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Subject:

Overview of Multilevel Inverter Topologies

Realized by

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Presented publicly, the 30 / 06 / 2025

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Dedication

First and foremost, I express my deepest gratitude to God,
the Source of all knowledge and strength,
for granting us, as humans, the extraordinary ability to explore, learn, and build the sciences that shape our world.

I wholeheartedly dedicate this work to my beloved parents,
whose unconditional love, sacrifices, and constant encouragement
have been the foundation of my growth throughout more than two decades of my life.

To my brother, and to the extended family,
for their unwavering moral support and heartfelt joy, which mean so much to me.

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Lotfi

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Abstracts

ملخص

يتناول هذا المشروع دراسة شاملة لهياكل العاكسات متعددة المستويات، مع التركيز على خصائصها وتكوينها وتقييم أدائها من حيث عدد المكونات، تعقيد التحكم، والفعالية الطاقوية. تشمل الطوبولوجيات التي تم تحليلها عاكس الجسر المتدرج ،(CHB) وعاكس نقطة التعادل المحايدة ،(NPC) وعاكس المكثفات الطائرة .(FC) تم إجراء مقارنة مفصلة بين هذه الهياكل لتحديد مزايا وعيوب كل منها من حيث التصميم والتكلفة وكفاءة التشغيل.

الكلمات المفتاحية : العاكسات متعددة المستويات، الطوبولوجيا، ،CHB ،NPC ،FC مقارنة.

Abstract

This project presents a comprehensive overview of multilevel inverter topologies, focusing on their structure, operating principles, and performance characteristics. The study compares the Cascaded H-Bridge (CHB), Neutral Point Clamped (NPC), and Flying Capacitor (FC) inverter types. A detailed evaluation is conducted based on criteria such as component count, control complexity, and efficiency, providing insight into the advantages and limitations of each topology.

Keywords: Multilevel inverters, topologies, CHB, NPC, FC, comparison.

Résumé

Ce projet présente une vue d'ensemble des différentes topologies d'onduleurs multiniveaux, en mettant l'accent sur leur structure, leur principe de fonctionnement et leurs caractéristiques de performance. Les types d'onduleurs étudiés sont : le pont en cascade (CHB), le point neutre bloqué (NPC) et les condensateurs volants (FC). Une comparaison approfondie est effectuée selon plusieurs critères : nombre de composants, complexité de commande, coût et rendement, afin de mettre en évidence les avantages et les inconvénients de chaque topologie.

Mots-clés : Onduleurs multiniveaux, topologies, CHB, NPC, FC, comparaison.

Table of Contents

Table of Contents **4**

List of Figures **5**

List of Tables **6**

List of Abbreviations **6**

General Introduction **7**

1 modeling and topologies of multilevel inverter **8**
1.1 Modeling of multi-level inverters 9
1.2 Types of Multilevel Inverters 9
1.2.1 Neutral Point Clamped (NPC) Inverter 10
1.2.2 T-type Neutral Point Clamped (T-NPC) Inverter 11
1.2.3 Flying Capacitor (FC) Inverter 12
1.2.4 Cascaded H-Bridge (CHB) Inverter 13
1.3 SVM with Two active vectors 14

General Conclusion **15**

List of Figures

1.1 One phase leg of an inverter with (a) two levels, (b) three levels, and (c) n levels. [8] 9
1.2 volatage of One phase leg of an inverter with (a) two levels, (b) three levels, and (c) n levels. [8] 10
1.3 Diagrams of NPC converters with single legs: (a) 3-level, (b) n-level [10]. 10
1.4 Conduction paths depending on the sign of the current $i_a(t)$ in an inverter leg [10] 11
1.5 Diagram of a 3-level multi-level converter (T-NPC) for a single phase [13] 12
1.6 Capacitor-clamped multilevel inverter circuit topologies. (a)Three-level. (b) Five-level. [11] 12
1.7 Conduction path of currents [1] 13
1.8 structure of a cascaded H-Bridge 5 level multi-level inverter 13
1.9 Vector representation in (a): the *d-q* plane, and (b): the *x-y* plane [**?**]. 14

List of Abbreviations

General Introduction

Multilevel inverters have emerged as essential components in modern power conversion systems, offering enhanced performance in high-power and industrial applications such as transportation, renewable energy systems, and manufacturing processes [1, 2].

