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Simulation Research on PID Control of Single-Phase Full-Bridge Inverter Based on MATLAB/Simulink

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Abstract. Single-phase full-bridge inverters using open-loop SPWM can have serious waveform distortion. Also, the harmonic content is high. We design a dual closed-loop control structure with an outer voltage loop and an inner current loop, and then PI and PID control systems are constructed in this structure. Then we build simulation models on MATLAB/Simulink platform. These include open-loop SPWM and two closed-loop types. We compare the output voltage waveforms and THD under different operating conditions. Simulation results show that open-loop SPWM without LC filter has a THD of 52.82%, and it drops to 6.52% after applying the filter, while the dual closed-loop PI control with LC filter can reduce THD to 0.26% and the output waveform is smooth. The optimized dual closed-loop PID control with LC filter can achieve 1.15% THD. It has favorable transient potential. It is worth noting that these results can be used as a reference for control strategy selection and engineering implementation in small and medium-power single-phase inverters.

Keywords: single-phase full-bridge inverter, dual closed-loop control, PID control, SPWM modulation, total harmonic distortion (THD)

1. Introduction

Single-phase full-bridge inverters are widely used in small and medium-power conversion scenarios. These include distributed photovoltaic power generation and household energy storage systems. Also, uninterruptible power supplies (UPS) can use this topology, because it is simple and can provide high voltage utilization while the filtering difficulty is low and the overall cost can be reduced in practical applications with different load conditions [1]. Traditional open-loop sinusoidal pulse width modulation (SPWM) lacks feedback correction. In fact, output voltage is affected by load fluctuations and this results in substantial harmonic content with severe waveform distortion that makes it hard to meet the high-quality power supply standards required in practical engineering [2]. Dual closed-loop PI/PID control has a simple architecture. Also, it is reliable and the engineering implementation is straightforward, which can help improve the sinusoidal profile and steady-state accuracy of the inverter output voltage when the system is working in actual operating conditions with different load types [3]. Then we do a simulation-based comparative study of open-loop, dual closed-loop PI, and dual closed-loop PID control strategies, and it is expected to provide practical value for engineering applications.

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In recent years, inverter control technology has evolved. Many new methods have appeared, such as improved SPWM, compound control, fuzzy sliding mode control, and model predictive control, also fractional-order PID control [4-7]. But traditional PI/PID dual closed-loop control is still the mainstream benchmark for small and medium-power inverter systems, because engineers are familiar with the parameter tuning and it can show robust performance in actual applications. We focus on the dual closed-loop PI and PID control architectures commonly implemented in industrial engineering. It is worth noting that we provide a quantitative baseline for actual hardware selection, and we compare THD metrics and waveform quality under identical simulation boundaries.

We organize this paper as follows. Section 2 shows the main circuit topology of single-phase full-bridge inverter and the SPWM modulation principle. Also, the configuration of dual closed-loop control loops is described. Then, Section 3 gives the modeling details in MATLAB/Simulink environment. It is worth noting that Section 4 shows the time-domain waveforms and harmonic spectra analysis before and after LC filtering for all three control configurations and a performance benchmark matrix is given. Finally, Section 5 summarizes the conclusions and we propose some directions for future work.

2. Topology and control principle of single-phase full-bridge inverter

2.1. Main circuit topology

We use a single-phase full-bridge voltage-source inverter topology. The circuit structure is shown in Fig. 1. The main circuit has a DC power supply input, a full-bridge inverter switching block with four Insulated Gate Bipolar Transistors (IGBTs), a passive LC low-pass filter, and also a resistive load at the output side. The diagonal switching pairs are driven at the same time. But the upper and lower switches in the same bridge arm should work in a complementary way, which means when one is on, the other must be off. This switching action converts the DC input into high-frequency SPWM pulse voltages, and then the LC circuit filters out the high-frequency carrier harmonics so that the load can get a standard 50 Hz sinusoidal AC voltage [1].

