

The Essential Role and the Continuous Evolution of Modulation Techniques for Voltage Source Inverters in Past, Present and Future Power Electronics

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Abstract—The cost reduction of power electronic devices, the increase in their reliability, efficiency and power capability, lower development times, together with more demanding application requirements, have driven the development of several new inverter topologies recently introduced in industry, particularly medium-voltage converters. New more complex inverter topologies and new application fields come along with additional control challenges, such as: voltage imbalances, power quality issues, higher efficiency needs and fault tolerant operation, which necessarily requires the parallel development of modulation schemes. Therefore, recently there have been significant advances in the field of modulation of dc/ac converters, which conceptually has been dominated during the last several decades almost exclusively by classic pulse width modulation methods. This paper aims to concentrate and discuss the latest developments on this exciting technology, to provide insight on where the state-of-the-art stands today, and analyze the trends and challenges driving its future.

Index Terms—Multilevel systems, Modulation.

I. INTRODUCTION

POWER CONVERTERS have become over the last decades an enabling technology for a wide range of industrial applications mainly due to higher efficiency and performance. Converter topologies such as the ac/ac matrix converter, cycloconverters, current source inverters, load-commutated inverters, dc/dc converters, dc/ac converters and diode or thyristor-based rectifiers cover a wide range of different nominal power applications [1]. In particular dc/ac converters, commonly known as voltage source inverters (VSI),

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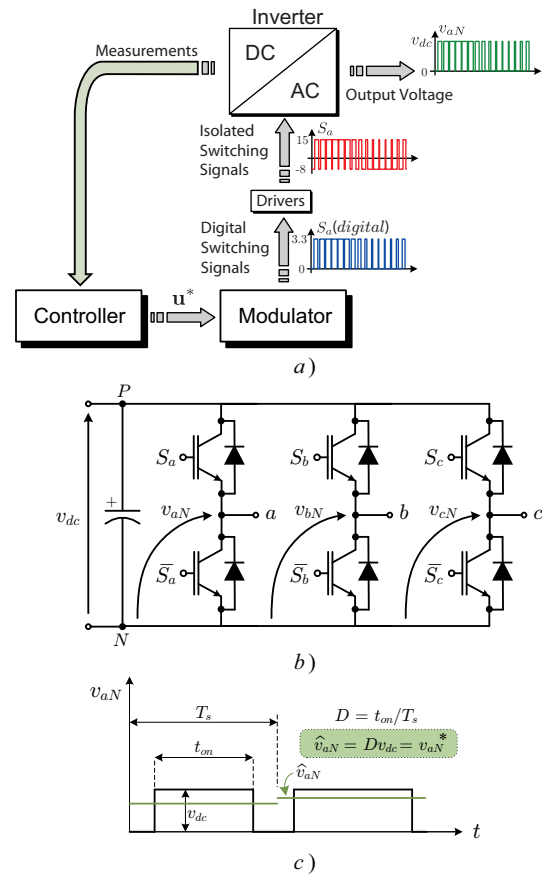


Fig. 1. Introduction of the modulation concept. a) Typical structure of a control and modulation method of a voltage source inverter b) Three-phase two-level voltage source dc/ac converter c) Switched waveform and average value of the phase voltage v_{aN} .

are used to power a wide variety of applications in a non-stop energy demanding society with high efficiency, robustness and economical cost and possibility to reach high nominal power with reduced passive filters [2], [3].

The rich diversity of industrial applications require inverters that have very different power rating, output frequency, semiconductor devices, number of phases, operate at different voltage/current levels, and even have different types and number of dc input sources (current or voltage). Therefore, a wide range of different topologies have been developed over the years, particularly in the last decade for medium-voltage

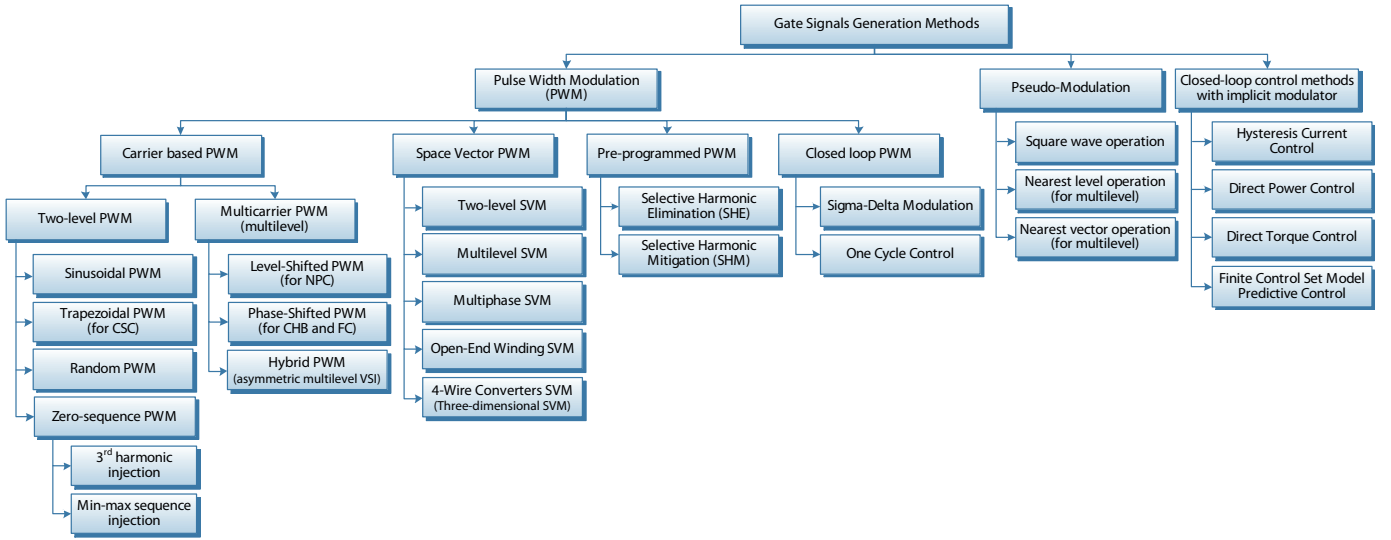


Fig. 2. General classification of gate signals generation methods for voltage source dc/ac power converters.

applications, to cater the needs and fulfil the specifications of each niche.