Initially conceptualized in the 1970s to address the limitations of traditional two-level inverters, multilevel topologies were developed to improve power quality and reduce harmonic distortion. The diode-clamped multilevel inverter (DCMLI), introduced by Nabae et al. in 1981 [3], marked a significant step forward by utilizing clamping diodes to generate multiple voltage levels. Later innovations, including the flying capacitor multilevel inverter (FCMLI) by Tolbert et al. [4] and the cascaded H-bridge inverter (CHB) by Mohan, expanded the topology landscape. These architectures allow the synthesis of stepped waveforms with controllable frequency, phase, and amplitude, offering key advantages such as reduced voltage stress on switches and superior output spectral quality through minimized harmonic distortion [5, 6].

Despite their benefits, multilevel inverters introduce design complexities, including switching losses, voltage balancing challenges, leakage currents, and increased cooling requirements due to a higher component count [6]. Two primary development paths have been pursued : enhancing traditional two-level converters using advanced semiconductors with higher voltage and current ratings (up to 8 kV and 6 kA), and designing novel topologies using standard devices [5]. While high-performance semiconductors enable operation in the 1–30 MW range, they often necessitate costly filters to maintain power quality. In contrast, multilevel converters achieve comparable output using cost-effective devices, albeit with more complex control strategies [5]. Ongoing research continues to refine these systems, focusing on hybrid configurations, improved control techniques, and fault-tolerant designs that expand their application in driving multiphase machines and optimizing efficiency in high-power environments.

Chapitre 1

modeling and topologies of multilevel inverter

1.1 Modeling of multi-level inverters

The general concept behind multilevel inverters is to use several intermediate voltage levels between the maximum and minimum output, which improves the quality of the output waveform. These inverters are used to minimize harmonics and reduce the stress on power components by generating a waveform that closely approximates a sine wave. [7]

For an inverter with n levels, the output voltage can take on any of n distinct values, ranging from $-V_{max}$ to $+V_{max}$, with intermediate steps that create smoother transitions between the levels. The more levels there are, the closer the output waveform becomes to an ideal sinusoidal waveform, which reduces harmonic distortion and improves overall efficiency. The levels of voltage can be represented mathematically as [8] :

$$V_{out}(t) \in \{-V_{max}, -\frac{V_{max}}{2}, \ldots, 0, \ldots, \frac{V_{max}}{2}, V_{max}\}$$

The number of switches required in the inverter increases as the number of levels increases. For an n-level inverter, $n-1$ switches are typically required per phase. The switching control is usually implemented using a Pulse Width Modulation (PWM) technique, where the width of the pulses is adjusted to produce the desired voltage levels. [8]

The primary advantage of multilevel inverters is their ability to produce higher quality output, which is especially beneficial for applications like motor drives, power generation, and energy storage, where high power and low harmonic distortion are required. However, with the increase in the number of levels, the complexity of the control system and the cost of the inverter also rise. [9]

