



People's Democratic Republic of Algeria
Ministry of Higher Education and Scientific Research



Echahid Hamma Lakhdar University of El-Oued

Faculty of Technology

Department of Electrical Engineering

MASTER'S THESIS

Presented in Partial Fulfilment of the Requirements for the Degree of

ACADEMIC MASTER

Domain: Sciences and Technologies

Field: Electrotechnics

Specialty: Electrical Control

Presented by: **Ammari Aymen**

Thesis Title

**Design and Implementation of Three-phase Voltage source
Inverter with Gate Drive Circuits**

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Academic Year: 2025 – 2026

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بِسْمِ اللَّهِ الرَّحْمَنِ الرَّحِيمِ

Acknowledgments

First and foremost, I give thanks to Allah, the Almighty, for His countless blessings, guidance, and mercy. I am deeply grateful to Him for granting me the health, patience, determination, strength, and perseverance necessary to complete my studies and successfully accomplish this thesis.

My deepest gratitude goes to my supervisor, **Dr. Cherif Hakima**, whose invaluable guidance, unwavering support, and scientific expertise have been essential throughout this work. Her insightful advice, encouragement, and dedication played a fundamental role in the completion of this thesis.

I am equally grateful to my co-supervisor, **Dr. Maamir Madiha**, for her valuable guidance, constructive suggestions, and continuous encouragement during this research. Her expertise and insightful comments greatly enriched this work and contributed significantly to its successful completion.

Special thanks are extended to **Dr. Labiod Chouaib** for his invaluable efforts, guidance, and continuous support, which were instrumental in the successful completion of this project. I would also like to express my sincere appreciation to all the members of the **LEERE** Laboratory and the Institute Vision Expertise Formation (**IVEF**) for their assistance, encouragement, and the stimulating environment they provided throughout the course of this research.

I would also like to thank:

- The distinguished members of the jury for their willingness to evaluate this work and for the time and attention they devoted to its examination.
- All the teachers who taught, guided, and inspired me throughout my academic journey.
- The administrative and technical staff of the Department of Electrical Engineering at the University of El Oued for their assistance and cooperation.
- My classmates and all members of the Electrotechnics graduating class of 2026 for the support, friendship, and memorable experiences shared over the years.

Finally, I extend my sincere appreciation to everyone who contributed, directly or indirectly, to the realization of this thesis.

Dedication

اللهم لك الحمد كما ينبغي لجلال وجهك وعظيم سلطانك
على كل نعمة أنعمت بها علينا، والصلاة والسلام على
سيد الخلق، سيدنا محمد النبي الأمي، الحبيب العالي
القدر، العظيم الجاه، واغني بفضلك عن سواك، وعلى
آله وصحبه وسلم

أهدي عملي هذا المتواضع

إلى عيني التي أرى بها الدنيا، ومن ملأت قلبي ورداً
وروحى عطراً... إلى قلبها الذي وسع ما في الكون من
أسى فلما مر على قلبها أينع، وما في القلب من قسوة
فلما مر على قلبها رق، وما في الكون من ظلام فلما
مر على قلبها أضاء...

أمي الحبيبة

إلى من كلله الله بالهبة والوقار... إلى من علمني
العطاء بدون انتظار... إلى من أحمل اسمه بكل
افتخار... إلى مثلي الأعلى الذي تعب من أجل مستقبلي
وأفنى عمره في نشأتي... إلى من تحمل عناء التعب
والشقاء... أرجو من الله أن يمد في عمرك...

أبي الغالي

إلى سندي وقوتي وملاذي بعد الله... إلى من بهم أكبر
وعليهم أعتد... إلى من آثروني على أنفسهم... إلى
شمعات متقدة تنير ظلمة حياتي... إلى من بوجودهم
أكتسب قوة ومحبة لا حدود لها... إلى من عرفت معهم
معنى الحياة...

إخوتي

إلى الشموع التي تنير درب حياتي... اصدقائي الاعزاء
:

محمد الامين ، سعد ، يونس ، معتز بالله ، جمال ، (
علي ، ضياء ، طارق)

.إلى كل أهل والأقارب
وأخيراً، أعتذر ممن سقطوا سهواً من ذاكرتي ولم
يذكرهم قلّمي

ملخص البحث

يهدف هذا العمل إلى دراسة وإنجاز عاكس جهد (Voltage Inverter) ودوائر القيادة الخاصة به (Drivers) باستخدام تقنيات البوتستراپ (Bootstrap) ، والمتحكم بها بواسطة تقنية تعديل عرض النبضة PWM وتحديدها Sinusoidal PWM وال ePWM ويمكن تلخيص هذا المشروع في ثلاثة أجزاء رئيسية على النحو التالي:

أولاً: دراسة مرجعية حول تصميم وبنية (Topology) مختلف أنواع العواكس (Inverters) ، بالإضافة إلى الدوائر وتقنيات تشغيل البوابات (Gate driving) سواء لترانزستور الجانب العلوي (High side) أو الجانب السفلي (Low side) ، فضلاً عن مبدأ عملها وتطبيقاتها.

ثانياً: نمذجة ومحاكاة عاكس الجهد واستراتيجيات التحكم، مع استخراج نتائج المحاكاة المتمثلة في منحنيات الجهد والتيار وفقد للترددات المستخدمة في المحاكاة.

في الجزء الثالث: تم اختيار المكونات الإلكترونية لدائرة التحكم ودائرة الاستطاعة (Power circuit)، ثم تنفيذ النموذج المقترح على منصة EasyEDA للتحقق من صحة الدوائر المقترحة وطباعة ال PCB على الصفيحة النحاسية. وأخيراً تم تركيب المكونات الإلكترونية على اللوحة، ومن ثم برمجة المتحكم الدقيق LAUNCHXL-F28379D لتطبيق مختلف استراتيجيات تقنية ال PWM مع حمولة مقاومة R وحمولة مقاومة-تخريضية RL. وقد أعطت نتائج هذه التجربة أفضل النتائج المطلوبة.

الكلمات المفتاحية:

، عاكس ثلاثي الأطوار (Three Phase Inverter)، تعديل عرض النبضة (Pulse Width Modulation)، سائق قيادة البوابة (Gate-Drive Driver)، تقنية البوتستراپ (Bootstrap Technique)، العزل الضوئي (Optical Isolation)

Résumé

L'objectif de ce travail est l'étude, la conception et la réalisation d'un onduleur triphasé à source de tension ainsi que de ses circuits de commande de grille basés sur la technique du bootstrap, commandés à l'aide de stratégies de modulation de largeur d'impulsion (PWM), notamment la modulation sinusoïdale de largeur d'impulsion (SPWM) et la modulation PWM améliorée (ePWM).

Ce projet est divisé en trois parties principales. Dans un premier temps, une étude bibliographique est présentée sur la conception et les topologies des différents types d'onduleurs, ainsi que sur les circuits de commande de grille et les techniques de commutation des transistors côté haut (high-side) et côté bas (low-side). Les principes de fonctionnement et les domaines d'application de ces systèmes sont également abordés.

La deuxième partie est consacrée à la modélisation et à la simulation de l'onduleur triphasé ainsi qu'à ses stratégies de commande. Les résultats de simulation sont analysés à travers l'étude des formes d'onde de tension et de courant pour différentes fréquences de fonctionnement.

Dans la troisième partie, les composants électroniques nécessaires aux circuits de commande et de puissance ont été sélectionnés. Le système proposé a ensuite été conçu et validé à l'aide de la plateforme EasyEDA, puis le circuit imprimé (PCB) a été fabriqué. Après l'assemblage des composants électroniques, le microcontrôleur **LAUNCHXL-F28379D** a été programmé afin de mettre en œuvre différentes stratégies PWM avec des charges résistives (R) et résistive-inductives (RL). Les résultats expérimentaux démontrent l'efficacité du système d'onduleur proposé et confirment ses performances satisfaisantes dans différentes conditions de fonctionnement.

Mots-clés : Onduleur triphasé à source de tension, Modulation de largeur d'impulsion (PWM), Modulation sinusoïdale de largeur d'impulsion (SPWM), Circuit de commande de grille, Technique du Bootstrap, Isolation optique, LAUNCHXL-F28379D

Abstract

The objective of this work is the study, design, and implementation of a three-phase voltage inverter and its gate-driver circuits based on the bootstrap technique, controlled using Pulse Width Modulation (PWM) strategies, including Sinusoidal PWM (SPWM) and Enhanced PWM (ePWM).

This project is divided into three main parts. First, a bibliographical study is presented on the design and topology of different types of inverters, as well as gate-driving circuits and switching techniques for both high-side and low-side transistors. The operating principles and applications of these systems are also discussed.

The second part focuses on the modelling and simulation of the three-phase voltage inverter and its control strategies. Simulation results are analysed through the evaluation of voltage and current waveforms under different operating frequencies.

In the third part, the electronic components required for both the control and power circuits were selected. The proposed system was then designed and validated using the EasyEDA platform, followed by the fabrication of the printed circuit board (PCB). After assembling the electronic components, the **LAUNCHXL-F28379D** microcontroller was programmed to implement various PWM strategies with both resistive (R) and resistive-inductive (RL) loads. The experimental results demonstrate the effectiveness of the proposed inverter system and validate its satisfactory performance under different operating conditions.

Keywords: Three-Phase Voltage Inverter, Pulse Width Modulation (PWM), Sinusoidal PWM (SPWM), Gate Driver, Bootstrap Technique, Optical Isolation, LAUNCHXL-F28379D.

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General Introduction

Over the past few decades, the field of power electronics has experienced exponential growth, fundamentally reshaping the landscape of modern electrical engineering and industrial automation. At the heart of this technological revolution is the ability to efficiently convert and control electrical energy to meet the strict demands of diverse applications, ranging from renewable energy integration and electric mobility to heavy industrial motor drives. Among the various power conversion topologies, the DC-AC converter, commonly known as the inverter, plays an indispensable role [1], [2].

In industrial environments, three-phase alternating current (AC) is the standard for power transmission and the operation of heavy machinery. Three-phase asynchronous machines represent the vast majority of industrial actuators due to their robustness, low maintenance, and high reliability. However, directly connecting these machines to the grid limits them to a fixed speed and subjects the mechanical systems to severe electrical and mechanical stress during startup. Furthermore, the rising integration of direct current (DC) sources, such as photovoltaic arrays, battery storage systems, and DC microgrids necessitates a highly efficient interface to convert this energy into usable three-phase AC power. Consequently, the three-phase inverter has become a critical focal point in electrical engineering, serving as the bridge between DC sources and AC loads while providing dynamic control over voltage and frequency [5].

Despite the maturity of inverter technology, the physical implementation and optimization of these systems present significant engineering challenges. The core operating principle of an inverter relies on the high-frequency switching of power semiconductor devices to synthesize an AC waveform from a DC input. Because the output is generated through discrete switching events, the raw voltage supplied by the inverter is not a pure, continuous sine wave, but rather a sequence of rectangular pulses.

This chopped voltage waveform inherently contains high-order harmonics. If left unmitigated, these harmonics cause severe issues: they induce supplementary thermal losses in the magnetic cores of connected motors, create detrimental torque pulsations that can degrade mechanical couplings, and cause electromagnetic interference (EMI). Moreover, injecting high total harmonic distortion (THD) back into the electrical grid violates strict power quality standards. Therefore, the challenge lies not merely in converting DC to AC, but in doing so with maximum efficiency, minimal switching losses, and the highest possible power quality. Overcoming this requires the

careful selection of modern electronic switches such as MOSFETs or IGBTs and the implementation of sophisticated mathematical control strategies to optimize the switching sequences.

The objective of this thesis is to study, design, simulate, and implement a three-phase voltage source inverter controlled by SPWM techniques. The work aims to bridge the gap between theoretical concepts and practical hardware realization by developing a complete inverter prototype capable of supplying three-phase loads under different operating conditions.

This thesis is organized into three chapters.

Chapter 1 presents the theoretical background of power inverters, including their operating principles, classifications, advantages, disadvantages, and selection criteria.

Chapter 2 focuses on the mathematical modelling and simulation of the three-phase inverter. The principles of Pulse Width Modulation (PWM) and Sinusoidal Pulse Width Modulation (SPWM) are introduced, and the proposed control strategy is validated through MATLAB/Simulink simulations.

Chapter 3 describes the hardware implementation and experimental validation of the proposed inverter system. It includes component selection, gate-driver design, printed circuit board (PCB) development, microcontroller programming, and the analysis of experimental results obtained under different loading conditions.

Finally, the thesis concludes with a summary of the main achievements, followed by recommendations and perspectives for future work.

Chapter 1

Theoretical background of the inverters

1.1 Introduction

The continuous advancement of power electronics has fundamentally transformed the efficiency and control of modern industrial systems. At the core of this technological shift is the DC-AC converter, commonly known as the inverter [1], [2]. In high-demand industrial applications such as constant-pressure pumping systems, the three-phase inverter is an indispensable component [4]. It serves not only as an energy conversion interface but also provides the precise dynamic control required to maintain strict operational stability. This chapter presents the theoretical background necessary for understanding inverter technology. It begins with an overview of inverters and their main classifications, including single-phase, three-phase, and multilevel topologies. The chapter then discusses the criteria for selecting an appropriate inverter for a given application, followed by an analysis of the main advantages and disadvantages of inverter-based systems.

1.2 Overview of Inverters

1.2.1 Definition of the inverter:

An inverter is fundamentally defined as a static power electronic converter that transforms a direct current (DC) input into an alternating current (AC) output with the desired voltage magnitude and frequency [1]. This energy conversion is achieved through the systematic high-frequency switching of semiconductor power devices, such as Insulated Gate Bipolar Transistors (IGBTs) or Metal-Oxide-Semiconductor Field-Effect Transistors (MOSFETs) [15], [27]. arranged in various bridge topologies according to the required output configuration [1]. Since these semiconductor devices operate in two distinct states fully conducting or fully blocking the raw output voltage of the inverter consists of a sequence of discrete rectangular pulses rather than a pure sinusoidal waveform. Consequently, modern inverter architectures employ advanced modulation techniques, most notably Pulse Width Modulation (PWM) [16], [23], to precisely control the switching instants and generate an AC output waveform that closely approximates a sinusoidal signal [2].

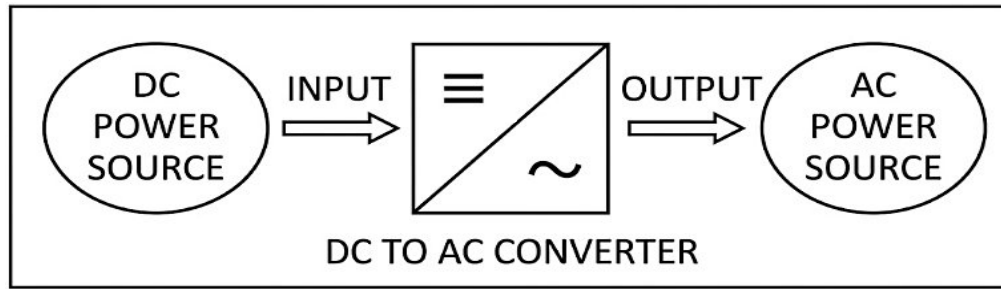


Figure 1.1 Block diagram of DC-AC power conversion [1].

1.2.2 Types of inverters

1.2.2.1 Single-Phase Voltage Source Inverter

❖ Single-Phase Half-Bridge Voltage Source Inverter

This type of inverter delivers a single-phase alternating voltage at its output. Depending on their topology, single-phase inverters can be divided into two main configurations.

Figure 1.2 illustrates the basic circuit diagram and the output voltage across the RL load of a single-phase half-bridge inverter:

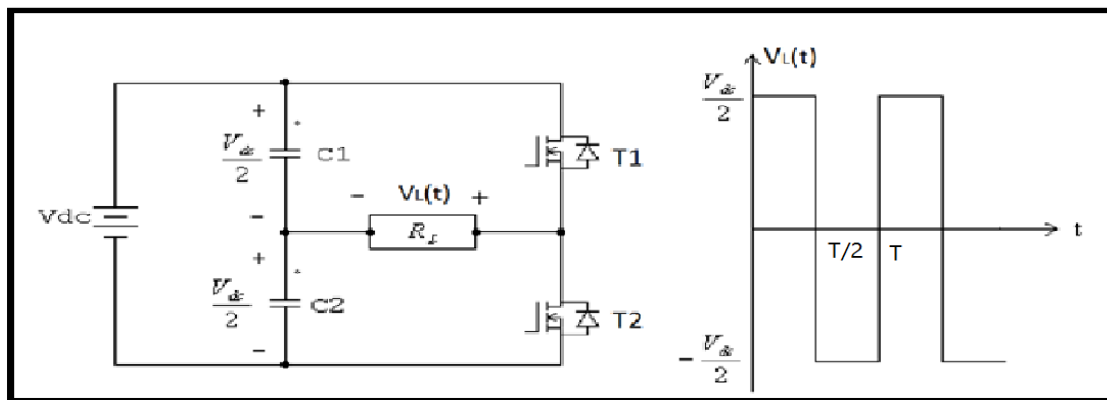


Figure 1.2 the basic circuit diagram single-phase half-bridge inverter [3].

The single-phase half-bridge inverter consists of a single leg containing two power switches, denoted as T1 and T2, which operate with complementary control signals [3]. These power switches can be MOSFETs, IGBTs, or similar devices. Two diodes are connected in anti-parallel with the switches; these freewheeling diodes allow the inductor to discharge its stored energy when the active switches are turned off [3].

➤ Operating Principle

In this circuit, the switching operation of switches T1 and T2 is executed such that if one is open (turned off), the other is necessarily closed (turned on), and vice versa.

- During the first half-period ($0 \leq t \leq T/2$), switch T1 is closed (T2 is open), and the voltage across the RL inductive load is:

$$V_L(t) = \frac{V_d}{2}$$

- During the second half-period ($T/2 \leq t \leq T$), when switch T2 is closed (T1 is open), the voltage is:

$$V_L(t) = \frac{-V_d}{2}$$

Closing both switches T1 and T2 simultaneously causes a short circuit across the input voltage source (V_{dc}). This results in a high surge of current (shoot-through) that is highly destructive to the power switches [4]. The Table1.1 presents the switching states of these components:

T1	T2	VL
ON	OFF	$V_{dc}/2$
OFF	ON	$-V_{dc}/2$

Table 1.1 single-phase half-bridge inverter output voltage

❖ Single-phase H-bridge Voltage Source Inverter

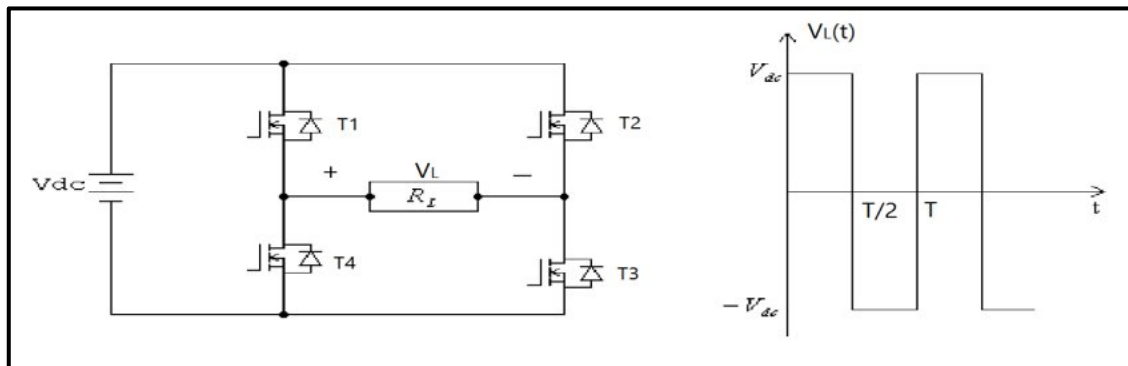


Figure 1.3: a single-phase H-bridge inverter [3].