Apart from well-known multilevel converter topologies such as neutral-point-clamped (NPC), flying-capacitor (FC) and cascaded H-bridge (CHB), in the last years a great deal of new inverter topologies have been introduced in industry, particularly in medium voltage multilevel converters like: modular multilevel converter (MMC), five-level active NPC (5L-ANPC), transistor clamped converter (TCC), stacked multicell, to name a few [4], [5]. In addition, multiphase applications have been gaining more and more attention due to a series of advantages like higher power density, lower torque ripples and fault tolerant operation [6]. As another example, open-end-winding fed drives also have different voltage space vector distribution and extension of classic modulation methods is not straight forward. All these new power converters come along with modulation challenges, which include additional voltage space vectors and different switching harmonics [7]–[12].

A modulation technique generates the power semiconductors gate signals of a power converter obtaining a switched output waveform in such a way that the fundamental component can be adjusted with an arbitrary magnitude, frequency and phase, which are essential for the proper control of the process fed by the inverter. Taking into account this fact, the modulation concept that has been the mainstream solution for two-level power converters in general, including inverters, from the early beginnings of power electronics is Pulse Width Modulation (PWM) [13], [14] which is a simple and effective way to produce a pulse or switched voltage (or current) waveform whose time average is equal to a desired reference as shown in Fig. 1. However, each new converter topology comes with new modulation and control challenges like dc voltage balancing, circulating currents, more available switching redundancies, and other issues that can be dealt with in the modulation stage. The aim of this paper is to summarize the state-of-the-art and analyze the more recent advances in modulation concepts and technology for voltage

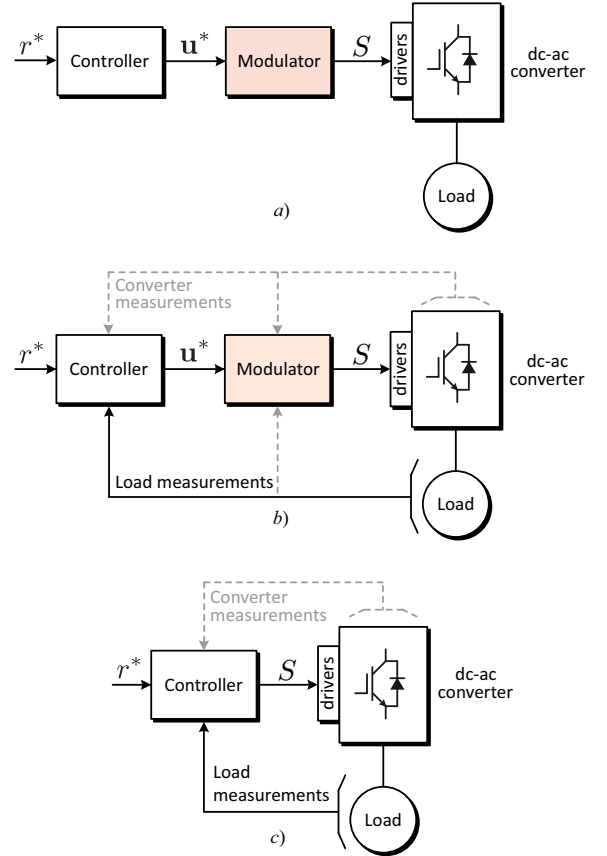


Fig. 3. Block diagrams to operate a dc/ac power converter. a) Open-loop operation b) Closed-loop operation using a controller and a modulator c) Closed-loop operation using a controller with implicit modulator.

source dc/ac converters, discussing the present challenges and possible future scenarios and trends.

II. TYPES OF VOLTAGE SOURCE DC/AC POWER CONVERTER CONTROL SCHEMES

VSI can operate using an open-loop or a closed-loop control method to generate the voltage references which determines the switching signals (S) for the gate drivers as shown in Fig. 3. The open-loop operation of an inverter consists in generating a fixed reference that does not depend on any measurement. Usually, this reference is determined externally (operator, outer control loop, etc.) for a certain operation point. It is mainly used for applications such as fans, pumps and fixed speed motor drives where the dynamic response is not a critical issue. This type of operation has become very successful due to its extreme simplicity at the expense of using a fixed operation point usually leading to performance losses.

The drawbacks introduced by the open-loop operation of an inverter can be reduced if a closed-loop control method is designed and implemented [15]. In this case, the controller has to follow one reference (or more) defined by the user; references such as currents, torque and flux, active and reactive power, etcetera. The output of the controller (desired value of \mathbf{u} , \mathbf{u}^*) is the input of the modulator and it is usually the voltage reference that the modulator has to generate during the next sampling time. This approach has become a mainstream solution for adjustable speed drives and a wide number of other applications where adjustable amplitude, frequency and phase are necessary for a higher performance of the drive or process. As examples, two vastly used closed-loop controllers are the proportional-integral regulator in current controls based on synchronous reference frame and the proportional-resonant regulators used in current controls based on stationary reference frames or in harmonic active filter applications.

