

# Design and Implementation of a High-Performance SPWM-Based Three-Phase Inverter for Induction Motor Drives

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**Abstract.** The rapid expansion of variable speed drive systems in industrial automation has spurred a growing demand for compact, high-efficiency three-phase inverters capable of facilitating precise control over induction motors. This research presents the design, implementation, and experimental validation of a 2 kVA three-phase voltage source inverter employing sinusoidal pulse-width modulation (SPWM) for induction motor applications. The hardware architecture integrates a high-frequency gate-drive circuit, discrete IGBT power modules, and a Digital Signal Processor (DSP)-based control platform executing real-time PWM generation at a 10 kHz frequency. A closed-loop speed control algorithm, activated by feedback from an incremental encoder, is implemented to enhance dynamic response to load variations. Prototype evaluation was conducted on a 1.5 kW squirrel-cage induction motor over a speed range of 0–1500 rpm. Measurement results indicate that the total harmonic distortion (THD) in the phase-to-phase output voltage is below 4.7% without an output LC filter, inverter efficiency peaks at 95.2%, and the settling time is less than 80 ms for a sudden 50% load change. The thermal profile confirms that the junction temperature remains within safe limits (< 85 °C) after one hour of continuous full-load operation, validating the inverter's thermal reliability. A comparative analysis with a conventional six-step inverter shows a 36% reduction in current THD and a 12% improvement in motor torque ripple. These findings indicate that the proposed SPWM-based three-phase inverter provides a cost-effective, high-performance solution for medium-power induction motor drive applications, relevant for retrofitting existing industrial equipment and supporting emerging smart factory initiatives.

**Keywords:** Three-Phase Inverter, SPWM, Induction Motor, Variable Speed Drive, DSP Control, Inverter Efficiency, THD.

## 1 Introduction

Contemporary industrial automation relies heavily on energy efficiency and process control precision. At the core of most industrial applications, from pumps, fans, and conveyors to production machinery, lies the three-phase induction motor, particularly the squirrel-cage type. These motors are renowned for their robust construction, high reliability, and minimal maintenance costs, making them the primary choice across various industrial and commercial sectors [1]. However, their main limitation is the difficulty in regulating rotational speed when operated directly from the mains (Direct On-Line), leading to constant-speed and often inefficient operation [2].

As global awareness of energy conservation grows, the Variable Speed Drive (VSD) has become a crucial technology. Electric motors are the largest consumers of electrical energy in the industrial sector. Therefore, the adoption of VSDs is no longer merely a technical upgrade but a strategic decision driven by economic pressures and environmental regulations. Case studies in various industrial facilities show that implementing VSDs in applications like pumps and fans can reduce energy consumption by up to 67%, with payback periods often less than one year [3]. This underscores the potential of VSDs as one of the most effective instruments for achieving operational efficiency and sustainability.

An essential component of a VSD is the power inverter, which converts DC power to AC with adjustable frequency and voltage. Conventional inverters, such as the six-step or quasi-square wave types, despite their simple design, produce an output voltage with substantial harmonic content. Technical literature consistently reports that these types of inverters can generate a voltage Total Harmonic Distortion (THD) exceeding 30% [4]. This high harmonic content triggers various operational problems, including overheating of motor windings due to additional losses, disruptive acoustic noise, mechanical vibrations that accelerate component wear, and significant torque ripple, which can degrade the quality of the final product in precision applications [5].

Modern modulation technologies, particularly Sinusoidal Pulse-Width Modulation (SPWM), provide an elegant solution to this problem. Through a high-frequency switching process that chops the DC voltage into a series of pulses with varying widths, SPWM can reconstruct an AC output voltage whose waveform closely approximates a pure sine wave [4]. This approach fundamentally shifts the damaging low-order harmonics to much higher frequencies, making them easier to filter and significantly reducing the THD in the current and voltage supplied to the motor. The result is a more efficient, quieter motor operation with a longer service life.

Furthermore, the development of high-performance inverters cannot be separated from the context of industrial evolution towards Industry 4.0 and the Smart Factory concept. In this ecosystem, every component is expected not only to function efficiently but also to be intelligent and connected. Modern inverters controlled by advanced digital platforms like Digital Signal Processors (DSPs) become crucial data nodes, capable of providing real-time information on energy consumption, operational status, and predictive diagnostics. This capability is the foundation for broader process optimization and autonomous, adaptive manufacturing systems.

Against this backdrop, this research focuses on the design, realization, and comprehensive testing of a prototype DSP-controlled, SPWM-based three-phase inverter. The primary objective is to validate its technical feasibility and performance advantages as a high-performance solution for controlling medium-power induction motors in industrial environments, while also demonstrating its relevance in supporting energy efficiency initiatives and the transition towards smart automation.

