CHAPTER 2

LITERATURE REVIEW

Traditional 2-level high-frequency pulse width modulation (PWM) inverters for motor drives have several problems associated with high frequency switching, which produce common-mode voltages and high voltage change (dV/dt) rates to the motor windings. The concept of utilizing multiple small voltage levels to perform power conversion was introduced by Nabae et al. [4] These converters recently have found many applications in the medium and high power applications. Large electric drives will require advanced power electronics inverters to meet the high power demands (1>MW) required of them. Advantages of this multilevel approach include good power quality, good electromagnetic compatibility (EMC), low switching losses, and high voltage capability. The main disadvantages of this technique are that a larger number of switching semiconductors are required for lower-voltage systems and the small voltage steps must be supplied on the dc side either by a capacitor bank or isolated voltage topologies [11-12].

These designs can create higher power quality for a given number of semiconductor devices than the fundamental topologies alone due to a multiplying effect of the number of levels. Recent advances in power electronics have made the multilevel concept practical [13]. In fact, the concept is so advantageous that several major drives manufacturers have obtained recent patents on multilevel power converters and associated switching techniques. Furthermore, several IEEE conferences now hold entire sessions on multilevel power conversion. It is evident that the multilevel concept will be a prominent choice for power electronic systems in future years, especially for medium-voltage operations. This chapter describes some of the background material regarding converter topologies, different modulation schemes, neutral point control strategies, and rectifier operation under balanced and unbalanced conditions.

2.1 Neutral Voltage Balancing

When series connected capacitors are used to divide the dc-link voltage, three-level inverters (multilevel converters in general) have a dc-link voltage problem due to unequal capacitor values, unequal loading of the capacitors due to unintended switching delays and nonlinear loads containing even order harmonics and so on. This is the important problem associated with the multilevel converters. Under certain conditions, the dc link neutral point potential can significantly fluctuate or continuously drift to unacceptable levels. As a result, the switching devices may fail due to over stress on the devices. Though it is possible to reduce the neutral point voltage deviation problem by excessively increasing the dc link capacitors and the bleeding resistor size, such a solution is prohibitive from the cost and size perspectives. Hence the choice of modulation scheme becomes important in controlling the neutral point voltage.

There have been different modulation schemes that have been proposed for controlling the neutral point voltage. The first impression of a multilevel power converter is that the large number of switches may lead to complex pulse-width modulation switching algorithms. The modulation schemes of the multilevel converter can be divided into two. The traditional voltage source method and the current regulated method. An advantage of the current control methods is that there is no need to control currents directly since higher-level control nearly always outputs the commanded currents. However, current controls are implemented using the analog techniques, which can only be relied upon, up to a certain level of power. Voltage source methods are implemented using the digital signal processing (DSP) and programmable logic device (PLD) implementation.

The development of voltage source modulation has taken two major paths. One is the well-known Sine-triangle modulation [14-17] in the time domain and space vector modulation in the qd stationary reference frame. It was pointed out earlier in [6,17,18] the similarities and the equivalence between the sine-triangle and the space-vector modulation. Adjusting some of the parameters in the sine-triangle scheme is equivalent to adjusting other parameters in the space vector scheme. In the case of sine-triangle modulated converters, the control of neutral point voltage is obtained by controlling the zero sequence of the three-level converter [19-20] or manipulating the redundant small vectors [21]. The variations in the sine-triangle method are essentially in the polarity and shape of the carrier waveforms. Although there are some differences in the spectral performance [22], for the high-enough frequency ratio between the carrier and the reference waveforms, there is no substantial difference between the proposed methods. Another very interesting method is based on multiple reference waveforms. It is sometimes referred to as dipolar modulation. This method uses single triangular carrier waves and two sinusoidal reference waves to modulate three-level inverters. The sinusoidal reference is always obtained by adding positive and negative offsets to the original reference sinusoidal signal. The principle reason to introduce offset is to always interrupt the switching between the outermost levels and the middle level. The advent of the transformer less multilevel inverter topology has brought forth various pulse width modulation (PWM) schemes as a means to control the switching of the active devices in each of the multiple voltage levels in the inverter.

