

# Transients and Stability: Electrical Systems Study with PID Tuning Methods Controller

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**Abstract:** The transient response of electrical circuits often exhibits undesirable oscillations that hinder precise voltage regulation. This paper presents a comprehensive simulation-based study of a series RLC circuit and a buck converter controlled by proportional-integral-derivative (PID) controllers. Four tuning strategies are compared: manual tuning, Ziegler-Nichols, particle swarm optimization (PSO), and genetic algorithm (GA). Performance is assessed using time-domain metrics (overshoot, settling time, IAE, ITAE) and frequency-domain tools (Bode, Nyquist, sensitivity functions). Robustness is evaluated through parameter variations ( $R$ ,  $L$ ,  $C$ ,  $\omega_0$ ,  $\zeta$ ), dynamic setpoint tracking, external disturbances, and Monte Carlo analysis ( $\pm 20\%$  component tolerances). The open-loop RLC circuit exhibits 80% overshoot and a settling time of 0.382 s. Manual PID tuning reduces overshoot to 13.7%, settling time to 0.024 s, and eliminates steady-state error. Ziegler-Nichols yields zero overshoot but an extremely slow response (rise time 0.617 s). PSO and GA produce the fastest rise times (5.6 ms) but increase overshoot to  $\approx 21\%$  and reduce phase margins to  $\approx 8^\circ$ , indicating fragility to model uncertainties. The manual PID demonstrates robust performance under all tested variations and maintains acceptable metrics under Monte Carlo simulation (mean overshoot 13.1%). For the buck converter, an optimized PID reduces the IAE by a factor of 2.5 compared to manual tuning, with identical control energy. This study confirms that the choice of PID tuning involves a clear trade-off between speed, overshoot, robustness, and control effort. Manual tuning offers the best balance for the RLC circuit, while optimization is highly beneficial for fast power electronics applications.

**Keywords:** PID Control, Transient regimes, Robustness, Ziegler-Nichols Method, Particle swarm optimization, Buck converter, Bode diagram, Sensitivity functions, Damping Factor  $\zeta$ , Natural Frequency  $\omega_0$

## 1. INTRODUCTION

The transient behavior of electrical systems is a critical aspect that determines their stability, efficiency, and reliability in practical applications. When a sudden change occurs such as a power-up, a load variation, or a fault, any dynamic system undergoes a temporary phase called the transient regime [1, 2]. During this phase, the system's output may exhibit oscillations, overshoots, or prolonged settling times before reaching its steady-state condition [3]. In many engineering domains, including power electronics, communication systems, and automatic control, such transient phenomena can degrade performance, cause component stress, or even lead to instability if not properly managed [4, 5]. Among the most common and fundamental electrical circuits, the series RLC network (composed of a resistor, an inductor, and a capacitor) is widely used as a benchmark for studying second-order dynamics [6]. Its natural response can range from overdamped to underdamped, the latter being particularly problematic because it generates sustained oscillations that hinder precise voltage or current regulation [7, 8]. Therefore, designing effective control strategies to shape the transient response of RLC circuits is not only a theoretical exercise but also a practical necessity for ensuring reliable operation in devices such as filters, resonant converters, and impedance matching networks [9, 10].

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To address these challenges, proportional-integral-derivative (PID) controllers remain the most prevalent solution in both industrial and academic settings due to their simplicity, intuitive structure, and remarkable effectiveness [11, 12]. A PID controller acts on the error between the desired setpoint and the measured output by combining three actions: proportional (reacts to the current error), integral (eliminates steady-state offset), and derivative (anticipates future error based on its rate of change) [13]. However, the performance of a PID controller is highly sensitive to the choice of its three gains. Poor tuning can lead to excessive overshoot, slow response, or even instability [14, 15]. Consequently, numerous tuning methods have been developed over the years, ranging from empirical rules (such as Ziegler-Nichols) to optimisation-based approaches (e.g., particle swarm optimisation, genetic algorithms). Moreover, real-world systems rarely operate under ideal conditions; component tolerances, aging, temperature drifts, and external disturbances can significantly alter the circuit parameters ( $R$ ,  $L$ ,  $C$ , natural frequency  $\omega_0$ , damping factor  $\zeta$ ) [16, 17]. Hence, a thorough evaluation of a PID controller must go beyond nominal performance and assess its robustness against such uncertainties, as well as its ability to track changing setpoints and reject disturbances [18, 19]. This paper presents a comprehensive simulation-based study of a series RLC circuit controlled by a PID tuner, comparing manual, Ziegler-Nichols, PSO and GA tunings. The analysis is extended to a buck converter to demonstrate the practical relevance of the methodology. Using time-domain metrics (overshoot, settling time, IAE, ITAE, etc.) and frequency-domain tools (Bode, Nyquist, sensitivity functions), we evaluate both performance and robustness, and we validate the results through Monte Carlo simulations.

Consider a series RLC circuit driven by a voltage source  $V_{in}(t)$  and controlled by a PID controller (Fig. 1.1).

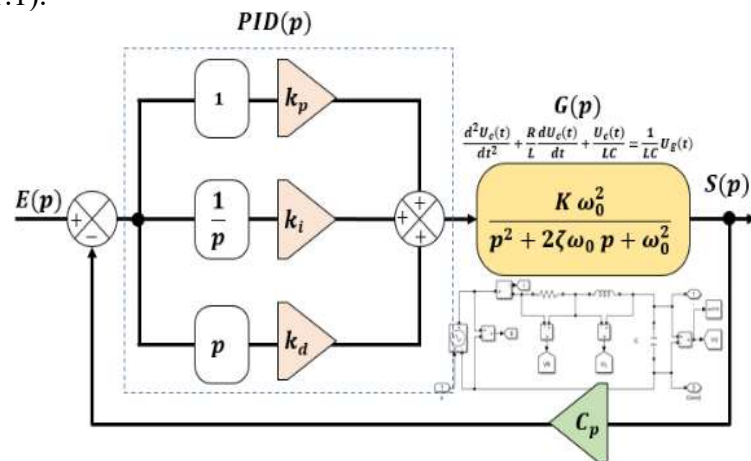


Fig. 1.1. PID-RLC: Second-order system functional diagram

The performance of the PID controller depends heavily on the tuning of its gains. This study aims to:

- Compare the open-loop response of an RLC circuit with PID control using manual, Ziegler-Nichols, particle swarm optimization (PSO) and genetic algorithm (GA) tunings.
- Test robustness against parameter variations ( $R$ ,  $L$ ,  $C$ ,  $\omega_0$ ,  $\zeta$ ), dynamic setpoint changes, and external disturbances.
- Analyse stability using Bode, Nyquist, sensitivity functions, gain/phase margins.
- Extend the methodology to a buck converter, comparing manual and optimized PID.

All simulations are performed in MATLAB using the nominal parameters listed in Table 1.1. The “Varied values” in Table 1.1 are examples of the magnitude of variations used in robustness tests for  $R$ ,  $L$ ,  $C$  (each varied independently, not simultaneously). The specific varied values for  $R$ ,  $L$ ,  $C$ ,  $\omega_0$ , and  $\zeta$  are detailed in the results for each scenario.

**Table 1.1.** Nominal and varied values for the RLC circuit study

| Scenarios      | R ( $\Omega$ ) | L (H)              | C ( $\mu F$ ) | Voltage setpoint (V) |
|----------------|----------------|--------------------|---------------|----------------------|
| Nominal values | 100            | 5                  | 10            | 9 V                  |
| Varied values  | 2500           | 250                | 500           | 9 V                  |
| Buck converter | 0.2            | $50 \cdot 10^{-6}$ | 100           | 5 V                  |

Figure 1.2 illustrates the impact of varying the natural angular frequency  $\omega_0$  on the step response of the PID-controlled RLC circuit, with a fixed damping factor  $\zeta = 0.1$ . A higher  $\omega_0$  (faster response) leads to more pronounced oscillations, while a lower  $\omega_0$  produces a slower but smoother response. The different curves correspond to the  $\omega_0$  values listed in Table 1.2.