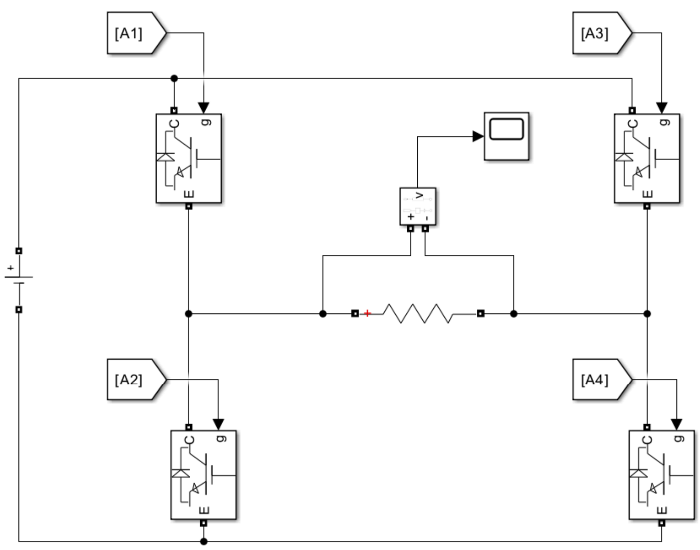

Figure 1. Topology of the single-phase full-bridge voltage-source inverter

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2.2. Main circuit parameters

To ensure repeatability and analytical consistency, the operational parameters for the main circuit are standardized as follows:

DC input voltage: 400 V
Output power frequency: 50 Hz
Switching frequency: 10 kHz
Filter inductance: L=2 mH
Filter capacitor: C=20 μF
Rated load: 50 Ω

2.3. SPWM modulation principle

We generate switching signals by comparing a 50 Hz fundamental sine wave (modulating wave) with a 10 kHz triangular wave (carrier wave) using magnitude comparison [2]. The pulse-width distribution follows a sinusoidal profile. These discrete pulse blocks pass through a passive low-pass filter. It is worth noting that high-frequency switching harmonics around the carrier frequency are suppressed, so a fundamental sine wave can be obtained at the load.

2.4. Dual closed-loop control principle

To achieve superior voltage regulation under dynamic load states, a cascaded control strategy is adopted.

Outer Voltage Loop: Collects the instant load output voltage and compares it with the ideal sinusoidal reference value. This loop eliminates steady-state voltage errors and maintains voltage stability.

In inner current loop, we collect the filter inductor current to track the reference from outer loop, and this can increase the system dynamic response speed. It is worth noting that it can also provide the overcurrent protection limit boundaries.

PI Control: Combines proportional action to reduce tracking errors and integral action to eliminate steady-state offset with minimal tuning complexity [6].

PID Control: Introduces a derivative term onto the PI backbone, which senses the error rate of change to enhance transient performance and counteract sudden disturbances [3].

3. Simulation platform and model construction

3.1. Simulation environment

We use MATLAB/Simulink together with Simscape Electrical toolbox. The modeling work and transient evaluation can be done in this environment, and we also do the harmonic FFT analysis here. It is worth noting that this integrated platform can provide the numerical reliability which is required for high-frequency switching assessments and spectral decomposition with good accuracy because the Simscape Electrical toolbox has good performance in circuit simulation [1].

3.2. Composition of simulation model

To systematically evaluate the control performance, three distinct configurations are constructed:

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We show the open-loop SPWM model in Fig. 2. This model includes DC source, standard H-bridge switching components, an SPWM driver and output filter stage and there is no closed-loop feedback path in this model [2].

Dual Closed-Loop PI Control Model: Illustrated in Fig. 3, this model introduces a cascaded loop where both the voltage and current loops are regulated using traditional PI controllers [6].

Dual Closed-Loop PID Control Model: Detailed in Fig. 4, this model substitutes the PI controllers in both loops with complete PID control configurations to analyze the effect of derivative actions [3].

Each structural layout is thoroughly tested under two operating conditions—without the LC filter block and with the LC filter block—allowing for a transparent comparison of filtering demands.

