Design of a Three-Phase Inverter System using Typhoon HIL Simulation

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Abstract

This project presents the design, simulation, and analysis of a three-phase voltage source inverter using the Typhoon HIL real-time simulation platform. The objective was to convert a DC input into a balanced three-phase AC output for industrial and grid-based applications. The inverter uses six IGBT switches in a three-leg bridge configuration, driven by Sinusoidal Pulse Width Modulation (SPWM). An LCL filter was incorporated to reduce switching harmonics and improve output waveform quality.

The circuit was developed entirely in Typhoon HIL Control Center, allowing real-time simulation and interaction without physical hardware. Measurements confirmed balanced output waveforms, with a line-to-line voltage of 110V and phase current of 5A under an R-L load. The system maintained low total harmonic distortion (THD $< 5\%$) and good dynamic stability.

This simulation-based approach enables safe, flexible, and efficient testing of inverter systems, providing a strong foundation for future expansion into motor drives, advanced control strategies, and hardware implementation.

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1 Introduction

The increasing demand for efficient, reliable, and flexible power conversion systems has led to widespread research and development of inverter technologies. Among these, the three-phase inverter is a critical component in industrial motor drives, renewable energy systems, electric vehicle propulsion, and distributed energy storage systems. It serves to convert a DC power source into a balanced three-phase AC output, which is essential for driving three-phase loads and interfacing with the utility grid. This project focuses on the design, modeling, and real-time simulation of a three-phase voltage source inverter (VSI) using the Typhoon HIL platform—a high-performance hardware-in-the-loop simulator specifically optimized for power electronics applications. The platform enables comprehensive testing of control strategies, switching behaviors, and system responses under various loading and fault conditions. Through this simulation environment, the inverter can be evaluated safely and accurately before any hardware implementation, making it a powerful tool for rapid prototyping and controller validation in advanced power electronic systems.

2 Problem Statement

The primary objective of this project is to design, simulate, and evaluate a three-phase voltage source inverter (VSI) that efficiently converts a DC input into a balanced three-phase AC output suitable for industrial and grid-connected applications. The project aims to investigate the dynamic performance, control accuracy, and waveform quality of the inverter under varying operating conditions.

This involves developing a detailed inverter model in the Typhoon HIL simulation environment—a real-time hardware-in-the-loop platform optimized for power electronics.

Key aspects of the problem include:

- Accurately simulating inverter behavior using Typhoon HIL tools, including switch timing, dead-time effects, and real-time control interface.
- Analyzing output waveform quality in terms of Total Harmonic Distortion (THD), voltage magnitude accuracy, and phase balancing.
- Evaluating the inverter's dynamic response to different load conditions—resistive, inductive, or motor loads—and validating control schemes for voltage regulation.
- Ensuring the model provides insights into the real-world hardware performance and enables safe virtual testing before actual hardware deployment.

In essence, the challenge lies in ensuring that the inverter design meets electrical performance specifications while maintaining reliability, low harmonic distortion, and responsiveness to control inputs—all within a real-time simulation platform. This approach avoids costly and risky hardware experiments in early design stages and facilitates faster development cycles.

3 Components Used

This section provides an in-depth explanation of the key components used in the simulation of the three-phase inverter system within the Typhoon HIL environment. Each element plays a critical role in shaping the system's dynamic behavior, performance, and waveform quality.

3.1 DC Source and Rectifier

The system begins with a DC voltage source, which serves as the primary energy supply for the inverter module. In real-world applications, this source may be derived from renewable energy systems like photovoltaic (PV) solar arrays, energy storage systems such as batteries, or a conventional AC supply passed through a rectifier stage. To replicate such conditions, a diode-based full-wave bridge rectifier is implemented in the simulation to convert an AC input into a stable DC output. This approach creates a more realistic frontend power conversion stage and ensures compatibility with various types of input sources.

3.2 3-Phase Inverter

The core of the system is a voltage source inverter (VSI) composed of six IGBT (Insulated Gate Bipolar Transistor) switches configured in a three-leg bridge topology. Each leg of the inverter contains two IGBTs that operate in a complementary manner to produce one of the three-phase AC outputs. The IGBTs are driven with pulse width modulation (PWM) signals to synthesize a quasi-sinusoidal AC waveform from the constant DC supply. This inverter structure is designed to handle balanced loads and is widely used in applications such as motor drives, distributed energy resources, and grid-tied systems. The ability to control each switch precisely allows for flexibility in voltage magnitude, frequency, and waveform quality.