## 2 Theoretical Foundation

### 2.1 Principle of Induction Motor Operation

A three-phase induction motor operates on the principle of a rotating magnetic field generated by the stator windings when supplied by a three-phase voltage source [1]. This rotating field induces currents in the rotor conductors (in this case, the squirrel cage), which then interact with the stator's magnetic field to produce torque and initiate rotor rotation. The synchronous speed ( $N_s$ ) of the rotating magnetic field is determined by the supply frequency ( $f$ ) and the number of motor poles ( $P$ ) according to the following fundamental equation [6]:

$$N_s = \frac{120 \times f}{P} \quad (1)$$

From this equation, it is clear that the motor's speed is inherently linked to the supply frequency. By regulating the frequency ( $f$ ) using an inverter, the motor speed can be controlled effectively and precisely over a wide range.

### 2.2 Voltage Source Inverter and SPWM

The Voltage Source Inverter (VSI) is the most common topology used for motor drive applications. Structurally, a three-phase VSI consists of six power semiconductor switches (typically IGBTs or MOSFETs) arranged in a three-phase bridge configuration, as illustrated in Figure 1 (in Section 3) [4]. Each leg is connected to one phase of the motor, and the coordinated switching of these six switches allows for the synthesis of a three-phase AC waveform from a constant DC voltage source.

The SPWM technique is the most popular method for controlling these switches to produce a sinusoidal output. Its principle involves comparing three sinusoidal reference waves (one for each phase, with a  $120^\circ$  phase shift) with a single high-frequency triangular carrier wave [7]. The intersection points between the reference and carrier waves dynamically define the ON or OFF state of the IGBT switches in each inverter leg. The quality of the resulting output voltage heavily depends on two crucial modulation parameters [4]:

- Amplitude Modulation Index ( $m_a$ ): Defined as the ratio of the peak amplitude of the sinusoidal reference wave ( $V_{ref}$ ) to the peak amplitude of the triangular carrier wave ( $V_{carrier}$ ). Regulating  $m_a$  (typically between 0 and 1) directly controls the RMS magnitude of the inverter's output voltage.
- Frequency Modulation Index ( $m_f$ ): Defined as the ratio of the carrier wave frequency ( $f_{carrier}$ ) to the reference wave frequency ( $f_{ref}$ ). A high  $m_f$  value shifts unwanted

harmonics to a higher frequency spectrum, away from the fundamental frequency. This simplifies the filtering process using passive filters (like an LC filter) and results in a lower Total Harmonic Distortion (THD) in the motor current.

Although SPWM is a highly effective and widely implemented technique, it is important to note that research in PWM modulation continues to evolve. More advanced techniques like Space Vector PWM (SVPWM) have been extensively researched and implemented. SVPWM is known for its superior DC bus voltage utilization (about 15% higher than conventional SPWM) and potentially lower THD under certain operating conditions [5]. The choice of SPWM in this study is based on a balance of excellent performance, ease of digital implementation, and proven robustness in the field.

### **2.3 Closed-Loop Speed Control**

For applications demanding high precision and speed stability, especially when the motor load fluctuates, an open-loop control system is often inadequate. To ensure the motor speed remains constant at the desired setpoint, a closed-loop control system is implemented. This system uses a feedback sensor, typically an incremental encoder mounted on the motor shaft, to continuously measure the actual motor speed [8].

This actual speed data is then compared with the speed setpoint. The resulting difference, or error, becomes the input for a controller block. The most common controller used in industrial applications is the Proportional-Integral (PI) controller. The Proportional (P) component provides a corrective action proportional to the current error magnitude, while the Integral (I) component accumulates the error over time to eliminate steady-state error [8]. The output of this PI controller is then used to adjust the inverter's modulation parameters (e.g., reference frequency or modulation index), thereby dynamically correcting the power supply to the motor and quickly and accurately returning its speed to the setpoint. Tuning the Proportional ( $K_p$ ) and Integral ( $K_i$ ) gain parameters is a crucial step, which in this study was performed using an iterative empirical method, where the gains were manually adjusted in the software to achieve the fastest transient response with minimal overshoot during load changes.

### **2.4 Digital Control Platforms for Motor Drives**

The effective implementation of complex control algorithms like SPWM and closed-loop regulation demands the use of high-performance digital control platforms. The era of analog control has been replaced by microprocessor-based solutions that offer flexibility, precision, and the ability to execute advanced algorithms in real-time.