Figure 1.3 represents a single-phase H-bridge inverter and its output voltage waveform across an RL load

➤ Operating Principle

The control of the single-phase H-bridge inverter is established as follows:

- **When switches T1 and T3 are closed** during the first half-period ($0 \leq t \leq T/2$), switches T2 and T4 are open. At this moment, the output voltage across the load equals V_{dc} .
- **When switches T2 and T4 are closed** during the remainder of the period ($T/2 \leq t \leq T$), switches T1 and T3 are open. The output voltage across the load becomes V_{dc} .

Consequently, the output voltage alternates between the positive and negative terminals during the first and second half-periods, respectively.

T1	T2	T3	T4	$V_L(t)$
ON	OFF	ON	OFF	V_{dc}
OFF	ON	OFF	ON	$-V_{dc}$
ON	OFF	OFF	ON	0
OFF	ON	ON	OFF	0

Table 1.2 single-phase H-bridge inverter output voltage

To prevent the issue of short-circuiting the input voltage, a **dead time** is maintained between two switching operations. The table below represents the switching states of the single-phase bridge inverter [4].

1.2.2.2 Two-level Three-Phase Voltage Source Inverter

The two-level three-phase inverter is generally used for medium-power applications. The structure of this inverter can be obtained by placing three single-phase half-bridge inverters in parallel, as shown in **Figure 1.4** [5].

Each leg contains two switches that operate with **complementary control** to ensure that the input voltage is never short-circuited. This type of inverter is widely used with Pulse Width Modulation (PWM) to power balanced three-phase loads with variable voltage and frequency [5]. Each of the three output voltages is phase-shifted by $3/2\pi$ relative to one another [6] [17].

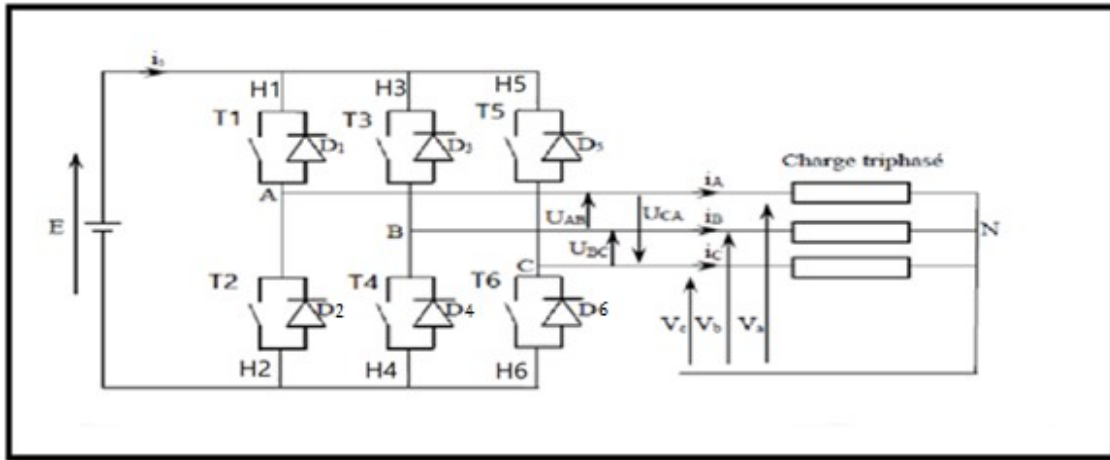


Figure 1.4: Two-level Three-Phase Voltage Source Inverter [3].

The characteristics of the inverter are primarily defined by its power components. These determine the power, voltage, and maximum switched current, as well as the maximum switching frequency and dead time. These last two characteristics are very important because they will influence the design.

The maximum switching frequency is determined by the switching times (the opening and closing times of the switches) and by the dead time, which serves to prevent the risk of short-circuits [29] on a leg between the opening of a switch and the closing of its complementary switch

1.2.2.3 Multi-Level Inverter (MLI) Technology

Multi-level inverters have emerged as a pivotal research area in power electronics [7] [21], [22]. These static DC-AC converters utilize an array of power semiconductors and multiple DC voltage sources implemented via capacitors or independent supplies to synthesize a **staircase output waveform** [7] [28].

➤ Operating Principle of Multi-Level Inverters

Figure (1.5) represents the basic schematic of a single inverter leg for various levels, in which the semiconductors are replaced by ideal switches.

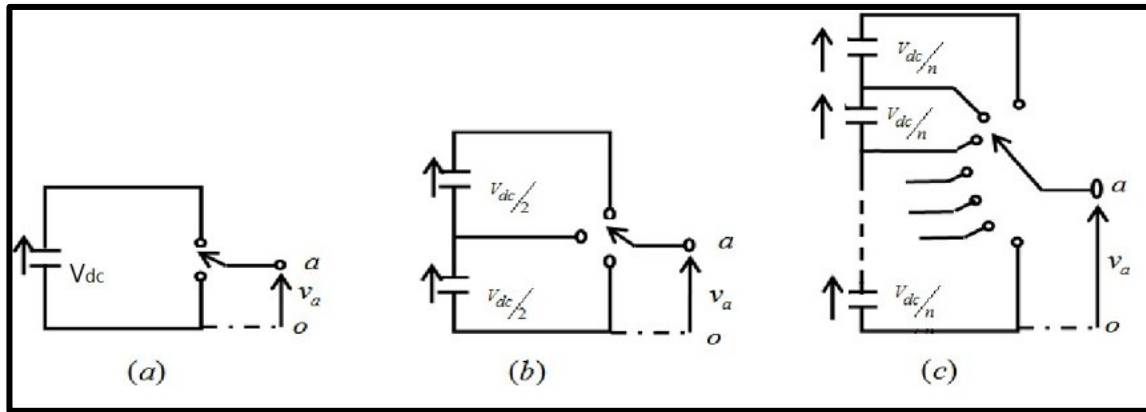


Figure 1.5: the basic schematic of a single inverter leg for various levels [10].

The two-level inverter generates an output voltage pivoting between two values (two levels): V_{dc} and 0, relative to the negative terminal of the capacitor **Figure 1.5.a**. In contrast, the three-level inverter shown in **Figure 1.5.b** generates three output voltage levels ($V_{dc}/2, 0, -V_{dc}/2$), and this logic continues for the N-level inverter **Figure 1.5.c**. By increasing the number of inverter levels, the output voltages consist of multiple steps, resulting in a waveform that increasingly approximates a sampled sine wave. Consequently, compared to the output voltage of a two-level inverter, multi-level inverters exhibit a lower distortion rate and reduced harmonic pollution.

➤ Comparative Analysis of Inverter Topologies

Table 3. summarizes the main characteristics, advantages, and limitations of the inverter topologies discussed in this chapter.

Inverter Type	Main Advantages	Main Disadvantages	Typical Applications
Single-Phase Half-Bridge VSI	-Simple and economical structure. -Requires only two controlled switches and two diodes.	-Each switch must withstand twice the maximum load voltage. -Power regulation requires PWM.	-Low-power converters, - educational laboratories, small UPS systems.

	-Reduced voltage drop since only one switch conducts at a time.	Limited maximum operating frequency.	
Single-Phase H-Bridge VSI	-Each switch blocks only the maximum load voltage. -PWM phase-shift control enables power regulation. Simple implementation.	-Additional conduction and switching losses. Harmonic distortion. -Limited to specific single-phase applications.	-Single-phase motor drives, residential inverters, UPS systems.
Two-Level Three-Phase VSI	-Simple structure and control. Suitable for medium/high-power applications. -Compatible with PWM techniques.	-Harmonic distortion at low switching frequencies. -Requires dead time. May require output filters.	-Industrial motor drives, pumping systems, renewable energy systems.
Multilevel Inverter (MLI)	-Low THD. High voltage capability. -Reduced voltage stress. Improved output quality.	-Complex topology. More switches and components. Higher cost.	-High-power drives, HVDC, FACTS, renewable energy plants.

Table 1.3 Comparative Analysis of Inverter Topologies

1.3 Criteria for Choosing an Inverter

Selecting the appropriate inverter for an industrial application such as driving a high-power three-phase asynchronous motor or a pumping system is a critical engineering decision. The choice directly impacts the system's efficiency, mechanical reliability, and compliance with power quality standards [10]. The primary criteria for selecting an inverter include:

- **Power and Current Capacity:** The inverter must be dimensioned to handle not only the nominal continuous power of the load but also the transient peak currents experienced during motor startup or sudden load variations [26].
- **Operating Voltage and Frequency Range:** The inverter's input DC-link voltage must be compatible with the rectified source, and it must be capable of synthesizing the required AC output voltage (e.g., 400V three-phase). The allowable output frequency range is also crucial for adjustable speed operations [20].
- **Semiconductor Technology:** The core components must match the application's demands. The choice between MOSFETs (ideal for higher switching frequencies) and IGBTs (standard for high-power, high-voltage industrial drives) dictates the thermal management requirements and switching loss profiles of the system [27], [34].
- **Power Quality and Harmonic Limits (THD):** For heavy industrial equipment, the inverter must strictly comply with local grid regulations (such as SonelGaz standards). The ability of the inverter topology paired with appropriate LC or LCL output filters to minimize Total Harmonic Distortion is a major selection criterion to prevent grid degradation.
- **Control Interface and Embedded Compatibility:** Modern implementations require inverters whose power stages and gate drivers can seamlessly interface with external digital control systems. Compatibility with microcontrollers (such as Arduino or ESP32 architectures) or Digital Signal Processors (DSPs) is essential for executing precise, real-time Pulse Width Modulation (PWM) algorithms.

1.4 Advantages and Disadvantages of Inverters

The deployment of static inverters in modern electrical systems offers significant operational benefits, though it is accompanied by inherent technical challenges that must be engineered around.

1.4.1 Advantages:

- **Dynamic Load and Speed Control:** Inverters allow for the precise regulation of an AC motor's speed and torque by dynamically varying the output voltage and frequency [19], [20]. This capability is vital for systems requiring constant flow and pressure, as it

eliminates the mechanical shock and hydraulic surges associated with direct-on-line (DOL) starting [9].

- **Energy Efficiency:** By controlling the motor to operate only at the required optimal speed rather than running constantly at full speed and throttling the mechanical output inverters drastically reduce overall energy consumption [19], [9].
- **Versatile Interfacing:** They provide a critical, controllable interface that bridges DC power networks and the standard three-phase AC grid, making them indispensable for modern industrial automation [9], [25], [30], [33].

1.4.2 Disadvantages:

- **Harmonic Generation:** The fundamental mechanism of an inverter relies on high-frequency switching, which inherently produces severe harmonic distortion. If left unfiltered, these harmonics cause localized overheating in motor windings, acoustic noise, torque pulsations, and electromagnetic interference (EMI) [9], [18], [24], [31].
- **System Complexity:** Designing a robust inverter system requires sophisticated mathematical control algorithms, fast-acting isolated gate drivers, and advanced digital processors. This increases both the initial cost and the engineering complexity of the system [9].
- **Thermal Constraints:** Even highly efficient semiconductors experience conduction and switching losses, generating significant heat. This necessitates bulky aluminum heat sinks, active cooling systems, and rigorous thermal monitoring to prevent catastrophic component failure [9], [34].

1.5 Introduction to Semiconductors

Semiconductors are the foundational material class driving modern electronics, computing, and power electronic conversion. Positioned between electrical conductors (such as copper and aluminum) and insulators (such as glass and rubber), semiconductors possess a unique electrical conductivity that can be precisely altered and controlled. This tunability is achieved through external factors such as thermal energy, light exposure, electric fields, or the deliberate introduction of chemical impurities through a process known as doping [27].

While elemental semiconductors such as Silicon (Si) and Germanium (Ge) have historically formed the bedrock of the solid-state revolution, compound semiconductors such as Gallium Arsenide (GaAs), together with wide-bandgap materials including Silicon Carbide (SiC) and Gallium Nitride (GaN), have significantly expanded the capabilities of modern electronic systems into high-frequency, high-efficiency, and high-power operating regimes. These advanced materials offer superior switching performance, higher temperature tolerance, and reduced power losses, making them particularly attractive for contemporary power electronic applications [27], [34].

1.5.1 The MOSFET (Metal-Oxide-Semiconductor Field-Effect Transistor)

The Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET) is one of the most widely used semiconductor devices in modern power electronics due to its high switching speed, simple gate-drive requirements, and excellent efficiency. Unlike bipolar devices, the MOSFET is a voltage-controlled device in which the application of a gate-to-source voltage (V_{GS}) creates an electric field that controls the conduction channel between the drain and source terminals [35].

A key advantage of the MOSFET is its extremely high input impedance, which results from the insulated gate structure. Consequently, the gate draws negligible steady-state current, reducing the power required for control circuitry. However, the gate behaves as a capacitive load, requiring the gate driver to provide sufficient charging and discharging currents to achieve fast switching transitions [35].

The switching performance of a MOSFET is largely determined by the charging and discharging rates of its internal capacitances, particularly the gate-to-source and gate-to-drain capacitances. Fast switching speeds minimize switching losses and improve overall converter efficiency, making MOSFETs highly suitable for high-frequency power conversion applications such as inverters, switched-mode power supplies, and motor drives.

Modern power MOSFETs are capable of switching within nanoseconds, enabling operation at frequencies significantly higher than those achievable with conventional bipolar devices. Furthermore, their positive temperature coefficient of on-state resistance enhances current

sharing when multiple devices are connected in parallel, contributing to improved reliability and thermal stability in high-power applications [35].

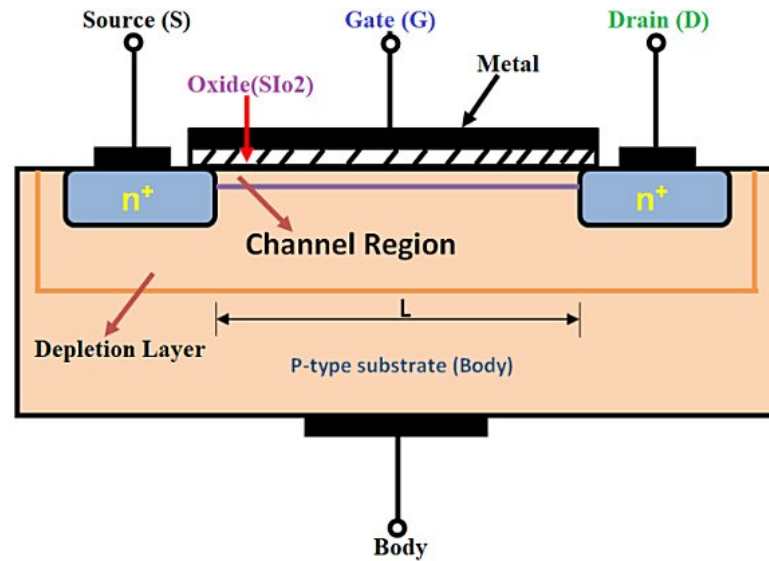


Figure 1.6: internal structure of MOSFET

➤ Operating Principle

A MOSFET operates by controlling the flow of current between the drain and source terminals through an electric field generated by the voltage applied to the gate terminal. The gate is electrically insulated from the semiconductor channel by a thin oxide layer, resulting in very high input impedance and negligible gate current during steady-state operation [35].

When the gate-to-source voltage (V_{GS}) is below the threshold voltage (V_{TH}), no conductive channel exists between the drain and source, and the MOSFET remains in the OFF state. As V_{GS} exceeds V_{TH} , an inversion layer is formed beneath the gate oxide, creating a conductive channel that allows current to flow from drain to source. The drain current increases as the gate voltage rises, enabling the MOSFET to operate as an electronically controlled switch [35].

During switching operation, the gate capacitances—namely the gate-to-source capacitance (C_{GS}) and gate-to-drain capacitance (C_{GD})—must be charged and discharged. The speed at which these capacitances are charged determines the switching performance of the device. When the gate voltage reaches the threshold voltage, the MOSFET begins conducting. As the

gate voltage continues to increase to the Miller plateau region and beyond, the channel becomes fully enhanced, reducing the drain-to-source resistance and minimizing conduction losses.

Because of its high switching speed, low gate-drive power requirement, and excellent efficiency, the MOSFET is widely used in power converters, inverters, motor drives, and switched-mode power supplies [35].

1.5.2 The SiC MOSFET (Silicon Carbide Metal-Oxide-Semiconductor Field-Effect Transistor)

A Silicon Carbide (SiC) MOSFET is a wide-bandgap power semiconductor device that utilizes silicon carbide instead of conventional silicon as the base material. Due to the superior material properties of SiC, including a wider bandgap, higher critical electric field, and greater thermal conductivity, SiC MOSFETs exhibit significantly improved performance in high-power and high-voltage applications. These devices are capable of operating at higher junction temperatures and switching frequencies while maintaining lower switching and conduction losses compared to traditional silicon MOSFETs. The higher breakdown electric field of SiC enables thinner drift regions, resulting in reduced on-resistance and improved efficiency. Additionally, SiC MOSFETs demonstrate reduced reverse recovery losses and enhanced switching speed, making them particularly suitable for high-efficiency power conversion systems. As a result, SiC MOSFETs are widely adopted in applications such as electric vehicle powertrains, renewable energy inverters, industrial motor drives, and high-frequency power supplies, where high efficiency, compact size, and thermal robustness are critical requirements.

➤ Operating Principle

The operating principle of a Silicon Carbide (SiC) MOSFET is based on the electrostatic control of a conductive channel between the drain and source terminals using an insulated gate structure, similar to conventional MOSFETs, but implemented in a wide-bandgap silicon carbide semiconductor. When a positive gate-to-source voltage exceeding the threshold voltage is applied, an electric field is established across the gate oxide, which induces the formation of an inversion channel in the P-type body region. This channel allows majority carriers (electrons in an N-channel device) to flow from the source to the drain through the low-resistance drift region. In the OFF state, when the gate voltage is below the threshold, the channel is absent, and the high-resistivity drift region blocks the applied drain-to-source voltage. The use of silicon

carbide significantly enhances the device's performance by enabling a higher critical electric field, which allows a thinner drift region for a given voltage rating, thereby reducing on-resistance and conduction losses. Additionally, the intrinsic material properties of SiC contribute to faster switching behavior by reducing charge storage effects and eliminating slow reverse recovery characteristics commonly observed in silicon-based devices, resulting in improved efficiency during high-frequency switching operations.

1.5.3 The IGBT (Insulated Gate Bipolar Transistor)

The IGBT is a four-layer, semiconductor device that combines the voltage characteristics of a bipolar transistor (collector – emitter) and the drive characteristics of a MOSFET. The concept was first documented in a Japanese patent by Yamagami, which was filed in 1968. The first devices were of a planar technology, but more recently vertical, trench devices have been made popular [36].

The popularity of the IGBT has soared in recent years due to an increase in high voltage, high power applications at which they excel. While the switching speeds are slower than a MOSFET, the $V_{CE(SAT)}$ characteristics are a significant improvement over those of a MOSFET at high currents, especially for high voltage devices. They are available in a range of voltage ratings from 300 to over 1200 volts and current ratings of 15 to 100 amps for a single die. IGBT modules have current ratings well into the 100s of amps [36]

➤ Operating Principle

The operation of an IGBT is controlled by the voltage applied between the gate and emitter terminals. When the gate-to-emitter voltage (V_{GE}) is below the threshold value, the device remains in the OFF state, preventing current flow between the collector and emitter. When V_{GE} exceeds the threshold voltage, a conductive channel is formed in the MOS gate structure, allowing electrons to flow and activating the bipolar conduction mechanism inside the device.

Once turned on, the IGBT conducts current from the collector to the emitter with a relatively low voltage drop. The injected minority carriers reduce the device's on-state resistance, enabling efficient operation at high current levels. This characteristic makes IGBTs particularly suitable for high-power applications where MOSFET conduction losses would become excessive.

During turn-off, the gate voltage is removed, causing the MOS channel to disappear and interrupting the flow of charge carriers. However, because of the stored charge in the drift region, the collector current does not cease instantaneously and exhibits a phenomenon known as the current tail, which contributes to switching losses and limits the maximum switching frequency of IGBTs compared to MOSFETs.