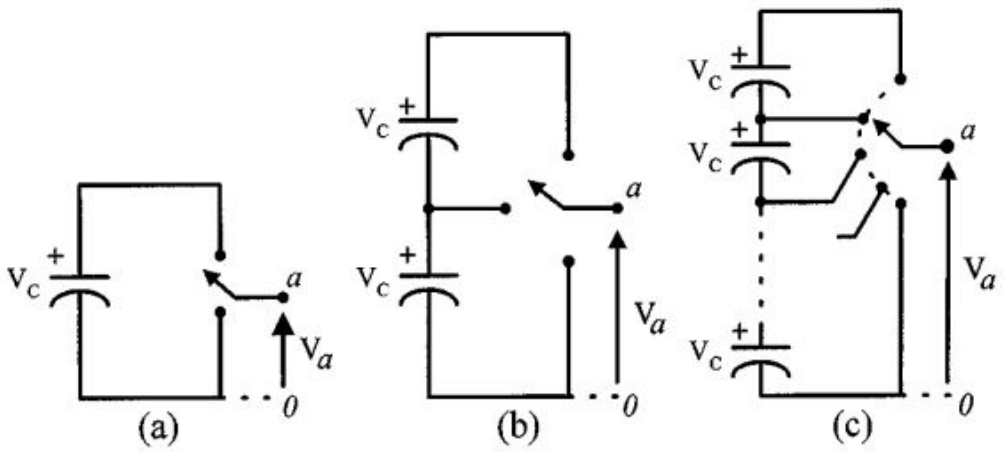


Fig. 1.1 : One phase leg of an inverter with (a) two levels, (b) three levels, and (c) n levels. [8]

1.2 Types of Multilevel Inverters

Several topologies have been developed to implement multilevel conversion, each with its own structural characteristics and control requirements. The most prominent types include :

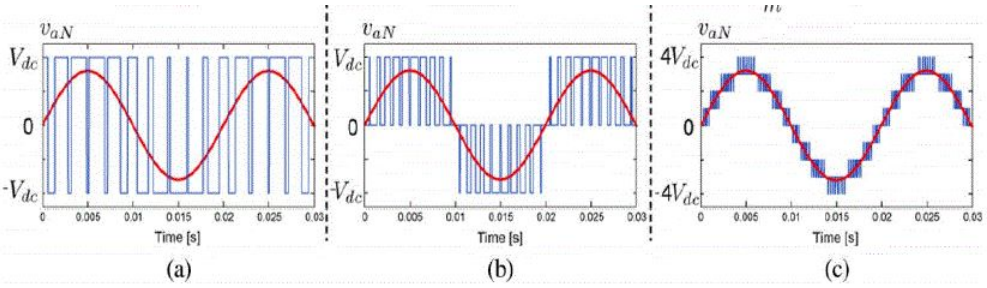
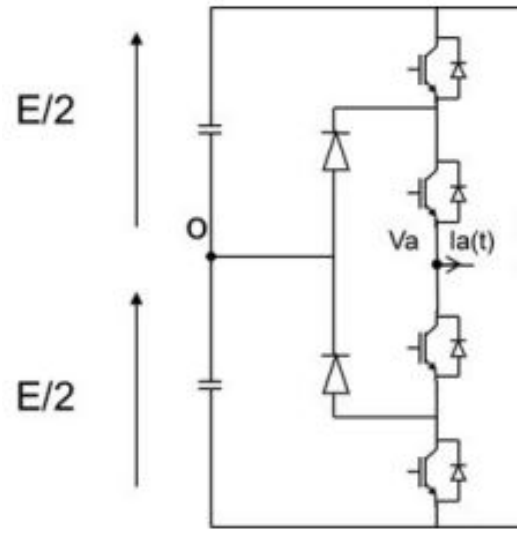


FIG. 1.2 : volatage of One phase leg of an inverter with (a) two levels, (b) three levels, and (c) n levels. [8]

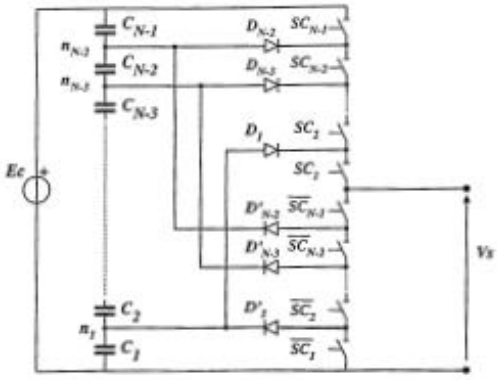
1.2.1 Neutral Point Clamped (NPC) Inverter

The NPC inverter employs clamping diodes to divide the DC bus voltage into multiple levels, reducing voltage stress on switching devices [10]. It features :

- Lower harmonic distortion compared to two-level inverters.
- Shared DC bus across all phases.
- Challenges in balancing capacitor voltages at higher levels.