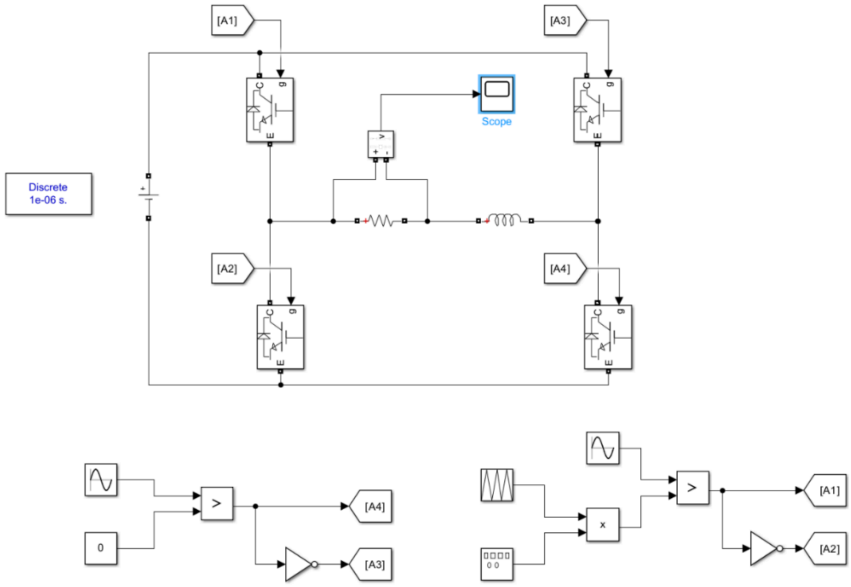

Figure 2. Simulink model of the single-phase full-bridge SPWM inverter with LC filter

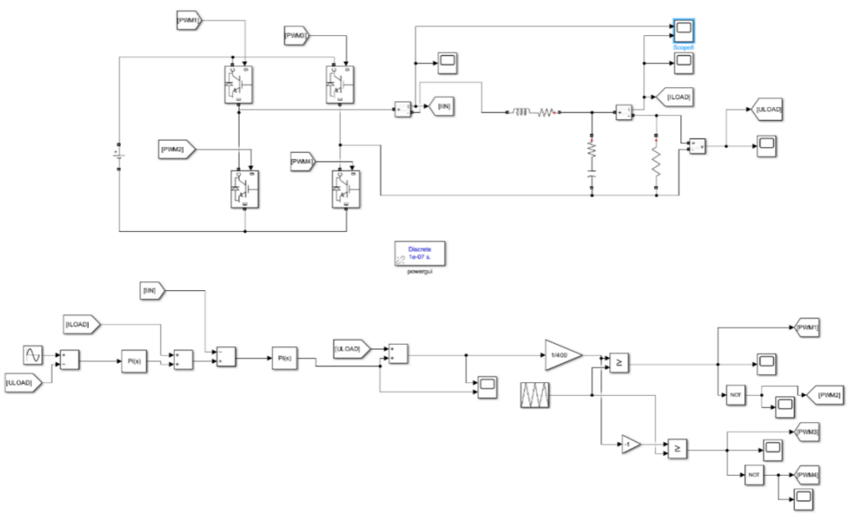

Figure 3. Simulink model of the single-phase full-bridge inverter with dual closed-loop PI control