**Table 1.2.** Second-order system natural frequency  $\omega_0$  variation ( $\zeta = 0.1$  fixed)

| Damped oscillations    | Frequency $\omega_0$ (rad/s) |      |       |      |       |
|------------------------|------------------------------|------|-------|------|-------|
| Robustness: $\omega_0$ | 628                          | 31.4 | 12.56 | 6.28 | 1.256 |

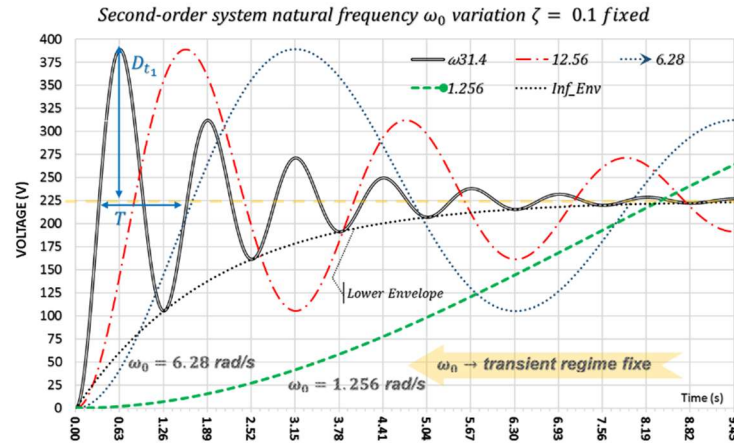
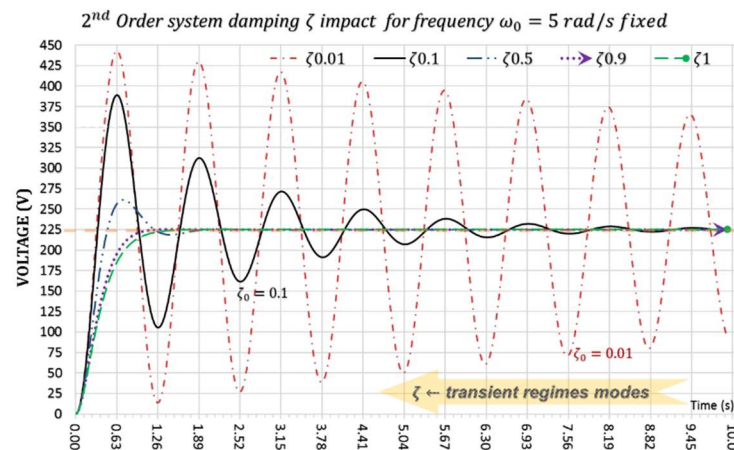
**Fig. 1.2.** PID robustness – variation of natural frequency  $\omega_0$ 

Figure 1.3 shows the effect of varying the damping factor  $\zeta$  on the transient response, with  $\omega_0$  fixed at 5 rad/s. A smaller  $\zeta$  gives more oscillatory and poorly damped behavior, whereas a  $\zeta$  approaching or exceeding 1 produces a smooth, over-damped response. The values are given in Table 3.

**Table 1.3.** Damping factor  $\zeta$  variation ( $\omega_0 = 5$  rad/s fixed)

| Regime              | Damped oscillations |     |     |     | Critically Damped |
|---------------------|---------------------|-----|-----|-----|-------------------|
| Robustness: $\zeta$ | 0.01                | 0.1 | 0.5 | 0.9 | 1                 |

**Fig. 1.3.** PID Robustness: Damping  $\zeta$  Variations Comparison

The transient regime is characterized by dynamic oscillations, overshoots, or undershoots, which eventually die out. Following the transient period, the system settles into its steady-state regime, where its output becomes constant or follows a predictable pattern. RLC circuits can

naturally exhibit numerous oscillations during their transient phase, particularly when they are underdamped, making it difficult to achieve stable and accurate output control.

Automatic control systems are necessary to reduce these temporary instabilities and ensure that the system outputs remain at the desired setpoints during steady-state operation. The PID controller is the most widely used and adaptable feedback control system, both in industry and academia. It is effective because it can modify the system output based on the current error (proportional), past errors (integral), and expected errors (derivative). The performance and stability of a PID controller, however, depend heavily on the careful selection of its tuning parameters (proportional, integral, and derivative gains) and its ability to maintain the desired performance levels even in the face of system uncertainty or external disturbances.

Using MATLAB simulations, this study aims to thoroughly explore the dynamic behavior of an RLC circuit under PID control. The main challenge lies in managing the capacitor voltage so that it operates reliably, accurately, and consistently, both in transient and steady-state conditions, regardless of operating conditions.

The main objectives are:

- To study and compare the response of a bare RLC circuit to environmental variations with its behavior under active PID control.
- To test the effectiveness of alternative PID tuning methods, particularly by comparing manual tuning with well-known empirical methods such as the Ziegler-Nichols method, as well as with optimisation algorithms (PSO, GA).
- To thoroughly test the PID controller's ability to handle expected real-world problems, such as variations in RLC circuit parameters ( $R$ ,  $L$ ,  $C$ , natural frequency  $\omega_0$  and damping factor  $\zeta$ ), dynamic setpoint tracking, and external disturbances.
- To measure controller performance in all situations using a comprehensive set of time-based performance indices (rise time, settling time, overshoot, steady-state error, IAE, ISE, ITAE, ITSE) and frequency stability margins (gain margin, phase margin, sensitivity functions).
- To automate the entire simulation, analysis, and data reporting process in a single MATLAB environment, facilitating methodical evaluation.

The remainder of this paper is structured as follows: Section 2 describes the mathematical modelling of the RLC circuit and the PID controller. Section 3 presents the results of the various comparison and robustness scenarios. Section 4 discusses these results and their impact on controller performance and resilience. Finally, Section 5 concludes the study and suggests avenues for future research.

## 2. SECOND-ORDER SYSTEM MATHEMATICAL MODELLING

This section presents the differential equations governing the series RLC circuit, the PID controller with derivative filter and anti-windup, and the overall closed-loop system. The modelling is extended to a buck converter for the power electronics application. The second-order differential equation is given as:

$$\ddot{s}(t) + 2\zeta\omega_0 \dot{s}(t) + \omega_0^2 s(t) = \omega_0^2 e(t) \quad (1)$$

Where:

- $s(t)$  is the system output (variable to model, e.g., voltage or current);
- $e(t)$  is the system input (e.g., an applied voltage);
- $\tau_0$  is the system time constant;
- $\omega_0 = \frac{1}{\tau_0} = 2\pi f_0$  is the system's natural frequency;
- $\zeta$  is the system damping factor.

The solution is analyzed based on the damping factor  $\zeta$ . Typical responses are studied for standard inputs such as step, ramp, or causal sinusoidal signals. The general solution of the

differential equation (1) combines homogeneous and particular responses. For a step input  $e(t) = Eu(t)$ , the system response is categorized as follows:

- **Overdamped Regime ( $\zeta > 1$ ):** Non-oscillatory response with two distinct exponential solutions

$$s(t) = \left( \frac{\omega_2}{\omega_1 - \omega_2} e^{\omega_1 t} - \frac{\omega_1}{\omega_1 - \omega_2} e^{\omega_2 t} + 1 \right) E \quad (2)$$

- **Critically Damped Regime ( $\zeta = 1$ ):** Fastest response without oscillation

$$s(t) = (1 - (\omega_0 t + 1)e^{-\omega_0 t})E \quad (3)$$

- **Underdamped Regime ( $0 < \zeta < 1$ ):** Damped oscillations

$$s(t) = \left( 1 - \frac{e^{-\zeta \omega_0 t}}{\sqrt{1 - \zeta^2}} \sin(\omega_0 \sqrt{1 - \zeta^2} t + \arccos(\zeta)) \right) E \quad (4)$$

- **Periodic Regime ( $m = 0$ ):** Purely oscillatory

$$s(t) = (1 - \cos(\omega_0 t))E \quad (5)$$

Pseudo-Period and Overshoot

The pseudo-period  $T$  of oscillation is:

$$T = \frac{2\pi}{\omega_{ex}} = \frac{2\pi}{\omega_0 \sqrt{1 - \zeta^2}} = \frac{2\pi \tau_0}{\sqrt{1 - \zeta^2}} \quad (6)$$

The first overshoot  $M_p$ , defined as the deviation of the first peak  $s(t)$  from its final value  $E$ , occurs at time  $t_1$ :

$$t_1 = t_p = \frac{\pi}{\omega_{ex}} = \frac{\pi \tau_0}{\sqrt{1 - \zeta^2}} \quad (7)$$

The overshoot value is:

$$M_p = e^{-\frac{\zeta \pi}{\sqrt{1 - \zeta^2}}} \quad (8)$$

## 2.1. Series RLC Circuit Dynamics

Consider a series RLC circuit (Fig. 1.1) consisting of a resistor  $R$ , an inductor  $L$ , and a capacitor  $C$ , driven by an input voltage  $V_{in}(t)$ .

