Controller and Observer Design using Active Disturbance Rejection Control

Final year Project Report

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CERTIFICATE

This certifies that the project "Controller and Observer Design using Active Disturbance Rejection Control" that Ritika Meena (20225076) and Ratan Kumar (20225074) presented for the End Evaluation is their original work under my supervision.

With an emphasis on the Active Disturbance Rejection Control (ADRC) method, the study explores contemporary robust control strategies. The design and analysis of the Extended State Observer (ESO), the selection of controller parameters, and the testing of disturbance-handling capabilities under various operating situations are all included in the research.

The paper shows a well-considered MATLAB-based simulation of several dynamic systems and demonstrates the students' solid understanding of the theoretical ideas. In terms of the students' modeling, execution, and comparative performance evaluation, the work is outstanding.

Supervisor

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We are thankful to all those who have been part of this project journey, both individuals and institutions. Their trust and support have been our strength.

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It is also impossible to overlook the gratitude to the professors. The theoretical foundation needed for this study project was supplied by their classes, observations, and conversations. Our knowledge of power electronics, control systems, and system modeling has been greatly learned from their lessons.

In the end, we thank the thoughtful contributions of researchers and authors in the areas of control theory, observer design, and power electronics. Their work has been a great source of reference and has guided the way of this study.

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Abstract

This work investigates the design and simulation of a control strategy based on Active Disturbance Rejection Control (ADRC) coupled with an Extended State Observer (ESO). The problem addressed is that dynamic systems challenged by uncertain or variable conditions, in which traditional control schemes fail due to unmodeled disturbances, parameter drift, and inaccuracies in system representation, don't have many reliable solutions.

The study is about devising a control architecture that is still able to deliver trustworthy performance in the presence of these uncertainties. As a result, a single framework is put together which essentially mixes the elements of ADRC for compensating unknown influences, the ESO for constantly estimating disturbances and unaccounted-for dynamics, a Tracking Differentiator for providing smooth reference signals, and parts of the structure that are taken from Luenberger observers for better state reconstruction. Stability concerns are handled via Lyapunov-based arguments. To make the framework more powerful and flexible, a Nonlinear ADRC (N-ADRC) organization is added to it to improve the speed and strength of systems exhibiting nonlinear nature or sudden disturbance changes.

Experiments on three sample systems—a DC–DC buck converter with second-order dynamics, a heat process described as a first-order plant, and a SEPIC converter with nonlinear and switching-dependent behavior—are used to illustrate the impacts of the suggested controller. Performance is evaluated using metrics like tracking accuracy, disturbance rejection, and transient characteristics in addition to PID control as the baseline. Generally speaking, ADRC outperforms PID controllers in every situation.

For the heat transfer system, the tracking error is halved, i.e., going from 0.440°C to 0.209°C (RMSE), and the response is faster with less overshoot. In the power electronic converters, the method results in voltage regulation improvement, transient-free quicker settling, and better parameter variation tolerance. Besides, the controller stays stable and efficient despite system parameters changing by up to $\pm 20\%$ and measurement noise being present. Altogether, the combination of ESO, TD, and N-ADRC mounts to a potent and versatile control approach that can be relied upon to deal with disturbances and uncertainties. The overall results point to ADRC as a strong option worth considering when seeking an alternative to PID control in a broad spectrum of engineering applications.

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Chapter 1

Introduction

Modern engineering applications such as industrial automation, power electronics, robotics, aeronautical systems, and process control all depend on control systems. They are made to control system outputs to get the intended performance while preserving stability in a range of operating circumstances. However, systems seldom function perfectly in real-world settings. System performance is frequently deteriorated and precise control is challenging due to unknown disturbances, environmental fluctuations, component aging, modeling errors, and measurement noise.