On the other hand, in the last decades several closed-loop control methods have been introduced with an implicit modulator implemented inside the control law. This kind of techniques are known as direct controllers and are conceptually simple and have easy digital implementation generating the switching signals of the inverter as a direct consequence of the control output avoiding the use of a modulator. This control scheme has been proved as a successful industrial solution during the last decades. Direct controllers such as hysteresis current controller or direct torque control in their conventional formulation are examples of closed-loop controllers with implicit modulators.

III. MODULATION PRINCIPLE FOR VOLTAGE SOURCE DC/AC POWER CONVERTERS

Before addressing the commonly used modulation methods for dc/ac converters, the modulation concept introduced in Fig. 1 should be clearly defined. Usually, in a power converter control scheme, a controller is designed to track several targets (typically active and reactive power, dc-link voltage, phase currents, etcetera) and its output \mathbf{u}^* is the voltage that the VSI has to generate in order to achieve them. For example, the conventional three-phase two-level VSI shown in Fig. 1b can only generate voltages 0 and $+v_{dc}$ in the phase voltages v_{aN} , v_{bN} and v_{cN} . Focusing on phase a , if a desired phase voltage v_{aN}^* has to be obtained, the modulator generates a

switched waveform which, in average over the sampling period T_s , is equal to the desired value as shown in Fig. 1c. So, the modulator has to calculate a switching sequence to properly switch the power semiconductor devices normally using the well-known duty cycle D (defined as the ratio t_{on}/T_s of the switching signal). The final obtained switched waveform presents a harmonic spectrum where undesired harmonic distortion appears due to the switching. This undesired distortion has to be below certain limits and it could lead to use expensive and bulky passive filters. So, there is a trade-off between the maximum switching frequency of the modulator (directly proportional the switching losses of the power converter and therefore its cooling system) and the filter size.

It is important to notice that the final switching is slightly modified due to the required inclusion of the dead-time (waiting time to avoid the shoot-through of inverter arms due to the dynamics of switching on/off of the power devices). The required dead-times increments the low-order voltage/current harmonics, non-negligible phenomenon if high-power devices are used as in the multi-megawatt power converters. Multiple methods have been proposed in the last decades in order to compensate the dead-time effects [16], [17].

IV. CLASSIFICATION OF MODULATION METHODS FOR VOLTAGE SOURCE DC/AC POWER CONVERTERS

A global classification of the gate signals generation methods for dc/ac power converters, which have had, recently or in last decades, industrial and/or academic impact to a lesser or greater degree is introduced in Fig. 2. These methods can be classified in three vast groups, addressed in the following sections.

V. TRADITIONAL PULSE WIDTH MODULATION TECHNIQUES FOR TWO-LEVEL VSI

Mainly, the required voltages to be generated by the VSI are sinusoidal and, in first approximation, a conventional two-level three-phase VSI could generate a square waveform in the phase voltages as shown in Table I for each phase. This leads to a maximum utilization of the dc voltage generating a waveform with maximum modulation index m (ratio between the output voltage peak and the dc voltage value) at the expense of high distortion in low-order harmonics of the obtained waveforms.

A. Carrier-based Pulse Width Modulation Techniques

The objective of a modulation technique is to generate a desired reference waveform with minimum distortion in the low-order harmonics moving the unavoidable distortion to the high-order harmonics making easier the filtering process. A dominant modulation concept from the early days of power electronics in the 60 s is PWM [18], [19]. PWM is a simple and effective way to produce a switched voltage waveform whose time average is equal to a desired reference. This basic concept is the foundation that all other variations of classic PWM have in common. The comprehensive and in-depth analysis performed by Prof. Holtz in [13], [14] has been

TABLE I
CLASSIC MODULATION SCHEMES FOR THREE-PHASE TWO-LEVEL VOLTAGE SOURCE INVERTERS

Item description	Square-wave Modulation	Pulse-Width Modulation	Space-Vector Modulation	Selective Harmonic Elimination
Operating principle				$m = \frac{4}{\pi} \sum_{i=0}^{k-1} [(-1)^i \sin(\alpha_i)]$ $0 = \frac{4}{j\pi} \sum_{i=0}^{k-1} [(-1)^i \sin(j\alpha_i)]$ <p>where $j = 5, 7, 11, \dots, q$</p>
Block diagram				
Voltage waveform				
Spectrum				
Pros	Simple implementation	Switching harmonics in m_f Industrially accepted	Switching sequence control Better usage of dc-link voltage	Low switching frequency No low order harmonics
Cons	f_1 not controlled, high THD Low order harmonics	Rigid switching sequence	Complex implementation Suitable only for 3-phase VSI	Off-line pre-programmed method Poor dynamic performance
References	[20]	[18] - [24]	[25] - [27]	[30] - [32]

for the last two decades, the main reference on PWM found in literature.

In PWM, the phase voltage is generated by comparing the reference voltage with a higher frequency carrier (usually triangular) as shown in Table I. The fundamental-frequency component in the output voltage can be adjusted by changing the amplitude of the modulation index m . The frequency modulation index m_f is defined as the ratio between the frequencies of the carrier f_{cr} and modulating waves f_m [20]. If m_f is an integer, the carrier wave is synchronized with the modulating waveform and the modulation scheme is known as synchronous PWM; otherwise, it is called asynchronous PWM, in which f_{cr} is usually fixed and is independent of f_m . However, when m_f is a small number (i.e. less than 21) its output spectrum contains low frequency harmonics (sub-harmonics) causing high currents in transformers and inductors. Note that in case of m_f being a large number, the amplitudes of the sub-harmonics are very reduced and do not pose critical problems with the currents by inductors and transformers [20].