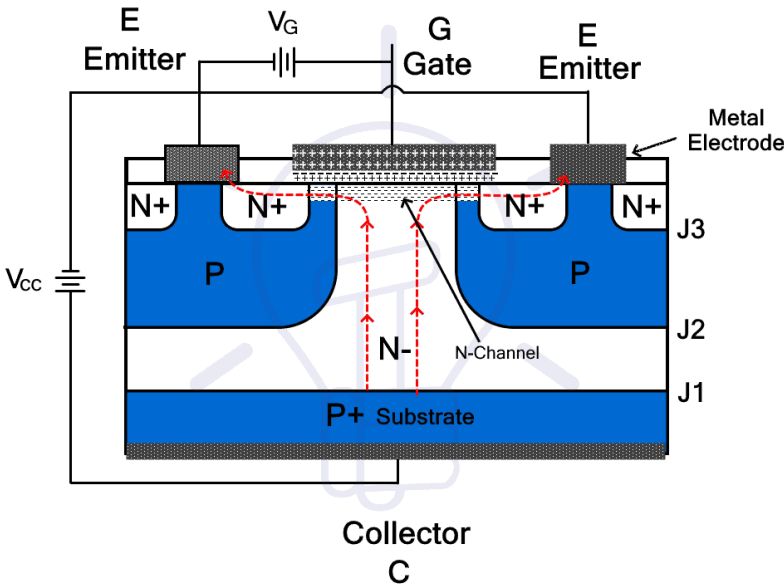


Figure 1.7: internal structure of IGBT

1.6 Comparative Performance Analysis of Silicon MOSFET, IGBT, and Silicon Carbide (SiC) MOSFET Power Semiconductor Devices

Parameter	Silicon MOSFET	IGBT	SiC MOSFET
Switching speed	Very fast (ns range). Majority-carrier device with no charge storage, enabling rapid turn-on and turn-off.	Slow to medium (μ s range). Minority-carrier device with tail current during turn-off due to charge recombination.	Very fast (comparable or faster than Si MOSFET in power range). Wide-bandgap material reduces capacitances and switching delays.

Internal resistance / conduction behavior	Conduction through ($R_{DS(on)}$). Resistance increases significantly with voltage rating, leading to higher losses in high-voltage applications.	No resistive channel; operates with nearly constant saturation voltage ($V_{CE(sat)}$), causing higher conduction losses at low-to-medium currents.	Very low ($R_{DS(on)}$) even at high voltage due to high critical electric field of SiC, enabling thin drift region and low conduction losses.
Switching losses	Low at low voltage, but increases with parasitic capacitances and body diode reverse recovery at higher power levels.	High due to tail current during turn-off and slow carrier recombination in drift region.	Very low due to negligible charge storage effects and minimal reverse recovery losses, enabling high-frequency operation.
Voltage capability	Low to medium voltage range (typically ≤ 600 V) due to silicon material limitations and increased ($R_{DS(on)}$) at higher voltages.	High voltage capability (600 V to several kV), widely used in medium and high-power industrial systems.	High to very high voltage capability (650 V, 1200 V, 1700 V and above) with improved efficiency due to wide-bandgap properties.
Switching frequency capability	High-frequency operation (tens to hundreds of kHz) suitable for low-voltage converters and SMPS applications.	Low-frequency operation (typically below 20 kHz) due to high switching losses.	High-frequency operation (100 kHz and above in many cases), enabling smaller passive components and higher power density.
Thermal performance	Limited thermal capability ($\sim 150^\circ\text{C}$ junction temperature).	Good thermal robustness but still limited by	Excellent thermal performance ($>200^\circ\text{C}$ junction temperature

	Performance degrades significantly at high temperature.	silicon material constraints.	capability) due to wide-bandgap and high thermal conductivity.
Efficiency in power systems	Moderate efficiency; best suited for low-voltage, high-frequency applications.	High efficiency at low switching frequency but poor at high frequency due to switching losses.	Very high efficiency across wide operating range due to low conduction and switching losses.
Typical applications	DC-DC converters, low-voltage SMPS, consumer electronics power stages.	Motor drives, industrial inverters ,railway traction systems, medium/high-power converters.	EV inverters, fast chargers,solar inverters, aerospace power systems, high-frequency high-efficiency converters.

Table 1.4 Comparative Performance Analysis of Silicon MOSFET, IGBT, and Silicon Carbide (SiC) MOSFET

1.7 Conclusion

This chapter has established the theoretical and technical foundations necessary for understanding DC-to-AC power conversion. By exploring the general architecture of inverters, evaluating the characteristics of primary semiconductor switches, and analyzing the strict criteria required for their industrial deployment, we have highlighted both the immense capabilities and the inherent challenges of these systems.

While inverters offer unparalleled dynamic control over heavy electromechanical loads enabling soft starting, energy efficiency, and precise process regulation they also introduce significant complexities, primarily in the form of high-frequency harmonic distortion and thermal management. To overcome these disadvantages and safely exploit the potential of modern power electronics, intelligent and highly responsive control strategies are imperative. Consequently, the subsequent chapter will focus on the mathematical formulation and practical

hardware implementation of these strategies, detailing the generation of Sinusoidal Pulse Width Modulation (SPWM) using advanced embedded microcontroller architectures.

Chapter 2

Review of Inverter Control Strategies and Simulation of the Proposed Three-Phase Inverter

Chapter 2: Review of Inverter Control Strategies and Simulation of the Proposed Three-Phase Inverter

2.1 Introduction

This chapter presents the theoretical and simulation aspects of the proposed three-phase voltage source inverter. It begins with an overview of the most commonly used inverter control strategies, highlighting their operating principles and main characteristics. Particular attention is given to Sinusoidal Pulse Width Modulation (SPWM), which is selected in this work due to its simplicity, reliability, and suitability for three-phase inverter applications. Next, the mathematical model of the three-phase inverter is developed by analysing its topology, switching states, and output voltage equations. These formulations provide the theoretical basis for understanding the inverter operation and the generation of three-phase AC voltages from a DC source. Finally, a MATLAB/Simulink model of the proposed inverter is implemented to evaluate its performance. The obtained simulation results, including the SPWM signals and output voltage and current waveforms under different load conditions, are presented and discussed to validate the effectiveness of the proposed system before hardware implementation.

2.2 Overview of Inverter Control Strategies

2.2.1 Pulse Width Modulation (PWM)

Pulse Width Modulation (PWM) or Pulse Duration Modulation (PDM) or Pulse Time Modulation (PTM) is an analog modulating scheme in which the duration or width or time of the pulse carrier varies proportional to the instantaneous amplitude of the message signal. The width of the pulse varies in this method, but the amplitude of the signal remains constant. Amplitude limiters are used to make the amplitude of the signal constant. These circuits clip off the amplitude, to a desired level and hence the noise is limited. **Figure 2.2 (a), (b), (c)** explain the types of Pulse Width Modulated Waves with different time slots [23] [24].

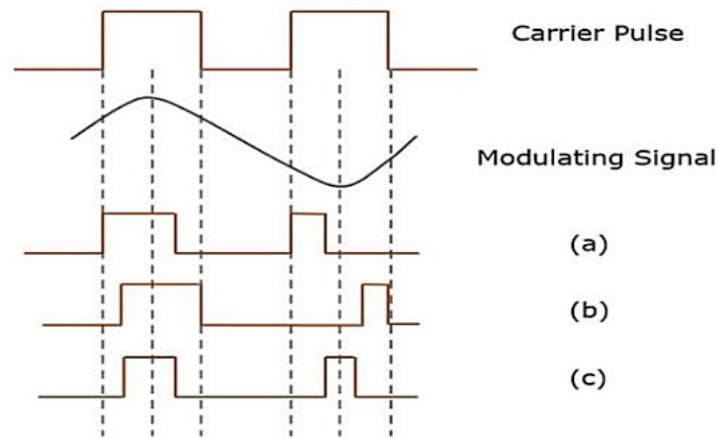


Figure 2.1 (a), (b), (c) Pulse Width Modulated Waves with different time slots

2.2.2 Sinusoidal Pulse Width Modulation (SPWM) Strategy

While standard PWM can control the average magnitude of the output voltage, driving an AC motor requires a specific modulation technique capable of synthesizing a continuous, low-frequency sinusoidal profile. The most prevalent technique utilized to achieve this in a voltage source inverter is Sinusoidal Pulse Width Modulation (SPWM).

The Intersection Method (Natural Sampling)

The fundamental principle of generating an SPWM signal relies on a continuous comparison between two distinct control signals within the digital domain of the microcontroller:

- 1. The Reference Signal (Modulating Wave):** A low-frequency sinusoidal wave that dictates the desired fundamental frequency (f_r) and the desired amplitude of the inverter's output.
- 2. The Carrier Signal:** A high-frequency triangular wave that dictates the switching frequency (f_c) of the inverter's power semiconductors.

By feeding both of these signals into a digital comparator, the exact switching instants are determined by their intersection points [23] [24].

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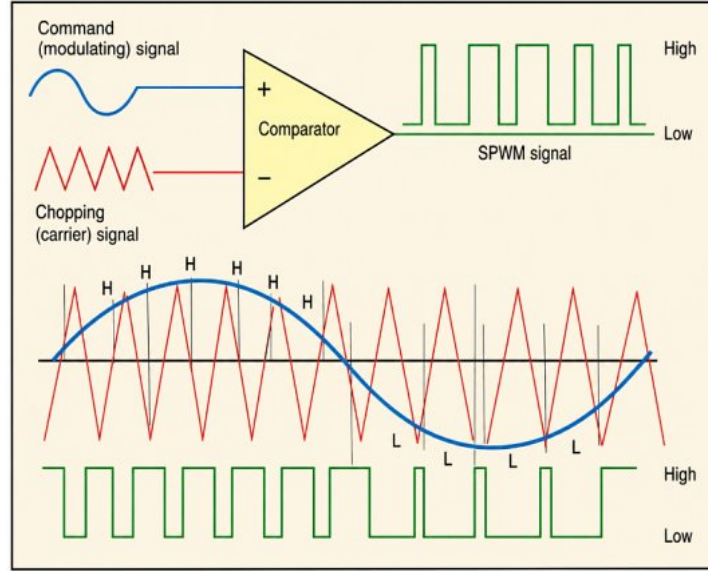


Figure 2.2 Sinusoidal Pulse Width Modulation (SPWM) Signal Generation Using a Comparator

Mathematical model of the SPWM Signals

To drive a three-phase bridge, three separate reference signals are required. These are pure sine waves, equal in magnitude but shifted in phase by 120 electrical degrees ($\frac{2\pi}{3} rad$). The mathematical expressions for the three modulating signals are defined as:

$$V_{ref,A}(t) = V_m \sin(\omega_r t)$$

$$V_{ref,B}(t) = V_m \sin\left(\omega_r t - \frac{2\pi}{3}\right)$$

$$V_{ref,C}(t) = V_m \sin\left(\omega_r t + \frac{2\pi}{3}\right)$$

Where:

V_m is the peak amplitude of the reference signal.

$\omega_r = 2\pi f_r$ is the angular frequency of the desired fundamental output.

These three reference signals are compared simultaneously against a single, common, high-frequency triangular carrier wave, $V_{\{tri\}}(t)$, which oscillates symmetrically between a peak amplitude of $+V_c$ and $-V_c$ [23] [24].

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2.2.3 Space Vector PWM (SVPWM)

Space Vector PWM (SVPWM) is an advanced inverter control method that represents output voltages as rotating vectors in the α - β plane and generates the desired signal by selecting and timing nearby switching states. Compared to sinusoidal PWM, it provides better DC-link utilization, lower harmonic distortion, reduced switching losses, and improved waveform quality.

In three-level NPC inverters, SVPWM uses the nearest three vectors to synthesize the reference voltage, helping balance the neutral point and improve power quality without extra hardware—making it especially useful in PV systems.

It is also widely used to reduce common-mode voltage (CMV), which helps lower leakage currents, EMI, and power losses in transformer-less PV setups. Modified versions like RCMV-SVPWM and VSVPWM further improve performance by minimizing or eliminating high-CMV switching states.

Overall, SVPWM is a highly efficient and flexible control strategy for modern multilevel inverters, especially in renewable energy applications [40] [41].

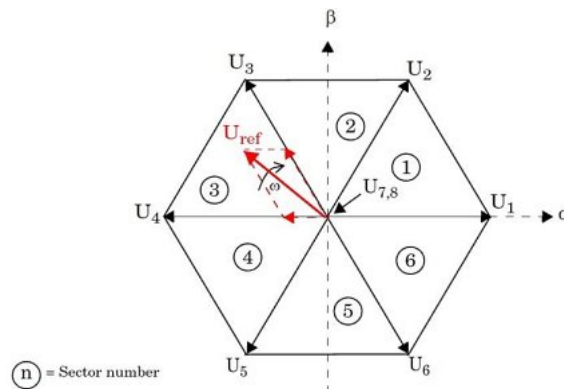


Figure 2.3 Hexagon of spatial vectors with basis vectors from U1 to U8[35].

2.2.4 Hysteresis Current Control

Hysteresis Current Control (HCC) is a simple and widely used technique for controlling voltage source inverters, ensuring that the output current closely follows a reference current. The method employs hysteresis comparators to regulate the inverter switching states based on current

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error. Its main advantages include fast dynamic response, robustness, and independence from load parameters. However, HCC suffers from a variable switching frequency, which can increase current ripple and complicate filter design. To overcome these limitations, adaptive hysteresis band algorithms have been developed, enabling improved current quality, reduced ripple, and effective grid synchronization with near-unity power factor [42] [43].

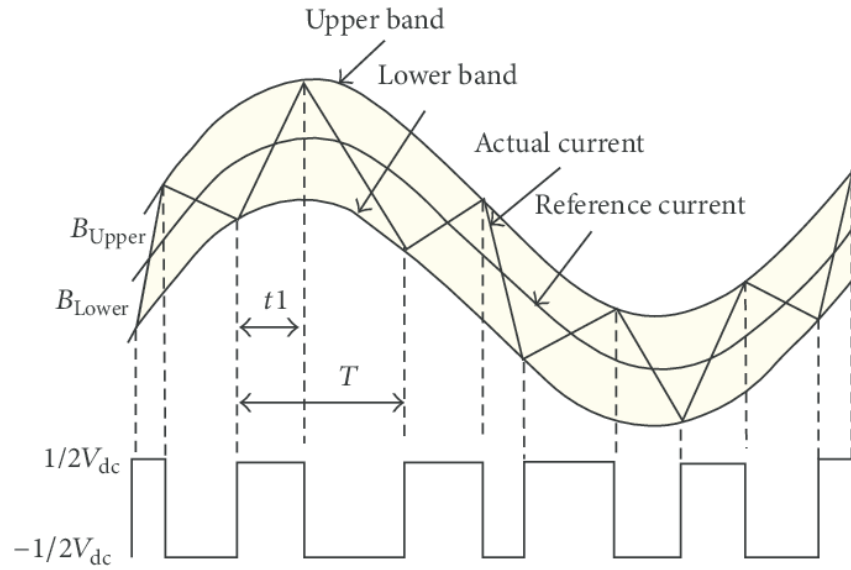


Figure 2.4 Diagram of hysteresis current control.

2.2.5 Voltage-Oriented Control (VOC) / Vector Control

Voltage-Oriented Control (VOC), also known as Vector Control, is a control strategy mainly used in grid-connected converters and AC motor drives to independently control active and reactive power. It works by transforming three-phase AC quantities into a rotating reference frame (dq-frame) aligned with the grid voltage. This simplifies AC variables into DC-like signals, making them easier to regulate using PI controllers.

In this framework:

- The d-axis controls active power (or DC-link voltage).
- The q-axis controls reactive power.

By decoupling these components, VOC achieves fast dynamic response, precise current control, and high efficiency. It is widely used in applications like renewable energy systems (PV, wind), motor drives, and active power filters [44] [45] [35].

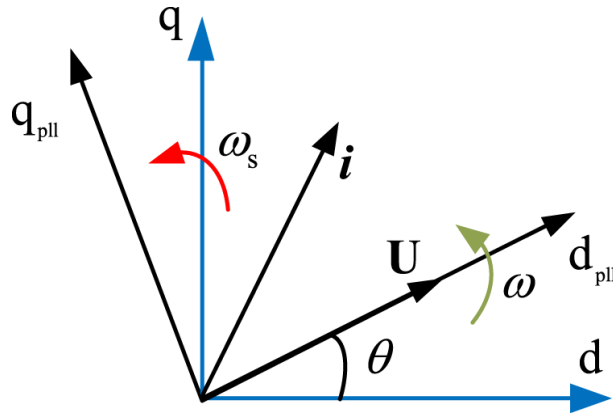


Figure 2.5 Voltage Oriented Control Strategy vectors

2.2.6 Direct Torque Control (DTC)

Direct Torque Control (DTC) can also be understood in the context of power inverters as a method for directly controlling the switching of a DC–AC converter without using a traditional PWM modulator. the inverter output (voltage and current) is used to estimate key variables such as output flux and power-related quantities. These estimated values are continuously compared with reference values. The errors are fed into hysteresis controllers, which decide whether the inverter output should increase or decrease the voltage vector magnitude. Based on this decision and a predefined switching table, the most suitable inverter switching state is selected and applied directly to convert the DC input into the desired AC output [35].

Instead of generating sinusoidal PWM signals, the inverter directly switches between discrete voltage vectors to shape the AC waveform from the DC source.

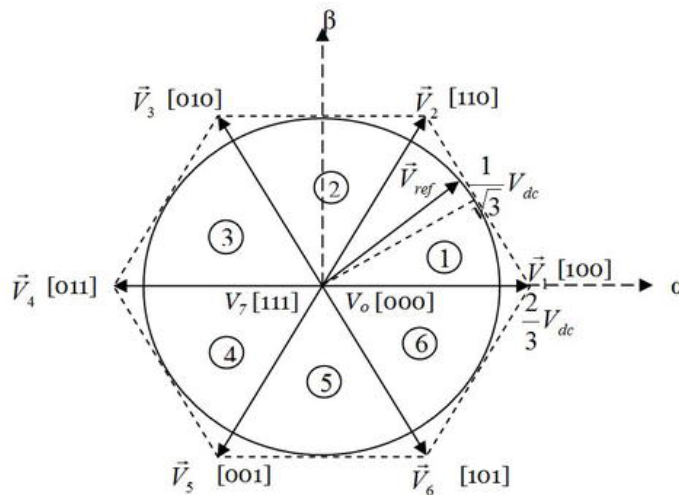


Figure 2.6 Direct Torque Control vectors

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2.2.7 Model Predictive Control (MPC)

MPC uses a mathematical model of the inverter and its output filter/load to predict how the output voltage and current will evolve for each possible switching state of the inverter. At each sampling instant, the controller evaluates all (or a selected set of) possible switching combinations and predicts their future behavior over a short time horizon. A cost function is then used to compare these predictions with the desired AC reference (typically sinusoidal voltage or current). The switching state that minimizes this cost function is selected and applied to the inverter. This process is repeated at every sampling step, meaning the inverter continuously “re-optimizes” its switching decisions to directly generate AC output from the DC source [39].