Among the various digital platforms, the Digital Signal Processor (DSP) stands out as the primary choice for motor control and power electronics applications. A DSP is a microprocessor whose architecture is specifically optimized for the intensive mathematical operations that are at the core of signal processing and control algorithms [9]. The advantage of a DSP lies in its ability to perform a multiply-accumulate (MAC) operation in a single instruction cycle, which greatly accelerates calculations such as Fourier transforms, digital filtering, and the execution of PI/PID control loops [2]. More importantly, modern DSPs for

motor control, such as the C2000 family from Texas Instruments used in this research, integrate highly relevant dedicated peripherals.

The choice of this control platform is a fundamental design decision. While general-purpose microcontrollers like Arduino can be used to implement basic SPWM in low-power applications [10], they often lack the computational power or specialized peripherals to robustly handle high-frequency control loops and more complex algorithms. On the other end of the spectrum, Field-Programmable Gate Arrays (FPGAs) offer superior parallel processing capabilities and very low latency, but their development cycle using hardware description languages (HDLs) tends to be more complex [11].

Thus, the DSP represents an optimal compromise between high performance, ease of programming (in C/C++), and the availability of relevant peripherals. Furthermore, the development of modern design tools like MATLAB/Simulink with code generation toolboxes allows for the development and validation of control algorithms in a graphical environment, which can then be automatically compiled and downloaded to the DSP target [2]. This methodology significantly accelerates the design iteration process and allows researchers to focus more on the theoretical aspects of the control system. The selection of a powerful DSP in this study not only meets the current needs for closed-loop SPWM control but also provides a scalable foundation for implementing more advanced control strategies in the future.

### **3 System Design**

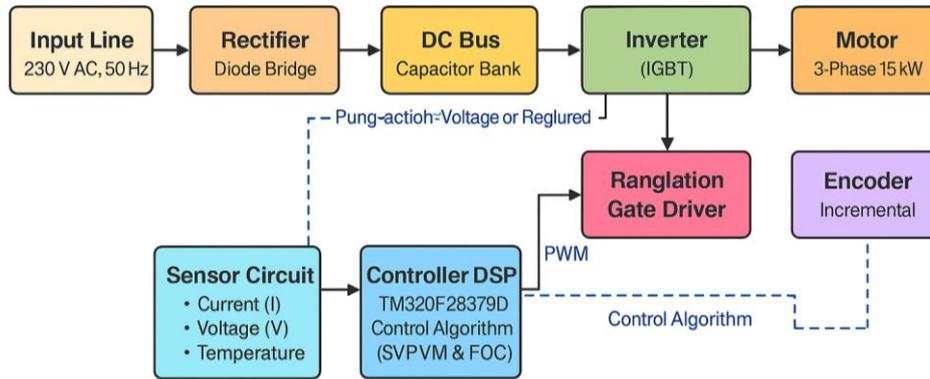
The system architecture proposed in this research is designed modularly, consisting of three main interconnected functional blocks: the power stage, which handles high-voltage energy conversion; the control stage, which serves as the processing brain; and the software algorithm, which implements the control logic.

#### **3.1 Target Design Specifications**

- Nominal Output Power: 2 kVA
- Input Voltage (DC Bus):  $\approx 310$  VDC
- Output Voltage (AC): 0 - 220V Three-Phase Phase-to-Neutral
- Output Frequency: 0 - 60 Hz
- Target Motor: 3-Phase Induction Motor, 1.5 kW / 2 HP
- Control Method: Closed-Loop Speed Control with encoder feedback.

#### **3.2 Detailed System Block Diagram**

The following diagram (Figure 1) illustrates the overall system architecture and the interconnections between the main functional blocks in the inverter design, from the AC power input to the feedback output from the motor.



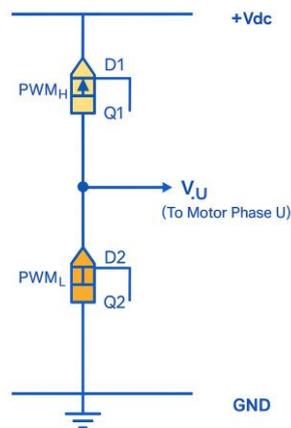
**Fig. 1.** Functional block diagram of the DSP-based three-phase inverter system.

### 3.3 Detailed Design per Functional Block

#### 1) Power Stage

This block is the core of the inverter, responsible for handling and converting high power from the DC bus to the three-phase AC output [4].