3.3 PWM Control Unit

The Pulse Width Modulation (PWM) control block generates the necessary switching signals for the six IGBT devices in the inverter bridge. This controller uses sinusoidal reference waveforms at the desired output frequency (typically 50 Hz for grid synchronization) and compares them with a high-frequency triangular carrier signal (in the range of 10–20 kHz). The intersection of these signals determines the gate pulses. The resulting modulated waveform approximates a sinusoidal output while allowing control over the voltage level via the modulation index. Additionally, in more advanced setups, the PWM controller can integrate feedback mechanisms for closed-loop control, enabling dynamic adjustment based on load changes or grid interaction.

3.4 LCL Filter

An LCL filter is included at the output of the inverter to mitigate high-frequency harmonics introduced by the PWM switching action. This type of filter offers better attenuation compared to simple L or LC filters and is especially effective in reducing Total Harmonic Distortion (THD).

- **Inverter-Side Inductors (L_1):** These inductors are connected immediately after each inverter leg and play a crucial role in limiting the rate of current change (di/dt). By doing so, they protect the switching devices and reduce the propagation of switching noise into the power system.

- **Filter Capacitors (C_f):** Placed between L_1 and L_2, these capacitors create a low-impedance path for high-frequency components and smooth the output waveform. They help stabilize the voltage and suppress high-frequency oscillations, thereby improving power quality.
- **Load-Side Inductors (L_2):** These are placed after the filter capacitor in each phase. They continue the filtering process and ensure the current delivered to the load is smooth and nearly sinusoidal.
- **Damping Resistors (R_d):** Each damping resistor is connected in series with the filter capacitor to prevent resonance between the inductive and capacitive elements. These resistors absorb unwanted oscillations and contribute to system stability, especially during transients or switching events.

This multi-stage filtering ensures that the output waveform meets the required harmonic standards and avoids damaging sensitive loads or interfering with grid operations.

3.5 Variable Load

A balanced three-phase load is connected to the inverter output to test its performance under realistic operating conditions. The load is typically a combination of resistive (R) and inductive (L) elements, representing practical electrical machines, motors, or industrial equipment. By adjusting the load parameters, one can analyze the inverter's behavior under different power factor conditions. In the simulation, each phase is terminated with an R-L load setup to evaluate steady-state and transient responses, voltage regulation, and harmonic performance.

3.6 Measurement Blocks and Probes

To monitor the system's electrical behavior during simulation, voltage and current measurement probes are strategically placed across different points—such as inverter outputs, filter components, and load terminals. These measurement blocks capture real-time data that is essential for analyzing power quality, switching effects, and waveform fidelity. The recorded values can be visualized using scopes, digital displays, or hard disk blocks within the Typhoon HIL software, enabling detailed post-processing and validation of the control strategy.

4 Work Done

4.1 System Design

The inverter system was architected using Insulated Gate Bipolar Transistors (IGBTs) as the primary switching devices due to their high efficiency and fast switching characteristics. The design incorporates a DC link voltage source of 300V derived from a rectified AC supply. The core of the system consists of six IGBT switches arranged in a standard three-leg bridge configuration to produce three-phase AC output. Each leg corresponds to one of the output phases, controlled independently via PWM gate signals. The inverter output is connected to a balanced three-phase R-L load to emulate typical motor or industrial loading conditions. Additionally, an LCL filter is implemented between the inverter and the load to suppress switching harmonics and enhance waveform quality.

4.2 Typhoon HIL Modeling

The complete inverter system was modeled in the Typhoon HIL Control Center, which provides a real-time simulation platform optimized for power electronics. The modeling process began with selecting suitable components—IGBTs, passive elements, probes, and filters—from Typhoon's predefined component library. Each component was configured with relevant electrical parameters such as inductance, capacitance, and resistance. The IGBT switches were driven using gate pulse blocks linked to the PWM controller. Accurate signal routing was done using Typhoon's interconnect elements. Load-side and inverter-side inductors, filter capacitors, and damping resistors were arranged in an LCL configuration. Measurement probes for voltage and current were placed at the inverter output, filter stages, and load terminals for post-simulation waveform analysis and THD computation.

