, resultant theory, and genetic algorithms (Wells et al 2007). In these modulations, a high difference among the conducting times in the output waveforms of the cells, this produces an unbalanced power distribution. In Perez et al (2008), this effect is reduced by a simple change of conducting angles. This modulation technique can be applied to symmetrical inverters when the number of output voltage levels is high or when the inverter has non-equal DC links.

The second approach is to combine the original SHE with the multilevel version in which there are several switching angles per voltage level (Hosseini et al 2007). In this case, the number of harmonics eliminated is independent from the number of output voltage levels, and the switching frequency is higher than the fundamental. It is possible to note that there are several different possibilities to synthesize the output voltage, allowing a further optimization in terms of switching frequency.

The harmonic quality of the output voltage is an important criterion in selecting the optimum control angles, and elimination of as many low-order harmonics is the optimum approach. In Agelidis et al (2008), it is presented as generalization of SHE, a way to achieve a wide range of modulation index with minimized THD of the synthesized waveforms. In general, a stepped waveform, which comprises many switching angles, can be divided into many modulation index zones. By using this technique, low switching frequencies and minimized harmonic contents can be achieved even at low modulation indexes.

However, the complexity of the SHE increases by increasing the number of voltage levels due to the increase in the number of switching angles and the corresponding number of polynomial equations which must be solved. The SHE angles are computed based on the Fourier series and the assumption of steady-state sinusoidal voltages; hence, for variable-speed operation, these angles will not fully eliminate the harmonics, which, through feedback, can greatly be amplified by the closed-loop controller, degrading overall performance, and therefore is limited in practice to low-dynamic performance demanding drive applications.

2.6 SPACE VECTOR MODULATION

Space Vector Modulation (SVM) is a technique where the reference voltage is represented as a reference vector to be generated by the power converter. All the discrete possible switching states of the converter lead to discrete output voltages and they can be also represented as the possible voltage vectors that can be achieved. The SVM technique generates the voltage reference vector as a linear combination of the state vectors obtaining an averaged output voltage equal to the reference over one switching period (Wei et al 2003).

SVM has also been extended and even generalized for N-level inverters using 2-D and 3-D algorithms (Gupta and Khambadkone 2007). A common characteristic to all SVM based schemes is that the modulation algorithm is divided into three stages: in the first, a set of switching states or vectors needs to be selected for modulation, which usually are the three closest vectors to the reference (Celanovic and Boroyevich 2001); the second stage computes the duty cycles of each vector to achieve the desired reference over a time average; and the final stage is the sequence in which the vectors are generated. Usually, center-distributed or symmetric sequences are favored due to synchronous digital sampling of the current.

Compared with other conventional SVM strategies, the recent SVM strategies have reduced the computational burden and the complexity of the algorithms (Franquelo et al 2008, Aneesh et al 2009). The triangle identification and duty cycles can be calculated by using very simple calculations. The new SVM does not require the calculation of trigonometric functions, or the use of look-up tables or coordinate system transformations. In addition, the algorithm can be easily extended to a higher number of the voltage levels without increasing the computational load.

The different contributions that report variations on the three basic stages of SVM pursue different goals, which, in many cases, are one or more of the following: switching frequency reduction, lower computational cost, common-mode voltage elimination or reduction, lower THD, SVM for multiphase systems, unbalanced system operation, capacitor voltage balance, feed-forward of DC link ripple, etc. Despite all these reported improvements, SVM based multilevel algorithms are not the dominant modulation scheme found in industrial applications to this date.

A main reason is that carrier based PWM requires only the reference and carrier signals and a simple comparator to deliver the gating signals, whereas even very low complexity and low computational cost SVM methods require an algorithm with at least the three stages mentioned before. Recently, it has been demonstrated that the same voltage waveform generated by the most common SVM algorithms can be obtained in a much simpler way by using carrier based space vector modulation (Kanchan et al 2007). The advantages are that it can easily be extended to converters with any number of levels, hereby reducing the design, implementation, and computation complexity usually associated to SVM algorithms.

2.7 MULTILEVEL SINUSOIDAL MODULATIONS

MSPWM techniques are based on a single modulating or reference signal, which in most cases is sinusoidal. This reference waveform is compared and sampled through a number of triangular waveforms. The MSPWM control is proven to be able to effectively reduce the lower order harmonic components. The modulating signals for MSPWM are logically compatible with the required switches in the standard MI topologies. The main advantages of MSPWM are easy implementation in analog or digital circuitry, or using software techniques, is easily extended to all MI topologies, shows good performance at moderate switching frequencies, good dynamic performance, and suitable for closed loop control.