The output of interest is the capacitor voltage  $V_C(t)$  and  $V_L(t)$ . Applying Kirchhoff's voltage law:

$$V_{in}(t) = V_R(t) + V_L(t) + V_C(t) = E \quad (9)$$

Where:  $V_R(t) = R \cdot I(t)$ ,  $V_L(t) = L \dot{I}(t)$ , and the current through the capacitor is  $I(t) = C \dot{V}_C(t)$

Substituting these relations yields a second-order differential equation:

$$\ddot{V}_C(t) + \frac{R}{L} \dot{V}_C(t) + \frac{1}{LC} V_C(t) = \frac{1}{LC} V_{in}(t) \quad (10)$$

For numerical simulation, it is convenient to rewrite (10) as a system of two first-order ordinary differential equations (state-space form). Define the state variables:

$$x_1(t) = V_C(t), \quad x_2(t) = \dot{V}_C(t)$$

Then,

$$\begin{cases} \dot{x}_1(t) = x_2(t) \\ \dot{x}_2(t) = \frac{1}{LC} (V_{in}(t) - RC x_2(t) - x_1(t)) \end{cases} \quad (11)$$

## 2.2. PID Controller with Derivative Filter and Anti-Windup

The objective of the PID controller is to maintain the capacitor voltage  $V_C(t)$  at a desired setpoint  $V_{ref}(t)$  by adjusting the input voltage  $V_{in}(t)$ , which becomes the control signal  $V_{ctrl}(t)$ . The control error is:

$$e(t) = V_{ref}(t) - V_C(t) \quad (12)$$

A classical PID controller computes the control signal as:

$$V_{ctrl}(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \dot{e}(t) \quad (13)$$

where  $K_p$ ,  $K_i$ , and  $K_d$  are the proportional, integral, and derivative gains.

In practice, a pure derivative term amplifies high-frequency noise, so a first-order low-pass filter is added to the derivative action. The filtered derivative is implemented by introducing an additional state variable  $x_4(t)$  that represents the filtered derivative of the output (or of the negative output, since the setpoint is often constant). The common “derivative on output” form with filter time constant  $T_f$  is:

$$\dot{x}_4(t) = \frac{-\dot{V}_C(t) - x_4(t)}{T_f}, \quad D_{filt}(t) = K_d x_4(t) \quad (14)$$

Thus, the derivative term acts on  $-\dot{V}_C$ , which equals  $\dot{e}$  when the setpoint is constant. The integral term requires an additional state variable  $x_3(t) = \int_0^t e(\tau) d\tau$ , so that  $\dot{x}_3(t) = e(t)$ .

To prevent integral windup, an anti-windup mechanism is implemented: when the computed control signal exceeds the physical limits of the actuator (here  $V_{ctrl}$  is clamped between 0 and 20 V), the integral state is frozen if the error has the same sign as the saturation direction. More precisely:

$$\dot{x}_3(t) = \begin{cases} 0, & \text{if } (V_{ctrl,raw} > V_{max} \text{ and } e(t) > 0) \text{ or } (V_{ctrl,raw} < V_{min} \text{ and } e(t) < 0) \\ e(t), & \text{otherwise} \end{cases} \quad (15)$$

Where:  $V_{ctrl,raw} = K_p e + K_i x_3 + K_d x_4$  and the saturated output is  $V_{ctrl} = \text{clamp}(V_{ctrl,raw}, V_{min}, V_{max})$  with  $V_{min} = 0V$ ,  $V_{max} = 20V$ .

### 2.3. Complete Closed-Loop System

When the PID controller is active, the input to the RLC circuit is  $V_{in}(t) = V_{ctrl}(t) + V_{dist}(t)$ , where  $V_{dist}$  is an optional external disturbance. Combining (2), (5) and the integral state dynamics, we obtain a system of four first-order ODEs:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = \frac{1}{LC} (V_{ctrl} + V_{dist} - RC x_2 - x_1) \\ \dot{x}_3 = \begin{cases} 0, & (\text{anti-windup condition}) \\ e = V_{ref} - x_1, & (\text{otherwise}) \end{cases} \\ \dot{x}_4 = \frac{-\dot{x}_2 - x_4}{T_f} \end{cases} \quad (16)$$

Note that  $\dot{x}_2$  appears on the right-hand side of the last equation; this is handled implicitly because the solver updates all states simultaneously. In the actual MATLAB implementation, the derivative filter uses  $-\dot{V}_C$  instead of  $-\dot{x}_2$  for consistency.

This model is used for all closed-loop simulations (manual tuning, Ziegler-Nichols, PSO, GA) and for the robustness analyses (variations of  $R$ ,  $L$ ,  $C$ ,  $\omega_0$ ,  $\zeta$ , dynamic setpoint, disturbance).

### 2.4. Buck Converter Model

The same modelling framework applies to a buck converter, which is a DC-DC step-down power converter. Its averaged dynamic model (ignoring switching ripple) is also a second-order system.

For a buck converter with series resistance  $R$  (including inductor resistance), inductance  $L$ , output capacitance  $C$ , and duty cycle  $d(t)$ , the output voltage  $V_o(t)$  approximately satisfies:

$$\ddot{V}_o(t) + \frac{R}{L} \dot{V}_o(t) + \frac{1}{LC} V_o(t) = \frac{1}{LC} V_{in}(t) d(t) \quad (17)$$

In our PID control configuration, the duty cycle is generated by the PID controller output (scaled to a maximum of 1, but we directly use the control voltage as the input to the RLC-type equation, because the buck converter is simulated with the same state-space structure as (11)

where the input is the continuous control voltage limited to 0–20 V). The nominal parameters for the buck converter are  $R = 0.2\Omega$ ,  $L = 50\mu H$ ,  $C = 100\mu F$ , and setpoint  $V_{ref} = 5 V$ .

The PID gains for the manual case are  $K_p=0.5$ ,  $K_i=200$ ,  $K_d=1\times 10^{-5}$  with derivative filter time constant  $T_f = 1\mu s$ .

### 2.5. Performance Metrics

To quantitatively assess the controller performance, the following time-domain metrics are computed from the step response:

- **Rise time**  $t_r$ : time from 10% to 90% of the final setpoint.
- **Settling time**  $t_s$ : time after which the response remains within 2% of the setpoint.
- **Overshoot**  $M_p$ : peak deviation above the setpoint, expressed as a percentage.
- **Steady-state error**  $ess$ : final difference between output and setpoint.

Additionally, integral error indices are used to measure the cumulative tracking error:

$$IAE = \int_0^\infty |e(t)|dt, ISE = \int_0^\infty e(t)^2 dt, ITAE = \int_0^\infty t|e(t)|dt, ITSE = \int_0^\infty te(t)^2 dt$$

In the frequency domain, the stability of the closed-loop system is analysed using:

- **Gain margin**  $GM$  and **phase margin**  $PM$  obtained from the open-loop transfer function  $L(s) = C(s)G(s)$ , where  $C(s)$  is the PID transfer function (including the filter) and  $G(s) = \frac{1}{LCs^2 + RCs + 1}$ .
- **Sensitivity functions**: sensitivity  $S = \frac{1}{1+L}$ , complementary sensitivity  $T = \frac{L}{1+L}$ , and control sensitivity  $KS = \frac{C}{1+L}$ . Their infinity norms ( $M_S, M_T, M_{KS}$ ) indicate robustness to model uncertainties.

All simulations are carried out with a fixed time span of 5 seconds and a time step of 0.1ms, using the variable-step Runge-Kutta solver ode45 (and ode15s for stiff buck converter cases).

## 3. RESULTS AND DISCUSSION

This section presents the complete simulation outcomes for the series RLC circuit and the buck converter. All results are derived from the MATLAB environment using the nominal parameters listed in Table 1.1. The performance is evaluated through time-domain metrics (rise time, settling time, overshoot, steady-state error, IAE, ISE, ITAE, ITSE) and frequency-domain tools (Bode, Nyquist, sensitivity functions). The discussion is integrated with the results to highlight the key findings and trade-offs.