Due to their ease of use and simplicity, traditional control methods like proportional-integral-derivative (PID) control have become widely accepted in industry. PID controllers, however, rely significantly on set operating conditions and exact parameter tuning. The performance of PID controllers may decline in reaction to changes in system parameters or unforeseen disturbances, leading to poor disturbance rejection, higher overshoot, and delayed transient response.

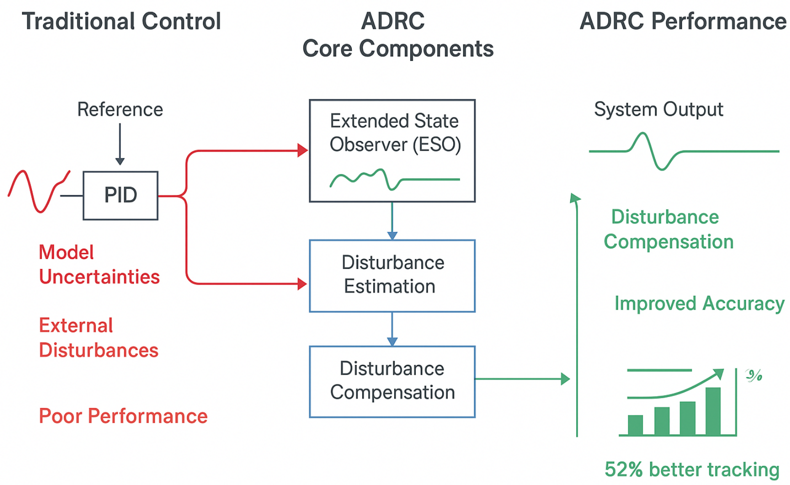

Figure 1.1: Comparison between PID Control and ADRC

Disturbance Rejection in Control Systems

Internal factors such as unmodeled system dynamics and parameter variations, along with external influences like load changes, environmental variations, and noise, can disrupt control performance. A controller must identify these effects and adjust accordingly to prevent a decline in output quality. Traditional controllers react only after disturbances have already influenced the output, often resulting in slower correction and reduced efficiency.

Observer-based control strategies address this limitation by using measured outputs to estimate internal states and disturbances. Approaches such as the Luenberger observer and the disturbance observer have been widely studied. Although they depend on accurate system models and fixed parameters, they provide valuable estimates that improve disturbance rejection.

Active Disturbance Rejection Control (ADRC)

ADRC is a control method that handles disturbances by checking for uncertainties like disturbances in real time and adjusting the control action within the loop. Instead of relying on an exact system model like PID , ADRC treats all unknown dynamics and disturbances as one combined disturbance(the extended state) that can be estimated and rejected. This makes the controller more robust and less dependent on detailed mathematical modeling.

the core of ADRC is the Extended State Observer . The ESO adds an extra state to represent the total disturbance(also known as virtual disturbance) acting on the system. It then estimates both the system states and this disturbance in real-time. Using these estimates, the controller cancels the disturbance effect, making the system easier to control and improve overall performance.

Tracking Differentiator (TD)

In ADRC, sudden changes in input signals can cause excessive control action and oscillations. A Tracking Differentiator is introduced to solve this problem by generating a smooth input signal and estimating its derivatives continuously . Instead of giving the controller abrupt input(setpoints), the TD provides a gradually varying setpoint , which improves stability and reduces transient peaks.

it smoothes the reference and , the Tracking Differentiator produces a reliable estimate of the input(reference) rate of change. This thing allows the controller to react more precisely to changing inputs and improves the behavior during system starts and reference changes.

Nonlinear Active Disturbance Rejection Control (N-ADRC)

While standard ADRC provides excellent performance for many linear systems, practical systems often exhibit nonlinear characteristics such as saturation, switching behavior, and fast-changing dynamics. Nonlinear Active Disturbance Rejection Control (N-ADRC) extends conventional ADRC by introducing nonlinear feedback mechanisms that improve system behavior under strong disturbances and operating nonlinearities.