In these carrier-based modulations, each level in a phase requires a carrier of its own. For the CMI, this means that every module has its own carrier, which is compared with the reference voltage. These modulations control each phase leg of the inverter separately and allow the line to line voltage to be developed implicitly. Two fundamental requirements for carrier based PWM schemes should observe are synchronism with the fundamental frequency and quarter and half wave symmetry.

(i) Synchronism with the fundamental frequency means ensuring the switching frequency f_c is an integer multiple of the synthesized fundamental frequency f_o. That is, the pulse number $P = \frac{f_c}{f_o}$ must be an exact integer. The frequency spectrum of the PWM waveform will then consist of discrete frequencies at multiples of the fundamental frequency, where P is an integer.

(ii) Quarter and half wave symmetry ensures that no even harmonics will exist in the output spectrum and to keep the harmonic distortion low. This can be achieved by choosing P odd. An important even harmonic which is eliminated is the DC component. No frequency components below the fundamental frequency will exist. This is important since an undesired harmonic component near zero frequency, even if small in amplitude, can cause large currents to flow in inductive loads. Beyond these basic requirements, there are many different ways of generating PWM pulses.

The performance of MSPWM is determined by its modulation signals. However, carrier affects the superior performance of the modulator, too. The PWM waveform must be synchronized with its own fundamental to totally eliminate the sub-harmonics in the output voltages. Further, three-phase symmetry must also be maintained to ensure that every frequency component is balanced among the three phases. Thus, the PWM strategies for high-power drives must produce synchronized PWM waveforms with all of the waveform symmetries listed above.

2.7.1 Phase Shifted Carrier Modulation

The principle of PSC modulation is to retain sinusoidal reference waveforms for the two phase legs of each FBI that are phase shifted by 180° and then to phase shift the carriers of each cell to achieve additional harmonic sideband cancellation around the even carrier multiple groups. Figure 2.1(a) illustrates the carrier and reference arrangements for a five-level CMI structure. The required carriers, all with the same amplitude and frequency, depend on the number of levels; in a converter with N levels, (N-1)/2 carriers are necessary. A phase shift is introduced between the carrier signals of contiguous cells, producing a phase-shifted switching pattern between them.

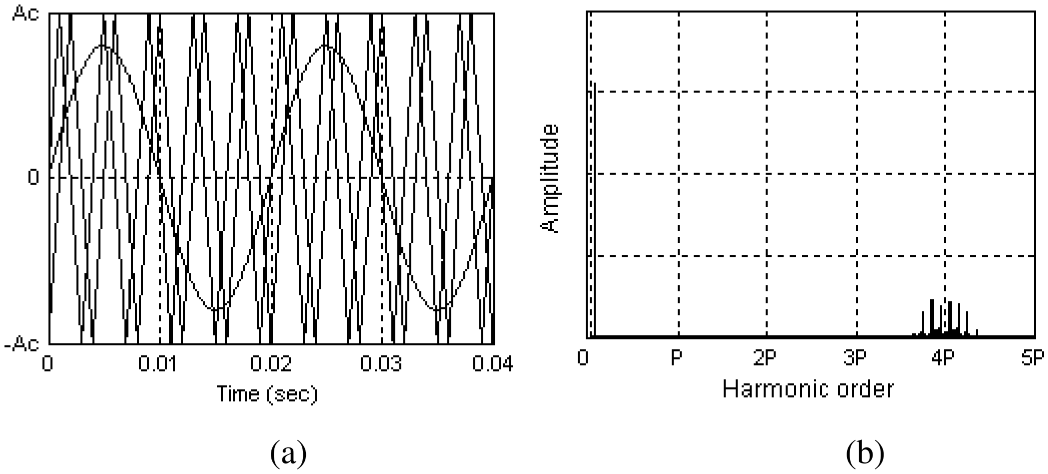


Figure 2.1 (a) Sinusoidal reference and carriers for five-level PSC modulation (b) Spectrum of the output voltage waveform