### 3.1. Open-Loop Response and PID Control (Manual vs. Ziegler-Nichols)

**Open-loop behaviour:** Fig. 3.1 shows the capacitor voltage  $V_C(t)$  and inductor voltage  $V_L(t)$  for the bare RLC circuit without any controller. The response exhibits a large overshoot of 80.05% and a settling time of 0.382 s (Table 3.1). The steady-state error is negligible because the circuit is stable and the step input is 12 V, but the oscillatory nature (underdamped,  $\zeta=0.1$ ) makes it unacceptable for applications requiring precise voltage regulation.

**Manual PID tuning:** With gains  $K_p = 100$ ,  $K_i = 1000$ ,  $K_d = 0.5$  and a derivative filter time constant  $T_f = 0.001 s$ , the closed-loop response (Fig. 3.2) is dramatically improved. The overshoot drops to 13.67%, the settling time reduces to 0.0238 s, and the steady-state error becomes zero (Table 3). The rise time remains very short (0.006 s). The control signal (Fig. 3.3) saturates briefly at 20 V but quickly settles to a steady value of 9 V.

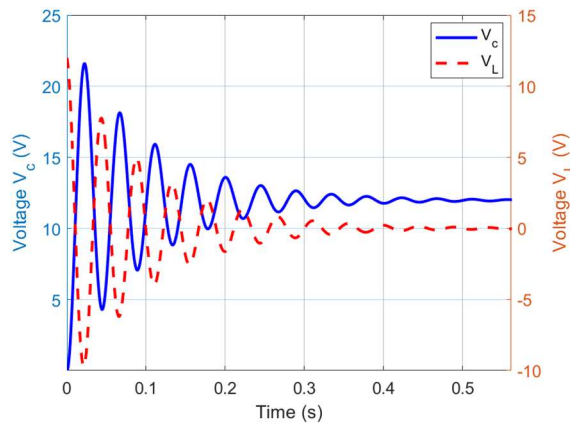


**Fig. 3.1.** Capacitor and inductor voltages – open-loop

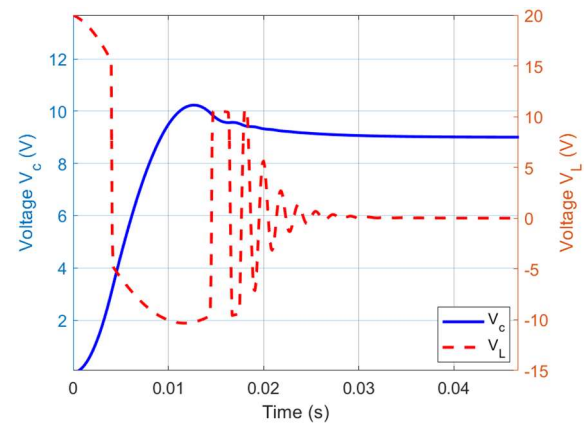


**Fig. 3.2.** Capacitor and inductor voltages – manual PID

**Ziegler-Nichols tuning:** Using the ultimate gain method, the gains are  $K_p = 0.08485$ ,  $K_i = 3.8197$ ,  $K_d = 4.71 \times 10^{-4}$ . The step response (Fig. 3.2) shows **no overshoot** but an extremely slow rise time of 0.617 s and a settling time of 1.084 s. The control effort (Fig. 3.3) is much smaller (peak 9 V) and remains within limits, but the sluggish response is often impractical.

Fig. 3.4 shows comparison of capacitor voltages for all PID tunings eliminate steady-state error. Manual and optimised (PSO/GA) tunings give fast responses; Ziegler-Nichols is very slow but overshoot-free.

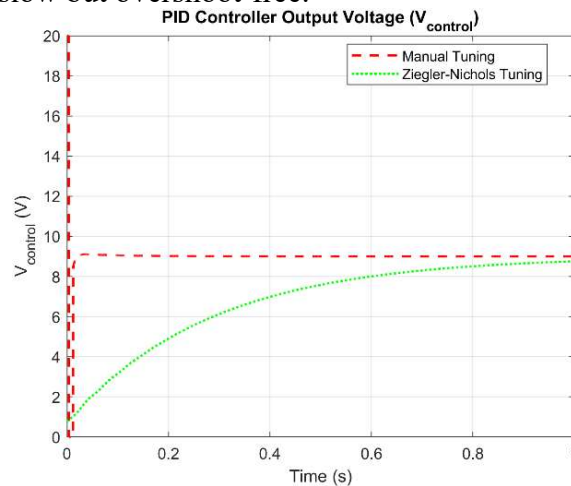


**Fig. 3.3.** PID Controller Output Voltage: Manual vs Ziegler-Nichols Tuning

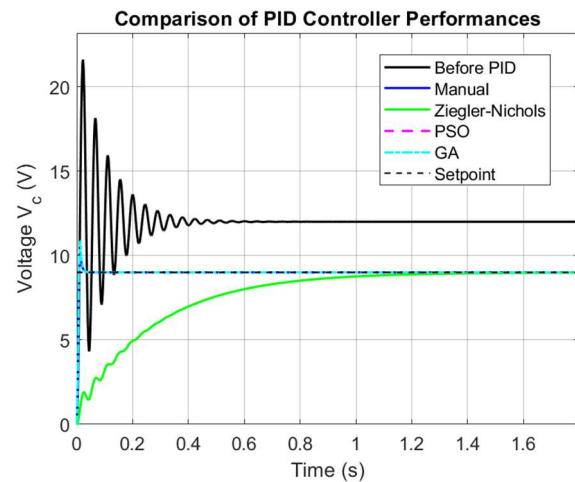


**Fig. 3.4.** Comparison of capacitor voltages: open-loop, manual PID, Ziegler-Nichols, PSO, GA.

**Quantitative comparison:** Table 3.1 summarises the key indices. Although Ziegler-Nichols eliminates overshoot, its IAE (2.356) and ITAE (0.666) are **two orders of magnitude larger** than those of manual tuning (IAE=0.0555, ITAE=0.000303). Hence, for this RLC circuit, manual tuning provides a superior balance between speed and accuracy.

**Table 3.1.** Performance indices for open-loop, manual PID and Ziegler-Nichols

| Scenario        | Rise time (s) | Settling time (s) | Overshoot (%) | IAE    | ITAE     |
|-----------------|---------------|-------------------|---------------|--------|----------|
| Open-loop       | 0.0076        | 0.3820            | 80.05         | 0.7677 | 0.07633  |
| Manual PID      | 0.0060        | 0.0238            | 13.67         | 0.0555 | 0.000303 |
| Ziegler-Nichols | 0.6172        | 1.0843            | 0.00          | 2.356  | 0.6657   |

### 3.2. Robustness to Parameter Variations ( $R$ , $C$ , $L$ , $\omega_0$ , $\zeta$ )

The PID controller (manual tuning) was tested against large changes in individual component values, while keeping the other parameters at nominal.

**Variation of R, C, L:** Fig. 3.5 compares the responses when  $R$  is multiplied by 25 ( $2500\ \Omega$ ),  $C$  by 50 ( $500\ \mu\text{F}$ ), and  $L$  by 50 ( $250\ \text{H}$ ). The controller maintains stability in all cases, but performance degrades as expected (Table 3.2):

- **R increase** (more damping) reduces overshoot to 0.97% but lengthens rise time to 0.015 s (IAE=0.093).
- **C increase** (lower natural frequency) gives 26.4% overshoot and IAE=0.454.
- **L increase** (higher inertia) causes 88.6% overshoot and IAE=1.585, yet the system still settles eventually.

**Variation of  $\omega_0$ :** Fig. 3.6 shows that reducing  $\omega_0$  from its nominal value (447.2 rad/s) to  $0.5\times\omega_0$  ( $\approx 223.6$  rad/s) results in a slower response with 41.1% overshoot and IAE=0.146. For very low  $\omega_0$  (e.g., 1.256 rad/s, not shown), the response becomes extremely sluggish but remains stable.

**Variation of  $\zeta$ :** Fig. 3.6 illustrates the effect of  $\zeta$ . At  $\zeta=0.01$  (highly underdamped), the overshoot reaches 18.5% and the IAE is 0.0602. As  $\zeta$  increases to one (critical damping), the overshoot disappears and the response becomes faster.