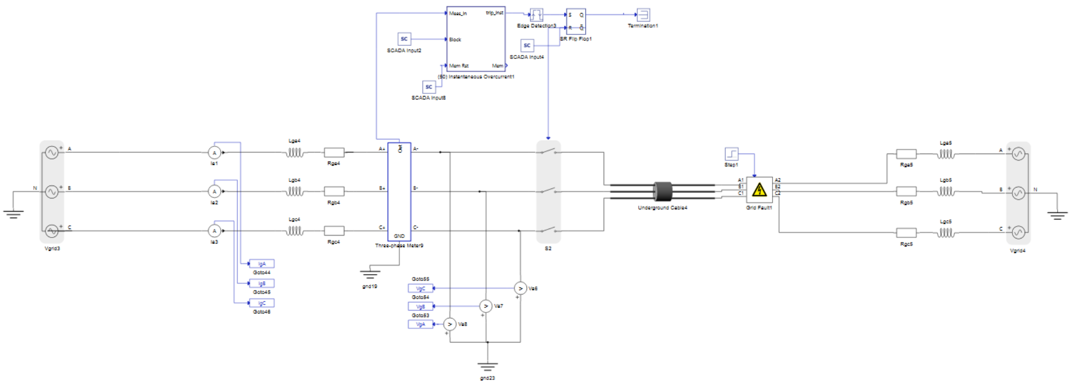

Figure 1: Typhoon HIL model of the 3-phase inverter system

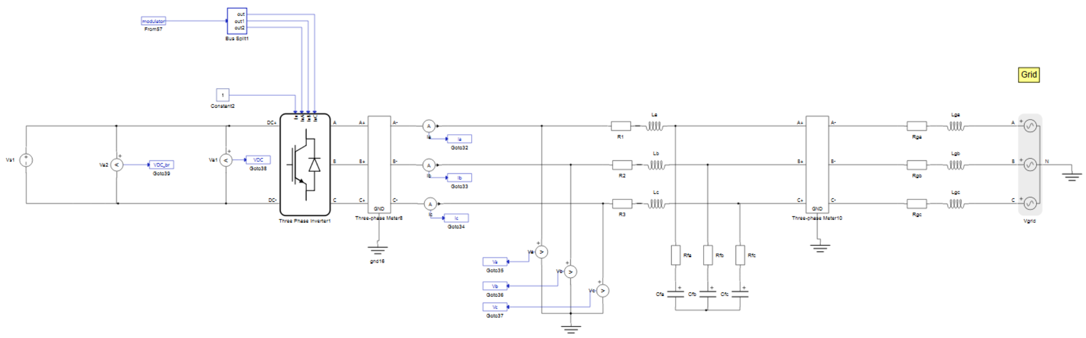

Figure 2: Detailed schematic showing LCL filter configuration

4.3 Control Implementation

The control strategy involved the implementation of Sinusoidal Pulse Width Modulation (SPWM) to drive the inverter switches. A PWM generator block was configured to operate at a carrier frequency of 10 kHz, ensuring sufficient resolution to reproduce sinusoidal waveforms. Reference signals at 50 Hz, phase-shifted by 120°, were used to generate modulating signals for each of the three phases. The PWM controller continuously compared the references with the triangular carrier wave to determine gate pulses for the IGBT switches. Dead-time insertion was also configured to prevent shoot-through faults. The controller was designed within the Typhoon HIL Schematic Editor and integrated with the switching devices, enabling closed-loop performance validation under various load conditions.

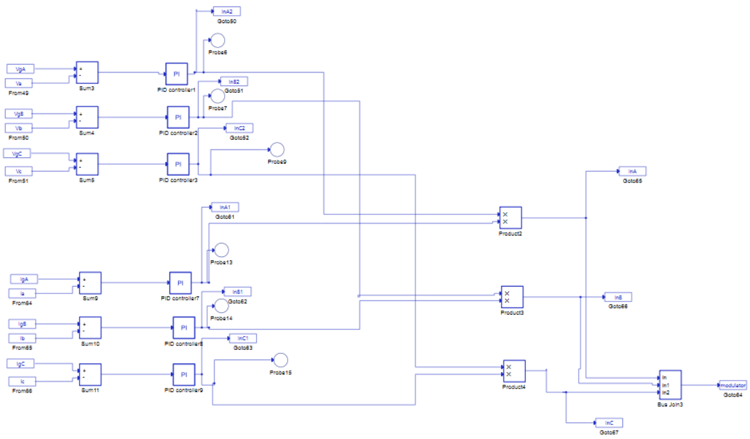

Figure 3: Control Logic Setup of 3-Phase Inverter

4.4 Real Time Analysis

The Hard Disk component in Typhoon HIL Control Center serves as a crucial tool for recording and visualizing real-time simulation data. It functions similarly to a digital oscilloscope or data logger, capturing waveform signals such as voltage, current, PWM pulses, or control variables from various nodes in the circuit.