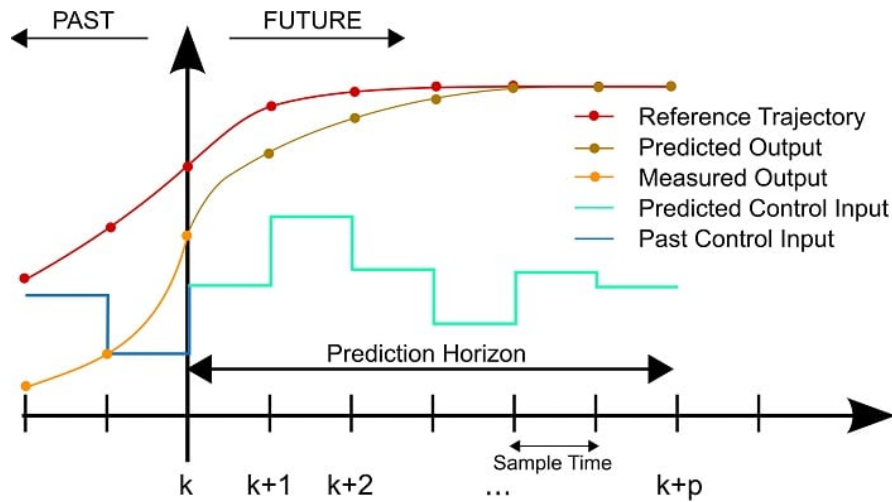


Figure 2.7 Model Predictive Control over time

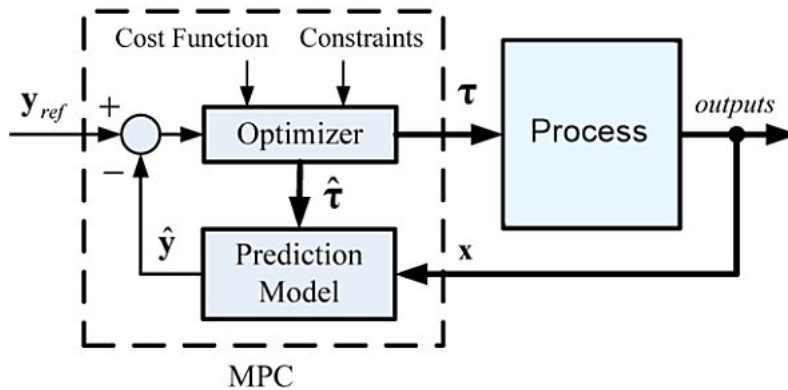


Figure 2.8 Model Predictive Control block

Chapter 2: Review of Inverter Control Strategies and Simulation of the Proposed Three-Phase Inverter

2.3 Mathematical Model of the Three-Phase Inverter

To accurately simulate and control the energy transfer from the DC source to the AC load, a precise mathematical model of the inverter's power stage must be established. This model defines the mathematical relationship between the discrete states of the power switches and the continuous voltages applied to the motor or load.

2.3.1 Inverter Topology

The standard three-phase Voltage Source Inverter (VSI) consists of three parallel branches (or legs), each corresponding to one output phase (A, B, and C). As illustrated in **Figure 2.9**, each leg contains two power semiconductor switches equipped with anti-parallel freewheeling diodes. The system is fed by a stiff DC voltage source, denoted as V_{DC} , and drives a three-phase star connected load.

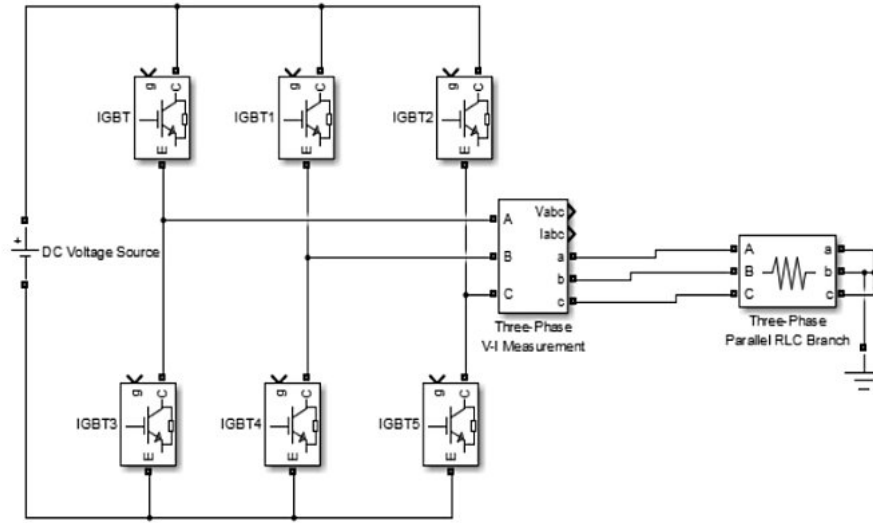


Figure 2.9 Block diagram of DC-AC power conversion

2.3.2 Switching States and Constraints

To prevent a catastrophic short-circuit across the DC-link (a shoot-through event), the upper and lower switches within the same leg must never conduct simultaneously. This strict complementary operation is modeled using a discrete switching function, S_i , for each phase

i (where $i = A, B, C$):

Chapter 2: Review of Inverter Control Strategies and Simulation of the Proposed Three-Phase Inverter

$$S_i = \begin{cases} 1, & \text{Upper switch is ON, Lower switch is OFF} \\ 0, & \text{Upper switch is OFF, Lower switch is ON} \end{cases}$$

With three independent legs having two possible states each, the inverter inherently possesses $2^3 = 8$ possible switching configurations. Two of these are "zero states" (where all three load phases are shorted to either the positive or negative DC bus, resulting in zero output voltage), while the remaining six are "active states" that synthesize the voltage vectors.

2.3.3 Output Voltage Equations

Using the discrete switching functions defined above, the line-to-line voltages V_{AB} , V_{BC} , V_{CA} can be expressed directly as a function of the DC-link voltage and the instantaneous switching states:

$$V_{AB} = V_{DC} (S_A - S_B)$$

$$V_{BC} = V_{DC} (S_B - S_C)$$

$$V_{CA} = V_{DC} (S_C - S_A)$$

For a balanced, star-connected three-phase load without a neutral return line, the phase-to-neutral voltages V_{AN} , V_{BN} , V_{CN} are mathematically derived by applying Kirchhoff's Voltage Law (KVL) and assuming the sum of the phase voltages is zero $V_{AN} + V_{BN} + V_{CN} = 0$. By substituting the line-to-line equations into this balanced condition, the phase voltages are formulated as the following fundamental matrix system:

$$\begin{bmatrix} V_{AN} \\ V_{BN} \\ V_{CN} \end{bmatrix} = \frac{V_{DC}}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} S_A \\ S_B \\ S_C \end{bmatrix}$$

This matrix represents the definitive mathematical model of the inverter's power stage. It demonstrates a critical principle of three-phase systems: the instantaneous phase voltage applied to any single leg depends not only on its own switching state but also simultaneously on the states of the other two legs. This mathematical relationship is responsible for generating the characteristic stepped phase-voltage waveform that was experimentally verified in Chapter 3.

2.4 Simulink Model

To verify the operation of the proposed three-phase voltage source inverter and validate the mathematical model developed in the previous sections, a simulation model was implemented

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using MATLAB/Simulink 2016b. The model consists of the DC voltage source, the three-phase inverter bridge, the SPWM generation block, and the load. The switching signals generated by the SPWM controller are applied to the inverter switches to produce the desired three-phase AC output voltages. Figure 2.10 illustrates the overall Simulink model used to analyze the inverter performance under different operating conditions before proceeding to hardware implementation.

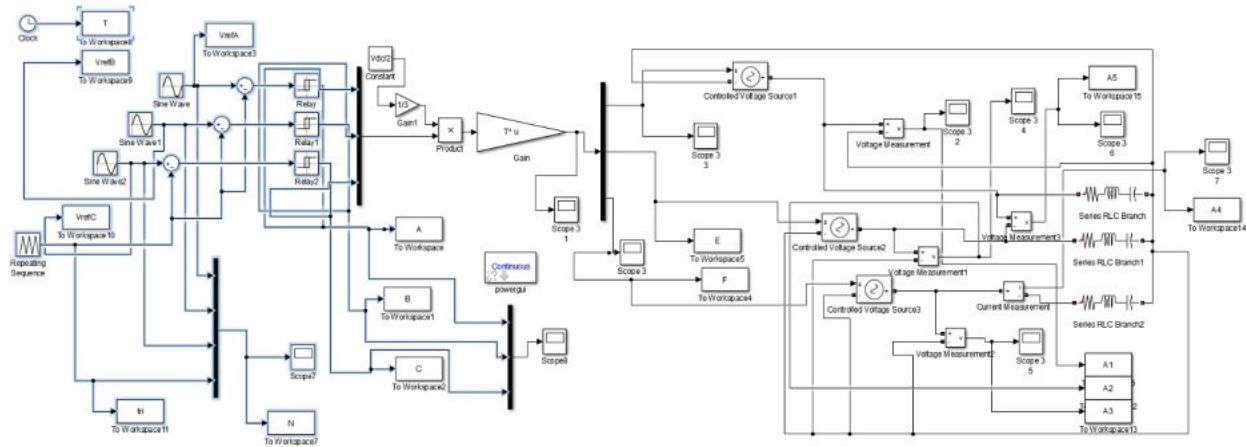


Figure 2.10 full system block diagram.

2.4.2 Digital Implementation and Simulation of SPWM

The SPWM control strategy was implemented in MATLAB/Simulink using the comparison method described in Section 2.2.2. As shown in Figure 2.11, three sinusoidal reference signals with identical amplitudes and frequencies, phase-shifted by 120° , are generated to represent the three phases of the inverter output. A high-frequency triangular carrier signal is produced using a Repeating Sequence block and is simultaneously compared with each reference signal.

The comparison process is performed using subtraction blocks followed by Relay blocks acting as digital comparators. Whenever the instantaneous value of a reference signal exceeds that of the carrier signal, the comparator output switches to a logic HIGH state; otherwise, it remains in a logic LOW state. This process generates the switching signals corresponding to the three inverter legs, which are subsequently used to control the power switches and synthesize the desired three-phase AC output voltage.

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Figure 2.11 illustrates the MATLAB/Simulink implementation of the SPWM signal generation process based on the comparison between sinusoidal reference signals and a triangular carrier wave.

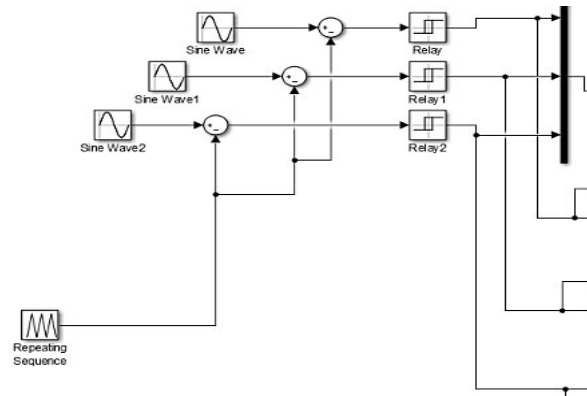


Figure 2.11 MATLAB/Simulink implementation of SPWM signal generation using sinusoidal reference signals and a triangular carrier wave.

2.4.3 Results and Discussion

After implementing the SPWM control strategy and integrating it with the three-phase inverter model, simulations were carried out to evaluate the system performance under different load conditions. The analysis begins with the verification of the generated control signals, including the sinusoidal reference waves, the triangular carrier signal, and the resulting SPWM switching signals. Subsequently, the output voltage and current waveforms of the inverter are examined for both resistive (R) and resistive-inductive (RL) loads. This analysis makes it possible to assess the effectiveness of the proposed control strategy and to evaluate the dynamic behavior of the inverter under different operating conditions.

Figure 2.12 illustrates the three sinusoidal reference signals, phase-shifted by 120° , together with the high-frequency triangular carrier wave used in the SPWM technique. The intersections between the reference signals and the carrier wave determine the switching instants of the inverter switches. Figure 2.13 presents the corresponding three-phase SPWM switching signals generated by the comparator-based implementation. The pulse widths vary according to the instantaneous values of the sinusoidal references, producing the characteristic SPWM pattern required for inverter operation. These results confirm the correct implementation of the SPWM algorithm and its suitability for generating balanced three-phase switching signals.

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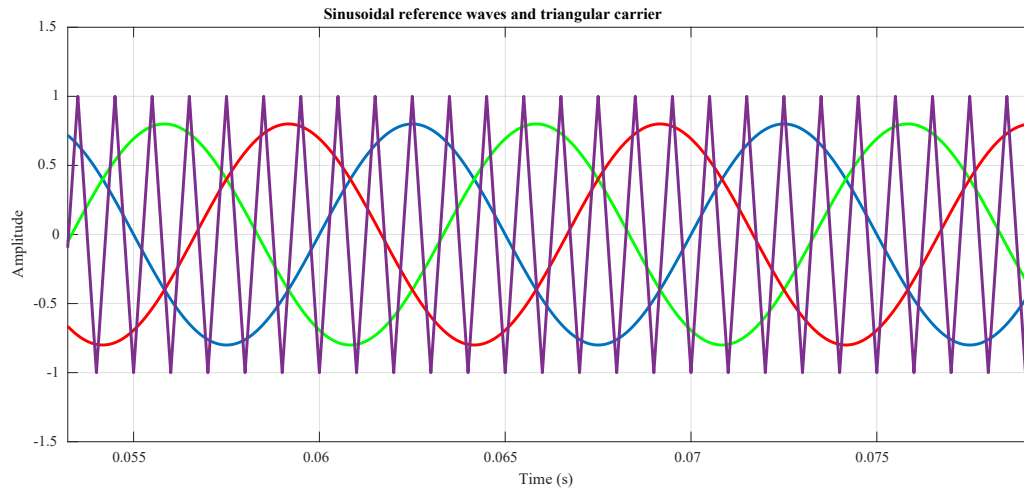


figure 2.12 Sinusoidal reference waves and triangular carrier wave intersection for three-phase SPWM.

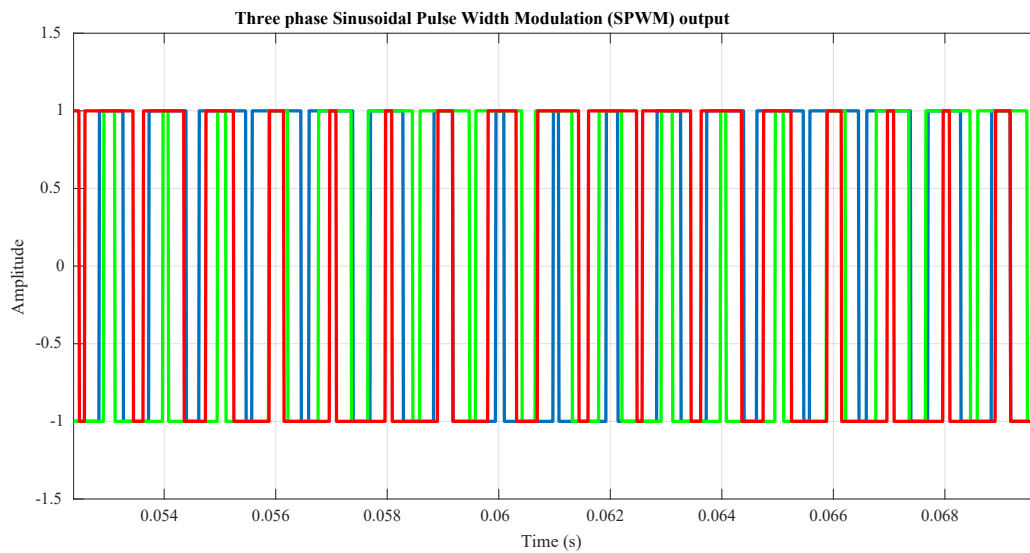


Figure 2.13 Three phase Sinusoidal Pulse Width Modulation (SPWM) output

2.4.3.1 Resistive Load (R)

To evaluate the performance of the proposed inverter under a purely resistive load, simulations were carried out using the SPWM control strategy. The obtained results include the three-phase output voltages, the phase voltage and current, and the line-to-line voltage and load current. These waveforms provide insight into the quality of the generated voltages and the behavior of the load current under resistive operating conditions.

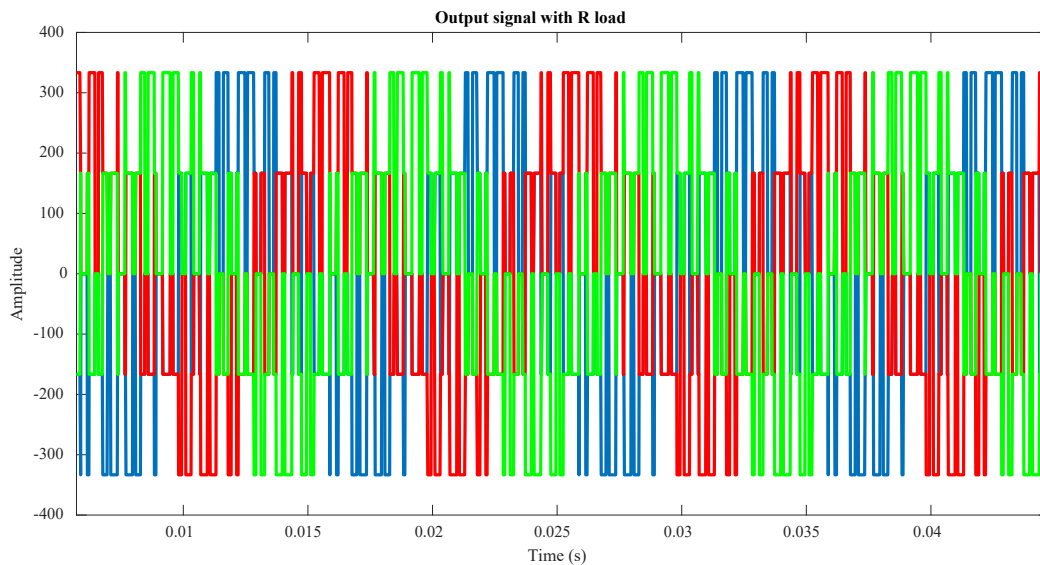


Figure 2.14. Three-Phase Output Voltages (V_{an} , V_{bn} , and V_{cn}) under Resistive Load

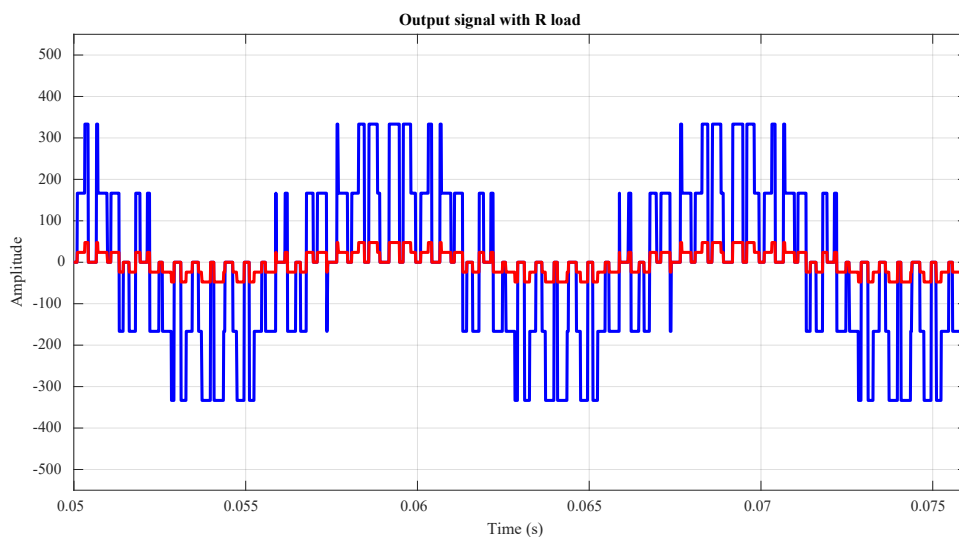


Figure 2.15. Phase Voltage (V_{an}) and Phase Current (I_n) under Resistive Load

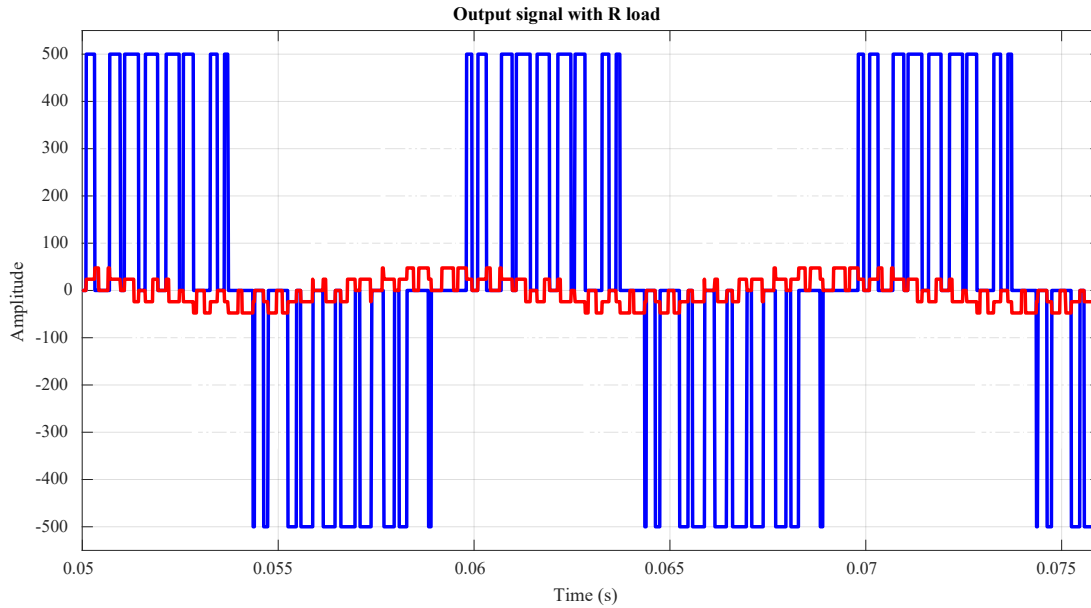


Figure 2.16. Line-to-Line Voltage (V_{ab}) and Load Current (I_n) under Resistive Load

The figure 2.14 shows the three phase-to-neutral voltages V_{an} , V_{bn} , and V_{cn} generated by the inverter. The three voltages are balanced and displaced by 120° from one another, confirming the correct operation of the three-phase SPWM modulation strategy. The stepped waveform pattern results from the switching action of the inverter, which alternately connects each phase to the positive and negative DC bus voltages. The symmetrical distribution of the voltage levels demonstrates the proper generation of balanced three-phase output voltages.