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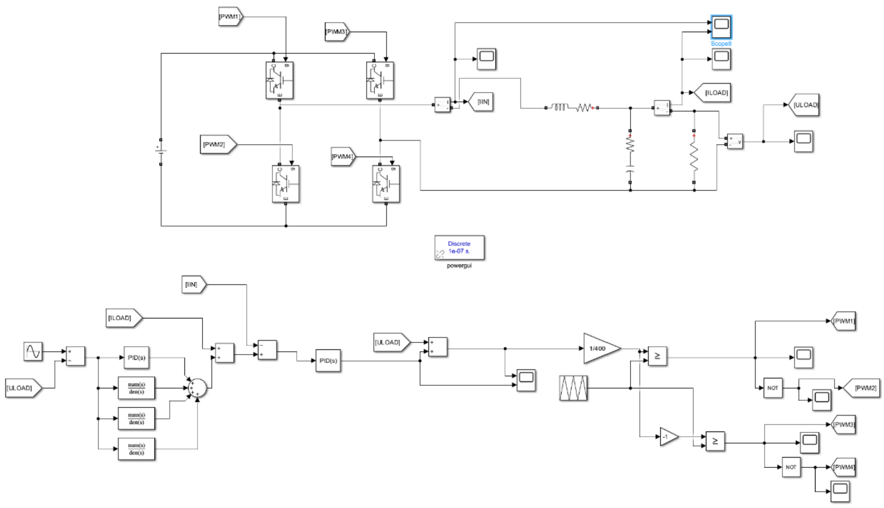

Figure 4. Simulink model of the single-phase full-bridge inverter with dual closed-loop PID control

3.3. Simulation settings

We use a fixed-step discrete solver in MATLAB/Simulink and it can capture switching transients while harmonic spectrum matrices can be computed with good accuracy because the discrete solver is suitable for this kind of problem and can avoid numerical errors. The simulation step size is set to a precise value. This time-step can sample the 10 kHz switching pulses with good fidelity. Also, spectrum aliasing artifacts can in principle be avoided during the post-simulation FFT processing, which is important for the accuracy. In fact, the total execution time is 0.5 seconds and it gives adequate duration to check the system's transition from initial startup dynamics to stable steady-state operations.

3.4. Controller parameter tuning based on Ziegler-Nichols method

Finding the controller gains for dual closed-loop controllers by trial-and-error is not efficient. We use the classic Ziegler-Nichols (Z-N) closed-loop tuning method. In fact, the ultimate sensitivity method is selected because it can determine the PID parameters without empirical testing. In a cascaded control structure, the coupling effect between the inner current loop and outer voltage loop is strong and we should tune them in sequence from inside to outside. The specific steps are described as follows:

Tuning the inner current loop: First, we deactivate the outer voltage loop. In the inner current loop controller, we set the integral term and derivative term to zero, so Ki = 0 and Kd = 0. Then we increase Kp from a small baseline value while introducing small step disturbances and this continues until the inductor current waveform shows a periodic oscillation with stable amplitude that can be sustained. It is worth noting that the proportional gain at boundary stability condition is defined as the ultimate gain Ku1, and the corresponding oscillation period is measured as the ultimate period Pu1.

For the outer voltage loop tuning, we first apply the calculated Z-N parameters to inner current loop. This can make response stable. Then the outer voltage loop is reconnected. It is worth noting that we deactivate integral and derivative actions (Ki = 0, Kd = 0) and increase the proportional gain. The critical state can be achieved when the output load voltage enters equal-amplitude

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oscillation, which means the system is oscillating with constant amplitude and this yields the outer loop ultimate gain Ku2 and ultimate period Pu2 and we can use these parameters in the next step.

We first get the critical parameters Ku and Pu from simulation platform. Then the controller coefficients Kp, Ti, Td can be calculated by the Z-N empirical design rules in Table 1. In fact, the standard parallel PID block in MATLAB/Simulink needs discrete gains Kp, Ki, Kd and it cannot use continuous-time constants, so we can convert the continuous coefficients into the standard block format using Eq. (1) and Eq. (2):

$$K_i = \frac{K_p}{T_i} \tag{1}$$

$$K_d = K_p * T_d \tag{2}$$

Table 1. Ziegler-Nichols closed-loop tuning rule formulas

Controller Type	Proportional Gain (Kp)	Integral Time (Ti)	Derivative Time (Td)
Proportional-Integral (PI)	0.45 Ku	0.83 Pu	0
Proportional-Integral-Derivative (PID)	0.60 Ku	0.50 Pu	0.125 Pu

In the practical simulation implementation, because the raw parameters derived from the Z-N rules typically inherently present an aggressive transient response with a higher overshoot (approximately 10% to 30%), a fine-tuning phase is marginally applied to down-scale the proportional gains by 10% to 15%. This engineering compromise ensures sufficient mitigation of overvoltage risks on the semiconductor switching devices while retaining the high dynamic tracking potential.