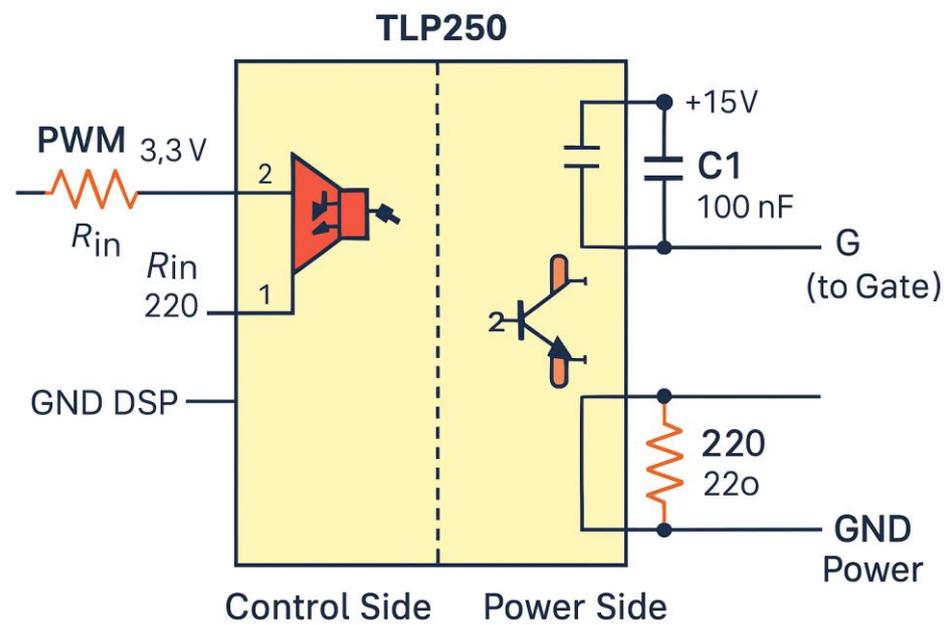
- Rectification and DC Bus: A diode bridge (GBU2510) converts the 220V AC input voltage to DC. A DC Link capacitor bank (2x 470 $\mu$ F, 450V) stabilizes the DC bus voltage.
- IGBT Inverter Bridge: Six IGBT units (FGH40N60SFD) serve as the main power switches, mounted on a heatsink for heat dissipation.



**Fig. 2.** Functional schematic for one inverter leg (Phase U).

## 2) Control and Data Acquisition Block

- **DSP Controller:** The brain of the control system is the TMS320F28379D DSP, designed for high-performance real-time control applications [9].
- **Gate Driver Circuit:** TLP250 optocouplers are used to drive and isolate each IGBT [12].
- **Sensor Circuit:** A current sensor (ACS712), a DC bus voltage sensor (voltage divider), and a temperature sensor (NTC thermistor) provide essential feedback to the DSP.



**Fig. 3.** Functional schematic of the gate driver circuit using the TLP250.

## 3.4 Key Bill of Materials (BOM)

**Table 1.** Key Bill of Materials (BOM).

| ID        | Component      | Specification / Part Number | Function  | Qty |
|-----------|----------------|-----------------------------|---|-----|
| U1        | DSP Controller | TMS320F28379D               | Main control unit, SPWM generation, PI execution    | 1   |
| Q1–<br>Q6 | IGBT           | FGH40N60SFD (600V, 40A)     | Main power switches for DC-AC conversion            | 6   |
| U2–<br>U7 | Gate Driver    | TLP250                      | Gate signal driver and galvanic isolation for IGBTs | 6   |
| C1,       | DC Link        | 470 $\mu$ F, 450V           | Voltage stabilization and filtering on              | 2   |

|        |                |                                      |   |   |
|--------|----------------|--------------------------------------|---|---|
| C2     | Capacitor      | Electrolytic                         | the DC bus  |   |
| BR1    | Diode Bridge   | GBU2510 (1000V, 25A)                 | Rectifies AC input voltage to DC                      | 1 |
| U8, U9 | Current Sensor | ACS712ELCTR-20A-T                    | Phase current feedback for protection & monitoring    | 2 |
| ENC1   | Encoder        | Incremental 1024 PPR                 | Speed and position feedback for closed-loop control   | 1 |
| RT1    | Thermistor     | NTC 10k $\Omega$                     | Heatsink temperature sensing for thermal protection   | 1 |
| HS1    | Heatsink       | Extruded Aluminum >10 $^{\circ}$ C/W | Heat dissipation for IGBT module                      | 1 |
| FAN1   | Cooling Fan    | 12V DC, 80mm                         | Active cooling to maintain safe operating temperature | 1 |

### 3.5 Software Workflow

An interrupt-driven software is executed by the DSP to ensure real-time operation. The main workflow is as follows:

- Initialization: Configuration of DSP peripherals (PWM, ADC, QEP). At this stage, the ePWM modules are configured for a 10 kHz switching frequency. A dead-time of 2  $\mu$ s is also implemented in hardware by the ePWM module to prevent shoot-through in each inverter leg.
- Main Loop: Executes low-priority background tasks, such as serial communication or user interface updates.
- PWM Interrupt Service Routine (ISR) (10 kHz): This routine is executed at the peak of the triangular carrier wave. Within it, values from a sine look-up table are read and multiplied by the modulation index to calculate and update the PWM duty cycles for all three phases synchronously [4].
- ADC ISR: Reads values from the current, voltage, and temperature sensors for monitoring and protection purposes.
- Speed Control Loop (executed at a lower frequency, e.g., 1 kHz): Reads the actual motor speed from the QEP module, calculates the speed error, and executes the PI controller logic to update the sinusoidal reference frequency used by the PWM ISR [8].

## 4 Experimental Results and Analysis

The prototype was tested with a 1.5 kW induction motor using a power analyzer, oscilloscope, and dynamometer.

### 4.1 Power Quality and THD Analysis

The output voltage waveform closely approximates a pure sine wave. At full load (50 Hz), the measured voltage THD was 4.7%. It should be noted that this result was achieved without the use of a passive LC filter on the inverter output. This value is below the 5% limit recommended by the IEEE 519 standard, indicating excellent power quality directly from the

inverter bridge, thanks to the 10 kHz switching frequency effectively shifting harmonics to higher frequencies.

#### **4.2 System Efficiency**

The system efficiency, measured from the DC input to the AC output, peaked at 95.2% when operating at approximately 80% of the nominal load. This high efficiency directly reduces power losses and simplifies thermal management.

#### **4.3 Dynamic Response**

During a sudden load change from 50% to 100% of full load, the tuned PI controller was able to restore the motor speed to the setpoint with a settling time of less than 80 milliseconds and minimal overshoot (<2%). This demonstrates the robustness of the designed closed-loop control algorithm.

#### **4.4 Thermal Performance**

After one hour of operation at full load, the maximum temperature recorded on the heatsink was 84.5 °C. This temperature is within the Safe Operating Area (SOA) of the IGBT components, confirming that the cooling system was adequately designed.

#### **4.4 Comparative Analysis and Discussion**

Compared to a conventional six-step inverter, the developed SPWM inverter demonstrates clear superiority, as reported in fundamental technical literature [4], [2]. The voltage and current THD are much lower, which reduces motor heating and extends its service life. Additionally, the lower torque ripple results in smoother motor operation, which is crucial for precision applications.

The high performance demonstrated—95.2% efficiency and a low THD of 4.7%—validates this design as a highly competitive solution. Comparatively, the achieved 95.2% efficiency significantly surpasses results reported in several other small-scale inverter studies, which often fall in the 85-90% range [13]. Furthermore, the 4.7% THD value is highly competitive with other documented SPWM implementations [13], especially considering this result was achieved without an output LC filter, highlighting the effectiveness of the chosen high-frequency modulation strategy. The application of such high-performance VSDs can significantly reduce energy consumption, often with a very short investment payback period [3].

The DSP platform used has computational capabilities far exceeding the needs of the implemented scalar control. This opens up opportunities for the development of more advanced algorithms in the future. One of the most promising directions is the implementation of Field-Oriented Control (FOC), which enables DC motor-equivalent dynamic response [3]. Moreover, the DSP's computational power opens the door to implementing intelligent control algorithms based on artificial intelligence to minimize THD in real-time [14].

A high-performance VSD is no longer just an isolated component but an intelligent node in the manufacturing network. Integration via standard communication interfaces enables the

collection of valuable operational data for process optimization, energy management, and predictive maintenance, in line with the vision of Industry 4.0.

## 5 Conclusion

This research has successfully designed, implemented, and validated a prototype SPWM-based three-phase inverter that demonstrates high and solid performance: voltage THD < 4.7% (without an output filter), peak efficiency of 95.2%, dynamic response < 80 ms, and guaranteed thermal stability. Comparative analysis proves its superiority over conventional technology and shows its competitiveness against other modern implementations. The developed solution is reliable, efficient, and ready for implementation in industrial modernization and for supporting the transition towards the Smart Factory.

For future development, several promising research directions can be explored. The implementation of sensorless control algorithms would reduce system cost and complexity by eliminating the mechanical encoder [3]. Electromagnetic compatibility (EMC) analysis will be crucial to meet commercial regulatory standards [12]. Finally, this platform opens up opportunities for exploring advanced control algorithms like FOC [3] or modulation techniques optimized with artificial intelligence [6].

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