This figure 2.15 presents the phase voltage V_{an} together with the corresponding phase current I_n . Since the load is purely resistive, the current follows the applied voltage without any noticeable phase shift, indicating a unity power factor. The current waveform exhibits the same general shape as the voltage waveform because no inductive element is present to smooth the switching harmonics. Consequently, the current responds instantaneously to variations in the applied voltage.

The figure 2.16 illustrates the line-to-line voltage V_{ab} and the corresponding load current. The line-to-line voltage exhibits the characteristic SPWM waveform with voltage levels switching between positive and negative values according to the modulation pattern. The load current remains synchronized with the voltage waveform due to the purely resistive nature of the load. The variation

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of pulse widths throughout the fundamental cycle reflects the sinusoidal modulation process, where wider pulses appear near the voltage peaks and narrower pulses occur around the zero-crossing regions. These results confirm the effectiveness of the SPWM technique in generating balanced output voltages and currents for resistive load operation.

2.4.3.2 Resistive–Inductive Load (RL)

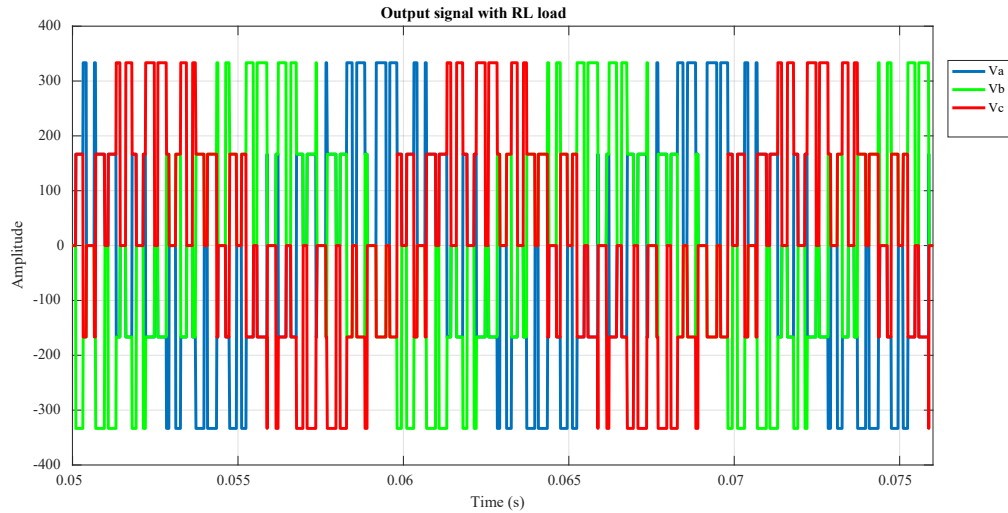


Figure 2.17. Three-Phase Output Voltages (V_{an} , V_{bn} , and V_{cn}) under resistive-inductive Load

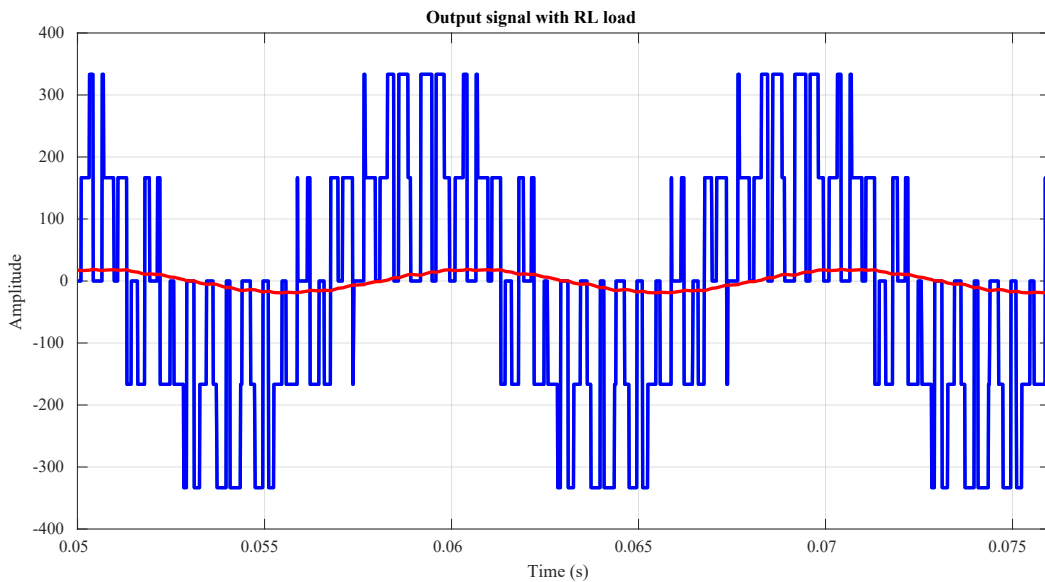


Figure 2.18. Phase Voltage (V_{an}) and Phase Current (I_n) under resistive-inductive Load

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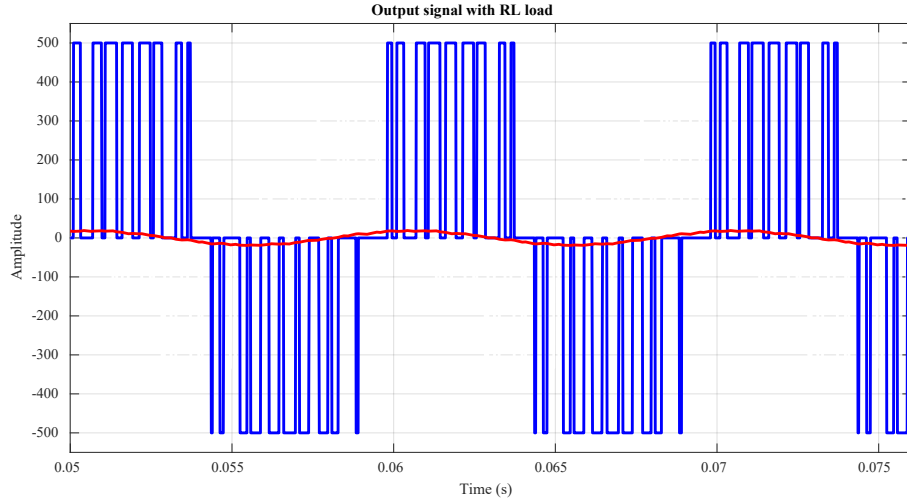


Figure 2.19. Line-to-Line Voltage (V_{ab}) and Load Current (I_n) under Resistive Load

Figure 2.17 presents the three phase-to-neutral voltages V_{an} , V_{bn} , and V_{cn} generated by the inverter when supplying a resistive-inductive (RL) load. The three voltages remain balanced and are phase-shifted by 120° , confirming the proper operation of the SPWM control strategy. Similar to the resistive-load case, the inverter produces stepped voltage waveforms as a result of the switching action of the power devices. The symmetrical distribution of the voltage levels and the periodic repetition of the switching pattern demonstrate the stability of the inverter and the correct generation of balanced three-phase output voltages.

Figure 2.18 shows the phase voltage V_{an} and the corresponding load current I_n for the RL load. Unlike the purely resistive case, the presence of inductance causes the current waveform to become smoother and introduces a phase shift with respect to the applied voltage. The inductive element stores and releases energy during each switching cycle, reducing the influence of high-frequency switching harmonics on the current waveform. Consequently, the current exhibits a more sinusoidal profile and improved waveform quality, which is characteristic of inductive loads supplied by PWM-controlled inverters.

Figure 2.19 illustrates the line-to-line voltage V_{ab} together with the corresponding load current I_n . The line-to-line voltage maintains the characteristic SPWM stepped waveform, alternating between positive and negative voltage levels according to the switching states of the inverter. In contrast, the load current appears significantly smoother due to the filtering effect of

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the inductance. A noticeable phase displacement exists between the voltage and current waveforms, indicating the reactive nature of the RL load. The reduction in current ripple and the more sinusoidal current shape demonstrate the ability of the inductive component to attenuate high-frequency harmonics and improve the overall output current quality of the inverter system.

2.5 Conclusion

This chapter began with a review of the most common control strategies used in Voltage Source Inverters (VSIs), including square-wave control, Sinusoidal Pulse Width Modulation (SPWM), Space Vector Pulse Width Modulation (SVPWM), and hysteresis current control. Their operating principles, advantages, limitations, and areas of application were discussed to establish a broad understanding of inverter control techniques and to justify the selection of SPWM for the proposed system.

Subsequently, a comprehensive theoretical and simulation framework for the three-phase Voltage Source Inverter (VSI) utilizing a Sinusoidal Pulse Width Modulation (SPWM) strategy was established. Beginning with the fundamental structural topology of the inverter bridge, the mathematical relationship between digital switching functions and physical output phase voltages was rigorously derived. This matrix transformation revealed the underlying five-level stepped voltage mechanism that defines phase-to-neutral outputs.

With the mathematical models and control logic thoroughly verified through digital simulation, the groundwork is fully prepared for physical realization. The following chapter will transition from theory to laboratory practice, detailing the hardware architecture, gate-driver protection circuit design, and experimental validation using the Texas Instruments LAUNCHXL-F28379D C2000 microcontroller platform.

Chapter 3

Hardware implementation and experimental validation

Chapter 3: Hardware implementation and experimental validation

3.1 Introduction

Transitioning from the theoretical models and mathematical control strategies established in the preceding chapters, this chapter focuses on the practical realization and hardware implementation of the three-phase inverter. The primary objective of this phase is to bridge the gap between idealized academic concepts and physical engineering, culminating in the hands-on fabrication, testing, and validation of a functional industrial prototype.

To achieve this, the chapter follows a rigorous engineering methodology centered around a professional-grade digital controller: the Texas Instruments C2000™ Delfino™ MCU LaunchPad (LAUNCHXL-F28379D). Chosen specifically for its industry-standard architecture in power electronics and motor drives, this dual-core microcontroller serves as the central intelligence of the inverter. We begin by establishing the overall system architecture, detailing how the C2000 is physically interfaced with high-power semiconductor switches, isolated gate drivers, and passive filtering elements to form a complete, robust power stage.

Subsequently, we explore the practical software implementation of the Sinusoidal Pulse Width Modulation (SPWM) algorithm. This section highlights the configuration of the microcontroller's Enhanced Pulse Width Modulator (ePWM) modules, placing a strong emphasis on the precise digital programming of the dead-band a critical hardware-level safety mechanism required to prevent catastrophic short-circuits across the inverter bridge. Before committing to the final physical hardware, a comprehensive schematic design and simulation phase is conducted to validate the integrity of the control logic and the expected output waveforms.

Finally, this chapter details the critical transition from verified schematics to a physical Printed Circuit Board (PCB). We will examine the specific design rules inherent to high-power electronics including trace width calculations for heavy currents, clearance and creepage distances for high voltages, and ground plane separation for mixed-signal integrity leading directly into the physical manufacturing and assembly processes required to build a reliable prototype.

3.2 System Architecture and Block Diagram:

The inverter consists of two essential sections: the control circuit and the power circuit. The control circuit features a gate drive circuit utilizing the bootstrap technique. Furthermore, an optical isolation circuit using an optocoupler has been integrated.

To better visualize the integration of these components and the overall signal flow from the digital controller, through the opto-isolation and gate drive stages, and finally to the power bridge the complete system architecture is illustrated in the block diagram below:

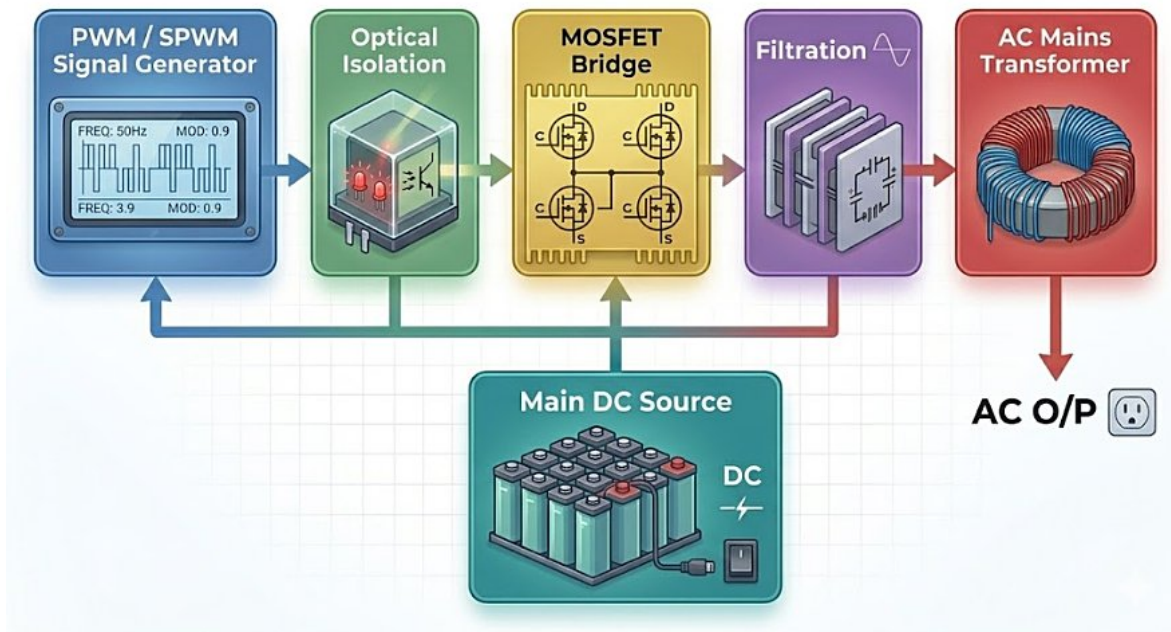


Figure 3.1: the general block diagram of an inverter

Because this prototype is designed for a simplified, purely open-loop operation meaning there is no active feedback from the motor load to adjust the control signals the flow of both energy and data is strictly unidirectional. The overall architecture is structured as follows:

1. **Digital Control Core:** At the heart of the system is the Texas Instruments C2000™ Delfino™ MCU (LAUNCHXL-F28379D). This microcontroller is responsible for generating the high-frequency Sinusoidal Pulse Width Modulation (SPWM) signals. Crucially, even in an open-loop configuration, the microcontroller enforces a strict "dead-

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band" delay between complementary signals to prevent short-circuits across the power bridge.

2. **Galvanic Isolation:** The 3.3V logic signals from the C2000 cannot directly interface with the high-voltage power stage. Therefore, high-speed optocouplers are utilized to transmit the SPWM signals across a secure optical barrier, protecting the microcontroller from high-voltage transients.
3. **Gate Drive Circuitry:** Once isolated, the signals enter the gate drivers. Utilizing a bootstrap capacitor technique, these drivers amplify the logic signals to the necessary voltage and current levels required to rapidly charge and discharge the gate capacitance of the high-power semiconductor switches.
4. **Three-Phase Power Bridge:** This stage consists of six high-power switches (MOSFETs or IGBTs) arranged in a standard three-phase bridge topology. It receives a stiff DC-link voltage (supplied from a rectified grid or external DC source) and chops it according to the SPWM signals.
5. **Output Filtering and Load:** Finally, the chopped rectangular voltage pulses are passed through a three-phase LC or LCL passive filter. This filter attenuates the high-frequency switching harmonics, delivering a smooth, continuous, and symmetrical three-phase AC waveform to the asynchronous motor load.

3.3 Component Selection and Datasheet Analysis

3.3.1 Microcontroller Selection (F2800x C2000): Processing capabilities and hardware timer utilization

3.3.1.1 LAUNCHXL-F28379D overview

The Texas Instruments C2000 platform, exemplified by development boards such as the LAUNCHXL-F28379D, is a class of real-time microcontrollers (MCUs) fundamentally designed for the rigorous demands of power electronics. Originating in 1997 with the integration of flash memory, ADCs, DSPs, and PWM modules into a unified architecture, the C2000 family has evolved to drive critical industrial and automotive systems. Its core defining characteristic is its capacity for absolute real-time control, providing the requisite performance, efficiency, flexibility, and protection vital for developing high-fidelity applications like electric vehicle drivetrains, renewable energy systems, and high-power inverters [11].

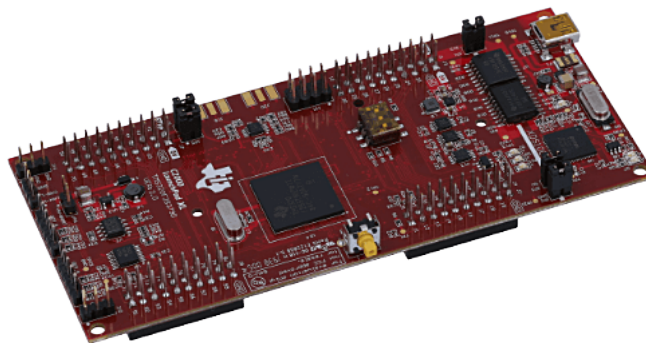


Figure 3.2: LAUNCHXL-F28379D [11].

Common C2000 Real-Time Control Applications

1. HEV/EV, Body & Lighting

This category covers applications related to hybrid and electric vehicles (HEV/EV) as well as general automotive body and lighting systems:

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- Power Conversion: On-board chargers and DC-DC converters.
- Drivetrain: Traction inverters.
- Automotive Motors: Small automated motors used for pumps, blowers, and fans.
- Climate Control: HVAC systems, including eCompressors and heaters.
- Illumination: Intelligent lighting systems for headlights and rear lights.
- Auxiliary Power: DC/AC auxiliary inverters. [11]

2. Motor Drives

This section highlights the C2000's role in various motor control and robotics applications:

- Drive Systems: Control for AC, servo, BLDC (Brushless DC), linear, and stepper motor drives.
- Robotics: Industrial, collaborative, mobile, and service robots.
- Consumer/Commercial Equipment: Major home appliances, air conditioners, garden tools, and power tools. [11]

3. Grid and Power Delivery

This category focuses on high-power energy generation, storage, and infrastructure:

- Renewable Energy: Solar energy inverters and power management.
- Energy Storage: Battery management and energy storage systems (ESS).
- EV Infrastructure: Electric vehicle charging stations.
- Telecommunications: Telecom rectifiers.
- Enterprise Power: Network and server Power Supply Units (PSU).
- Backup Power: Uninterruptible Power Supplies (UPS). [11]

3.3.1.2 C2000™ Real-Time MCU Series: System Components Overview

Highly Accurate Sensing

- **ADCs:** 12-bit and 16-bit analog-to-digital converters supporting up to 24 channels.
- **Comparators:** Full analog comparators integrated with built-in Digital-to-Analog Converters (DACs).
- **Positioning:** Integrated Quadrature Encoder and Capture Logic.