From the harmonic spectra represented in Table I, it can be observed that using the PWM method, the distortion has moved to harmonic orders around m_f and no low-order harmonics appear. This fact is extremely important in power conversion applications because the necessary output filters can be minimized or even avoided at the expense of increasing the switching losses if f_{cr} is too large [20].

A direct method to increase the maximum amplitude of

the output fundamental voltage is to raise m to be greater than unity, entering the nonlinear over-modulation region. The over-modulation generates low-order harmonics and thus is rarely used in practice. Therefore, to increase dc voltage utilization, modified modulation schemes based on injecting zero-sequence signals into the modulating waveforms can be employed provided that the neutral of the load is floating. Among all the possible injection methods for three-phase VSI, the third-order harmonic injection, min-max sequence injection and discontinuous PWM schemes have been proved to deliver the best results in terms of obtainable linear range and/or harmonic distortion [21]–[24].

B. Space-Vector Modulation Techniques

Space vector modulation (SVM) is basically a PWM method introduced originally for three-phase converters but using a vectorial representation of the VSI switching states in the well-known α - β frame as shown in Table I [13], [14], [21], [25]–[27]. SVM technique is also applicable to multiphase converters in general extending the concept. SVM technique determines the switching signals for the VSI gate drivers calculating a sequence of switching states to be applied during the sampling period. So, SVM technique deals with the modulation as a geometric mathematical problem obtaining the sequence of switching states and the corresponding duty cycles:

$$\mathbf{v}_s^* = \frac{1}{T_s}(t_1\mathbf{v}_1 + t_2\mathbf{v}_1 + t_0\mathbf{v}_0),$$

$$t_1 + t_2 + t_0 = T_s. \quad (1)$$

In SVM, VSI (regardless of number of phases) is considered as a whole to determine the gating signals, while carrier-based PWM approach considers each VSI phase separately. However, it has been demonstrated that SVM and carrier-based PWM are equivalent (zero-sequence injection explicitly present in carrier-based PWM and implicitly in SVM) leading to the same dc-link utilization and harmonic performance [28], [29].

C. Pre-programmed PWM Modulation Techniques

Pre-calculated PWM methods are not a conventional time-based modulation strategy like classic PWM or SVM but they are focused on the output harmonic spectrum of the VSI. Among these methods, the most well-known strategy is the selective harmonic elimination (SHE) technique. In the classical SHE, the times where the gating signals of the power converter are changed (usually named switching angles) are determined to work with an specific modulation index m eliminating some non-triple harmonics. The switching angles are determined by solving off-line a nonlinear equations system as shown in Table I [30]–[32] and are stored afterward in a look-up table. In order to facilitate the calculations, it is normally imposed a quarter period symmetry with $4k$ commutations per period. The number of commutations k determines the number of harmonics to be eliminated ($k-1$). Normally, k is small leading to keep the switching losses below reasonable limits to facilitate the cooling systems design for high power applications. In addition, the effort of the SHE method is focused on the elimination of low-order harmonics which is the most convenient solution to reduce as much as possible the necessary output filter in terms of weight, volume and economical cost. Although SHE achieves good results, it can be only applied to low dynamic power systems because of the low bandwidth of the closed-loop controller in order to follow the SHE patterns tightly (hence eliminating the harmonics adequately) rather than having a faster dynamic performance [33].

VI. PSEUDO-MODULATION METHODS

The family of pseudo-modulation methods shown in Fig. 2 directly imposes the VSI output voltage by a simple comparison of the desired reference voltage and imposing the switching state that leads to reduced errors. The simplest pseudo-modulation technique is the square-wave modulation (or staircase waveform) where the reference voltage is compared to zero as shown in Table I [20]. On the other hand, the nearest level control is a pseudo-modulation technique where the closest voltage level to the desired voltage is applied. The space-vector control is just an extension of the nearest level control but applied to three-phase systems and working with space vectors (see Table II) [34]. As a general rule, the pseudo-modulation schemes achieve good results when applied to VSI

with large number of levels reducing the switching losses at the expense of slightly increased total harmonic distortion (THD) and non-fixed switching frequency (leading to spread harmonic spectra).

VII. CONTROL TECHNIQUES WITH IMPLICIT MODULATOR

The classification shown in Fig. 2 also includes closed-loop control methods that directly generate the gate signals for the inverter. In this case, these gate signals are not necessarily related in principle with the fundamental component's amplitude, phase and frequency of a reference voltage, and therefore can not be considered modulation schemes. In this case, the switching of the inverter (S) is not related to follow a reference voltage but is determined to directly reduce the error of the controller goal. These techniques achieve good results usually at the expense of having a non-constant switching frequency leading to widespread harmonic spectra.

A. Hysteresis current control

In the hysteresis current control, S is generated to keep the phase currents inside hysteresis bands which surround the reference currents as shown in Table II. This control technique is the simplest implementation of a closed-loop control and has been extensively used in industrial products [20].

B. Direct torque control / Direct power control

Direct torque control (DTC) is a well-established (in academia and industry) direct control method for motor drives applications where the torque and flux references are tracked using hysteresis controllers and using look-up tables (LUT) to choose the best switching state to achieve both objectives (see Table II for more details) [35]. On the other hand, direct power control (DPC) is the dual method for grid connected applications where active and reactive power are the controller objectives instead torque and flux [36].

C. Finite-states Model Predictive Control

Finite-states model predictive control (FS-MPC) predicts the behavior of the VSI for all the possible switching states (n) and determines the final switching of the VSI by a minimization of an objective-defined cost function evaluated for all n switching states as shown in Table II:

$$g_i(t_{k+1}) = |x^*(t_{k+1}) - x_{pi}(t_{k+1})|, i = 1, \dots, n$$

$$S = \min\{g_i(t_{k+1})\} \quad (2)$$

Multiple objective variables can be included in the cost function to be part of the control targets such as phase currents, dc voltages, switching losses and common-mode voltages [37], [38].