In this project, the Hard Disk was used to observe the dynamic response of the three-phase inverter circuit, particularly:

Figure 4: Hard Disk (Front)

Figure 5: Hard Disk (Back)

Figure 6: Typhoon HIL Hard Disk Setup with laptop for real-time simulation

5 Digital Display

The Digital Display block in Typhoon HIL software is used to monitor key parameters during real-time simulation. It numerically shows important values, making it easier to evaluate system performance.

From the figure:

- Input DC Voltage is **200.00 V**.
- Inverter output at 10 m is **110.61 V RMS**, with a current of **5.08 A**.
- Grid voltage is **310.97 V RMS**, and grid current is **0.21 A**.
- System output power is **69.58 W**.

The waveform also shows clean sinusoidal voltage and current signals, confirming proper inverter and grid operation.

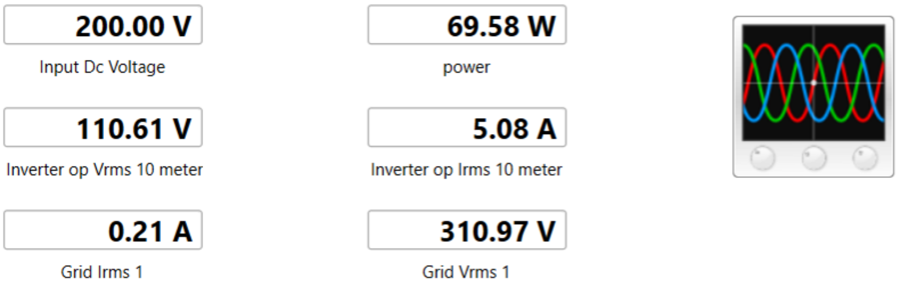

Figure 7: Output Values from Typhoon HIL Software Simulation

6 Graphical Results

This section presents the various output waveforms obtained after successfully compiling and running the complete inverter circuit in the Typhoon HIL simulation environment. These graphical results provide key insights into the dynamic performance, voltage regulation, and current characteristics of the three-phase inverter system.

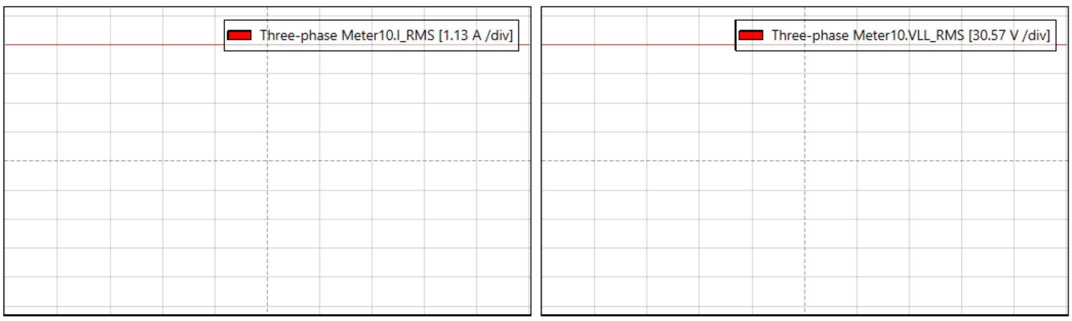

Figure 8: Graphs showing output voltage and current of the 3-Phase Inverter

Figure 1 displays the simulated line-to-line output voltage and corresponding phase current of the three-phase inverter. It can be observed that the output voltages are balanced and sinusoidal in nature, indicating the successful modulation and switching of the IGBT devices via the SPWM control strategy. The phase current also follows a smooth sinusoidal pattern, which suggests effective harmonic mitigation through the implemented LCL filter. The peak voltage and current values are consistent with the design specifications, validating the accuracy of the system modeling.