(a) Diagram of a 3-level NPC converter with a single leg



(b) Diagram of an n-level NPC converter with a single leg.

FIG. 1.3 : Diagrams of NPC converters with single legs : (a) 3-level, (b) n-level [10].

The following figure (Figure 1.7) illustrates the different conduction cases of the components according to the sign of the current $i_a(t)$. The switching commands of transistors T11 and T13 are complementary, as are those of T12 and T14.

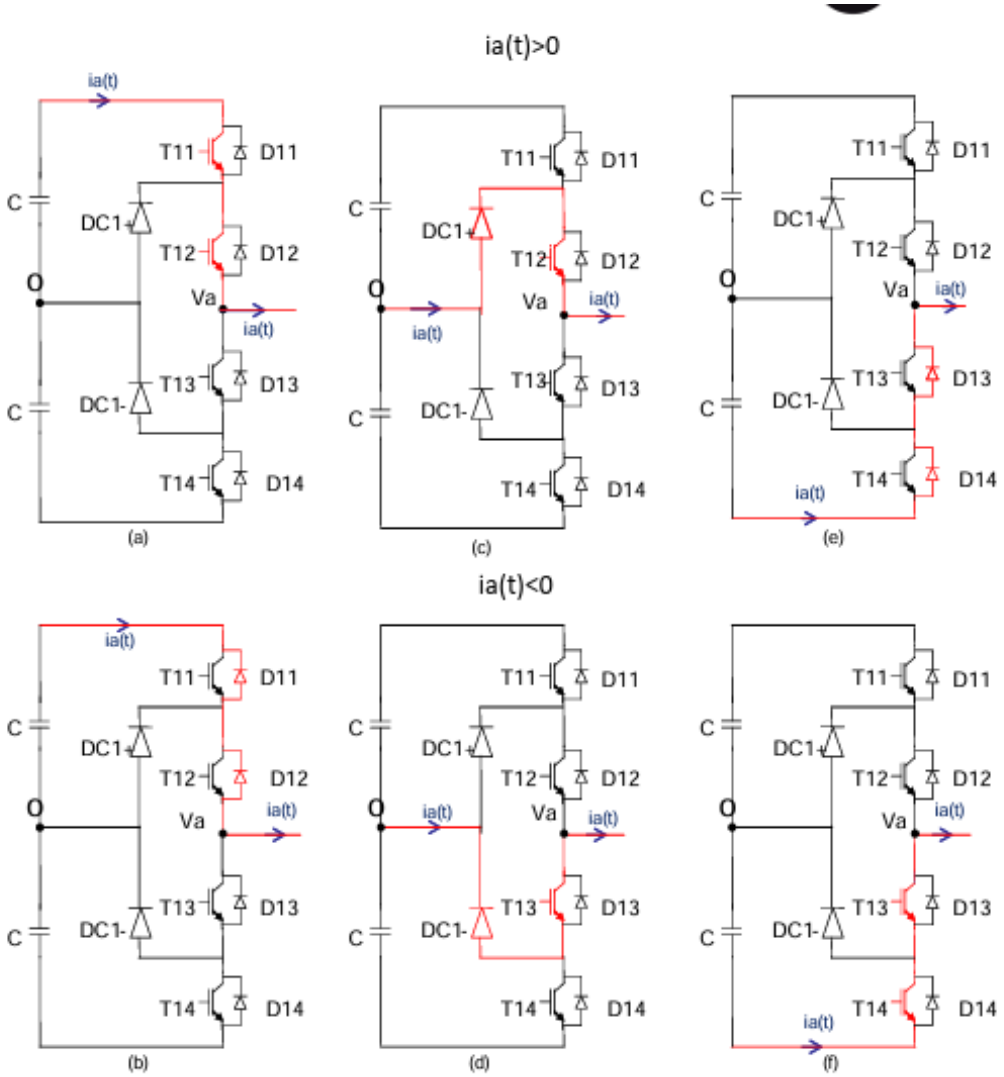


FIG. 1.4 : Conduction paths depending on the sign of the current $i_a(t)$ in an inverter leg [10]

1.2.2 T-type Neutral Point Clamped (T-NPC) Inverter

Introduced to enhance efficiency, the T-NPC topology replaces clamping diodes with bidirectional switches, reducing the number of switches per arm. [**?**, 12]. Key characteristics :

- Suitable for high-frequency operation.
- Retains PWM techniques from conventional NPC inverters.
- Increased voltage stress on vertical switches.