TABLE II
PSEUDO-MODULATION AND CLOSED-LOOP METHODS WITH IMPLICIT MODULATOR

Item description	Hysteresis Control	Nearest Level/Vector Control	DTC / DPC	Model Predictive Control
Operating principle				
Block diagram				
Pros	Simple implementation	Simple implementation	Fast dynamic control Simple design, Look-Up Table based	Conceptually simple High dynamic performance Flexible (can include constraints)
Cons	Variable switching frequency Dispersed harmonic spectrum Only for two-level converters	Variable switching frequency For converters with high # levels \uparrow THD when modulation index \downarrow	Variable switching frequency Only for two-level converters	Dispersed harmonic spectrum High computational burden Empirical weighting factor design
References	[20]	[34]	[35], [36]	[37], [38]

VIII. ADVANCES ON CARRIER-BASED PWM TECHNIQUES

Conventional carrier-based PWM technique has been extended using of multiple carriers being extensively studied in the last decades since the new family of multilevel converters appeared [39]. Among the multi-carrier PWM techniques, the phase-shifted PWM (PS-PWM) and the level-shifted PWM (LS-PWM) methods are the most common.

The use of PS-PWM for CHB converters has been demonstrated very convenient (unipolar PWM with carriers phase shifting between consecutive H-bridges equal to π/k (where k is the number of power cells of the CHB) as shown in Table III) achieving equal power distribution and equalization of the power losses among the H-bridges, multiplicative effective of the output voltage switching frequency ($2km_f$) and reduced distortion in the input currents (when the dc voltages of the CHB inverter are fed by multiple diode bridges). [40]. In addition, PS-PWM method has been also applied to the flying-capacitor converter (bipolar PWM with phase shifting between consecutive carriers equal to 2π divided by the number of flying-capacitor cells) achieving multiplicative effect of the output voltage switching frequency and natural balance (but with low dynamic behavior) of the floating dc voltages of the converter [41]. The concept of use multiple phase-shifted carriers can be also applied to any modular converter with series connection of different power cells. For instance, for the MMC, it is possible to apply a bipolar carrier-based PWM method for each power cell with phase shifting between consecutive carriers equal to 2π divided by the number of power cells of each branch, upper or lower. In this case, the dc voltage balancing issue can be solved by slightly changing the voltage reference of each power cell [42]–[44].

On the other hand, LS-PWM technique is very suitable to

be used in the NPC topology with direct generation of the switching signals by simply comparing with multiple voltage-shifted carriers as shown in Table III [21], [39].

Comparing both multi-carriers PWM techniques (LS-PWM and PS-PWM) with the same final effective switching frequency of the phase voltage, LS-PWM has been demonstrated superior by placing harmonic energy into a carrier component in each phase voltage and relying upon the cancellation of this component when the line-to-line voltages are formed [45]. In this way, several authors have been focused on developing LS-PWM methods for the flying-capacitor and the CHB converters [46]–[48]. Usually, these modified LS-PWM methods implement a conventional voltage level disposition of the triangular carriers but carry out an interleaving between them associating the gate signals sequentially to the carriers. These methods have the harmonic advantages of the LS-PWM technique and the even power distribution of the PS-PWM method but also the floating voltage balancing for the flying-capacitor converter and the reduced harmonic distortion of the input currents in the CHB converter. The idea of using the interleaved carriers have been also recently applied to conventional two-level converters to reduce the common-mode voltage obtaining superior performance [49].

In recent years, the number of new multilevel converter topologies has increased and several of them can be already found as industrial products such as the 5L-ANPC [5]. All of them can generate the gate signals using some multi-carrier PWM method. Many of the new converter topologies are based on the series connection of different power cells and therefore the PS-PWM method or a hybrid modulation are suitable to be used for symmetrical and asymmetrical converter topologies respectively. For instance, the 5L-ANPC can use a hybrid

modulation implemented by a square-wave modulation for the high-voltage power devices and a modified PS-PWM method for the medium-voltage devices which achieves natural balance of the dc voltages of the floating capacitors (see Table IV) [50].

One of the most important concerns about multilevel converters is the dc voltage control of the capacitors (dc-link voltage imbalance of the NPC topology, floating voltages of the flying capacitors in the FC and, in general, dc voltage control) when multilevel converters are working as active rectifiers or static synchronous compensators (STATCOM). The control of these voltages can be assumed completely by the controller using a raw modulator but other solution is to design modified modulation techniques to deal with this issue [51]–[53]. A high-performance control of the voltage imbalance of the three-level NPC can be achieved using a LS-PWM technique but adding a zero-sequence signal to the reference waveforms [54], [55]. A similar idea has been also applied to five-level NPC converters using the offset voltage to regulate the average currents flowing into and out of the inner junction without affecting output line-to-line voltage [56]. This can be considered solved for three-level NPC but it presents stability problems with NPC converters with higher number of levels where usually an external hardware is used to achieve the proper operation [57].

It has to be noticed that PWM methods can be also implemented in microprocessors using mathematical algorithms which digitally describe the conventional concept of the comparison of the reference waveform with the triangular carriers [58]. In this way, the mathematical implementation of the multi-carrier PWM methods can obtain exactly the same gate signals. Researchers have designed modified mathematically described multi-carrier PWM methods in order to achieve extra control targets such as minimization of the switching losses and dc voltage control [59]–[61].