Optimum harmonic cancellation is achieved by phase shifting each carrier by $(i-1)\,\frac{\pi}{K}$, where i is the i^{th} FBI cell (Naderi and Rahmati 2008). Therefore, for two FBI with carrier phase shift of 90^o, harmonic cancellation up to side bands around multiples of $4f_c$ will be achieved. For three cascaded FBI with carrier phase shift of 60^o, harmonic cancellation up to side bands around multiples of $6f_c$ will be achieved and so on. This harmonic cancellation is not dependent on the pulse ratio and is valid even for very low pulse ratios. In addition, triplen side band harmonic cancellation around $2k^{th}$ carrier and its multiples will also occur between the phase legs as a separate process because of the 120^o phase difference that occurs between the fundamental reference components of a three phase system. In the presented case, the reference is common for all the carriers even if there are some versions of PSC-PWM which involve more references. The comparison between each carrier and the reference are PSC-PWM pulses.

The output switching frequencies results to be higher than carrier one and the relationship between output and carrier switching frequencies, f_{out} and f_c respectively.

$$f_{out} = (N-1)f_c \tag{2.1}$$

Moreover, due to the particular disposition of the carriers, the output is generated switching among the two levels nearest to the reference, which minimizes output harmonic content. This kind of modulation is particularly suited for CMI because the comparison signals can directly drive converter switches, while some hardware is necessary in between for other topologies.

Complete harmonic cancellation of the switching harmonics up to $2K^{th}$ carrier group side band harmonics is again clearly evident from Figure 2.1(b) together with the expected cancellation of the triplen harmonics from the $2N^{th}$ carrier group sidebands. It is essential that all FBI have exactly the same DC bus voltage to achieve effective harmonic side band cancellation for a CMI. In the over-modulation region, new harmonic components are only created in the base band region. The important consequence of this characteristic is that the harmonic cancellation of the side band harmonics in CMI is not affected by over-modulation.

PSC-PWM is the best choice for CMI due to appropriate distribution of harmonics power density and simple generation strategy. Also, it offers an even power distribution among cells and it is very easy to implement independently of the number of inverters. This modulation shifts the phase of each carrier in a proper angle to reduce the harmonic content of the output voltage. Moreover, it is possible to work in the over modulation region when a common-mode term is added to the reference.

Since all the cells are controlled with the same reference and same carrier frequency, the switch device usage and the average power handled by each cell is evenly distributed. For CMI, multi-pulse diode rectifiers can be used to reduce input current harmonics. Another interesting feature is the fact that the total output voltage has a switching pattern with K times the frequency of the switching pattern of each cell. This multiplicative effect is produced by the phase-shifts of the carriers. Hence, better THD is obtained at the output, using K times lower frequency carriers. Also, the bandwidth is increased by the number of carriers multiplied with their equal frequency.

2.7.2 Level Shifted Multilevel Sinusoidal Modulation

LSPWM uses more carriers (N-1) with the same peak-to-peak amplitude and same frequency is disposed in such a way so that the bands they occupy are contiguous and form an N-level line to neutral output voltage waveform. These methods have the property of producing signals with significantly lower switching frequency than the carrier frequency. The carriers span the whole amplitude range that can be generated by the converter (Kouro et al 2008).

The modulation index is a performance criterion to measure the operating range of the PWM methods. For LSPWM, it is defined as $M = \frac{A_m}{KA_c}$, where A_m is the amplitude of the modulating signal. The reference voltage, on the other hand, can have values between –M K A_c and M K A_c. To cover the whole voltage range, the carriers are shifted vertically so that the carrier of the first module covers the range from zero to V, while the second covers the range from V to 2V. The last module covers the voltage from (K−1)V to KV. At the negative side, the order of the carriers is shuffled. The carriers of the LSPWM can also have a phase shift between each other. The switching instants are obtained by comparing the voltage reference with the module carrier. The module state is determined to be +V if the reference is higher than the positive carrier. For the negative carrier, the comparison is made vice versa, and otherwise, the module produces a zero voltage (Loh et al 2003).

The most evident modulation is called phase disposition. The interval of possible voltage reference values is subdivided into one zone for each carrier which modulates the output only when the reference belongs to its zone. When the reference does not belong to a zone, associated carrier comparison output is fixed to high or low: it is high when the reference is above the carrier; vice versa it is low when the reference is under the carrier. The comparison output, obtained in this way, and its negation can directly drive a couple of switches. The sum of all the comparison outputs is a signal proportional to the instantaneous required output level.