N-ADRC replaces linear feedback functions with nonlinear error correction laws that allow fast response when the tracking error is large and smooth behavior when the error becomes small. As a result, the controller responds aggressively during large mismatches and gently near the steady state, leading to better accuracy and reduced oscillations.

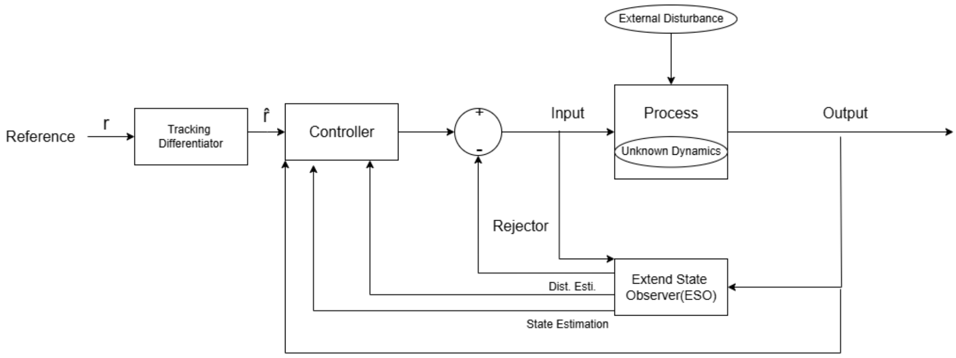

Figure 1.2: Block Diagram of Nonlinear Active Disturbance Rejection Control (N-ADRC)

Working Principle of N-ADRC Block Diagram

The Tracking Differentiator, Extended State Observer, Nonlinear Control Law, and the Controlled Plant are the four primary parts of the N-ADRC control system.

A smooth intended trajectory and its derivative are produced by the Tracking Differentiator after processing the reference signal. This stabilizes reference tracking and removes abrupt jumps in control input.

After receiving the plant output, the Extended State Observer calculates the overall disturbance and system states. The observer offers real-time insight into unidentified impacts operating on the system and updates continually.

The predicted system states and nonlinear error feedback functions are used by the Nonlinear Control Law to calculate the control signal. When the error is high, this structure enables the system to respond rapidly, and when steady operation is approaching, it settles smoothly.

Finally, the estimated disturbance is actively cancelled inside the controller, simplifying the system behavior and improving robustness. By continuously identifying and rejecting disturbances, N-ADRC ensures stable and accurate performance even under changing conditions and unpredictable operating environments.

Scope of This Work

This project is focused on analyzing the behaviour of PID and ADRC controllers When subject to Different Models Such as Heat Control System , DC-DC Buck Converter

, SEPIC Converter when they are subjected to uncertain models or disturbances.

Objectives

- To model practical systems with uncertainties and disturbances.
- To design and implement PID and ADRC controllers.
- To study the effect of disturbance rejection using ESO.
- To analyze the impact of Tracking Differentiator on transient response.
- To compare performance using simulation analysis.

Organization of the Report

This report is organized as follows: Chapter 2 discusses the literature survey and previous research work. Chapter 3 presents the modeling of all three systems. Chapter 4 describes controller and observer design. Chapter 5 discusses simulation implementation. Chapter 6 includes results and comparisons. Chapter 7 presents complexity analysis. Chapter 8 concludes the work and outlines future scope.

Chapter 2

Literature Survey

This chapter reviews research contributions related to PID control, observer-based strategies, disturbance observers, and Active Disturbance Rejection Control (ADRC), with special focus on applications in power electronics. The aim is to highlight existing approaches, their limitations, and the motivation for adopting ADRC in thermal systems and DC–DC converters including SEPIC.

2.1 Review of PID Control Techniques

Proportional–Integral–Derivative (PID) control remains widely used in industrial systems due to its simple structure and ease of tuning. Standard control references show that a well-tuned PID controller can provide satisfactory performance for linear time-invariant plants under nominal conditions [1]. However, PID assumes fixed model characteristics, and performance degrades when parameters change due to aging, load variation, or operating condition changes [2].