High Performance Processing

- **Core Architecture:** Floating-point DSP C28x™ core featuring a parallel multi-core architecture.
- **Performance:** Instruction set specifically optimized for control math, delivering up to 925 MIPS.

Highly Flexible, High-Resolution Control

- **PWM Outputs:** Up to 32 high-resolution Pulse Width Modulation (PWM) outputs.
- **Timing:** PWMs are tightly coupled with the sensing domain to ensure fast response times.
- **DACs:** Includes buffered output DACs.

Integrated Communications Interface

- **Standard Protocols:** CAN, CAN-FD, LIN, UART, SPI, I2C, PMBus, and USB.
- **Industrial Networking:** 10/100 Ethernet MAC, EtherCAT®, and XEMIF.

Leading Innovation Subsystems

- **CLB:** Configurable Logic Block for advanced peripheral customization.
- **FSI:** Fast Serial Interface optimized for high-speed communication.
- **ERAD:** Embedded Real-time Analysis and Diagnostics for enhanced system profiling and fault diagnostics. [11]

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Functional Safety & Reliability

- **Compliance:** Fully Functional Safety Compliant, supporting all Safety Integrity levels for both Automotive and Industrial applications.
- **Support ecosystem:** Includes built-in hardware features for safety, dedicated software libraries, device drivers, and comprehensive safety certification documentation.
- **Heritage:** Built upon 25 years of expertise in real-time control systems, with extensive software libraries and reference designs available.

General Device Specifications

- **Voltage:** 1.2-V core, 3.3-V I/O design.
- **Memory:** Up to 1.5 MB Flash memory and 256 KB RAM (ECC protected).
- **Packaging:** Available in QFN, QFP, and BGA packages.
- **Temperature Range:** Rated for -40°C to 125°C operation. [11]

3.3.2 HCPL2530 Dual-Channel Optocoupler:

3.3.2.1 Component overview

The HCPL2530 is a popular dual-channel high-speed phototransistor optocoupler. As an optocoupler, its primary function is to provide electrical isolation between input and output circuits. It uses an infrared LED for each channel to optically couple an input signal to a phototransistor output [14].

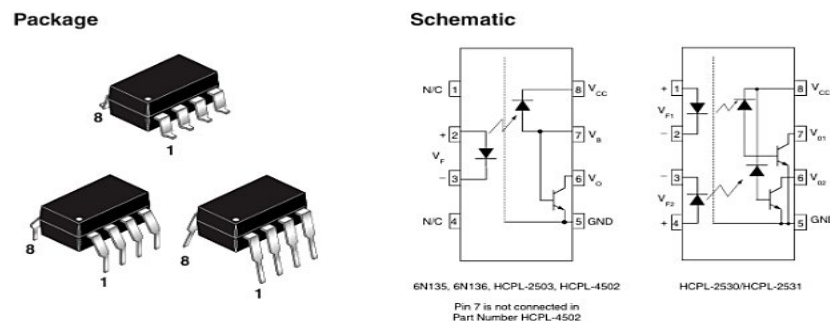


Figure 3.3: HCPL2530 Dual-Channel Optocoupler [14].

3.3.2.2 Key Datasheet Highlights

- **Data Rate:** up to 1 Mbit/s
- **Channels:** Dual-channel optocoupler
- **Common Mode Rejection (CMR):** 10 kV/ μ s
- **Isolation Voltage:** 2500 VRMS
- **Working Voltage:** 480 VRMS
- **Supply Voltage:** up to 30 V
- **Operating Temperature:** -55°C to +100°C [14]

3.3.2.3 Important Electrical Characteristics

- **Forward LED voltage:** typically, 1.45 V at 16 mA
- **Current Transfer Ratio (CTR):** typically, 18% for HCPL-2530
- **Logic low output voltage:** about 0.18 V typical
- **Propagation delay:** around 0.45 μ s typical [14]

3.3.3 Power Switches (MOSFET IRFP250N):

3.3.3.1 Component overview

The selected switching element for the power stage of the inverter is the IRFP250N, a fifth-generation N-channel HEXFET® Power MOSFET originally developed by International Rectifier. This specific semiconductor was chosen for its advanced processing capabilities, which achieve an exceptionally low on-resistance per unit of silicon area. When combined with its inherent high-speed switching characteristics and ruggedized device design, the IRFP250N provides an efficient and reliable solution for the demanding switching requirements of three-phase power circuitry. Furthermore, its heavy-duty TO-247AC package is highly suited for commercial-industrial applications where elevated operating power levels preclude the use of standard TO-220 devices, offering an isolated mounting hole for superior thermal and structural management [12].



Figure 3.4: The IRFP250N Power MOSFET [12].

3.3.3.2 Primary Characteristics

- **Drain-to-Source Breakdown Voltage (V_{DSS}):** 200 V
- **Static Drain-to-Source On-Resistance ($R_{DS(on)}$):** 0.075 Ω (measured at $V_{GS} = 10$ V, $I_D = 18$ A)
- **Continuous Drain Current (I_D):** 30 A (at $T_C = 25$ °C) / 21 A (at $T_C = 100$ °C)
- **Gate Threshold Voltage ($V_{GS(th)}$):** 2.0 V (Min) to 4.0 V (Max) [12]

3.3.3.3 Absolute Maximum Ratings

- **Pulsed Drain Current (I_{DM}):** 120 A
- **Maximum Power Dissipation (P_D):** 214 W (at $T_C = 25$ °C)
- **Linear Derating Factor:** 1.4 W/°C
- **Gate-to-Source Voltage (V_{GS}):** ± 20 V
- **Single Pulse Avalanche Energy (E_{AS}):** 315 mJ
- **Avalanche Current (I_{AR}):** 30 A
- **Operating Junction and Storage Temperature Range (T_J, T_{STG}):** -55 °C to 175 °C [12]

3.3.4 Gate Driver ICs IR2104:

3.3.4.1 Component overview

The IR2104 is a high-voltage, high-speed power MOSFET and IGBT driver featuring de-pendent high- and low-side referenced output channels. Utilizing proprietary HVIC (High Voltage Integrated Circuit) and latch-immune CMOS technologies, the device provides a ruggedized monolithic construction ideal for harsh industrial environments.

In the context of the three-phase inverter power stage, the IR2104 serves as a critical intermediary. It is designed to take low-voltage logic inputs compatible with standard 3.3 V, 5 V, and 15 V CMOS or LSTTL outputs (such as those generated by the primary real-time microcontroller) and effectively drive N-channel power MOSFETs in a high-side configuration operating at up to 600 V. The output drivers feature a high-pulse-current buffer stage specifically engineered to minimize driver cross-conduction. Further-more, the IC incorporates internal deadtime and cross-conduction prevention logic, which are paramount for safeguarding the inverter bridge against shoot-through short circuits [13].

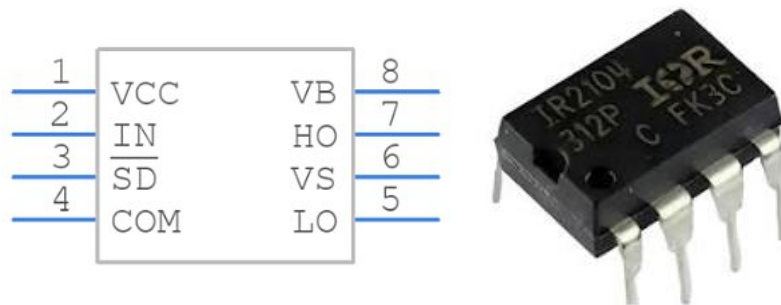


Figure 3.5: The IR2104 high-speed gate driver [13].

3.3.4.2 Primary Characteristics

- High Side Floating Supply Offset Voltage (VOFFSET): Up to 600 V max.
- Gate Drive Output Voltage Range (VOUT): 10 V to 20 V
- Output Short Circuit Pulsed Current (I_{o+}/I_{o-}): 130 mA (source) / 270 mA (sink)
- Undervoltage Lockout (UVLO): Integrated on VCC supply.
- Dynamic Switching Characteristics

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- Turn-on Propagation Delay (t_{on}): 680 ns (typical)
- Turn-off Propagation Delay (t_{off}): 150 ns (typical)
- Internal Deadtime (DT): 520 ns (typical)
- Delay Matching (MT): 60 ns maximum discrepancy between high and low side channel [13].

3.4 Prototype development and laboratory validation

The transition from theoretical design and software simulation to physical hardware is arguably the most critical phase of any power electronics project. While mathematical models and simulations provide a pristine environment free of parasitic elements, real-world implementation introduces a multitude of physical challenges, ranging from trace inductance and signal noise to thermal management and grounding issues.

3.4.1 Schematic Capture and Component Integration

Before manipulating physical wires, the entire system architecture had to be rigorously defined within our electronic design automation (EDA) software. The schematic serves as the definitive blueprint for the inverter, mapping the logical flow of signals from the digital domain of the MCU to the high-power analog domain of the load.

Our primary focus during the schematic design was ensuring robust isolation and signal integrity. The F28379D microcontroller operates on a strictly 3.3 V logic level, which is highly susceptible to the electromagnetic interference (EMI) generated by the switching of the power stage. Therefore, the schematic explicitly details the connections between the Enhanced Pulse Width Modulator (ePWM) pins of the C2000 LaunchPad and the logic inputs of the HCPL2530.

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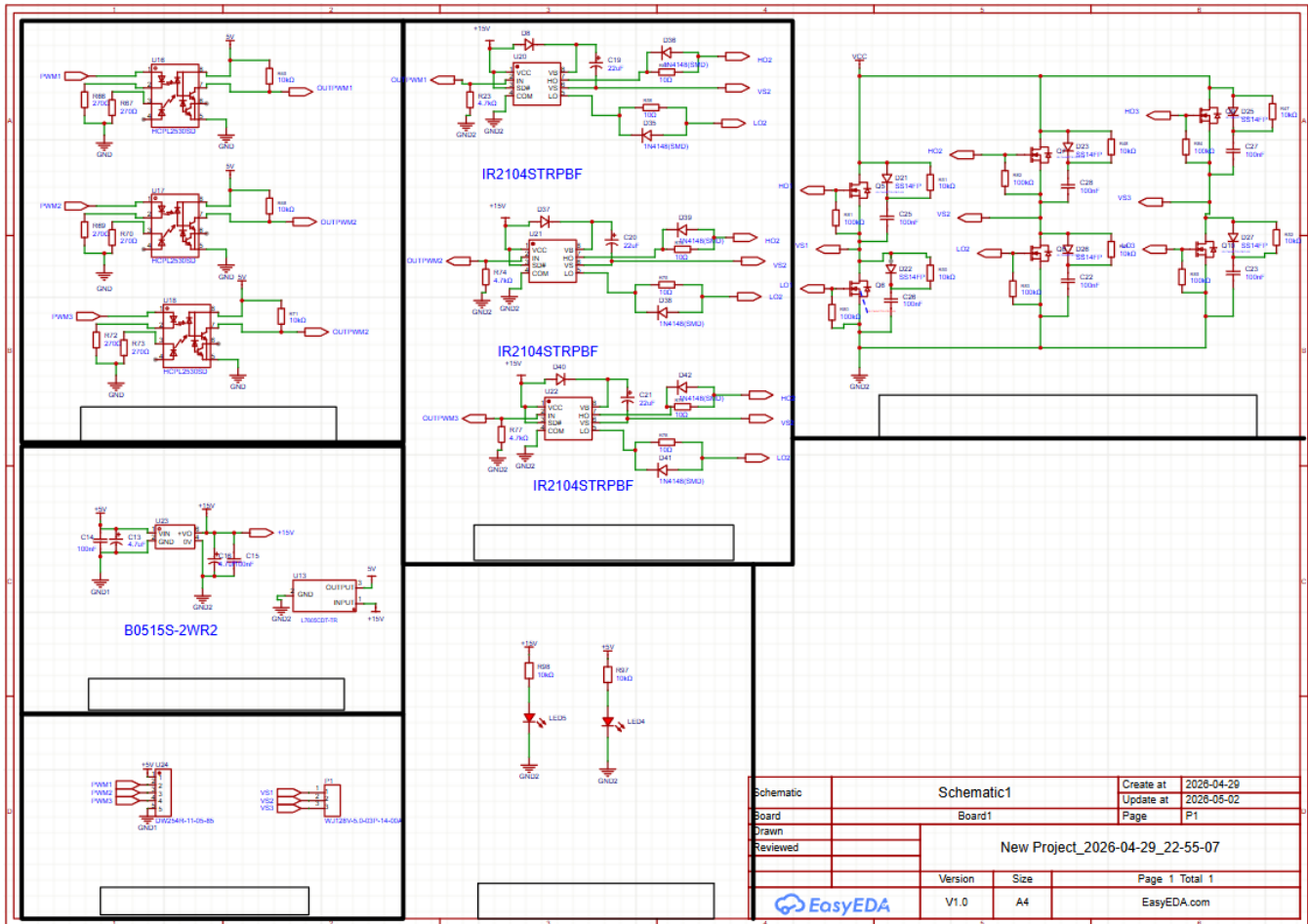


Figure 3.6: Overall system schematic.

Special attention was given to the bootstrap circuitry in the schematic. To drive the high-side IRFP250N MOSFETs, the IR2104 requires a floating power supply. We carefully calculated the required bootstrap capacitor values to ensure they could hold sufficient charge to keep the high-side gate fully enhanced during the longest anticipated duty cycle, while also selecting fast-recovery diodes to prevent reverse leakage during the switching transitions.

3.4.2 Breadboard Prototyping: The Proof of Concept

With the schematic finalized, we moved to the first physical iteration of the project: the breadboard prototype. While breadboards are inherently unsuitable for final high-power, high-frequency circuits due to high parasitic capacitance and contact resistance, they are an invaluable tool for preliminary logic verification and low-voltage integration testing.

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3.4.2.1 Wiring and Setup

The breadboarding phase was a meticulous process of translating the schematic into a web of jumper wires. We began by establishing the low-voltage control plane. The IR2104 gate drivers were seated across the breadboard trench, and we routed the SPWM signals from the Texas Instruments LAUNCHXL-F28379D to the respective IN and SD (Shutdown) pins.

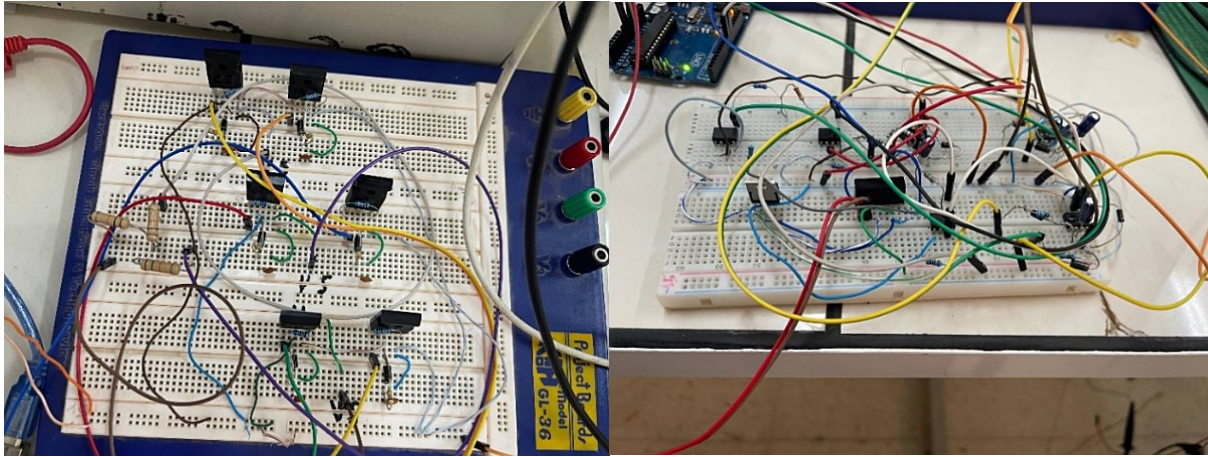


Figure 3.7: Photograph of the initial breadboard prototype.

To mitigate the risk of catastrophic failure during this early stage, we did not immediately apply the full DC link voltage. Instead, we utilized a current-limited benchtop power supply set to 12 V for both the control logic (stepped down to 5 V/3.3 V where necessary) and the primary DC bus.

3.4.2.2 Challenges Encountered on the Breadboard

Testing on the breadboard immediately revealed the physical realities of power electronics. One of our first major hurdles was signal ringing. When observing the gate drive signals on the oscilloscope, we noticed significant high-frequency oscillations (ringing) on the rising and falling edges of the PWM pulses.

This ringing was a direct consequence of the stray inductance introduced by the long jumper wires connecting the gate drivers to the MOSFET gates. If left unchecked, this ringing could exceed the maximum gate-to-source voltage (VGS) rating of the IRLZ44N, or cause unintended false turn-ons (shoot-through) due to the Miller effect. To counteract this on the breadboard, we had to keep

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our gate wires as short as physically possible and introduce small gate resistors to dampen the resonant circuit formed by the wire inductance and the MOSFET's input capacitance.

Furthermore, we had to be extremely cautious with the grounding scheme. The breadboard's internal rails are not designed for heavy currents. We quickly realized that mixing the noisy power ground return with the sensitive logic ground of the C2000 MCU caused erratic behavior. We resolved this by establishing a strict star-grounding point, separating the logic and power return paths as much as the breadboard would allow.

3.4.3 Printed Circuit Board (PCB) Design and Routing

Having validated the circuit design and control logic on the breadboard, it was imperative to move to a permanent, reliable hardware platform. The PCB represents the final, professional manifestation of the inverter, resolving the parasitic inductance and thermal limitations inherent to breadboarding.

3.4.3.1 Layout Strategy and Trace Routing

The transition from schematic to PCB layout required careful spatial planning. Our primary goal was minimizing the loop area of the high di/dt paths specifically, the loop formed by the DC link capacitor, the high-side MOSFET, and the low-side MOSFET. By keeping these components tightly packed, we drastically reduced the stray inductance, thereby mitigating voltage spikes during switching and minimizing EMI emissions.