The phase opposition disposition uses the same translation of carriers as PD, but the carriers associated to negative levels are in opposition of phase as depicted in Figure 2.2(b). Even in POD, this signals are proportional to the level required. The APOD, depicted in Figure 2.2(c), has the carriers alternatively in phase or in opposition. The difference among these three LS-PWM is related to the symmetry of the output they produce. Indeed, POD and APOD have odd symmetry, while PD positive half-wave can be mirrored and translated to coincide with the negative one.

Each switch commutates at the carrier frequency only when the reference belong to the zone related. Otherwise the switch is hold, but the converter is still commutating. This means that the switching frequency of the converter is equal to the carrier frequency, but the average switching frequency of the single switch (f_{sw}) is lower and, and it is given by Equation (2.2).

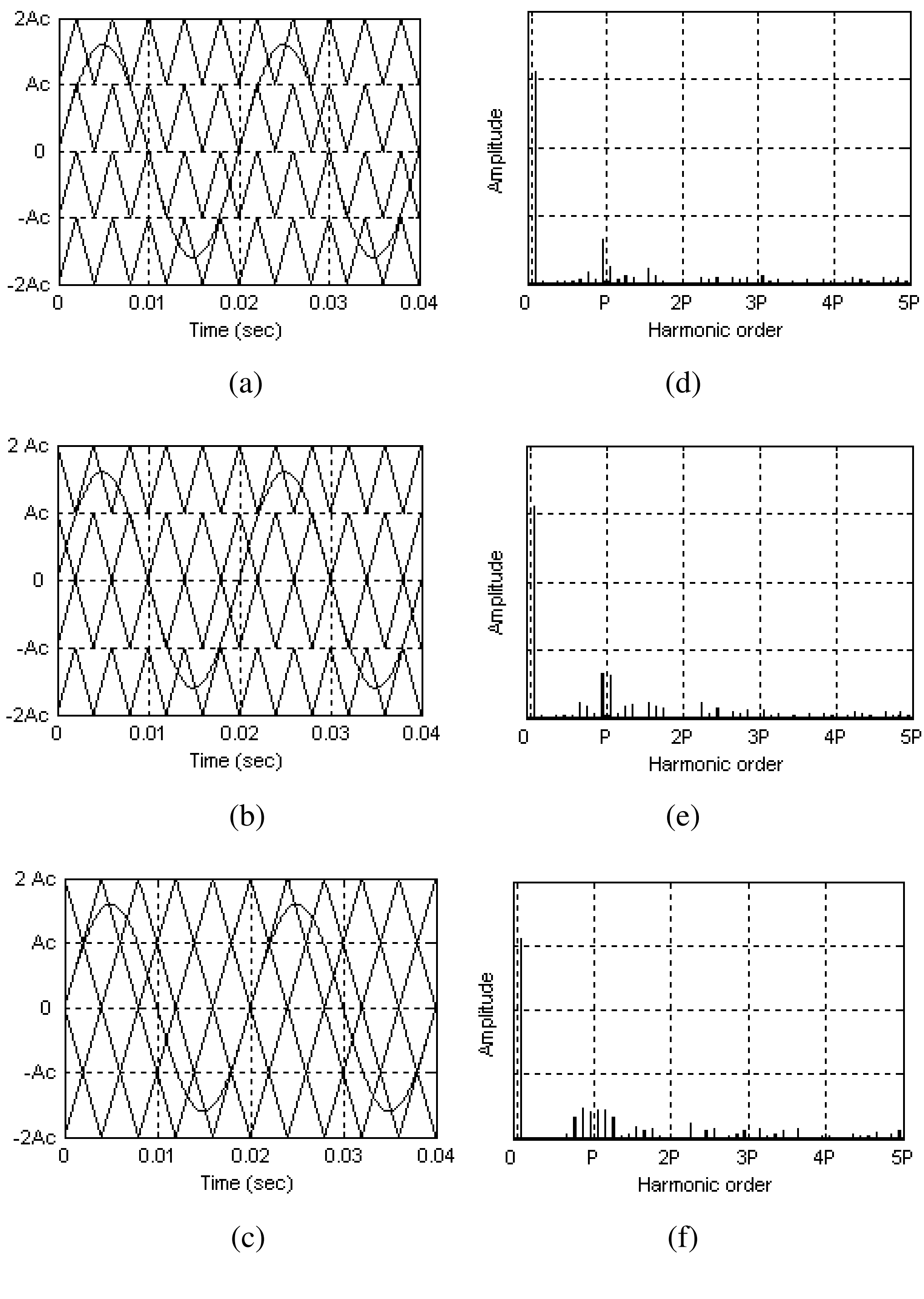


Figure 2.2 Five-level LSPWM operation: Sinusoidal reference and carriers for (a) PD, (b) POD, (c) APOD ; Spectrum of PWM waveforms for (d) PD, (e)POD, (f) APOD.