4. Simulation results and analysis

4.1. Simulation results of open-loop SPWM control

We first evaluate the single-phase full-bridge inverter under open-loop SPWM control to get a baseline for comparison. Without LC filter, the output voltage across load terminals is a raw PWM waveform and it switches between +Vdc and -Vdc. As shown in Fig. 5, the time-domain waveform consists of voltage pulses with high frequency and the FFT analysis indicates a THD of 52.82%. In fact, this value is severe. It comes from the switching-frequency harmonics centered around the 10 kHz carrier.

We integrate the passive LC low-pass filter (L = 2 mH, C = 20 μF) into the main circuit. Then these high-frequency carrier harmonics can be attenuated. As shown in Fig. 6, the output voltage across the resistive load is smoothed. It becomes a standard 50 Hz sinusoidal curve. It is worth noting that the post-filter FFT spectrum confirms the THD drops to 6.52%. Although the passive filter can recover the fundamental component, an open-loop system can not compensate for voltage drops when load variations exist. So closed-loop regulation is needed.

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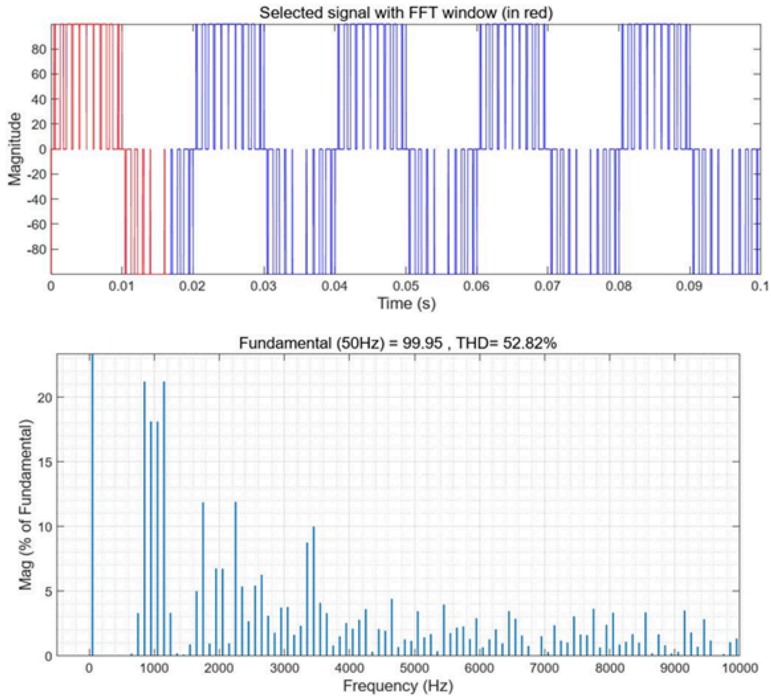

Figure 5. Unfiltered output voltage waveform and FFT analysis under open-loop SPWM control (THD = 52.82%)