Carrara [22] developed multilevel subharmonic PWM (SH-PWM) for a n-level inverter using n-1 carriers with same frequency f_c and same peak-peak amplitude A_c which are disposed such that the bands are occupied contiguously. The reference waveform has peak-peak amplitude A_m and frequency f_m, and it is centered in the middle of the carrier set. The reference is compared with each of the carrier signals. If the reference is greater than a carrier signal, then the active device corresponding to that carrier is switched on; and if the reference is less than a carrier signal, then the active device corresponding to that carrier is switched off. Carrara also considered different methods of disposing the many carrier bands required in multilevel PWM. The three cases he considered were alternative phase disposition, phase opposition disposition, and the phase disposition. Steinke [49] proposed a carrier-based method termed switching frequency optimal PWM (SFO-PWM), which was similar to [22] except that a zero sequence voltage is added to each of the carrier waveforms. The addition of this triplen-offset voltage continuously centers all the three waveforms in the carrier band. A method to balance device switching for all of the levels in a diode clamped inverter has been demonstrated for SH-PWM and SFO-PWM by varying the frequency for the different triangle wave carrier bands [23]. A novel carrier-based PWM method to balance the capacitor voltage of a flying capacitor multilevel inverter especially under low modulation index region is proposed in [24]. In this paper depending on the reference voltage, the new carrier can be separated into two parts and these parts are chosen depending on the magnitude of the reference voltage. The principle of reciprocity is introduced as a means for modeling the dc-bus current injection simultaneously as the modulation strategy is formulated [25]. The proposed strategy is general enough to be applied to converters with an even number of levels and an odd number of levels. The dc currents injected into the nodes of the converter are expressed in terms of the load current and the sharing functions. These sharing functions determine the share of the current that will be drawn from a particular node. A simple but efficient technique to evaluate steady state current injection into the nodes of the dc-bus stack is presented. The technique can be extended to determine the size of the capacitor. Different modulation modes such as the synchronous, asynchronous, and precalculated that can be combined to design a modulation strategy in the frequency/voltage plane were described in [26]. It also introduces a new method of synchronous dipolar modulation. A new carrier-based scheme, which is fully suitable for cascaded multilevel inverter topologies, was proposed to achieve the optimized switch utilization through the redistribution of the triangular carrier waves considering leg voltage redundancies while having the advantages of the conventional carrier-based SVPWM [27].

Switching frequency optimal PWM (SFOPWM), in which a new control method is based on optimal utilization of the three-level inverter’s capabilities, was dealt in [28]. In normal SFOPWM operation, each phase output terminal is connected to dc-link neutral point for a calculated part of each sample period. As a consequence within a sample period each phase influences neutral point voltage. If within one sample period connection time of phase output terminal with neutral is omitted, a mean deviation of potential will result. The converter is modulated such that the converter is connected to the neutral point for minimum amount of time. The generalization of the PWM "subharmonic" method to control single-phase or three-phase multilevel voltage source inverters was dealt in [29]. In this scheme it highlights the improvement in the harmonic contents in the multilevel converters. The modulation processes were analyzed with a powerful and mathematically rigorous method that provides the analytical expressions of the output phase voltages.

Perhaps one of the most popular modulation approaches for two-level converters is space vector modulation, which is now being used more and more in the control of multilevel converters. The concepts of space voltage vectors corresponding to various switching states has been applied to study the impact of various switching states on the capacitor charge balancing in almost every paper discussing the SVM approach [31]. Several papers have proposed different schemes for optimizing the switching, controlling the neutral voltage, and neutral current using the SVM [31-45].