$$f_{sw} = \frac{f_c}{N-1} \tag{2.2}$$

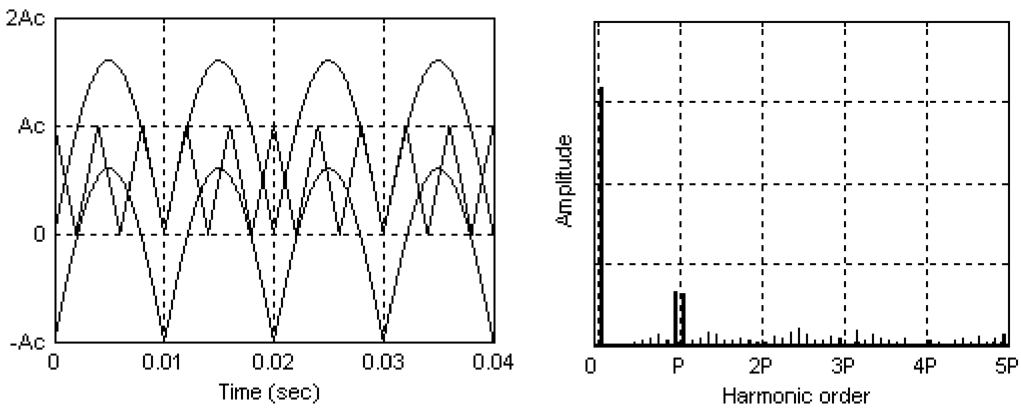
The harmonic content of the PWM waveforms using PD, POD, and APOD are shown in Figure 2.2(d)–(f), respectively. The main difference is in the first set of undesired harmonics. For APOD and POD, no harmonics exist at P due to odd symmetry of their PWM waveforms. For the PD case, however, the waveform is asymmetric and the harmonic is relatively high. Thus, APOD and POD are more convenient for single-phase inverters.

For three-phase inverters, the triplen harmonics of voltage will be eliminated due to connection of the load. Thus, the harmonic at P is eliminated if is chosen as a multiple of three. In this case, PD is more convenient due to the very little values of other harmonics (McGrath and Holmes 2000). These studies say that PD-PWM is harmonically superior across the bulk of the modulation region, because it is the only technique which places harmonic energy into a common mode carrier harmonic which cancels in the line voltage. Finally, it must be noticed that many more strategies have been proposed in order to improve some characteristics of the converter operation. McGrath et al (2006) has shown that the PSC modulation strategy achieves the same harmonic performance as the APOD technique when the switching frequencies are normalized so as to achieve the same overall number of switching transitions per fundamental cycle.

LSPWM is based on amplitude shifts between carriers. Each carrier is associated to a specific voltage level. When the reference is over one carrier, the corresponding level is generated. Therefore, when LSPWM is used with CMI, the inverter cells will be used only when the corresponding level is reached, producing an uneven power distribution and switching conditions between the cells. This will avoid the current harmonic cancellation at the input, and increase the input current distortion. These harmonics can be important due to the amount of power involved in high power applications, making its more difficult to meet standards. LSPWM leads to less distorted line voltages since all the carriers are in phase compared to PSC modulation (Holmes and McGrath 2001). In addition, since it is based on the output voltage levels of an inverter, this principle can be adapted to any MI topology.

2.7.3 Single Carrier Sinusoidal Modulation

SCSM is a unipolar PWM switching technique in which multiple sinusoidal modulating signals with a fundamental frequency f_o and amplitude of A_m compared to one carrier signal. The carrier signal is a train of triangular waveforms with a frequency of f_c and amplitude of A_c. The number of modulation signals is equal to the number of inverter cells in the CMI (Dahidah and Agelidis 2008).