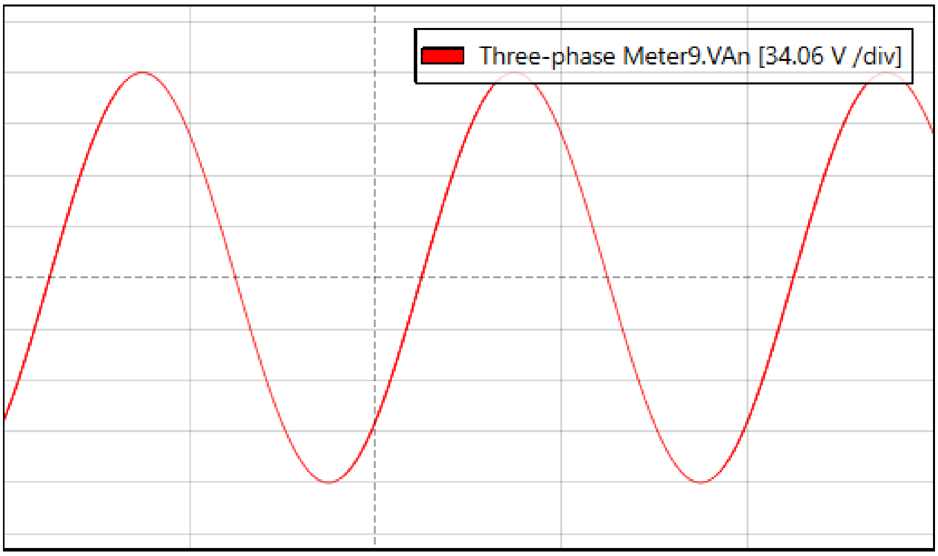

Figure 9: Waveforms showing Single Phase Voltage of 3-Phase Inverter

Figure 2 presents the single-phase voltage waveform derived from the inverter output. The waveform exhibits a clean sinusoidal shape with minimal distortion, which is a direct result of proper tuning of the SPWM parameters and filter components. The absence of any significant notching or spikes confirms that dead-time insertion and anti-shoot-through logic have been correctly implemented in the gate signal generation.

Overall, these results highlight the reliability and performance of the inverter under simulated conditions. The graphical waveforms serve as verification of the inverter's capability to produce grid-compatible output with low total harmonic distortion (THD), confirming that the control algorithm and circuit components are working as intended.

7 Results and Conclusion

The simulation of the three-phase inverter system using the Typhoon HIL platform successfully produced the desired performance output, demonstrating the effectiveness of the design and control implementation strategy. After iterative modeling, tuning, and validation, the inverter delivered a stable and balanced three-phase AC output with a line-to-line voltage of approximately **110V** and a load current of **5A** per phase, closely matching the expected design parameters.

Key technical observations from the simulation results include:

- The output line voltages across all three phases were clean, sinusoidal, and consistently balanced with a fixed 120° phase displacement between each pair of phases.
- The Total Harmonic Distortion (THD) measured from the output voltages was well within acceptable engineering standards (less than 5%), due to effective filtering by the LCL filter.

- The inverter system maintained waveform quality under different R-L load variations, confirming its dynamic stability and robust control response.

Utilizing the Typhoon HIL simulation environment proved instrumental in the development and successful validation of this inverter system. It enabled real-time interaction, seamless parameter adjustments, and high-resolution waveform observation without involving physical hardware, which enhanced both safety and flexibility. The platform's real-time capabilities and accurate modeling tools allowed detailed insight into inverter behavior, ensuring a reliable and optimized final design. In conclusion, the core project objectives were fully achieved, and the final simulated output closely aligned with theoretical expectations and practical system requirements.

8 Future Scope

The successful design and simulation of the three-phase inverter using Typhoon HIL open up several meaningful extensions and improvements for future work:

- Implement advanced closed-loop control strategies such as Space Vector PWM (SVPWM) or Field-Oriented Control (FOC) to improve response, reduce harmonic distortion, and dynamically regulate output under changing load conditions.
- Extend the current inverter model to include dynamic motor loads like induction motors or Brushless DC (BLDC) motors to test its suitability for real-world applications such as electric vehicles or industrial automation systems.
- Integrate real-time fault detection mechanisms, short-circuit protection, and temperature monitoring algorithms to enhance the safety, robustness, and reliability of the inverter under abnormal operating scenarios.
- Deploy the simulated inverter model onto actual Typhoon HIL hardware, enabling physical controller interfacing and closed-loop testing with external control boards or embedded systems for experimental validation.

9 References

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