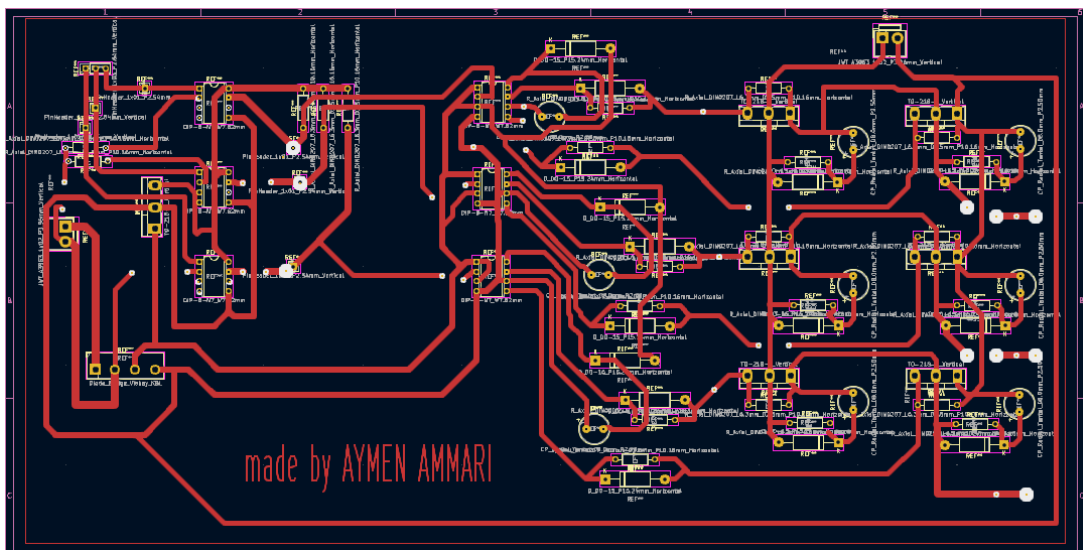


Figure 3.8: Printed Circuit Board Design

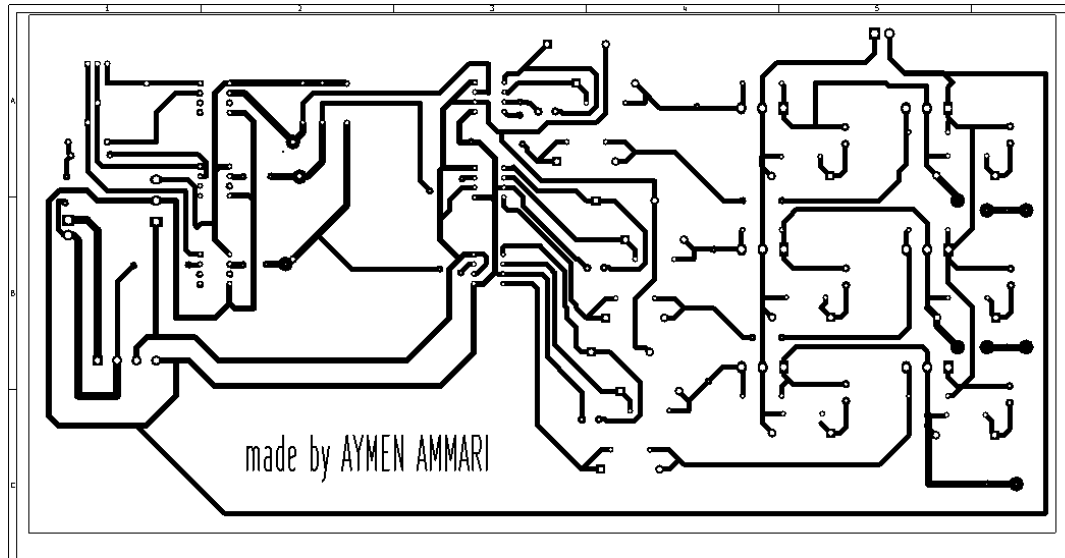


Figure 3.9: Printed Circuit Board routing layout.

As seen in the routing diagram (**Figure 3.9**), we employed a deliberate segregation strategy. The sensitive low-voltage components, including the headers for the TI Launch-Pad, are physically isolated from the high-power switching nodes.

For the power traces carrying the maximum continuous drain current to the IRLZ44N MOSFETs, standard signal trace widths are insufficient. We utilized heavily widened traces and polygon pours for the DC bus (+V and GND) and the phase outputs to ensure they could handle the thermal stress of high currents without excessive voltage drop or heating.

3.4.3.2 Final 3D Visualization and Assembly

Before committing to the physical manufacturing of the board, we utilized the 3D visualization tools within our EDA software to perform a final mechanical clearance check.

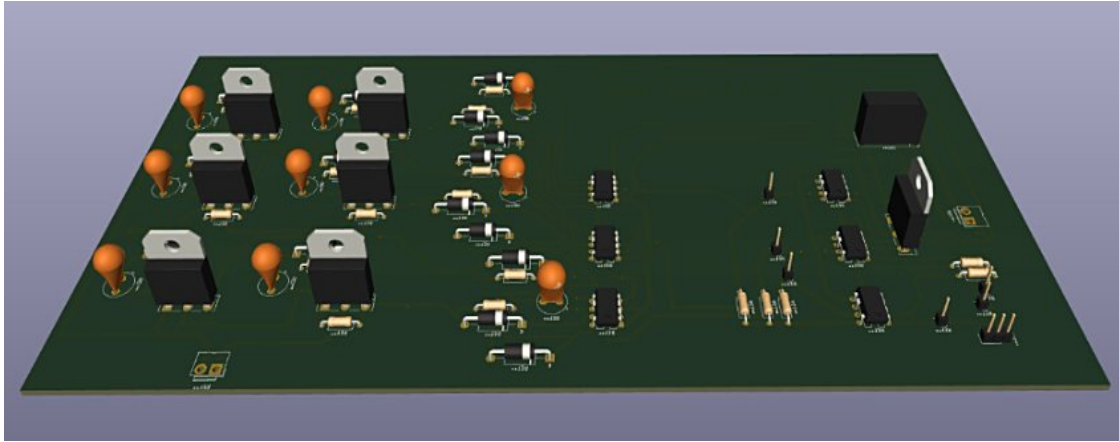


Figure 3.10: 3D rendering of the final PCB assembly.

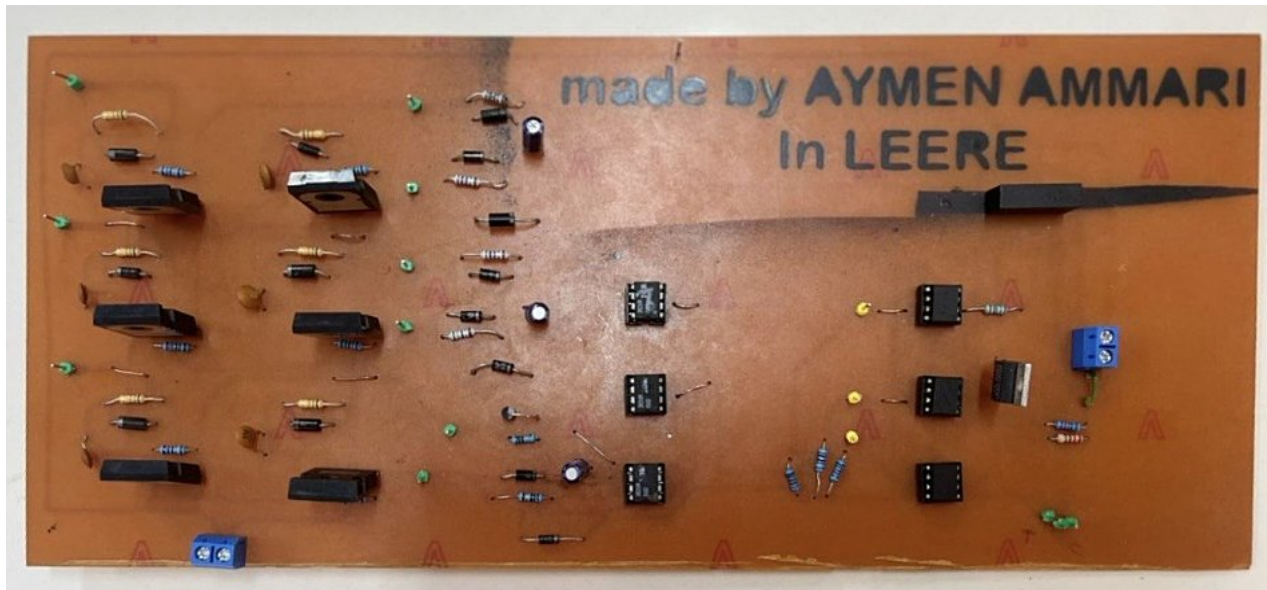


Figure 3.11: Isolated photograph of the complete hardware board

Figure 3.11 provides a comprehensive view of the finalized board layout. The TO-220 packages of the IRFP250N MOSFETs are aligned at the edge of the board to facilitate the attachment of a unified aluminum heatsink, which is critical for dissipating the 110 W maximum power dissipation capacity of the devices during continuous operation. The gate drivers and their associated bootstrap capacitors are located as close to the MOSFET gates as possible, ensuring crisp, uncorrupted switching signals.

3.4.4 Experimental Results and discussion

Chapter 3: Hardware implementation and experimental validation

Once the breadboard circuit was stabilized and the grounding issues were addressed, we initiated the open-loop SPWM control sequence from the microcontroller. The primary objective at this stage was to visually confirm that the physical output matched our theoretical MATLAB/Simulink models.

3.4.4.1 Validation of SPWM Control and Gate Drive Signals

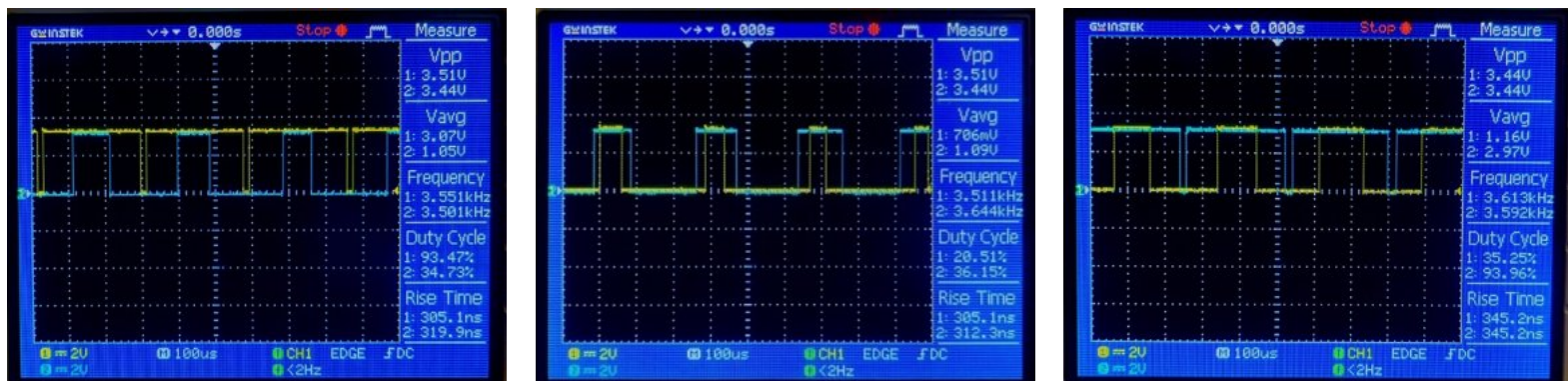
Before energizing the power stage with high voltage, the low-voltage control and driving circuits must be experimentally validated to ensure system safety. This section verifies the SPWM signals generated by the C2000 LaunchPad. First, we analyze the 3.3V SPWM outputs to confirm the correct complementary switching and accurate dead-band execution. Subsequently, we evaluate the signal integrity through the opto-isolators and verify that the bootstrap gate drivers successfully amplify these signals to the required gate-to-source voltage (V_{GS}) for efficient and safe semiconductor switching.

3.4.4.1.1 Microcontroller ePWM Output (SPWM Synthesis)

The initial validation focuses on the logic-level signals generated by the Texas Instruments C2000 LaunchPad. **Figure 3.12** displays the Sinusoidal Pulse Width Modulation (SPWM) signals (ePWM1A) utilized to control the inverter bridge. Unlike a standard square wave, the oscillogram confirms that the duty cycle of the 3.3V pulses is constantly varying, proving the successful algorithmic synthesis of the sinusoidal reference at a switching frequency of **20 kHz**.



Figure 3.12: the Sinusoidal Pulse Width Modulation signals



3.4.4.1.2 Opto-Isolation Signal Integrity

Following the generation stage, the 3.3V logic signals pass through the optical isolation barrier. **Figure 3.13** illustrates the SPWM signal measured immediately after the optocoupler. Because SPWM generates extremely narrow pulses near the zero-crossings of the fundamental sine wave, it is vital that the isolator does not filter them out. The captured waveform demonstrates that the isolation stage successfully transmits even the narrowest high-frequency PWM pulses without significant distortion. The propagation delay is minimal (measured at approximately **150 ns**), ensuring the precise timing of the SPWM profile is preserved.

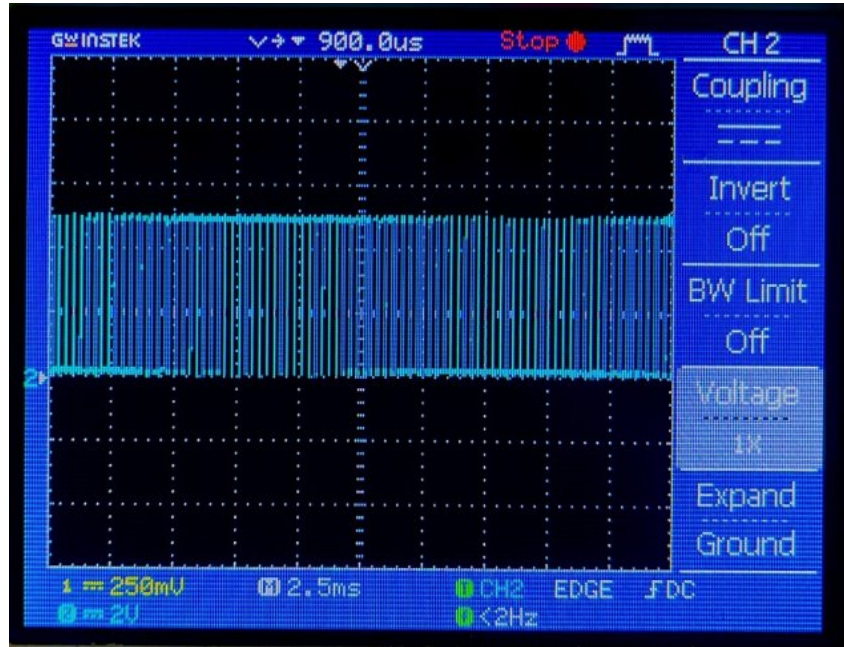
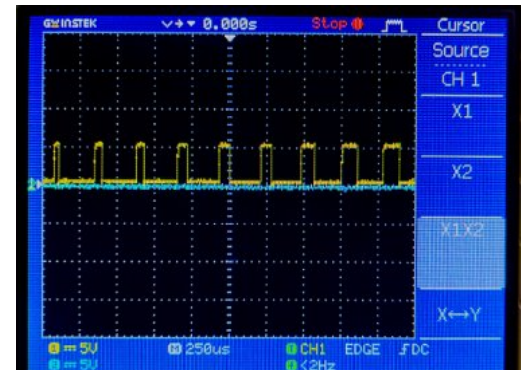
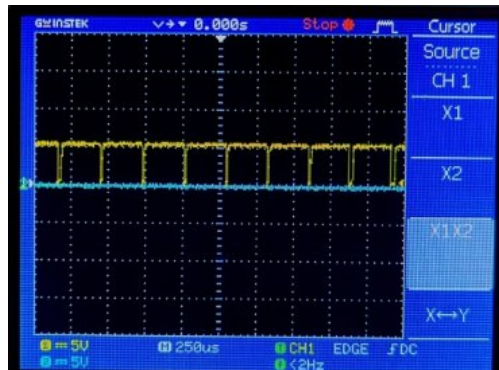
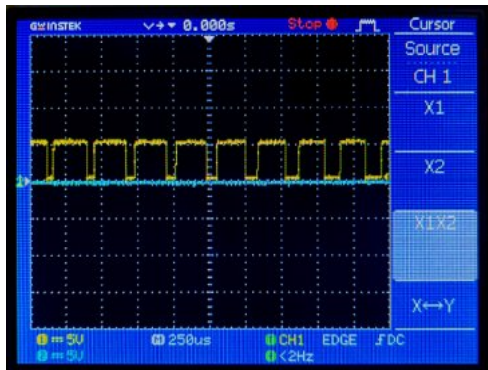


Figure 3.13: the SPWM signal measured after the optocoupler



Zoom in

3.4.4.1.3 Bootstrap Gate Driver Voltage (VGS)

The next validation involves the gate-to-source voltages V_{GS} applied to the power switches. **Figure 3.14** presents the output of the isolated gate drivers. The low-side V_{GS} signal clearly reaches the nominal driving voltage of +15V, ensuring the switch is fully driven into saturation. Furthermore, the measurement of the high-side V_{GS} confirms the proper operation of the bootstrap circuit under SPWM conditions. The oscillogram shows that the bootstrap capacitor successfully maintains the floating supply voltage without dangerous voltage droop, even during

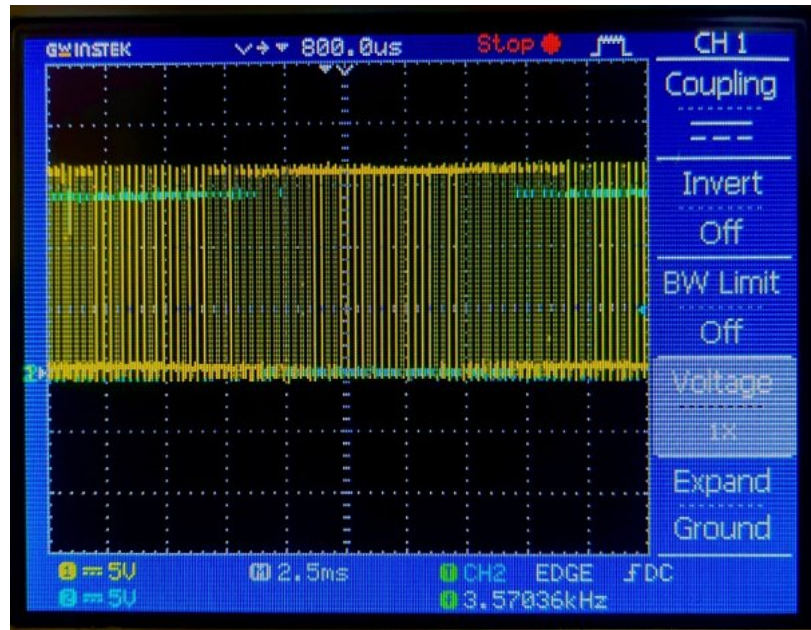
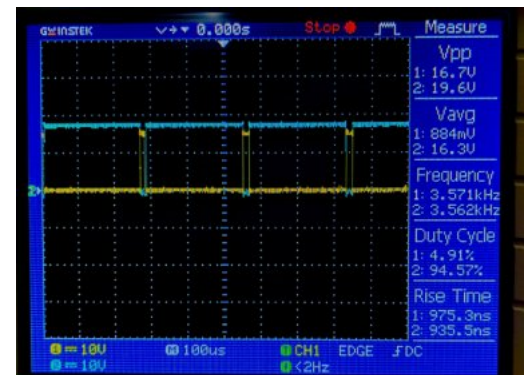
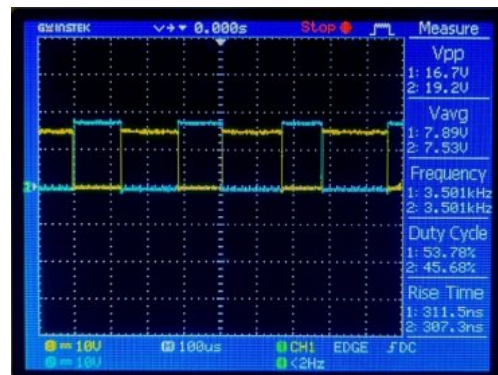
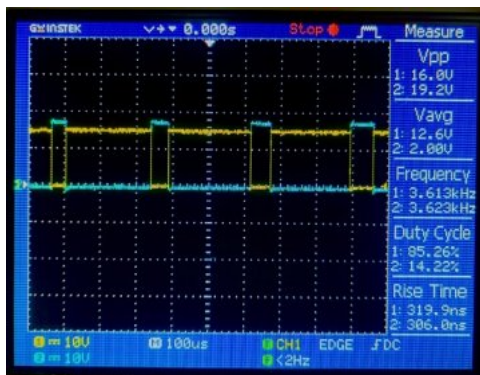


Figure 3.14: the SPWM signal measured after the gate drive



Zoom in

the peak of the sine wave when the high-side switch experiences its longest continuous 'ON' time. This proves the bootstrap capacitor is appropriately sized for the dynamic demands of SPWM.