(a) (b)

Figure 2.3 Five-level SCSM operation: (a) carrier and modulation waveforms (b) corresponding harmonic spectrum

The sinusoidal references are usually obtained by adding positive and negative offsets to the conventional reference signal. The principal reason to introduce the offset is to always interrupt the switching between the outermost levels and the middle level, as well as to avoid any minimum pulse width problems for low modulation indexes. For N-level SCSM needs K number of modulation signals have the same frequency f_o and amplitude of A_m with DC bias of A_c.

Figure 2.3 shows the modulation and carrier waveforms for the five-level SCSM. The carrier has constant period; therefore, the switches have constant switching frequency. Since the modulation is symmetric, the sinusoidal modulation signals are sampled by the triangular carrier signal once in every carrier cycle. Intersection between the modulation and carrier signal defines the switching instant of the SCSM. In order to ensure quarter wave symmetry, the starting point of the modulation signals ought to be phase shifted by one period of the carrier wave.

From the Figure 2.3(b), it is well known that the harmonics are controlled by the frequency of the carrier waveform. The main advantage with SCSM is to define the location of switching transitions that control or eliminate the selected harmonics. This PWM technique is aimed at high power inverter systems in utility applications and the output frequency is fixed to the utility's grid frequency. Moreover, the modulation index range does not change significantly and remains within a region of 0.7 to 1.

2.7.4 Carrier Based Space Vector Modulation

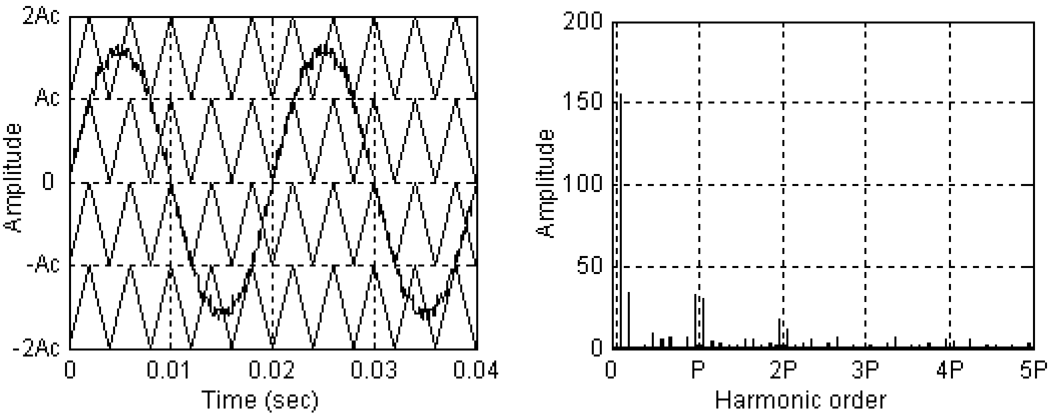
A powerful alternative for sinusoidal modulation is SVM, in which the converter is placed in a finite number of states in order to best approximate the reference voltage. This method offers better utilization of the DC bus voltage and provides several degrees of freedom for enhancement of the harmonic spectrum as well as switching losses. However, the converter has a higher number of levels or a higher number of phases, the representation of the control region becomes more complex, and the SVM strategies have to consider a large number of switching states. So, it is complex in implementation for higher level inverters. Therefore some researchers have studied the relationship between SVM and carrier-based PWM and try to use modified carrier-based PWM to achieve SVM's performance. Some techniques using common-mode injection in a carrier based PWM are developed to close to SVM (McGrath et al 2003).

Yao et al (2008) suggested that these techniques are harmonically equivalent, with the best spectral performance being achieved when the nearest three space vector states are selected with the middle two vectors centered in each half carrier switching interval. This strategy is known as Carrier Based Space Vector Modulation (CBSVM). CBSVM is derived from the addition of a common offset voltage to the three-phase references. This will center the active space vectors in the switching period, and hence match the carrier modulation to get optimized SVM (Kim et al 2008).

CVSVM pulse generation methodology was already presented for a general N-level inverter, where the PWM pulses are generated using only the three reference voltage signal amplitudes. Linearization of the voltage transfer characteristic in the over-modulation and its implementation was addressed for the first time in Kanchan et al (2007), for multi-level CBSVM signal generation, using a simple algorithm based only on the sampled amplitudes of phase references. The voltage transfer characteristic is a linear function of the modulation index throughout the modulation range extending up to six-step mode. This generalized N-level CBSVM signal generation algorithm is very simple, computationally efficient as compared with the conventional SVM algorithms and has linear voltage transfer characteristics throughout the modulation range extending up to six-step mode.