IX. ADVANCES ON PRE-CALCULATED PWM TECHNIQUES

As it has been commented previously, the SHE technique is usually a quarter-wave symmetry method simplifying the mathematical calculations to determine the switching angles. However, recently several studies have been done presenting solutions with half-wave symmetry [62] and non-symmetrical waveforms [63]. In both cases, the modification of the conventional SHE technique leads to find new solutions to eliminate the low-order harmonics because new degrees of freedom appear at the expense of increasing the computational cost of the heuristic mathematical search of the solutions. However, this can not be considered as an important drawback of these methods because all the calculations are carried out offline.

About this issue, the mathematical calculations to determine the switching angles of a SHE method are not simple and usually some mathematical search algorithm such as the Newton-Raphson method is applied. A great effort of the researchers has been focused on the simplification and the improvement of the accuracy of the mathematical determination of the switching angles [64]–[66]. Using these advanced mathematical search algorithms, local solutions are avoided

and global solutions are obtained with high accuracy. However, the computational cost of these algorithms is usually high and all the calculations have to be done offline previous to the operation of the power converter. This fact leads to the drawback of poor dynamic performance of power systems using pre-calculated PWM techniques.

In order to reduce this problem, the researchers have developed real-time algorithms to calculate the switching angles. In this way, the angles are not pre-calculated but they are determined online. The method to calculate the switching angles varies from artificial neural network to eliminate some low-order harmonics [67] to real-time Newton-Raphson algorithms to minimize the total harmonic distortion value [68].

On the other hand, the synchronous optimal PWM technique is another offline pre-calculated PWM method with the objective to generate a sinusoidal waveform with an specific modulation index and minimum total harmonic distortion which is an important target in motor drive applications [69]–[71] (see Table IV). The conventional method is used in open-loop low-performance drives such as industrial fans or pumps. The method has been improved in the last years to be used in closed-loop control systems to work in high-dynamic drives by extracting the fundamental component of the stator flux linkage vector from its distorted trajectory and modifying the conventional pulse pattern of the synchronous optimal PWM method [72].

The pre-programmed PWM methods, and specifically the SHE technique, are especially well suited for high-power systems because the number of commutations (related to the number of switching angles) is limited. This fact makes that a great amount of SHE techniques have been applied to different multilevel converter topologies which have been designed for medium-voltage high-power applications (as shown in Table III) by just defining the pre-calculated waveform and following the same rules introduced for conventional two-level VSIs. The study of generalized SHE methods for multilevel converters, and specially for CHB converters, has been the focus of the researchers in the last decade [73]. Another important research topic for SHE-based multilevel converters is related to the voltage balancing of the dc voltages of the power converter with topologies such as the cascaded rectifier [74], the active neutral-point-clamped (ANPC) [75], the 5L-ANPC [76] and the modular multilevel converter (MMC) [77].

Another recent advance of the pre-calculated PWM methods has been the consideration of grid codes in the determination of the switching angles. In this way, some authors have been focused on the implementation of a SHE technique but including the minimization of the non-eliminated harmonics [78].

Other publications have taken into consideration the maximum limit imposed by the grid codes and have included them into the heuristic search looking for solutions with distortion below the maximum limits. This method has been called selective harmonic mitigation (SHM) and obtains better results compared with the conventional SHE in terms of the weight, volume and cost of the necessary output filter of the power converter [79], [80] (see Table IV). The mathematical calculations of the SHM method are not simple because they

TABLE III
CONVENTIONAL MODULATION SCHEMES FOR MULTILEVEL VOLTAGE SOURCE INVERTERS

Item description	LS-PWM (3L-NPC example)	PS-PWM (5L-CHB example)	Multilevel SVM (3L example)	Multilevel SHE (3L example)
Operating principle				$m = \frac{4}{\pi} \sum_{i=0}^{k-1} [(-1)^i \sin(\alpha_i)]$ $0 = \frac{4}{j\pi} \sum_{i=0}^{k-1} [(-1)^i \sin(j\alpha_i)]$ where $j = 5, 7, 11, \dots, q$
Block diagram				
Voltage waveform				
Spectrum				
Pros	Simple implementation Superior harmonic performance Suitable for NPC, TCC	Multiplicative frequency effect Power and losses equalization DC voltage balance in FC	Switching sequence control Coding independent of # levels High switching redundancy	Low switching frequency No low order harmonics Look-Up Table based method
Cons	Harmonic distortion in m_f Not well-suited for CHB or FC Unequal losses distribution	Phase-shifting synchronization High THD with small m Sidebands harmonic distortion	Complex implementation Suitable only for 3-phase VSI	Off-line method Poor dynamic performance High non-eliminated harmonics
References	[39] - [58]	[39] - [58]	[83] - [89]	[62] - [78]

include a system of inequations imposing the limits of the grid code considered for the switching angles determination. However, it has to be noticed that these inequations are solved offline as in the conventional SHE case. The SHM concept can consider any grid code and can be applied to a dc/ac converter with any number of levels. In particular, it has been successfully applied to several multilevel converter topologies [79]–[82].

X. ADVANCES ON VECTOR-BASED METHODS

The introduction of more and more complex converter topologies (i.e. multilevel converters) has led to a high number of degrees of freedom which can be used by the SVM algorithm to improve the converter performance. In this way, in the last years the contributions related to SVM methods for multilevel converters have been mainly focused on the simplification of the computational cost of the modulation algorithm (calculation of the three nearest switching vectors and the corresponding duty cycles) and the use of the redundant state vectors (switching vectors located in the same position of the α - β frame) to control some power converter features as shown in Table III [83]–[85]. The equivalence between carrier-based PWM and SVM still is valid for multilevel converters as was analytically described in [60] where a simple single-phase modulator (which is a mathematical implementation of a multicarrier LS-PWM method and is addressed in Table IV as

the unidimensional modulator) is demonstrated to achieve the same switching sequence and the same duty cycles compared with the classical SVM technique introduced in [83].