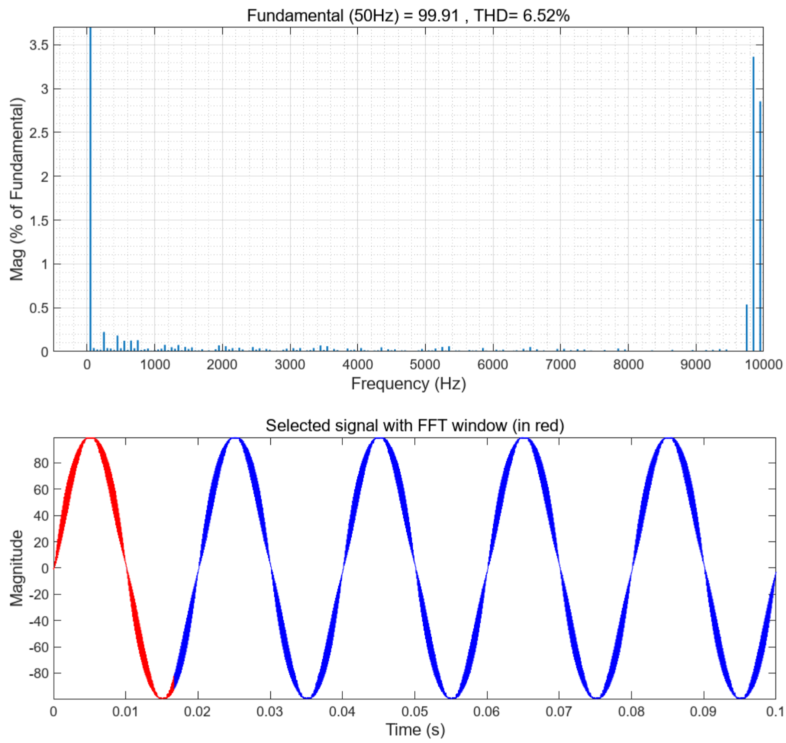

Figure 6. Filtered output voltage waveform and FFT analysis under open-loop SPWM control (THD = 6.52%)

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4.2. Simulation results of dual closed-loop PI control

We use a cascaded dual closed-loop PI control strategy with the LC filter network. It can improve steady-state tracking accuracy and reduce harmonic distortion. It is worth noting that the voltage outer loop and current inner loop work together. They can adjust the modulation index based on real-time feedback. The transient startup and steady-state voltage tracking waveforms are given in Fig. 7. The system passes through initial startup phase and can achieve stable sinusoidal tracking within a fraction of a fundamental cycle. Fig. 8 shows the steady-state FFT spectrum. The filtered output voltage has a sinusoidal profile and the THD value is 0.26%. This reduction from the open-loop baseline shows the PI controller has good performance in reducing steady-state tracking errors.

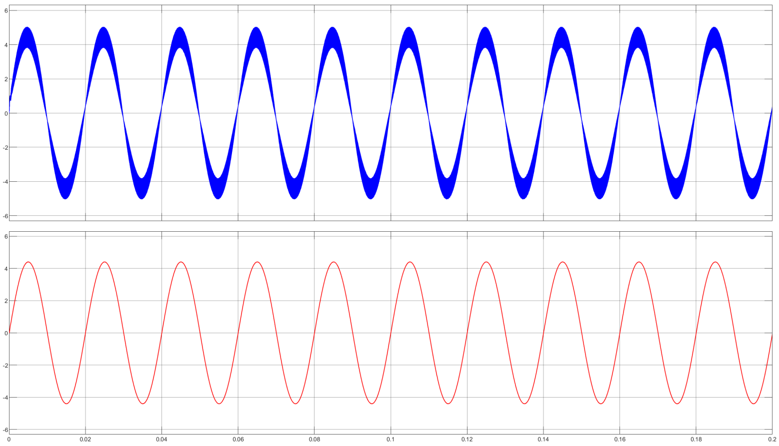

Figure 7. Transient and steady-state output voltage waveforms under dual closed-loop PI control