The modified phase references are obtained by adding off-set values to the reference waveforms. The modified modulation signals along with phase disposition carriers are shown in Figure 2.4(a). This method has the advantage of simplicity in expansion to higher levels, maintaining the property of SVM based on the voltage-second balance principle. This strategy is currently identified in the literature as the optimal harmonic approach for a carrier based multilevel control method.

For all MSPWM schemes are operating at high frequency and are better than the low frequency operation where the harmonic components could be shifted to high order. However at high frequency, more switching stress and power losses occur in the devices. Fundamentally, the choice of the PWM scheme will influence the complexity and performance of the inverter system.



(a) (b)

Figure 2.4 Five-level CBSVM operation: (a) modified reference and carrier waveforms (b) corresponding harmonic spectrum

2.8 HYBRID SPACE VECTOR MODULATIONS

A few publications are available in the area of hybrid modulations to improve the performance of the MI. The hybrid modulation is in part a PWM based method that is specially conceived for the CMI with unequal DC sources (Manjrekar and Lipo 1998). This type of modulation used only for a hybrid MI topology was realized based on the combination of a GTO and Insulated Gate Bipolar Transistor (IGBT) inverters for high power drives applications (Manjrekar et al 2000).The basic idea is to take advantage of the different power rating among the cells of the converters to reduce switching losses. This is achieved by controlling the high-power cells at a fundamental switching frequency, while the low-power cell is controlled using carrier based modulation.

Zaragoza et al (2009) has proposed a hybrid modulation technique for the three-level NPC converter. This strategy controls the low frequency voltage oscillations that appear at the neutral point in some operating conditions. But, it increases the switching losses of the converter. Also it fails to extend their operation in higher level systems.

Massoud et al (2008) introduced mapped hybrid SVM for reducing DSP processor execution time with SVM advantages. In this method, the complexity of conventional multilevel SVM is reduced by using phase shifted three-level SVM. Here, (N-1)/2 three-level SVM used for an N-level CMI with (N-1)/2 phase shifted up-down counters and one up counter, respectively for SVM implementation. This approach reduces DSP implementation complexity for levels higher than three. With this modulation method, the switching frequency and associated losses are increased by (N-1)/2 time that of conventional multilevel SVM.

In Narayanan et al (2008), Space vector based hybrid PWM technique is reported to reduce current ripple. In this technique, certain space vector switching sequences namely three-zone PWM, five-zone PWM and seven-zone PWM employ three, five, and seven different sequences, respectively, in every sector. The space vector switching sequences are selected, which results in the lowest RMS current ripple out of available sequences. Consequently, the total RMS current ripple over a fundamental cycle is reduced. These methods named as hybrid PWM, because it involves multiple sequences. The average switching frequency is maintained same as conventional SVM.

Recently, Zhao et al (2010) has extended hybrid space vector switching sequences for Voltage Source Inverter (VSI) to reduce switching loss with reduced harmonic distortion. The control methods available in (Narayanan et al 2008) and (D.Zhao et al 2010), are only for three phase two-level VSI. It has valuable merits with two-level PWM operation but can not be directly applied for MI.

Based on the detailed literature study, a few forms of hybrid modulation techniques are available to improve the performance of two-level and multilevel inverters, which are derived from SVM. Previously, the hybrid modulation means that the type of control for asymmetric CMI. New sequential switching hybrid sinusoidal modulations proposed by the author are only for general CMI. These modulations are developed from MSPWM for easy implementation in industrial applications.

2.9 MULTIPHASE INVERTER MODULATION SCHEMES

Multiphase variable-speed drives are nowadays considered for various industrial applications due to their inherent advantages. The major advantages of using a multiphase machine include improved reliability and increased fault tolerance, greater efficiency, higher torque density and reduced torque pulsations, lower per phase power handling requirements, enhanced modularity and improved noise characteristics. In order to fully exploit the potential of multiphase motor drives, a suitable and flexible modulation strategy for multiphase VSI has to be defined.

Most of the available work on PWM schemes for a five-phase VSI either covers carrier-based PWM or SVM schemes. Carrier-based methods for five-phase VSIs were analyzed in Grandi et al (2006). By extending the well-known third harmonic injection principle for three-phase VSI (Iqbal and Moinuddin 2006), it has been shown that in the case of a five-phase VSI injection of the fifth harmonic leads to an increase in the DC bus utilization in the linear modulation region, again by 5.15%.