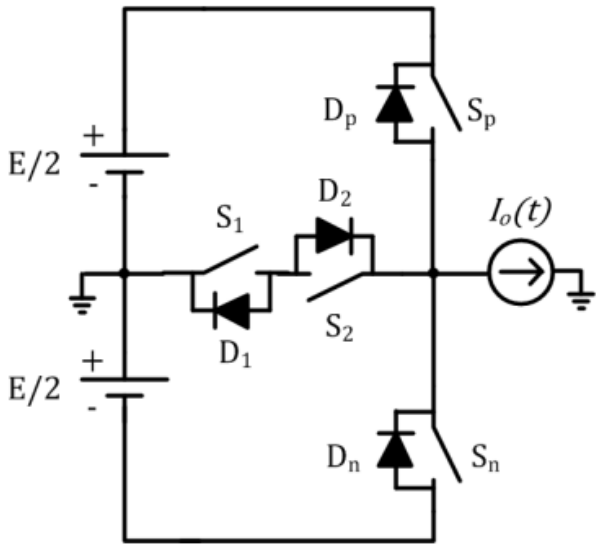


FIG. 1.5 : Diagram of a 3-level multi-level converter (T-NPC) for a single phase [13]

1.2.3 Flying Capacitor (FC) Inverter

This topology uses floating capacitors to generate intermediate voltage levels [11]. It offers :

- Elimination of clamping diodes.
- Capability to balance DC voltage levels.
- Complex control requirements and high capacitor failure rates.

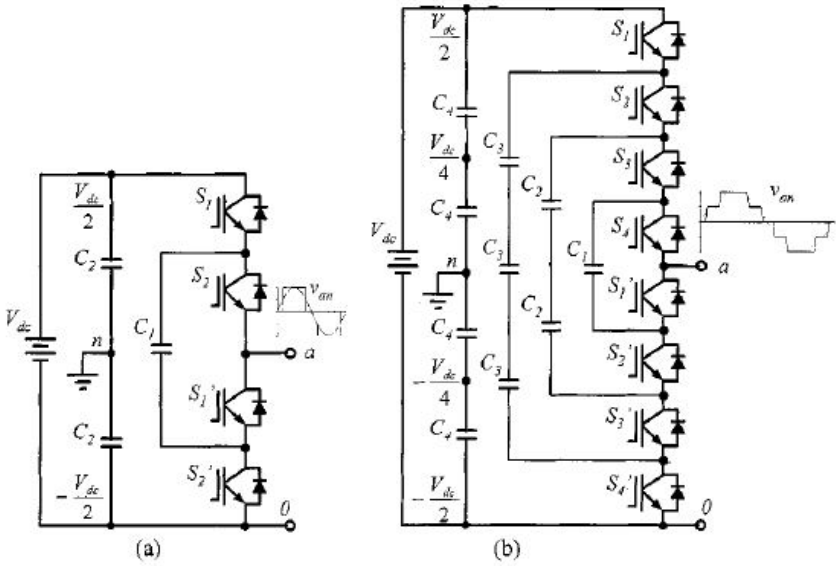


FIG. 1.6 : Capacitor-clamped multilevel inverter circuit topologies. (a)Three-level. (b) Five-level. [11]