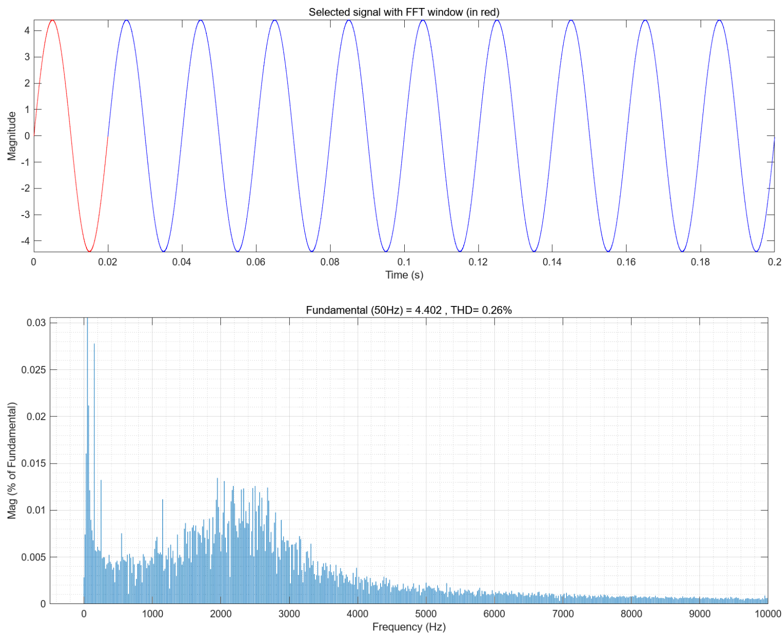

Figure 8. Filtered output voltage FFT analysis under dual closed-loop PI control (THD = 0.26%)

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4.3. Simulation results of dual closed-loop PID control

We evaluate the dual closed-loop PID control configuration in the same simulation environment to check how the derivative action affects the system performance. The transient voltage waveform at startup is recorded in Fig. 9. Because the derivative term has a predictive nature, the PID controller can sense how fast the error changes and this can accelerate the transient response when sudden variations happen in the system. When integrated with LC filter network, the PID control system can maintain a stable sinusoidal profile and no visible macroscopic distortion exists as shown in Fig. 10. It is worth noting that the FFT analysis indicates the steady-state THD can stabilize at 1.15%, and in fact this value can meet standard power quality codes, but there is a minor compromise on spectral purity compared to the pure PI variant (0.26%).

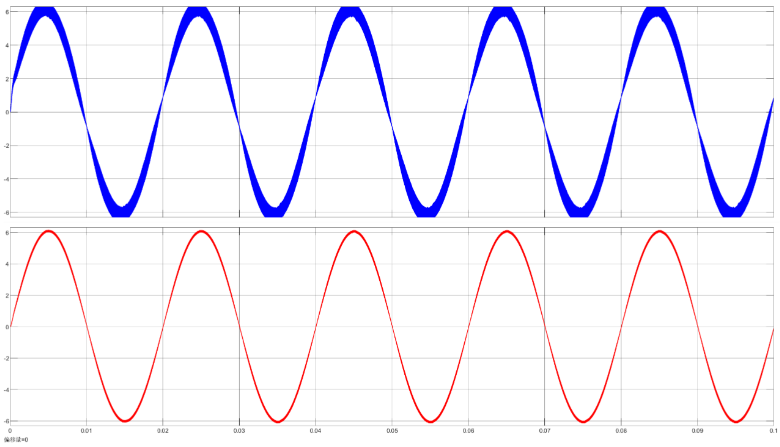

Figure 9. Transient and steady-state output voltage waveforms under dual closed-loop PID control