Taking into account the equivalence between PWM and SVM, there are two ways to face auxiliary control objectives such as the common-mode voltage minimization or the dc voltage control among others. If a PWM method is used, the usual way to face the problem is to include additional control loops in the controller design generating reference voltages \mathbf{u}^* which considers the control objective.

On the other hand, using a SVM method the problem can be directly solved choosing carefully the best redundant switching state once the sequence of voltage states is determined [86]–[88]. In this way, for instance, the control of the dc-link voltage imbalance in the NPC topology can be carried out by a SVM technique taking into account the redundant states present in the multilevel converter (see for instance the nearest virtual vector SVM method introduced in Table IV [89], [90]). Both ways to face the problem (using PWM or SVM) are valid and achieve very similar results, even identical. So, the decision about how to face the problem finally depends on the researcher know-how. The advantage of considering a SVM technique is the direct analysis of the effect of the redundant states in the power converter performance at the expense of a higher computational cost compared with using a PWM method where all the control objectives are tracked by the

TABLE IV
SOME RECENT CONTROL AND MODULATION TECHNIQUES FOR VOLTAGE SOURCE INVERTERS

Modulation Technique	Operating Principle / Block Diagram	Advantages / Drawbacks
Synchronous Optimal PWM [68]-[71]		<ul style="list-style-type: none"> ✓ Well suited for low-performance ac drives ✓ Optimal pre-programmed PWM patterns optimized for targets such as: <ul style="list-style-type: none"> - Minimum total harmonic distortion - Minimum peak values of the phase currents ✗ Originally poor dynamic performance (improved recently with modified patterns) ✗ Complex off-line calculations obtaining optimal switching patterns
Selective Harmonic Mitigation [79]-[82]		<ul style="list-style-type: none"> ✓ Fulfillment of grid codes dealing with individual harmonic distortion and THD ✓ Flexible tool for harmonic shaping reducing the filtering weight, size and cost ✓ Better results compared with SHE even with low number of switching angles ✗ Poor dynamic performance inherent to pre-programmed PWM methods ✗ Complex off-line solutions searching of a non-linear inequations system
Hybrid PWM (Example 5L-ANPC) [50]		<ul style="list-style-type: none"> ✓ High simplicity only including comparators and standard PWM ✓ Well suited for asymmetrical multilevel converters (asymmetric CHB, 5L-ANPC) ✓ Can obtain the advantages of using both LS-PWM/PS-PWM in the PWM stage ✗ Particular solution for each power converter topology ✗ Leads to unequal distribution of features (active power or switching losses)
Unidimensional and Multidimensional PWM [59]-[61]		<ul style="list-style-type: none"> ✓ Generalized and comprehensive PWM method ✓ Natural common-mode voltage elimination if applied to multiphase converters ✓ Multi-objective modulation technique added as extra features ✓ Specially well suited for multilevel cascaded converters (CHB, MMC) ✗ Not applicable to other topologies such as NPC, T-type or Flying-capacitor ✗ Requires extra calculations to achieve secondary control targets
Nearest Three Virtual Vectors SVM [89], [90]		<ul style="list-style-type: none"> ✓ Accurate DC voltage balance control with zero average neutral point current ✓ Possible extension for NPC with any number of levels using the same concept ✓ Optimized to achieve lower harmonic distortion for linear-and-balanced ac loads ✗ Slight increase of switching losses due to using switching redundancy ✗ Only suited for NPC or T-Type converters, not suitable for other topologies
DTC-SVM [97]		<ul style="list-style-type: none"> ✓ Fixed switching frequency leading to non-spread harmonic spectra ✓ Good performance at starting and low-speed operation ✓ Possible closed-loop control of both torque and flux of the machine ✓ Relatively low sampling frequency compared with hysteresis-based DTC ✗ More complexity in the overall control and modulation scheme ✗ High computational cost compared with simple hysteresis-based DTC

controller.

On the other hand, multiphase inverters are becoming attractive in the last decades for a wide range of applications. From the initial mathematical extension done in [91], SVM techniques have been generalized to be applied to multiphase power converters usually at the expense of making complex the representation of the space vectors since it is not possible to further use the conventional α - β frame with more than three phases. So, a conventional way to develop a SVM method for multiphase converters is to use multiple coupled d - q frames [92]. In this way, the SVM concept remains but the computational complexity usually increases with the number of phases. Generalized SVM strategies independent

of the number of phases of the VSI have been presented (even for multilevel multiphase converters). One interesting but conceptually complex generalized SVM method has been digitally implemented using matrices and carries out all the calculations by products and sorting processes making the modulation stage computationally efficient [93]. To simplify the calculations and mainly to make the modulation stage conceptually simple, in [60] it is demonstrated that the same results can be obtained by applying digital PWM to each phase of the converter.

Other recent interesting implementation of the SVM method has been related to the control of open-end winding machines operated with dual converters (connected to each side of the

open-end windings). This configuration, from the machine point of view, works as a multilevel converter and specific multilevel SVM techniques have been presented in order to generate the gate signals of the converter [94]. The power converters connected to each winding of the machine can have the same topology being the dual two-level three-phase configuration the most basic one. However, multiple modifications can be done and several topologies have been presented in the last years formed by different converters in each side of the machine leading to complex SVM structures [95], [96].