A generalized continuous carrier-based approach that allows control of both fundamental and the third harmonic, with emphasis on voltage limit problems, has been presented in Iqbal et al (2006), while discontinuous carrier based modulation schemes have been elaborated in Casadei et al (2005). As noted in Grandi et al (2006), carrier based PWM methods are much easier to implement in multiphase inverters than SVM, since SVM requires sector identification and lookup tables to determine time of application of different vectors; thus making implementation complicated. For all these reasons, MSPWM is considered more promising than SVM and its derivatives are developed for multiphase MI operation.

2.10 DC LINK CAPACITOR VOLTAGE BALANCING ISSUES

One challenging problem of the CMI is the imbalance of the DC link capacitor voltages for STATCOM applications (Barrena et al 2006). The imbalance is due to different switching patterns for different FBI cells, parameter variations of active and passive components inside cells and control resolution. To achieve higher voltage quality, the switching patterns are usually different for different cells in a phase. The differences of switching patterns mean that cells cannot equally share the exchanged power with the load (Song et al 2004). This causes uneven charging of capacitors. The parameter variations of components inherently cause different power losses of cells.

With the LSPWM, switching frequency is equal to the carrier frequency, while the switching frequencies of the modules vary depending on the carrier allocation. This method is not suitable for the CMI modulation, because the modules are not loaded equally. Comparing the load encountered by the modules, the K^{th} module has a low utilization rate, while the first module is utilized almost all the time. Therefore, the DC-link capacitors are loaded differently, and the voltage balance is not maintained between them. The imbalance of DC capacitor voltages will degrade the quality of the voltage output. In severe cases, this could lead to the complete collapse of the power conversion system. Moreover, it will cause excessive voltages across the devices and an imbalance of switching losses (Fujii et al 2005).

An adequate control strategy for avoiding the imbalance of DC capacitor voltages must satisfy the conditions of the impact on voltage quality should be as small as possible, balanced operation when components of cells have parameter variations and FBI switches with different switching patterns. The feedback control strategies presented in Barrena et al (2008) reshapes the output voltage of cells based on the feedback signals of the DC capacitor voltages. However, these techniques do not show if the control strategies work in different operating modes. Here, a simple base MSPWM circulation scheme is proposed for SSHSM circulation among the modules to overcome the problems of unbalanced DC-link capacitor voltages and unequal load sharing.

2.11 OBJECTIVE OF THIS RESEARCH

Depending on the switching frequency of MI and for specific application, the appropriate modulation scheme can be selected. Generally, high power applications require low switching frequency due to the lower switching losses. Thus, the use of SHE and multilevel SVC are preferred strategies since these methods can operate with the fundamental switching frequency. However, high-quality converter outputs can be obtained by increasing the switching frequency. In this case, the MSPWM and SVM can be used. These schemes are more suitable for high dynamic range applications. The main reason is to improve efficiency, extend the device limits, and have a practically feasible cooling system. Operating at lower switching frequency usually introduces lower order harmonics, so matching efficiency with high performance is still one of the major challenges in MI development.

To achieve high efficiency without performance deterioration is a desired objective in power conversion. So, for a given topology and operating conditions, the commutations can be reduced by avoiding unnecessary switching state transitions. These could be defined as the certain switching that, when omitted, will not affect the system desired behavior. Hence, a reduction of commutations improves the converter efficiency.

This thesis focuses on MI modulation to improve the performance and effectiveness of the control with a special emphasis on a CMI. SSHSM schemes are derived from MSPWM. The basic idea to reduce the switching losses is to reduce the number of commutations per unit of time in the inverter operation while retaining the leading advantageous of MSPWM, which implies a reduction of switching frequency that contributes to a reduction of the switching losses.

The main themes of this thesis are as follows.

- Design a sequential switching hybrid modulation controller to generate SSHSM pulses for CMI.
- Examine the feasibility of these modulations through simulation and experimental investigations. Comparison of the performance

measures such as switching loss, heat-sink temperature rise and harmonics of developed modulation methods with conventional techniques in linear and over modulation.

- DC-link capacitor voltage balancing and equal load sharing between the modules of the inverter.
- Generalization of SSHSM for higher level and multiphase inverter operations.