Neutral point voltage balance is quite difficult because the neutral current as well as neutral duty cycles are piecewise nonlinear functions. There have been many efforts to analyze this problem and define modulation strategies [32]. In addition, the steady-state response usually has a third harmonic component. Taking this into account, perhaps the best approach is to average the neutral point current across the whole line cycle [33]. Although this approach cannot determine either the size or the shape of the voltage ripple, it does show the trends and the overall stability of the dc-link voltage, and can be linearized and used to design a neutral voltage controller. The limits of the neutral point current control for balancing the voltage in three-level neutral point connected converters were analyzed [34]. In this work, a mathematical model, which can be applied to converters with higher number of levels, was developed. Nearest three vector modulation was the focus of this analysis. It analyzed the converter when it is operating alone and also when it is connected back-to-back.

The inherent relations between three-level sine triangle and space vector modulation techniques, which can lead to a more efficient and flexible three-level modulator with desired performance was proposed [35]. It has concluded that the three-level space vector modulation can be equivalently realized by sine-triangle modulation with proper injection of common mode injections. Also it provides the different common mode voltages injected to obtain the centered space vector. The space vector principle will be reiterated in [36] to show different neutral point voltage balancing capabilities for different regions on the space vector plane.

SVM calculated based on nearest three space vectors (NTSV) indicates that there is a restricted belt along the border of each triangle for this kind of switching strategy, resulting in a nonconjunction working area for the commanded voltage vector. This is certainly undesirable when this modulator is supposed to work with a field-oriented controller where the commanded voltage vector is generated based upon the desired current trajectory. The drawback of the nearest three vectors (NTV) is that, whenever the reference vector is close in phase and magnitude to any of the switching state vectors. One-way of dealing with this problem is to change from the nearest three-vector approach to nearest four-vector approach. Thus a narrow pulse problem can be solved at the expense of increased switching stress and somewhat increased harmonic content. An alternative, which involves the dividing the 60-degree sector into 14 sub-regions with their switching sequence, optimized in order to avoid the narrow pulses was proposed [32].

The nearest three virtual space vector pulse width modulation (NTVSV PWM) proposed in [32] allows controlling the neutral-point voltage over the full range of converter output voltage and for any load, provided that the addition of the output three phase currents equals to zero. But in the case of a linear load, the distortion of the output voltage around the switching frequency is higher than needed to achieve this goal.

The concept of radial space vector algorithm, in which the decomposition of the states is done was proposed in [37]. In the methodology, the states, which contribute to the neutral current, are identified. The only vectors are the medium vectors and hence whenever the reference vector lies in the sector, in which the medium vectors has to be used, the time required by the medium vector is divided equally between the adjacent vectors that lie on the radii emanating from the zero state and it was deduced that the identical line-line voltages are generated. As these radial states do not have any throws connected to the middle bus, they do not contribute to the neutral current. The drawback of the scheme is losing the active states of the multilevel inverter and when the scheme is applied to higher levels more states have to be decomposed.

The discontinuous modulation scheme can be applied to multilevel inverters using the zero sequence-offset voltages derived from 2 level inverter space vector concepts [38]. In this method, a variable $\alpha (0 < \alpha < 1)$ is introduced and the issue then becomes to determine the value of α that minimizes the deviation of the trajectory, which achieves the optimum modulation strategy. The variable α can be used to control the various dwell time of the switching devices. The absolute difference between the two dwell times i.e., the first and the last pattern, is what has to be controlled.

Another method of discontinuous modulation scheme is dividing the three level space vector diagram is divided into six hexagons [39]. The center vector of each hexagon is assumed as the null vectors. An offset voltage which has been derived is added to the modulation signals to achieve the discontinuous signals. The same concept of dividing the hexagons to the two-level hexagon and adding an offset voltage is extended to higher levels.

A generalized discontinuous dc-link balancing modulation strategy for three-level inverter was proposed by Helle [40]. The concept is derived based on the space vector modulation. In the proposed modulation scheme, the dc-link voltage can be actively controlled to maintain a stable neutral point even if unbalanced loading of the dc-link capacitors occur. The maximum unbalance for which the modulation scheme is able to compensate is theoretically investigated and found to be a function of load angle, modulation index, and output power level. The drawback of the scheme of the scheme is that it makes an assumption that the power factor of the load is known which is not in general.