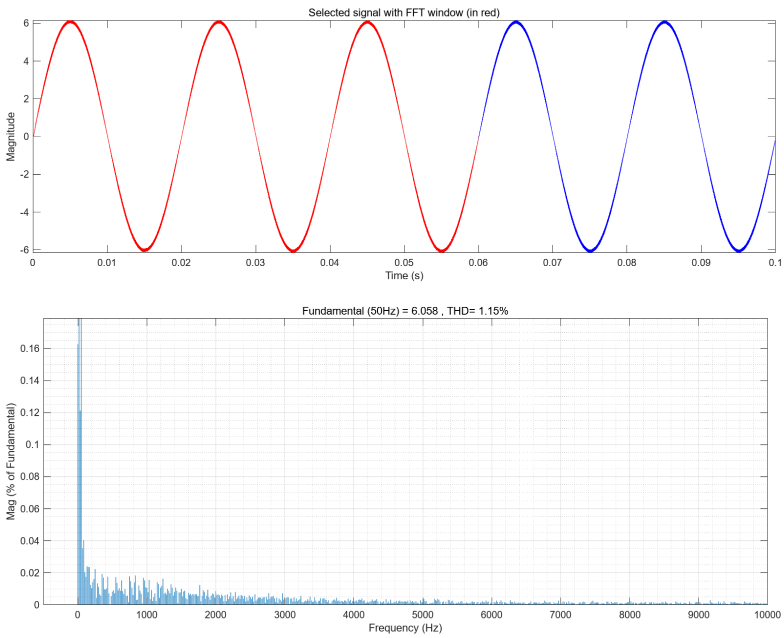

Figure 10. Filtered output voltage FFT analysis under dual closed-loop PID control (THD = 1.15%)

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4.4. Performance comparison of different control strategies

The performance indices of the evaluated control configurations under different scenarios are compiled in Table 2.

Table 2. Comparison of simulation results of each control strategy

Control Strategy	Filtering State	THD	Waveform Quality
Open-loop SPWM	Without filter	52.82%	Serious distortion
Open-loop SPWM	With LC filter	6.52%	Good
Dual closed-loop PI	With LC filter	0.26%	Optimal
Dual closed-loop PID	With LC filter	1.15%	Excellent

The comparative data in Table 2 yields several critical insights:

Passive filtering plays a key role in the system. It is worth noting that from open-loop SPWM benchmarks, we find the LC low-pass filter is needed to block high-frequency switching components centered around 10 kHz carrier frequency and this is important for the system performance. Without it, the output voltage remains a raw pulse train with THD of 52.82% and this is not suitable for a grid or household load. Adding LC filter provides passive attenuation and the open-loop baseline THD reaches 6.52%.

2) Steady-State Distortion vs. Controller Selection: When LC filter is working in the loop, using closed-loop feedback can improve the output power quality. It is worth noting that the dual closed-loop PI control achieves the lowest overall harmonic profile with a THD of 0.26%. However, the dual closed-loop PID system has a slightly higher steady-state THD of 1.15%.

3) The Derivative Noise-Amplification Trade-off: We observe that the steady-state THD of PID controller is higher than that of the PI controller, which comes from a basic trade-off existing in power electronics control where the designer must balance the dynamic performance and steady-state performance. The derivative term (D) calculates the rate of change of error signal. In practical simulation and physical hardware, residual high-frequency switching noise and ripples can pass through sensor feedback paths because the filter cannot remove all high frequency components and this is unavoidable in a real system. The derivative operation amplifies this high-frequency noise. It can inject minor ripple artifacts back into active SPWM modulation command. It is worth noting that PID controller can provide faster transient response speed and tighter tracking during sudden step-load disturbances. However, it should have some penalty in steady-state spectral purity compared with pure PI regulation.

5. Conclusion

We examine how to improve the output power quality of a single-phase full-bridge voltage-source inverter using MATLAB/Simulink simulations and the comparison is made among open-loop SPWM, dual closed-loop PI control and dual closed-loop PID under the same passive filtering state in order to see which one has the best performance. Results show that open-loop SPWM can work. However, the harmonic mitigation is limited even with LC filter and the THD is 6.52%, which means the power quality is not good enough for applications requiring high precision. It is worth noting that dual closed-loop PI with LC filter can achieve the lowest THD of 0.26%, which is the best result among all tested methods and the sinusoidal tracking is good, so this method can be used

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for steady-state applications. On the other hand, dual closed-loop PID has a good performance and it achieves 1.15% THD while the dynamic tracking is better because of the derivative error-rate action.

In future work, we test the system under non-linear and highly inductive step-loads. In fact, this should help us address current limitations. Also, we introduce advanced tuning methods including adaptive gain schedulers and model predictive control (MPC), while sliding mode control (SMC) is also considered, which can reduce the high-frequency noise amplification from the standard derivative term, and experimental validation is planned on a physical DSP-driven inverter prototype.

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