3.4.4.1.4 Dead-Band Verification

Finally, a critical safety verification was performed to confirm the hardware-level dead-band implementation between complementary signals (the high-side and low-side gate signals of the same leg). As observed in the zoomed-in capture **Figure 3.15**, a distinct delay is successfully enforced between the falling edge of the active signal and the rising edge of its complement. This

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dead-time, measured at **500 ns**, remains constant regardless of the varying SPWM pulse widths. This strict delay is absolutely necessary to prevent shoot-through short circuits across the DC-link during semiconductor switching transitions.

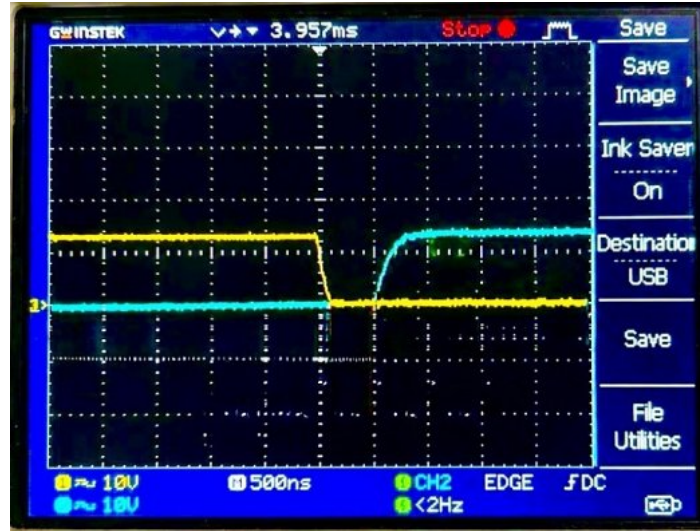


Figure 3.15: the high-side and low-side gate signals of the same leg

3.4.4.2 Inverter Performance with a Purely Resistive Load (R Load)

To evaluate the operational integrity of the power stage under load, the inverter was connected to a purely resistive star-coupled (Y) load, utilizing a $7\ \Omega$ resistor per phase. As illustrated in Figure A, the system was energized by a laboratory DC power supply set to a DC-link voltage (V_{DC}) of approximately 30 V. Operating at this safe, controlled voltage allows for precise observation of the switching characteristics and load responses without the risks associated with grid-level voltages.

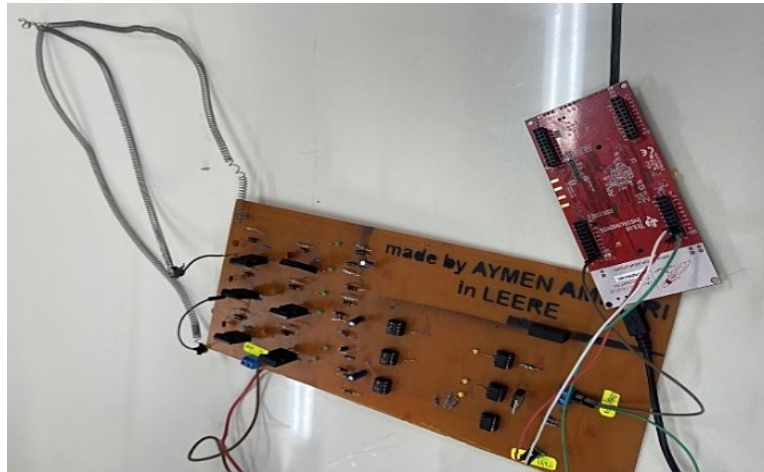


Figure 3.16 Resistive load mounted to the inverter



Figure 3.17 DC Power Supply

The first critical observation is the voltage distributed across the individual load components. **Figure 3.18** displays the phase-to-neutral voltage (the voltage measured between one phase leg and the star point of the load). In a star-connected three-phase system without a neutral return wire, the potential at the star point shifts dynamically based on the switching states of the inverter legs. Consequently, even with an SPWM control scheme, the macroscopic fundamental envelope of the phase-to-neutral voltage naturally forms a stepped profile. The voltage transitions through specific fractional levels of the supply voltage (specifically $\pm V_{dc}/3$ and $\pm 2V_{dc}/3$, corresponding to ± 10 V and ± 20 V in this test), resulting in the classic stepped waveform characteristic of a three-phase bridge driving a balanced Y-load.

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The blue trace represents the phase current flowing through the $7\ \Omega$ resistive load. In a purely resistive AC circuit, the current is directly proportional to the applied voltage and is governed purely by Ohm's law ($I = V/R$), meaning it possesses a power factor of 1.0. The experimental waveform perfectly validates this theoretical principle: there is zero phase shift between the voltage and the current. Furthermore, because a pure resistor does not filter high-frequency harmonics like an inductor would, the current waveform exactly mirrors the chopped, rectangular SPWM pulses of the applied voltage.

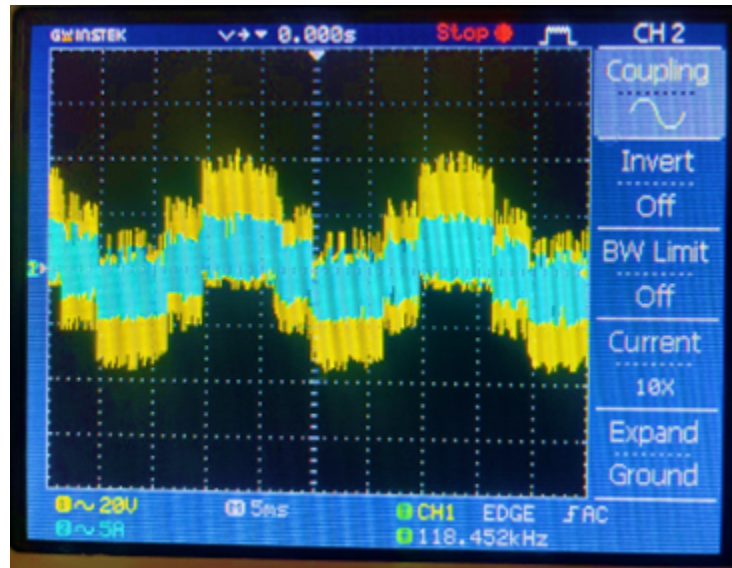


Figure 3.18: the phase-to-neutral voltage and current

Following the phase voltage analysis, the line-to-line switching behavior and the resulting load current were examined. **Figure 3.19** displays the line-to-line voltage (yellow trace)

The line-to-line voltage trace clearly demonstrates the high-frequency Sinusoidal Pulse Width Modulation (SPWM) action. The voltage chops dynamically between $+V_{dc}$ (+30 V) and $-V_{dc}$ (-30 V). As expected from the SPWM algorithm, the widths of these rectangular pulses vary continuously they are widest at the peak of the fundamental sinusoidal cycle and narrowest near the zero-crossings, effectively synthesizing the desired AC fundamental frequency.

This test conclusively proves that the power semiconductor bridge accurately executes the C2000's commands under load, successfully chopping the 30 V DC-link to drive proportional current through the $7\ \Omega$ resistors without significant voltage drops or switching failures.

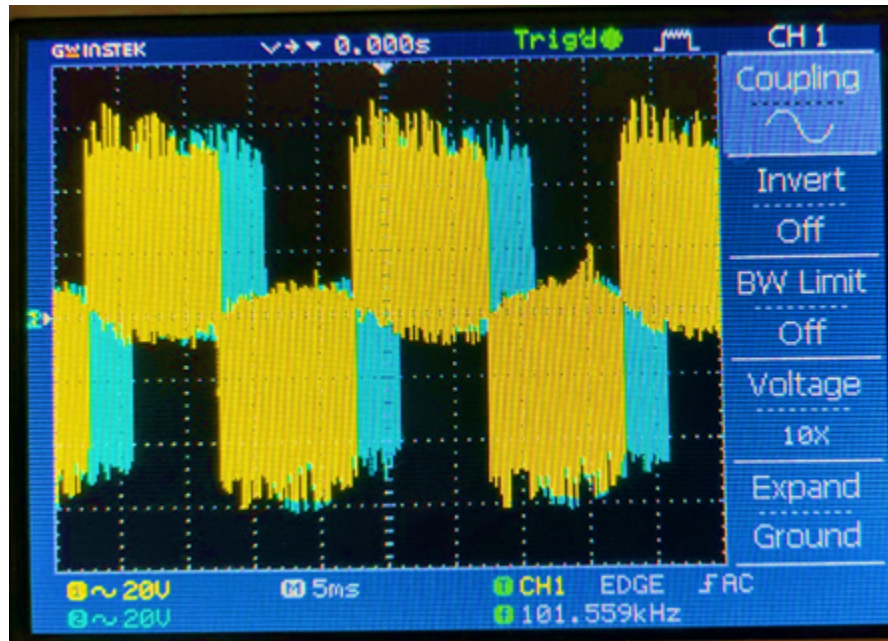


Figure 3.19 Line-to-Line Voltage

3.4.4.3 Inverter Performance with an Inductive-Resistive Load (RL Load)

While testing with a purely resistive load validates the basic switching operation, real-world industrial applications, such as the three-phase asynchronous motor targeted in this project are highly inductive. To accurately evaluate the inverter's performance under realistic conditions, the purely resistive load was replaced with a star-connected Inductive-Resistive (RL) load. This introduces reactive power into the system and thoroughly tests the freewheeling capabilities of the power bridge.

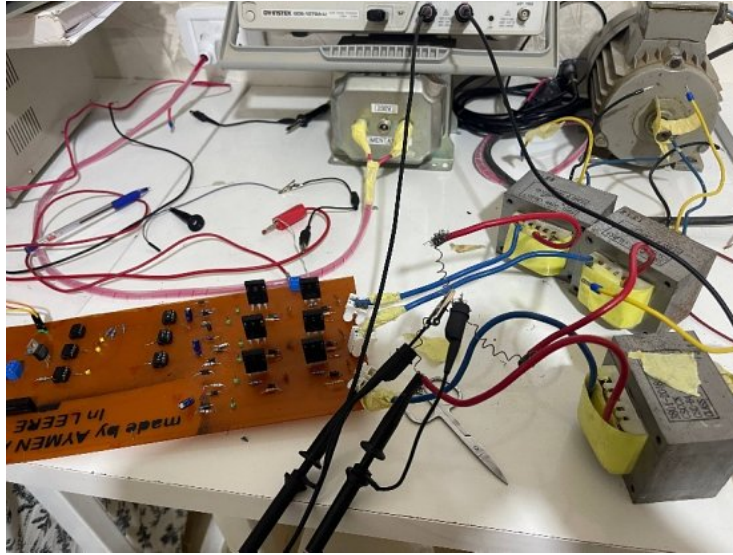


Figure 3.20 Resistive inductive load mounted to the inverter

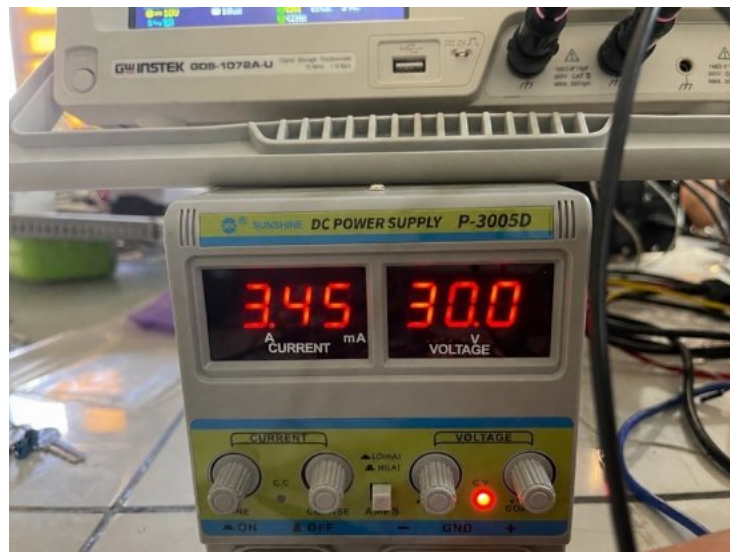


Figure 3.21 DC Power Supply

Figure 3.22 displays the chopped line voltage (blue trace) and the corresponding phase current (yellow trace).

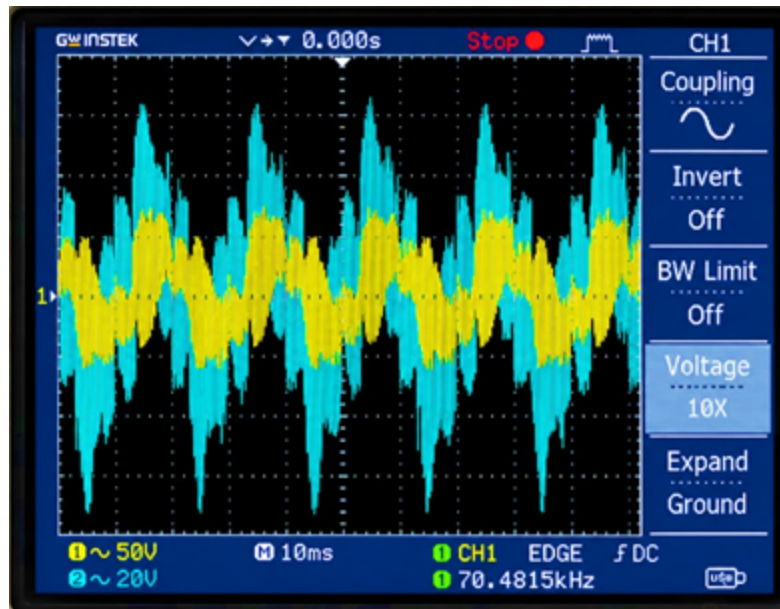


Figure 3.22: the phase-to-neutral voltage across the RL load.

Figure 3.23 illustrates the phase-to-neutral voltage across the RL load. Similar to the purely resistive case, the macroscopic envelope of the waveform maintains the characteristic stepped profile (transitioning through fractional DC-link voltage levels). However, the high-frequency SPWM chopping remains clearly visible. The voltage swings sharply between states as the C2000 microcontroller modulates the pulse widths to synthesize the fundamental frequency.

The most critical observations are found in the relationship between the applied voltage and the resulting load current.

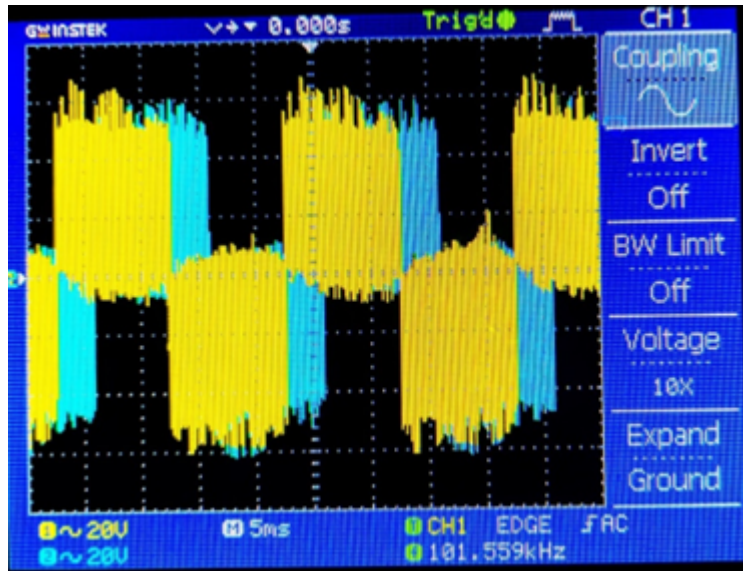


Figure 3.23: the line-to-line voltage across the RL load

Analyzing **Figure 3.22** and **Figure 3.23** oscillogram reveals several key characteristics inherent to driving inductive loads with SPWM:

1. **Inductive Filtering (Smoothing Effect):** The blue voltage trace consists of sharp, high-frequency rectangular pulses swinging rapidly between voltage extremes. However, the yellow current trace does not mirror these sharp transitions. Instead, it exhibits a much smoother, pseudo-triangular or rippled sinusoidal shape. This perfectly demonstrates the fundamental property of an inductor: it opposes instantaneous changes in current ($V = L \frac{di}{dt}$). The inductance naturally acts as a passive low-pass filter, absorbing the high-frequency switching harmonics and allowing primarily the fundamental low-frequency AC current to pass.
2. **Phase Lag:** Unlike the resistive load where voltage and current were perfectly in-phase, the RL load introduces a distinct phase shift. A careful examination of the waveforms reveals that the fundamental peak of the current (yellow) lags behind the fundamental envelope of the voltage (blue), which is the standard theoretical behavior of a lagging power factor in an inductive circuit.
3. **Role of Freewheeling Diodes:** The continuous nature of the current waveform despite the voltage frequently dropping to zero or reversing during the SPWM "off" periods proves

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that the anti-parallel freewheeling diodes across the power switches are functioning correctly. When a switch turns off, the stored magnetic energy in the inductor forces the current to keep flowing. The diodes provide a safe return path for this reactive current, preventing destructive voltage spikes across the semiconductors.

This experimental setup successfully verifies that the inverter power stage can reliably drive reactive loads, adequately handle inductive kickback currents, and successfully utilize the load's inherent inductance to smooth the chopped SPWM voltage into a usable AC current.

3.5 Conclusion

The journey from a theoretical schematic to a fully functional, routed PCB is a demanding but deeply rewarding engineering process. Our preliminary breadboard testing, despite its inherent physical limitations, successfully proved the viability of our C2000-based SPWM control scheme and the IR2104 gate driver implementation. The subsequent PCB design solidified this success, providing a robust, low-inductance platform capable of safely managing the high currents demanded by the power stage. With the hardware fully verified and the initial open-loop voltage waveforms confirming our design parameters, the system architecture has been thoroughly validated.

General conclusion

This final thesis project was dedicated to the theoretical study, mathematical modeling, numerical simulation, and practical implementation of a three-phase Voltage Source Inverter (VSI), alongside the establishment of an experimental test bench for its validation. The primary objective was to design and deploy a robust digital control strategy capable of synthesizing a high-quality, balanced three-phase voltage system.

The thesis is organized into three distinct chapters, structured as follows:

Chapter 1 established the theoretical foundations, highlighting the crucial importance of three-phase inverters and their vital applications in modern power electronics, such as electric motor drives and renewable energy integration. We examined the general structure of inverter bridges, power topologies, and the essential characteristics of gate driver circuits required to ensure the secure and reliable commutation of power semiconductors.

Chapter 2 focused on the mathematical modeling and simulation of the three-phase inverter within the MATLAB/Simulink environment. This chapter enabled the development of the Sinusoidal Pulse Width Modulation (SPWM) control strategy based on the natural sampling intersection method. The simulation results rigorously validated the model, clearly demonstrating the characteristic five-level stepped profile of the phase-to-neutral voltage and the perfect 120-degree electrical phase shift between the three phases. This confirmed the precise execution of the transformation matrix relative to theoretical derivations.

Chapter 3 covered the transition from digital simulation to physical hardware realization. The SPWM control algorithm was digitally implemented on the Texas Instruments LAUNCHXL-F28379D microcontroller platform (C2000 Delfino MCU), chosen for its high-precision processing capabilities in industrial control signals. Following the design and assembly of the isolation and protection circuits for the gate drivers, the experimental test bench was successfully commissioned. Practical testing conducted on an inductive-resistive (RL) load confirmed the proper operational functionality of the inverter. Oscilloscope captures demonstrated the effectiveness of the load's inherent inductive filtering, smoothing the output into a clean, stable sinusoidal current envelope that met all expected performance criteria.

General conclusion

In summary, the rigorous alignment between the theoretical equations, the voltage profiles obtained in simulation, and the experimental laboratory measurements definitively confirms the global validity of the methodology adopted throughout this project

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