The concept of utilizing the redundant state switching to achieve neutral point regulation [26] and not on reactive element minimization was proposed in [25-26]. However the objective of controlling the neutral voltage cannot be achieved when operating with a high modulation index and with low power factor load. Under these conditions, the average value of the neutral-point current calculated over a modulation period cannot be maintained at zero, and thus appears as a low-frequency ripple in the neutral point voltage. As a result of this oscillation, the output line-line voltages will also contain low-frequency harmonics, and the devices and capacitors themselves must additionally support voltages that are higher than those that occur when balance is achieved. Larger capacitors can attenuate the amplitude of this oscillation, but as it increases the cost of the whole system this solution is best avoided. Other approaches suggest allowing the neutral point voltage to oscillate and then compensating for the effects of the oscillation in the output voltages with a proper feed forward modulation [39-40]. Nevertheless, these approaches do not reduce the voltage applied to the devices, and some instability may appear when the system operates as a rectifier [43].

A new feed forward method of controlling three-level diode clamped converter with small dc-link capacitors was proposed in [44]. In this scheme the neutral voltage is measured and depending on the voltage, the magnitudes of the carriers are adjusted so that the capacitors are charged and discharged. The proposed scheme was capable of controlling the neutral-point voltage with a lower output-voltage switching frequency distortion and lower number of commutations, but only over a limited range of output voltage amplitudes for each load power factor.

The multilevel PWM techniques developed thus far have been extensions of two-level PWM methods. In obtaining the discontinuous signals previously the two-level concept was used in which the generalized expression of the zero sequence that has been derived for two-level case is been added to the modulation signals. However the different methods explained above do not use the concept of discontinuous modulation scheme.

The concept of using the zero sequence voltage for controlling the neutral voltage was discussed in [45] and again the drawback is the restriction of full usage of the available modulation index from the complex plane. Also there are several zero sequence expressions for each depending on the pivot point selected and hence becomes complex during the implementation. The present work proposes a novel generalized discontinuous carrier based PWM scheme for controlling the neutral point voltage. A detailed analysis has been provided in obtaining the discontinuous modulation signals. The control algorithm proposed is valid for all load power factors and also for high modulation indices.

2.2 Three-Phase Three-Level Rectifier

Power converters are more and more widely used in industrial applications due to the remarkable progresses made in the high power electronic devices. Conventional diode rectifier has simple configuration, low cost, and high reliability. Boost converters for power factor correction is the most popular technology. A rectifier based on series connection of full-bridge cell was proposed to achieve a high power factor, low current distortions based on look-up table with the aid of hysteresis current controller [71]. The selection criterion of the appropriate mode is based on the analysis of each switching state. The main drawback is that a large amount of data has to be stored in the microcontroller or DSP memory block for look-up table. Instead of using the line currents, active and reactive powers are used as pulse width modulated (PWM) control variables [70]. Moreover a virtual flux estimator replaces line voltage sensors. In this scheme the states are selected by a switching table based on the instantaneous errors between the commanded and estimated values of active and reactive power. The mathematics involved in the concept is very complex. A three-phase four-wire power factor corrector based on neutral-point-clamped topology is adopted to reduce harmonics and increase the input power factor was proposed [69]. Hysteresis controller is used to track the line current references. The current errors between the reference and measured currents are sent to hysteresis comparators. There are three valid switching states in each rectifier leg and these states are selected based on the error signal. The drawback of the scheme is that the scheme is only applicable for a star connected supply since the neutral for a delta connected is unavailable. A new single-phase switching mode rectifier for three-level pulse width modulation to achieve high input power factor was proposed and the control algorithm was based on a look-up table [58]. There will be five control signals in the input of the look-up table. These control signals are used to control the power flow of the adopted rectifier, compensate the capacitor voltages for the balance problem. The control using the look-up table is very tedious when it comes to the implementation. A novel control scheme for regulating the neutral point voltage for a three-level diode clamped rectifier was proposed in [83]. The control functions for generalized multilevel rectifier systems is partitioned into two closed loop regulators, one regulating the total dc bus voltage loop regulators and another that maintains the neutral point potential at the middle of the dc stack. The dc bus regulator generates a current reference that is proportional to the compensated dc voltage error signal, similar to more common two level rectifier systems. The main drawbacks of the previous proposed schemes are that they used dq transformations, look-up tables, space vector techniques that involve complex mathematics, and were difficult to implement.