In switching power electronic systems, PID controllers face additional difficulty due to nonlinear behavior and fast dynamics, often requiring frequent retuning [3]. These drawbacks make PID insufficient under varying operating conditions and strong disturbances.

2.2 Observer-Based Control Strategies

Observer-based techniques reconstruct system states from output measurements. Luenberger first proposed the state observer for linear systems, forming the foundation for modern state estimation [4]. Kalman further extended estimation theory to noisy systems using optimal stochastic estimation [5].

Although Kalman filtering performs well under noise, observer accuracy depends on system modeling and noise statistics, which are difficult to determine in real systems. Nonlinear observer designs have also been proposed, where disturbances are estimated along with system states. Chen demonstrated observer-based disturbance estimation for nonlinear systems [7], but modeling uncertainty still limits practical application.

2.3 Disturbance Observer Approaches

Disturbance observers explicitly estimate unknown inputs acting on the system. Ohnishi introduced DOBs for disturbance compensation in motion control systems [6]. DOBs significantly improve performance when system models are accurate.

Later studies extended DOB theory to robust control by improving filtering techniques and stability margins [7, 11]. Nevertheless, DOB requires plant inverse modeling, which becomes inaccurate under uncertainties, limiting effectiveness in switching systems.

2.4 ADRC in Control Applications

Active Disturbance Rejection Control was formally introduced by Han as an observer-based control structure that estimates all uncertainties as a single generalized disturbance [8]. The Extended State Observer estimates this disturbance and enables compensation in real time.

Gao proposed practical tuning rules using bandwidth parameters, simplifying ADRC implementation [9]. Guo and Zhao later provided a rigorous theoretical framework proving stability and convergence of ESO-based systems [10].

ADRC has shown strong results in robotic motion control, motor drives, and nonlinear processes. Zhang demonstrated improvement in robotic manipulators, while Li applied ADRC to motor speed control with significant robustness gains.

2.5 ADRC in Power Electronics

Power converters face nonlinear dynamics, component drift, and load fluctuations, making PID control unreliable. ADRC has been increasingly applied to converters such as buck, boost, and isolated converters.

Chiumeo et al. applied ADRC to a Dual Active Bridge converter and reported strong improvement in voltage regulation and robustness under load disturbance [15].

For SEPIC converters, Sierra-Herrera et al. presented a detailed comparison among ADRC, PI, and PID controllers [16]. Their analysis used IAE, ITAE, and ISE performance indices. Results showed ADRC achieved superior voltage regulation and faster disturbance rejection with moderate complexity increase.

Earlier research applied PID control to SEPIC using optimization methods, but performance weakened during large disturbances [17]. Recent work by Patel and Singh confirmed ADRC's superiority over PI and PID under load variation and input disturbance conditions [14].

2.6 Summary of Literature Review

The literature confirms that:

- PID control is effective only under fixed operating conditions.
- Observer-based and DOB approaches improve disturbance handling but depend heavily on accurate modeling.
- ADRC actively estimates unknown dynamics and disturbances, offering improved robustness.
- Power electronic systems strongly benefit from ADRC due to nonlinear and switching behavior.
- Recent studies on SEPIC clearly show ADRC outperforms PI and PID controllers.

These findings justify the application of ADRC to heat transfer, buck, and SEPIC systems in this work.

Chapter 3

System Modeling

This chapter develops the complete mathematical models of the three systems used in this work: the heat transfer system, the DC–DC Buck converter, and the SEPIC converter. For each power converter, both the switch-level dynamic equations and the averaged control-oriented model are derived from first principles. These derivations are important because ADRC relies on a generalized plant description that requires understanding the underlying physics of the system.

3.1 Heat Transfer System

The heat transfer system is a slow first-order thermal process used to validate ADRC on a disturbance-dominant plant.