XI. ADVANCES ON PSEUDO-MODULATORS AND CONTROLLERS WITH IMPLICIT MODULATORS

It can be affirmed that the modulation techniques have been greatly improved in terms of simplicity. This fact has been considered by several closed-loop control methods with implicit modulator such as the direct torque control (DTC), direct power control (DPC) and finite-states model-based predictive control (FS-MPC). These control methods have implicit generation of the gate signals which means that they do not use any modulator and the switching of the converter is imposed by a look-up table (for DTC and DPC) or a cost function minimization algorithm (FS-MPC). However, the extremely fast computational speed of the modern microprocessors makes possible to evaluate not only the finite switching states of the converter but also a high number of virtual states formed by a linear combination of the finite states. This reduced SVM modulator has been implemented in several recent works achieving good results in the control target tracking [97]–[99]. Also the harmonic spectrum of the obtained voltages and currents is improved because the switching frequency of the power converter is closer to the sampling time of the SVM technique. This phenomenon present in DTC-SVM (see Table IV), DPC-SVM and FS-MPC-SVM methods represents a great advantage when compared with the classical spread harmonic spectrum of the conventional DTC, DPC and FS-MPC techniques. Currently, the performance of these DTC-SVM, DPC-SVM and FS-MPC-SVM methods is only limited by the computational limitations of the hardware microprocessors to evaluate a large number of possible virtual states in the control stage.

On the other hand, pre-programmed PWM techniques have been implemented in an finite-states model predictive control (FS-MPC) method working in real-time in closed-loop operation. SHM technique using FS-MPC [100] was implemented as an extension of the FS-MPC technique with SHE proposed previously in [101]. In this cases, the harmonic shaping is carried out online by the minimization of the cost function of the FS-MPC which includes discrete fourier transforms components of the obtained waveforms.

On the other hand, as it has been commented previously, nearest level modulation and space-vector control are control methods very suitable to be used in multilevel converters with a high number of levels. They are based on using only one switching state because the high number of voltage levels permits it causing a very low error in the generation of the desired voltages. These techniques have gained great interest

since multilevel converters with a high number of building blocks are step by step becoming attractive to the industry for applications such as High-Voltage DC (HVDC). In this way, three-phase MMC converters for HVDC systems are normally operated using a nearest level control per phase (which is actually a space-vector control) with an additional voltage error sorting method to properly balance the floating dc voltages of each power cell [102], [103].

XII. FUTURE TRENDS

Since the first silicon power switches were developed in the middle of the last century, power electronics has been demonstrated to be the driving force of a technological revolution. From the beginning, the applications where power electronics are included have been growing and nowadays more and more systems have power electronics inside.

The two-level three-phase VSI has been installed extensively for different applications and the classical three-phase PWM was the conventional modulation technique to be widely used. This fact remained although other interesting modulation techniques were introduced in the last decades of the 20th century. However, in the last 25 years, power electronics have become mature, reliable and economically affordable leading to the appearance of ad-hoc power converter topologies for different applications with specific requirements. Electric vehicles, integration of renewable energy sources, high-power systems, power distribution and power quality applications have created the necessity to design particular power converter topologies dealing with topics such as efficiency, fault tolerant capability, modularity, galvanic isolation, power flow control, grid faults, high ac and dc voltages, etcetera. These topologies, with complex structure and multiple power semiconductor devices, usually require new tailored modulation techniques to obtain the best performance. In this way, the last decades have seen a huge evolution of different modulation techniques, usually modified enhanced versions of conventional PWM. This evolution is a non-stop process since power electronics will continue to be part of our lives in the future following the increasing demand of modern society. The objective of the perfect modulation is and will be to obtain the desired waveforms with minimum harmonic distortion (leading to minimum required filters) but also with minimum losses (maximizing the converter efficiency saving energy and making simpler the cooling system).

Current and future modulation techniques have to deal with issues like maximum power conversion efficiency, minimum harmonic distortion, costly efficient filters and auxiliary control tracking (dc voltage imbalance reduction, equalization of power losses, equal power distribution, etcetera). A huge effort has been done by the industry and academia to design advanced modulation methods in order to successfully meet the requirements making the power converters efficient, compact and economic. The computational cost of the modulation method, which was important some years ago, has become a minor issue since powerful digital microprocessors and FPGAs can carry out complex calculations in a short time [104].

Focusing on the power device implementation, new wide-band-gap (WBG) devices can be built using non-silicon ma-

materials such as SiC or GaN and are nowadays becoming more relevant. The use of these WBG devices (with fast commutations, high maximum working temperature and very reduced power losses) could make possible to use medium and high frequency based modulation methods for high-power converters which are currently limited by the switching losses and the cooling system design making bulky and expensive the filtering stage [105].

Although PWM based modulation methods are still extensively used in industrial products, new proposals seem to be very attractive for the next future. Vector based methods, which are in fact versions of PWM, can deal with control targets in a simple conceptual way using the switching redundancy of complex power converters. The focus of these modulation methods is on controlling dc voltage imbalances, eliminating the voltage fluctuations, reducing the common-mode voltage and reducing the switching losses. Normally, there is a trade-off between all these objectives and the application forces what to face first. Another interesting option is to use a pseudo-modulation method as the FS-MPC, the most recent and promising control technique for power converter applications because of its simplicity and good performance. The drawback of FS-MPC technique related to the spread harmonic spectrum can be solved using an specific harmonic shaping term in the cost function or, even better, introducing a simple modulator in the final stage and considering not only the finite-states in the evaluation of the cost function.

XIII. CONCLUSIONS

The search of maximum efficiency and highest performance is going hand in hand of the development of new power converter topologies and control methods. In this way, the modulation techniques have been playing and will play a major role in past, present and future power converters.

In this paper, a review of the modulation strategies from the conventional methods to the most recent ones has been addressed. This paper presents a state-of-the-art of the topic introducing the most important advances from the point of view of potential use for industrial applications, new motivating concepts possible to be extended to other topologies and applications, simplification of the conceptual modulation process and achievement of important control targets.

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