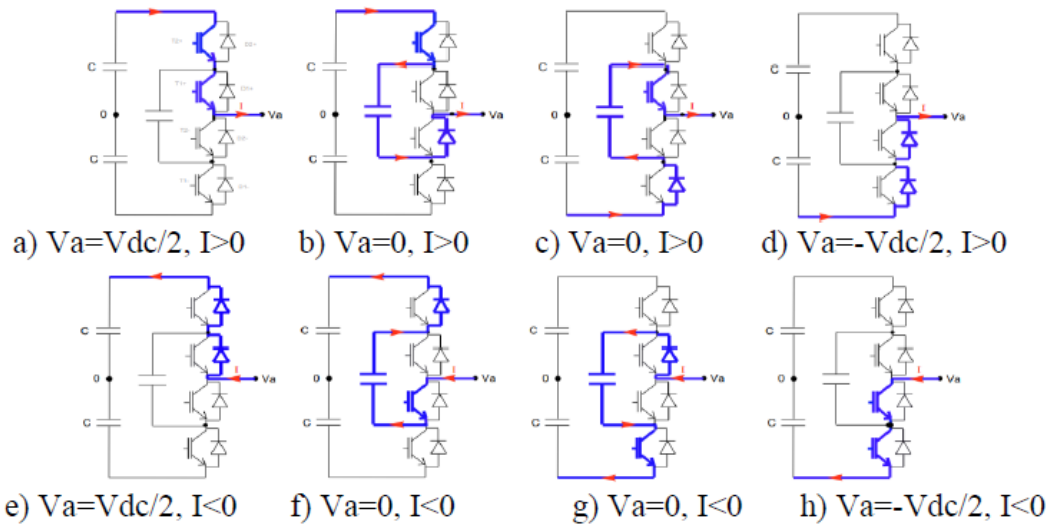


FIG. 1.7 : Conduction path of currents [1]

1.2.4 Cascaded H-Bridge (CHB) Inverter

CHB inverters consist of multiple H-bridges connected in series, each powered by a separate DC source.It was first introduced by W. McMurray in 1971 [?, 14] :

Their advantages include :

- Scalability to higher voltage levels.
- Lower device stress and modular structure.
- Requirement for multiple isolated DC sources.

The corresponding topology is :

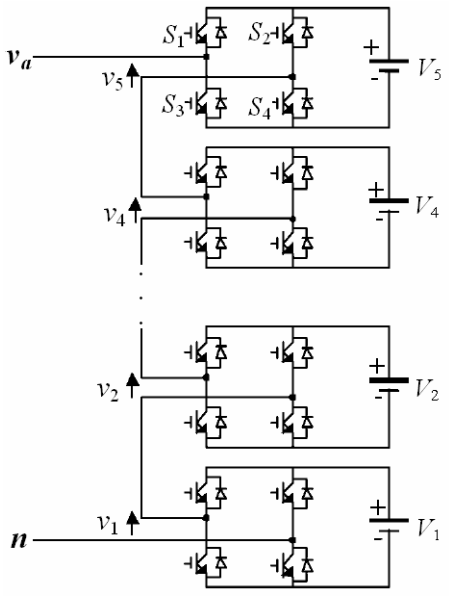


FIG. 1.8 : structure of a cascaded H-Bridge 5 level multi-level inverter

Each topology has specific applications and trade-offs, making the selection dependent on operational constraints and system requirements. Topologies such as NPC inverters and FC inverters divide their supply voltage (the output voltage is smaller than or equal to the input DC voltage). They can operate using a single DC supply. However, in cascaded H-bridge (CHB) structures, the maximum output voltage is greater than each of the supply voltages. Unlike other topologies, cell supplies cannot be derived from a single DC source without additional converters. [1]

Although the choice of a multilevel topology is directly related to the application and the list of features, to minimize losses, volume, and costs, the number of components usually plays the most important role.

1.3 SVM with Two active vectors

:

The Space Vector Modulation (SVM) algorithm is based on the vector representation of reference voltages in the Concordia two-phase frame. The required transformation is expressed as follows :

$$V_{\text{ref}}(d\text{-}q) = \frac{2}{5}\left(V_{an} + V_{bn}a + V_{cn}a^2 + V_{dn}a^3 + V_{en}a^4\right) \quad \text{with} \quad a = e^{j\left(\frac{2\pi}{5}\right)} \tag{1.1}$$

This transformation is also valid for the different switching states of the converter, making it possible to choose the set of vectors needed to generate the desired reference vector.