**Table 3.2.** Robustness metrics for parameter variations (manual PID)

| Variation             | Rise time (s) | Settling time (s) | Overshoot (%) | IAE    | ITAE    |
|-----------------------|---------------|-------------------|---------------|--------|---------|
| $R \times 25$         | 0.0151        | 0.0256            | 0.97          | 0.0931 | 0.00191 |
| $C \times 50$         | 0.0402        | 0.1544            | 26.38         | 0.4539 | 0.01951 |
| $L \times 50$         | 0.0319        | 0.4972            | 88.61         | 1.5853 | 0.2685  |
| $\omega_0 \times 0.5$ | 0.01          | 0.0404            | 41.1          | 0.1461 | 0.00261 |
| $\zeta \times 0.5$    | 0.0058        | 0.0256            | 18.49         | 0.0602 | 0.00057 |

These tests confirm that the manually tuned PID is **robust** over a wide range of parameter excursions, though extreme variations (e.g.,  $50\times$  inductance) cause large overshoots that may be unacceptable in some applications.

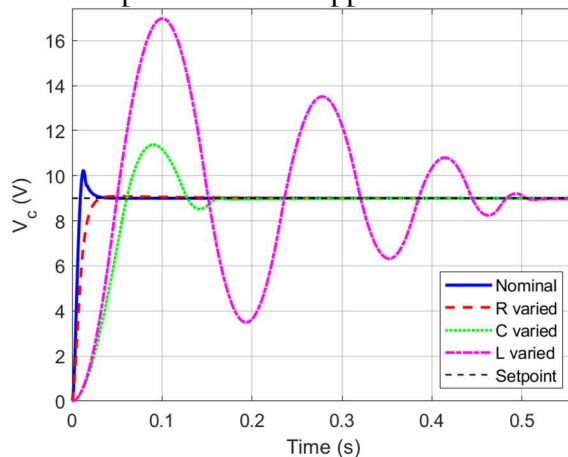


**Fig. 3.5.** PID robustness – R, C, L parameter variations.

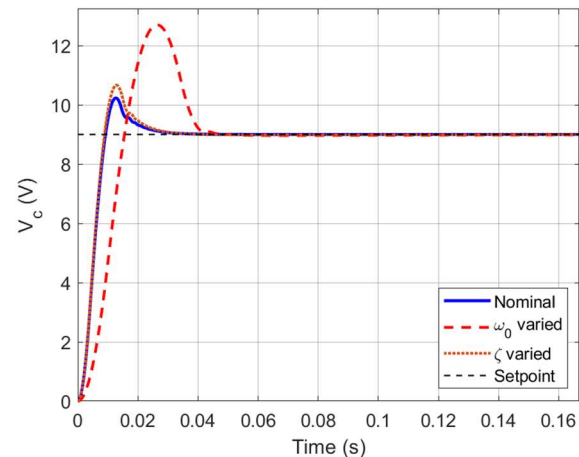


**Fig. 3.6.** PID robustness – natural frequency  $\omega_0$  and damping factor  $\zeta$ .

### 3.3. Dynamic Setpoint Tracking and Disturbance Rejection

**Setpoint change:** Fig. 3.7 shows the response when the reference voltage is stepped from 9 V to 13.5 V at  $t=2.5$  s. The controller tracks the new setpoint with an IAE of 0.0949 and a slight overshoot. The settling time after the change is approximately 0.03 s.

**External disturbance:** A 10 V step disturbance is applied at  $t=1.25$  s (Fig. 3.8). The output deviates temporarily but returns to the setpoint within 0.1 s. The IAE for this scenario is 3.807, indicating effective disturbance rejection.

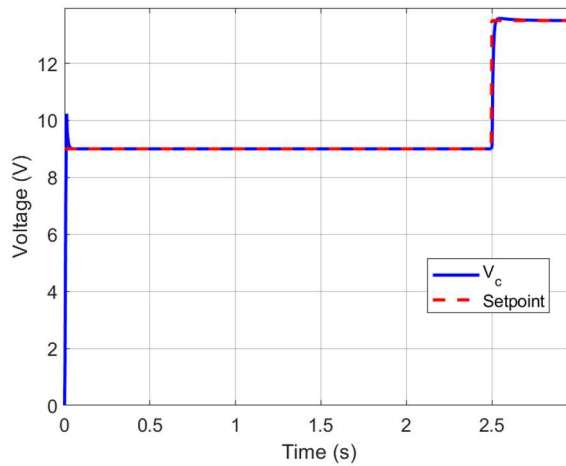


**Fig. 3.7.** PID Robustness: Dynamic Setpoint Tracking

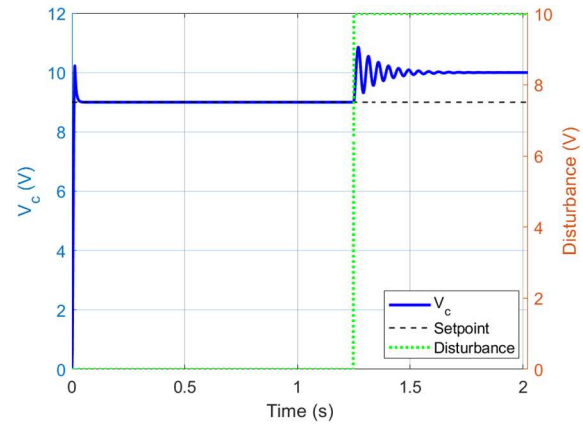


**Fig. 3.8.** PID Robustness: Disturbance Rejection

### 3.4. Optimisation of PID Gains (PSO and GA)

Both particle swarm optimisation (PSO) and genetic algorithm (GA) were used to minimise the ITAE criterion, with the same bounds ( $K_p \in [0,500]$ ,  $K_i \in [0,2000]$ ,  $K_d \in [0,5]$ ). After 30 iterations (population 20), the optimal gains are in Table 3.3:

**Table 3.3.** Optimal gains and ITAE (single run)

| Method | $K_p$ | $K_i$  | $K_d$ | ITAE                   |
|--------|-------|--------|-------|------------------------|
| PSO    | 316.2 | 1592.2 | 1.38  | $3.695 \times 10^{-4}$ |
| GA     | 384.8 | 1573.8 | 1.683 | $3.686 \times 10^{-4}$ |

Fig. 3.9 compares the ITAE comparison over 10 Independent Runs. The optimised controllers are **faster** (rise time 0.0056 s) than manual (0.006 s) but exhibit **higher overshoot** ( $\approx 21\%$  vs. 13.7%) and a slightly larger IAE (0.0598 vs. 0.0555).

This illustrates a classical trade-off: aggressive tuning reduces rise time at the cost of increased overshoot and reduced phase margin (see Section 3.5).

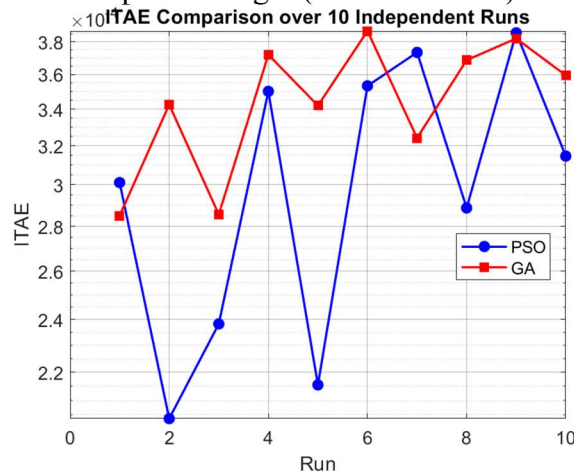


**Fig. 3.9.** ITAE comparison over 10 Independent Runs

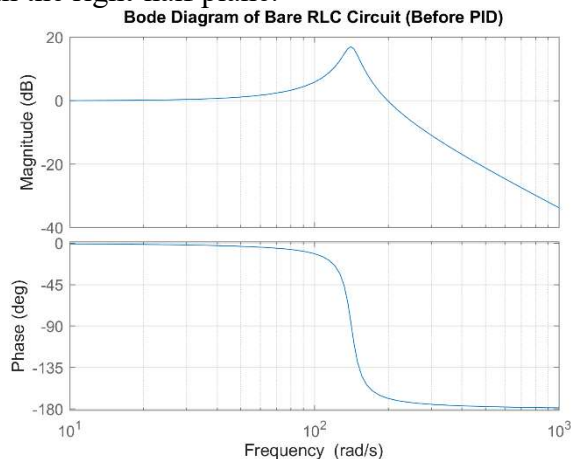
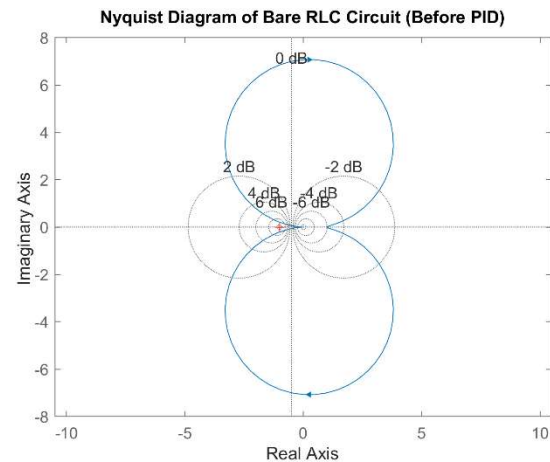
**Statistical analysis (10 runs):** Table 3.4 reports the means and standard deviations of the gains and ITAE for PSO and GA. Both methods show moderate variability; GA yields slightly lower ITAE on average ( $3.45 \times 10^{-4}$ ) than PSO ( $3.02 \times 10^{-4}$ ), but the difference is not significant. The large standard deviation of  $K_p$  and  $K_i$  indicates that many gain combinations can achieve similar ITAE values.