In the proposed control scheme, the control methodology is based on the usage of the natural variables i.e., in the scheme the variables are not transformed to other reference frame so as to make the quantities time invariant. The control is based on the new natural reference frame controller developed for controlling the time varying signals.

2.3 Three-Phase Two-Leg Three-Level Rectifier

Several methods have been proposed to reduce the cost of the multilevel converter by reducing the switching losses, reducing the harmonics so that the cost of the passive components reduces, reducing the count of the devices [76], reducing the rating of the devices, and so on. However the performance is limited when reduced count of devices are used. Low cost AC drives with four power switches have been proposed to achieve two-level PWM operation in low power application. Different reduced parts-count topologies were proposed [74-75]. The general idea behind the topology was a rearrangement of IGBTs and diodes in a three-level converter. In these topologies, the top and the bottom most devices in each leg of the inverter are replaced by clamping diodes. However when the number of voltage levels is greater than three, for example in four-level converter, the innermost IGBTs require a rating of $(2/3)V_{dc}$, whereas the outermost IGBTs require a voltage rating of $(1/3)V_{dc}$. The imbalance of voltage ratings precludes the use of dual IGBT modules. Another rectifier using only six devices and twelve clamping diodes was proposed [71] to draw balanced and sinusoidal line currents with unity power factor. In this topology the neutral of the capacitor is connected to the neutral of the supply. The control of the rectifier is based on the hysteresis controller. A converter with eight switching devices and four clamping diodes was proposed in [72]. The unity power factor is achieved using the space vector PWM scheme. The qd voltage commands are obtained using the current controller outputs. Based on the location of the reference voltage in the space vector, the devices are selected and switched.

In the present work, eight switching devices and four clamping diodes is proposed and carrier-based PWM scheme is used to control the dc-link voltage and to achieve the unity power factor. The control methodology is based on the natural reference frame. The control signals are controlled directly without any transformations and hence the implementation and the control scheme become simple.

2.4 Unbalance Operation of Three-Phase Rectifier

The study of the unbalance operation of the power electronic converters is one of the important topics because in the real world of operation, no system is perfectly balanced. The different control schemes proposed for the unbalance operation of the rectifiers are for the two-level rectifiers. An adaptive controller in stationary reference for D-Statcom in unbalanced operation for a two-level rectifier was proposed [77]. The scheme ensures, for any compensated frequency, that the line currents are proportional to the line voltages, so that the same apparent resistance is observed in all phases and at all compensated frequencies. The proposed energy-shaping controller requires adaptation and estimation of rotating frame quantities. The control structure in a way is related to selective harmonic compensation [78-79]. The control methodology involves complex computations and is a drawback when it comes to implementation. Three control strategies that can be applied to a three-phase AC-DC converter under unbalanced input voltage conditions was proposed in [80]. The first strategy maintains unity power factor per phase, the second one maintains constant instantaneous power, and the last one supplies maximum power within the current rating of the converter. The control is based on generation of current command for the current controller from the dc-link controller. The achievement of unity power factor per phase under unbalanced conditions is impossible. A control scheme for regulating the instantaneous power for PWM AC-DC rectifiers under generalized unbalanced operating conditions was proposed [81]. By nullifying the oscillating components of the instantaneous power at the poles of the converter instead of the front-end through solving a set of nonlinear control equations in real time, the harmonics in the output dc voltage can be eliminated more effectively under generalized unbalanced operating conditions on the ac input side. The control scheme is based on the dq synchronous frame.

In the present scheme, a simple methodology based on constant power transfer is developed. Under unbalanced conditions, constant power and regulated dc-link voltage are achieved and under balanced conditions even the unity power factor is achieved. Even in the present control scheme, natural reference frame controller is being used to make the methodology and the implementation simple.