Energy Balance Derivation

The dynamics follow conservation of energy:

$$mc_p \frac{dT(t)}{dt} = Q(t) - Q_{\mathrm{loss}}(t) \tag{3.1}$$

Heat loss components:

$$Q_{\mathrm{loss}} = Q_{\mathrm{conv}} + Q_{\mathrm{rad}} \tag{3.2}$$

1. Convective Loss

$$Q_{\mathrm{conv}} = AU(T - T_a) \tag{3.3}$$

2. Radiative Loss

$$Q_{\mathrm{rad}} = A\epsilon\sigma(T^4 - T_a^4) \tag{3.4}$$

Substituting:

$$mc_p \frac{dT}{dt} = Q(t) - AU(T - T_a) - A\epsilon\sigma(T^4 - T_a^4) \tag{3.5}$$

For control design, we approximate radiation as a small linear term and arrive at a first-order system:

$$\dot{T}(t) = f(t) + b_0 u(t) \tag{3.6}$$

where $f(t)$ includes all unknown thermal losses/disturbances.

This form is directly compatible with ADRC.

3.2 DC–DC Buck Converter

The Buck converter steps down input voltage and represents a well-behaved second-order system. We derive its averaged model starting from switch-level equations.

Buck Circuit

The main components are:

- Inductor L
- Capacitor C
- Load resistance R
- Switch (MOSFET) and diode

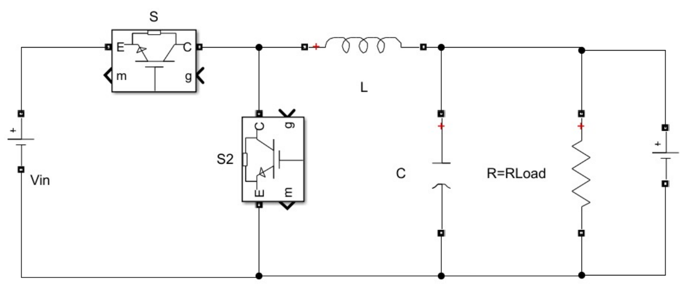

Figure 3.1: Buck Converter Circuit

3.2.1 Derivation of State Equations

The converter has two switching states.

Mode 1: Switch ON (S ON, S2 OFF)

When the main switch S is turned ON and the diode (or auxiliary switch) $S2$ is OFF, the inductor is directly connected to the input source V_{in}. The inductor current increases as energy is stored in the magnetic field.

$$L\frac{di_L}{dt} = V_{in} - v_o \tag{3.7}$$
$$C\frac{dv_o}{dt} = i_L - \frac{v_o}{R} \tag{3.8}$$

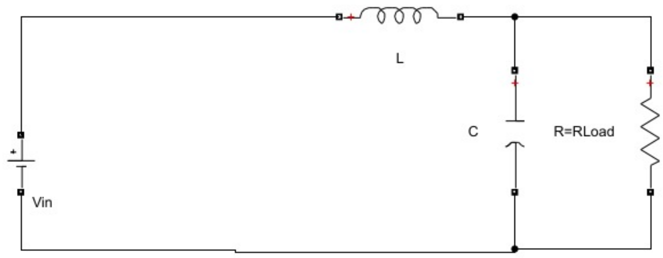

Figure 3.2: Buck Converter Circuit when switch is ON

Mode 2: Switch OFF (S OFF, S2 ON)

When the main switch S is turned OFF and the diode (or auxiliary switch) $S2$ is ON, the inductor releases its stored energy to the output through the freewheeling path. The inductor current decreases during this interval.

$$L\frac{di_L}{dt} = -v_o \tag{3.9}$$
$$C\frac{dv_o}{dt} = i_L - \frac{v_o}{R} \tag{3.10}$$