**Table 3.4** Statistics of PSO and GA over 10 independent runs

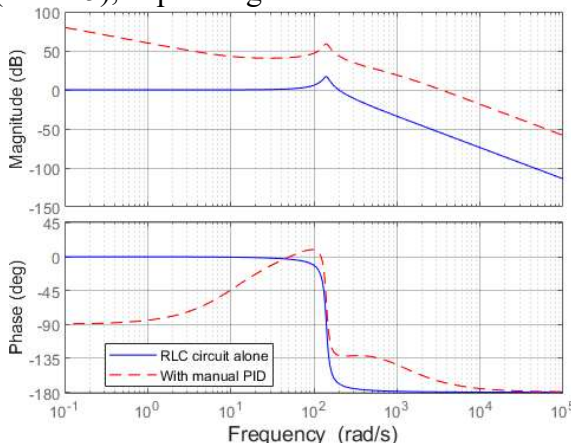
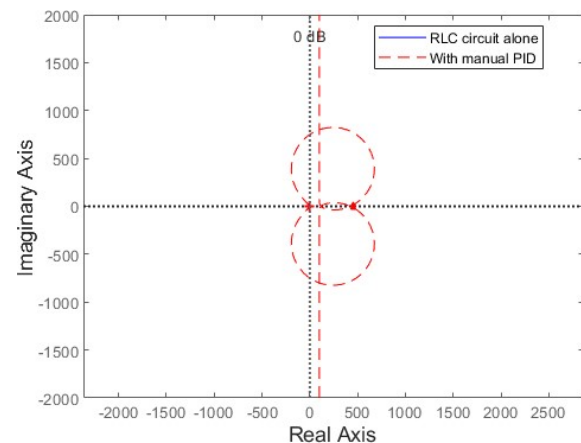
| Method | Parameter | Mean                  | Std                   | Min                   | Max                   |
|--------|-----------|-----------------------|-----------------------|-----------------------|-----------------------|
| PSO    | Kp        | 221.8                 | 127.4                 | 30.44                 | 457.6                 |
|        | Ki        | 1083.6                | 498.7                 | 556.2                 | 2000                  |
|        | Kd        | 1.118                 | 0.656                 | 0.175                 | 2.31                  |
|        | ITAE      | $3.02 \times 10^{-4}$ | $6.55 \times 10^{-5}$ | $2.04 \times 10^{-4}$ | $3.86 \times 10^{-4}$ |
| GA     | Kp        | 285.3                 | 106.9                 | 89.19                 | 413.4                 |
|        | Ki        | 1398.2                | 370.4                 | 884.5                 | 1911.3                |
|        | Kd        | 1.331                 | 0.542                 | 0.383                 | 2.146                 |
|        | ITAE      | $3.45 \times 10^{-4}$ | $3.68 \times 10^{-5}$ | $2.85 \times 10^{-4}$ | $3.87 \times 10^{-4}$ |

### 3.5. Frequency-Domain Analysis (Bode, Nyquist, Sensitivity)

**Bare RLC circuit:** The Bode diagram (Fig. 3.10) shows a resonant peak at the natural frequency ( $\approx 447$  rad/s), confirming underdamped dynamics. The Nyquist plot (Fig. 3.11) stays in the right-half plane.

**Fig. 3.10.** Bode diagram of bare RLC circuit**Fig. 3.11.** Nyquist diagram of bare RLC circuit

**Open-loop with PID:** Figs. 3.12 and 3.13 present the Bode and Nyquist plots for manual and ZN tunings. The gain margin is infinite for both (since the phase never crosses  $-180^\circ$ ). The phase margin (PM) is  $13.9^\circ$  for manual and  $94.7^\circ$  for ZN. The low PM of manual tuning explains the 13.7% overshoot (underdamped closed-loop poles), while the large PM of ZN yields a very sluggish but well-damped response. For PSO and GA, the PM drops to  $\approx 8^\circ$  (Table 5), explaining the 21% overshoot.

**Fig. 3.12.** Bode diagram – open-loop with manual PID**Fig. 3.13.** Nyquist diagram – open-loop with manual PID

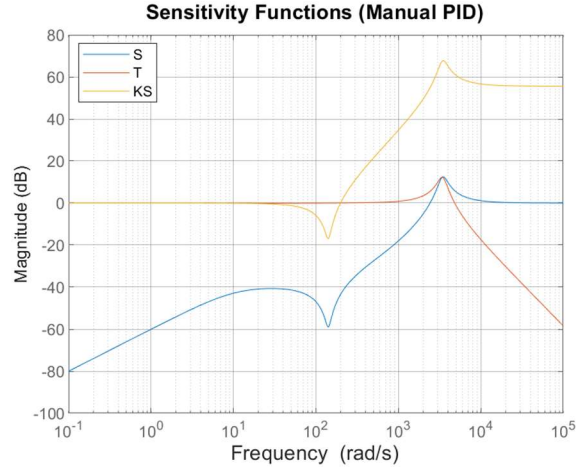
Sensitivity functions:

For PSO and GA,  $MS$  rises to 7–8 (Table 3.5), meaning these tunings are more sensitive to parameter variations – a drawback of their aggressive nature.

**Table 3.5.** Stability margins and sensitivity peaks for different tunings

| Tuning          | Phase margin (deg) | <i>MS</i> | <i>MT</i> | <i>MKS</i> |
|-----------------|--------------------|-----------|-----------|------------|
| Manual          | 13.9               | 4.25      | 4.13      | 2453       |
| Ziegler-Nichols | 94.7               | 1.16      | 1         | 1          |
| PSO             | 8.15               | 7.1       | 7.04      | 11883      |
| GA              | 7.39               | 7.82      | 7.76      | 15981      |

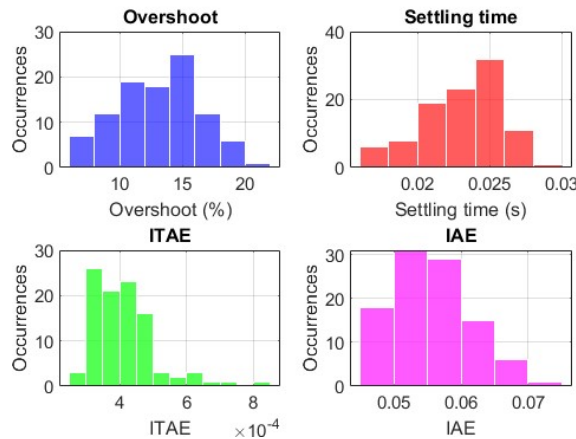
Fig. 3.14 plots *S*, *T*, and *KS* for the manual PID. The peak sensitivity *MS*=4.25 indicates moderate robustness to model uncertainties.

**Fig. 3.14.** Sensitivity functions (*S*, *T*, *KS*) for manual PID

### 3.6. Monte Carlo Analysis

One hundred simulations were performed with random variations of *R*, *L*, and *C* of  $\pm 20\%$  (uniform distribution). The manual PID tuning was used. The histograms of overshoot, settling time, ITAE, and IAE are shown in Fig. 15. The mean overshoot is 13.1% with a standard deviation of 3.24%; the mean ITAE is  $4.12 \times 10^{-4}$  (Table 6).

Monte Carlo Analysis (100 samples  $\pm 20\%$  on *R*, *L*, *C*)

**Fig. 3.15.** Monte Carlo histograms (100 runs,  $\pm 20\%$  on *R*, *L*, *C*)

These results confirm that the controller **maintains acceptable performance** even when all three components vary simultaneously within typical manufacturing tolerances.