In the case of a five-phase system, an additional vector representation should be considered. This alternative helps cancel out low-order harmonics, which is only possible when the resulting vector is zero. The corresponding transformation is as follows :

$$V_{\text{ref}}(x\text{-}y) = \frac{2}{5}\left(V_{an} + V_{cn}a + V_{en}a^2 + V_{bn}a^3 + V_{dn}a^4\right) \quad \text{with} \quad a = e^{j\left(\frac{2\pi}{5}\right)} \tag{1.2}$$

In our case, there are $3^5 = 243$ possible vectors. Figure **??** shows the representation of these vectors in the two reference frames : $(P) : 2$, $(O) : 1$, and $(N) : 0$.

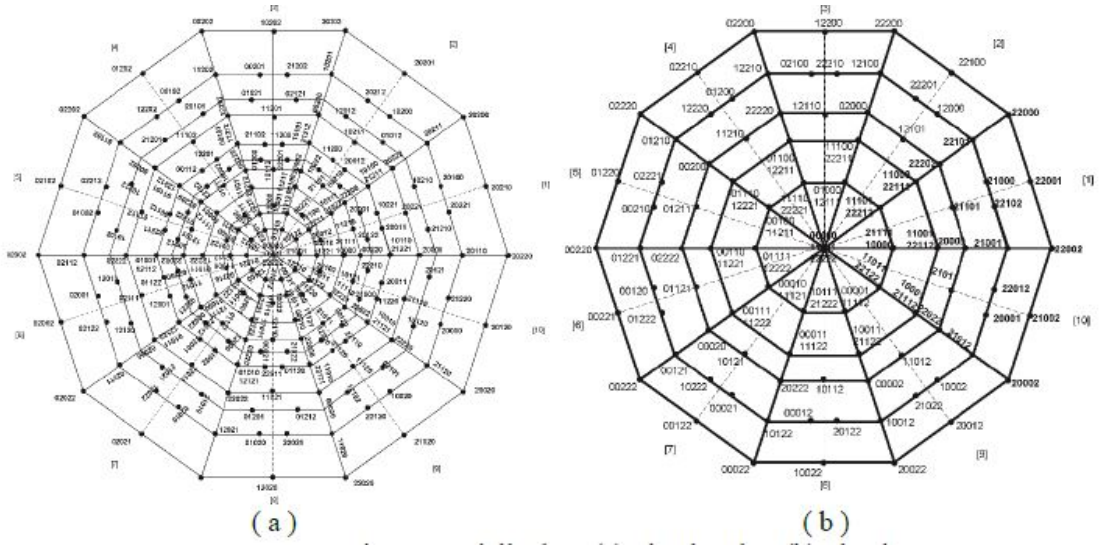


FIG. 1.9 : Vector representation in (a) : the d-q plane, and (b) : the x-y plane [**?**].

General Conclusion

This chapter has presented a comprehensive overview of multilevel inverter modeling and the main topologies currently used in power electronics. Through comparative analysis, it is evident that multilevel inverters offer significant advantages in terms of output waveform quality, reduced harmonic distortion, and improved efficiency. Topologies such as Neutral Point Clamped (NPC), Flying Capacitor (FC), and Cascaded H-Bridge (CHB) each offer unique structural benefits and limitations, with their suitability depending on specific application requirements and system constraints.

In addition, modulation techniques like Space Vector Modulation (SVM) with two active vectors was introduced, showing its effectiveness in generating high-performance control signals for multilevel converters. These techniques play a key role in achieving optimal voltage control, reducing switching losses, and enhancing the inverter's dynamic response.

Overall, understanding the diversity of topologies and control methods is essential for selecting and designing the most appropriate multilevel inverter system for a given application.

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