**Table 3.6.** Monte Carlo results (100 runs,  $\pm 20\%$  on *R*, *L*, *C*)

| Metric            | Mean                  | Std                   | Min                   | Max                   |
|-------------------|-----------------------|-----------------------|-----------------------|-----------------------|
| Overshoot (%)     | 13.08                 | 3.24                  | 6.33                  | 21.57                 |
| Settling time (s) | 0.0231                | 0.00279               | 0.016                 | 0.0289                |
| ITAE              | $4.12 \times 10^{-4}$ | $9.41 \times 10^{-5}$ | $2.69 \times 10^{-4}$ | $8.48 \times 10^{-4}$ |
| IAE               | 0.0556                | 0.0055                | 0.0459                | 0.0729                |

### 3.7. Buck Converter Application (Manual vs. Optimised PID)

The buck converter parameters are given in Table 1.1. Two PID tunings were compared: a manually chosen set ( $K_p = 0.5$ ,  $K_i = 200$ ,  $K_d = 1 \times 10^{-5}$ ) and a PSO-optimised set ( $K_p = 5$ ,  $K_i = 500$ ,  $K_d = 0.002074$ ). The derivative filter time constant is  $T_f = 1 \mu s$ .

**Time-domain response:** Fig. 3.16 shows the output voltage  $V_o(t)$  for both tunings. The optimised PID achieves a rise time of 4.3 ms compared to 14.2 ms for manual tuning (Table 3.7). The settling time is slightly reduced (23.2 ms vs. 26.3 ms). Both controllers exhibit zero overshoot and zero steady-state error. The control effort (Fig. 3.17) is almost identical in terms of energy ( $L_2$  norm: 11.17 vs. 11.18), but the optimised controller initially demands a higher peak voltage ( $\approx 8$  V vs.  $\approx 5$  V).

**Integral errors:** The IAE drops from 0.0250 (manual) to 0.0100 (optimised) – a **2.5-fold improvement**. Nearly half also reduce the ITAE.

**Frequency-domain:** Fig. 3.18 compares the closed-loop Bode plots. The optimised controller has a higher bandwidth, explaining the faster rise time. The sensitivity peaks (Table 3.8) are moderate:  $MS=2.30$  for the optimised case vs. 1.41 for manual, indicating a slightly lower robustness, which is acceptable for this application.

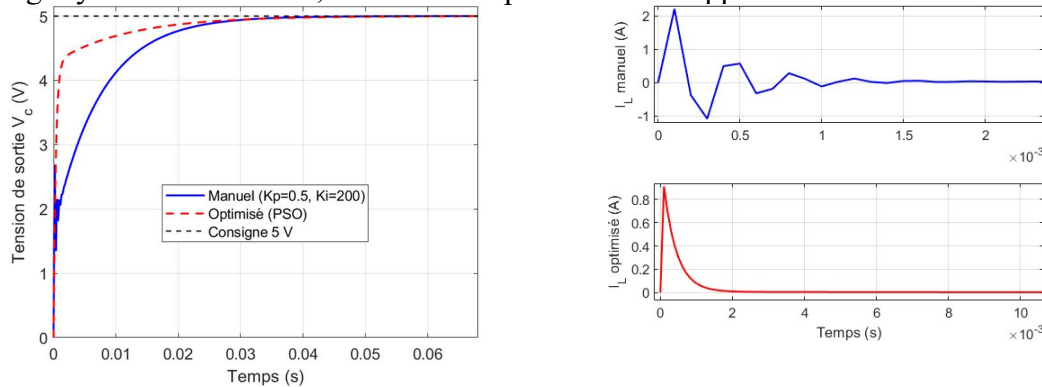


**Fig. 3.16.** Buck converter – output voltage (manual vs. PSO-optimised) and inductor current

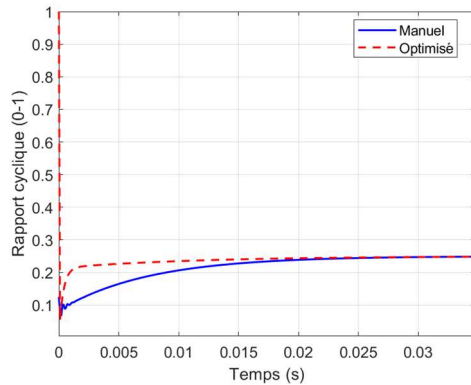


**Fig. 3.17.** Buck converter – duty cycle (control signal)

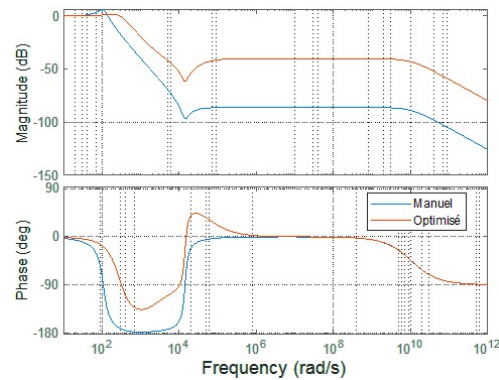


**Fig. 3.18.** Buck converter – Bode diagram of closed-loop system

**Table 3.7.** Buck converter performance (manual vs. PSO-optimised)

| Metric                   | Manual                | Optimised (PSO)       |
|--------------------------|-----------------------|-----------------------|
| Rise time (s)            | 0.0142                | 0.0043                |
| Settling time (s)        | 0.0263                | 0.0232                |
| Overshoot (%)            | 0                     | $\approx 0$           |
| IAE                      | 0.025                 | 0.01                  |
| ITAE                     | $1.87 \times 10^{-4}$ | $9.91 \times 10^{-5}$ |
| Control energy ( $L_2$ ) | 11.17                 | 11.18                 |

**Table 3.8.** Sensitivity peaks for buck converter

| Tuning    | $MS$  | $MT$  | $MKS$ |
|-----------|-------|-------|-------|
| Manual    | 1.406 | 1.052 | 10.5  |
| Optimised | 2.298 | 2.053 | 10.5  |

The higher  $MS$  of the optimised controller (2.30 vs. 1.41) indicates slightly reduced robustness to model uncertainties, but the value remains within acceptable limits ( $MS < 3$  is generally considered robust).

### 3.8. Discussion of Trade-Offs

The results clearly demonstrate that **no single tuning is universally optimal**; rather, the choice depends on the application requirements.

- **Manual tuning** offers a balanced compromise: fast response (6 ms rise), moderate overshoot (13.7%), low integral errors, and acceptable robustness ( $MS=4.25$ ). It is well-suited for general-purpose regulation.
- **Ziegler-Nichols** provides zero overshoot but at the expense of an extremely slow response (617 ms rise) and large integral errors. It may be useful only when overshoot is absolutely forbidden and speed is irrelevant.
- **PSO/GA optimisation** (minimising ITAE) pushes the system toward the stability boundary: rise times become even shorter (5.6 ms) but overshoot increases (21%) and phase margins drop below  $10^\circ$ , making the system sensitive to model uncertainties. The high  $MS$  values ( $\approx 7-8$ ) indicate poor robustness.
- **For the buck converter**, the optimised PID clearly outperforms the manual tuning, reducing the IAE by a factor of 2.5 with negligible increase in control energy. This is because the manual gains were not finely tuned; optimisation reveals that larger gains (especially  $K_p$  and  $K_i$ ) are beneficial for this fast power electronics system.

Robustness of the manual PID is confirmed by the Monte Carlo analysis: even with  $\pm 20\%$  variations in  $R$ ,  $L$ ,  $C$ , the overshoot stays below 22% and the settling time below 0.03 s. The robustness to parameter variations ( $\omega_0$ ,  $\zeta$ ) is also satisfactory, though extreme changes (e.g.,  $50\times$  inductance) cause large overshoots that may require retuning.

Frequency-domain metrics correlate well with time-domain behaviour: low phase margin leads to overshoot, high phase margin yields sluggishness, and high  $MS$  indicates fragility to model errors. The sensitivity analysis provides a valuable tool for predicting robustness without exhaustive time simulations.

In summary, the manual PID tuning developed in this study offers an excellent trade-off for the RLC circuit, while for the buck converter, the optimised PID is clearly superior. The methodology combining time-domain simulation, optimisation, Monte Carlo analysis, and frequency-domain validation proves effective for designing and assessing PID controllers in electrical systems.

## 4. CONCLUSION

This paper has presented a thorough simulation-based investigation of PID control applied to a series RLC circuit and a buck converter. The main findings are summarized as follows.

The open-loop RLC circuit exhibits 80% overshoot and a settling time of 0.382 s, which is unacceptable for most applications. All PID tunings eliminate steady-state error and drastically reduce overshoot and settling time.

- **Manual tuning** ( $K_p = 100$ ,  $K_i = 1000$ ,  $K_d = 0.5$ ) provides an excellent balance: rise time 6 ms, overshoot 13.7%, settling time 23.8 ms, IAE 0.0555, and phase margin  $13.9^\circ$ . The sensitivity peak  $MS = 4.25$  indicates moderate robustness.
- **Ziegler-Nichols** eliminates overshoot but is extremely slow (rise time 617ms, IAE 2.356), making it impractical for time-critical applications.

- **PSO and GA** (minimising ITAE) achieve the fastest rise times (5.6ms) but increase overshoot to  $\approx 21\%$ , reduce phase margins to  $\approx 8^\circ$ , and raise  $MS$  to 7–8, indicating poor robustness to model uncertainties. They are only recommended when speed is paramount and plant variations are negligible.

Tests with  $R$  multiplied by 25,  $C$  by 50,  $L$  by 50,  $\omega_0$  halved, and  $\zeta$  halved all maintained stability. Even under extreme variations (e.g.,  $L \times 50$ ), the system eventually settles, though overshoot reaches 88.6%. Monte Carlo analysis with  $\pm 20\%$  variations on  $R$ ,  $L$ ,  $C$  shows mean overshoot 13.1% and mean ITAE  $4.12 \times 10^{-4}$ , confirming that the controller tolerates typical component tolerances.

A step change from 9 V to 13.5 V at  $t=2.5$  s is followed with  $IAE = 0.0949$ . A 10 V disturbance is rejected within 0.1 s with  $IAE = 3.807$ .

Bode and Nyquist plots confirm closed-loop stability for all tunings. The phase margin correlates inversely with overshoot, and the peak sensitivity  $MS$  quantifies robustness to unmodelled dynamics. Manual tuning strikes a compromise with  $MS=4.25$ , whereas PSO/GA give  $MS>7$ .

Using the same PSO framework, the optimised PID ( $K_p = 5$ ,  $K_i = 500$ ,  $K_d = 0.00207$ ) reduces rise time from 14.2 ms to 4.3 ms and  $IAE$  from 0.0250 to 0.0100, with identical control energy. The sensitivity peak remains acceptable ( $MS=2.30$ ). This demonstrates that automatic tuning is particularly advantageous for fast power electronics systems where manual gains are often conservative.

Future work explore adaptive PID schemes that adjust gains online in response to changing operating conditions, fractional-order PID controllers for even greater flexibility, or the application of these optimisation methods to more complex converters (e.g., boost, buck-boost) with variable loads. Experimental validation on a hardware prototype would further strengthen the conclusions.

In summary, this study provides a comprehensive methodology for analysing, tuning, and validating PID controllers for electrical systems. The manually tuned PID offers the best overall compromise for the RLC circuit, while optimisation is highly recommended for power converters to unlock superior transient performance without increasing control energy. The combined time-domain and frequency-domain framework, together with Monte Carlo robustness analysis, serves as a practical guide for control engineers.

## REFERENCES

1. Abbasov, T., Yalçınöz, Z. & Keleş, C. (2024) Differential (Pukhov) transform method analysis of transient regimes in electrical circuits, *UNEC Journal of Engineering and Applied Sciences*, **4**(1), 5–19. doi: 10.61640/ujeas.2024.0501
2. Antohe, Ş. & Antohe, V.-A. (2025) *Transient phenomena in electrical circuits*, [Online]. Available: <https://iopscience.iop.org/book/mono/978-0-7503-5854-5/chapter/bk978-0-7503-5854-5ch8>
3. Aziz, G. A., Abdullah, F. N. & Shneen, S. W. (2024) Performance enhancement of DC motor drive systems using genetic algorithm-optimized PID controller for improved transient response and stability, *International Journal of Robotics and Control Systems*, **5**(1), 266–295. doi: 10.31763/ijrcs.v5i1.1602
4. Badrieh, F. (2018) *RLC circuits with feedback*, [Online]. Available: [https://www.researchgate.net/publication/324051572\\_RLC\\_Circuits\\_with\\_Feedback](https://www.researchgate.net/publication/324051572_RLC_Circuits_with_Feedback)
5. Devi, S. & Sahoo, S. K. (2023) Design and development of PV based hybrid multilevel inverter with Ziegler-Nichols Tuning method, *Proc. of 2023 International Conference on Intelligent and Innovative Technologies in Computing, Electrical and Electronics* (Bangalore, India), 850–854. doi: 10.1109/iitcee57236.2023.10090971.

6. E, I. A., Ikechukwu, O. & Paul, S. (2019) Comparative analysis of a PID controller using ziegler- Nichols and auto turning method, *International Academic Journal of Science and Engineering*, **06**(01), 51–66. doi: 10.9756/iajse/v6i1/1910005.
7. Kumar, A. & Pan, S. (2018) A PID controller design method using stability margin with transient improvement criteria, *Proc. of 2018 4th International Conference on Electrical Energy Systems* (Chennai, India), 506–510. doi: 10.1109/icees.2018.8442347
8. Matsushita, T. (2023) *Electricity. Electromagnetism and Electric Circuits*. Cham, Switzerland: Springer.
9. Mohamed, L. (2025) Investigating the interaction between electromagnetic and gravitational waves using an RLC circuit-based sensor, *SSRN*: 5275627, [Online]. Available: [https://papers.ssrn.com/sol3/papers.cfm?abstract\\_id=5275627](https://papers.ssrn.com/sol3/papers.cfm?abstract_id=5275627).
10. Nippatla, V. R. & Mandava, S. (2025) Performance analysis of permanent magnet synchronous motor based on Transfer Function Model using PID controller tuned by Ziegler-Nichols method, *SSRN*: 5134660, [Online]. Available: [https://papers.ssrn.com/sol3/papers.cfm?abstract\\_id=5134660](https://papers.ssrn.com/sol3/papers.cfm?abstract_id=5134660).
11. Nouman, D. & Hussain, T. (2023) Development of PID Controller Tuned by using Ziegler Nichols Method for Controlling the Fluid Level in Coupled Tank System, *International Conference on Innovative Academic Studies*, **3**(1), 646–670. doi: 10.59287/icias.1606
12. Patel, V. V. (2020) Ziegler-Nichols tuning method, *Resonance*, **25**(10), 1385–1397. doi: 10.1007/s12045-020-1058-z.
13. Pivoňka, P. (2021) Analysis and design of Fuzzy Pid Controller based on classical PID controller approach. In: Hampel, R., Wagenknecht, M. & Chaker, N. (Eds.) *Fuzzy Control. Advances in Soft Computing*, vol 6. Heidelberg, Germany: Physica, (pp. 186–199). doi: 10.1007/978-3-7908-1841-3\_14.
14. Steer, K. K., Kehoe, P. J. & Weldon, T. P. (2017) Measurement of a digital non-foster negative RLC circuit and digital positive RLC Circuit, *SoutheastCon 2017*, 1–5. doi: 10.1109/secon.2017.7925353.
15. Tadjeddine, A. A., et al. (2023) Transient Stability of Power in DFIG Wind Farm through Resilient with AFRR, IDA-PBC and PID Control, *Algerian Journal of Renewable Energy and Sustainable Development*, **5**(2), 104–117. doi: 10.46657/ajresd.2023.5.2.2
16. Sallam, A. A. & Malik, O. P. (2015) *Power System Stability: Modelling, Analysis and Control*. London, UK: The Institution of Engineering and Technology.
17. Karmalita, V. (2020) *Metrology of Automated Tests: Static and Dynamic Characteristics*. Berlin, Boston: De Gruyter.
18. Wang, M. (2019) *Understandable Electric Circuits: Key concepts (2<sup>nd</sup> Edition)*. London, UK The Institution of Engineering and Technology.
19. Yanou, A. (2019). A study on self-tuning PID control by Smart Strong Stability System, *Proc. of 2019 IEEE Conference on Control Technology and Applications* (Hong Kong), 816–821. doi: 10.1109/ccta.2019.8920435