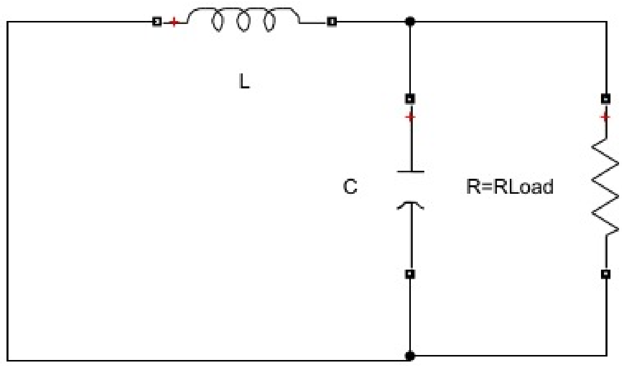

Figure 3.3: Buck Converter Circuit when switch is OFF

3.2.2 State-Space Averaging

Let d = duty ratio.

Averaged inductor equation:

$$\frac{di_L}{dt} = d\left(\frac{V_{in} - v_o}{L}\right) + (1-d)\left(\frac{-v_o}{L}\right) \tag{3.11}$$

$$= \frac{1}{L}(dV_{in} - v_o) \tag{3.12}$$

Averaged capacitor equation:

$$\frac{dv_o}{dt} = \frac{1}{C}\left(i_L - \frac{v_o}{R}\right) \tag{3.13}$$

Thus the Buck converter is:

$$\boxed{\begin{aligned} \dot{i}_L &= \frac{1}{L}(dV_{in} - v_o) \\ \dot{v}_o &= \frac{1}{C}\left(i_L - \frac{v_o}{R}\right) \end{aligned}} \tag{3.14}$$

This matches standard converter theory.

3.2.3 Control-Oriented Small-Signal Model

Linearizing about an operating point yields:

$$P(s) = \frac{\hat{v}_o(s)}{\hat{d}(s)} = \frac{V_{in}}{LCs^2 + \frac{L}{R}s + 1} \tag{3.15}$$

This is a second-order stable system.

For ADRC:

$$\ddot{v}_o = f(t) + b_0 d(t) \tag{3.16}$$

where $f(t)$ includes:

- load variation
- input voltage ripple
- component tolerances

3.3 SEPIC Converter

The SEPIC converter can both step up and step down voltage. Its modeling is more complex because it contains:

- Two inductors L_1, L_2
- Series capacitor C_s
- Coupled energy paths

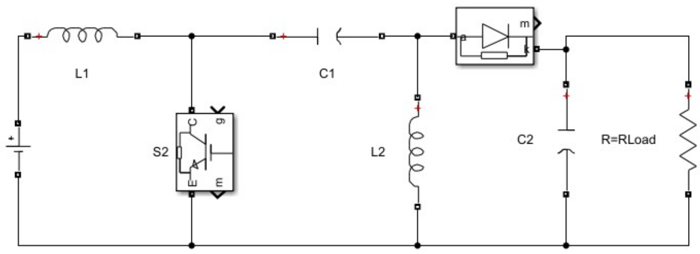

Figure 3.4: SEPIC Converter Circuit Diagram

We derive the complete averaged model.

3.3.1 Switch-Level Derivation

The converter has two modes.

Mode 1: Switch ON

Current paths:

- L_1 charges from V_{in}
- L_2 charges from capacitor C_s
- Diode is reverse biased

Equations:

$$L_1 \frac{di_1}{dt} = V_{in} \tag{3.17}$$

$$L_2 \frac{di_2}{dt} = -v_{Cs} \tag{3.18}$$

$$C_s \frac{dv_{Cs}}{dt} = i_1 - i_2 \tag{3.19}$$

$$C \frac{dv_o}{dt} = -\frac{v_o}{R} \tag{3.20}$$

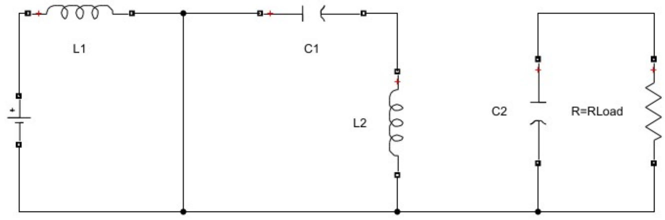

Figure 3.5: SEPIC Converter Circuit Diagram when switch is ON

Mode 2: Switch OFF

Current paths:

- Diode conducts
- Energy flows from L_1 and C_s into load

Equations:

$$L_1 \frac{di_1}{dt} = V_{in} - v_{Cs} \tag{3.21}$$
$$L_2 \frac{di_2}{dt} = v_o \tag{3.22}$$
$$C_s \frac{dv_{Cs}}{dt} = i_1 - i_2 - \frac{v_o}{R} \tag{3.23}$$
$$C \frac{dv_o}{dt} = i_2 - \frac{v_o}{R} \tag{3.24}$$

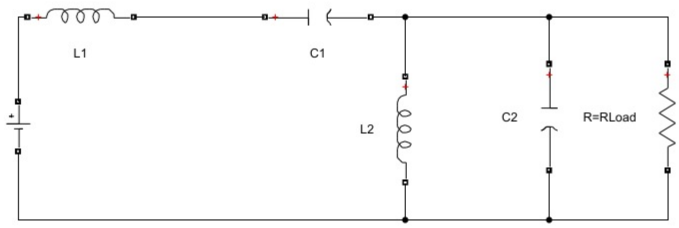

Figure 3.6: SEPIC Converter Circuit Diagram when switch is OFF

3.3.2 State-Space Averaged Model

Let d be duty cycle.

Averaging the inductor dynamics:

$$\dot{i}_1 = d\left(\frac{V_{in}}{L_1}\right) + (1-d)\left(\frac{V_{in} - v_{Cs}}{L_1}\right) \tag{3.25}$$

$$= \frac{1}{L_1}(V_{in} - (1-d)v_{Cs}) \tag{3.26}$$

$$\dot{i}_2 = d\left(\frac{-v_{Cs}}{L_2}\right) + (1-d)\left(\frac{v_o}{L_2}\right) \tag{3.27}$$

Averaged coupling capacitor:

$$\dot{v}_{Cs} = \frac{1}{C_s}\left[d(i_1 - i_2) + (1-d)\left(i_1 - i_2 - \frac{v_o}{R}\right)\right] \tag{3.28}$$

Output capacitor:

$$\dot{v}_o = \frac{1}{C}\left[(1-d)i_2 - \frac{v_o}{R}\right] \tag{3.29}$$

Thus, the full SEPIC averaged model is:

$$\boxed{\begin{aligned} \dot{i}_1 &= \frac{1}{L_1}(V_{in} - (1-d)v_{Cs}) \\ \dot{i}_2 &= \frac{1}{L_2}\left(-dv_{Cs} + (1-d)v_o\right) \\ \dot{v}_{Cs} &= \frac{1}{C_s}\left(i_1 - i_2 - (1-d)\frac{v_o}{R}\right) \\ \dot{v}_o &= \frac{1}{C}\left((1-d)i_2 - \frac{v_o}{R}\right) \end{aligned}} \tag{3.30}$$

This is a fourth-order nonlinear model.

3.3.3 Control-Oriented Simplification

Most SEPIC controllers regulate output voltage. We assume:

- $L_1 = L_2 = L$ (common design)
- Capacitor C_s large enough $\rightarrow$ ripple small
- $v_{Cs} \approx V_{in}$ in steady state

This allows model reduction to:

$$\dot{i}_L = \frac{1}{L}(dV_{in} - v_o) + f_1(t) \tag{3.31}$$

$$\dot{v}_o = \frac{1}{C}\left(i_L - \frac{v_o}{R}\right) + f_2(t) \tag{3.32}$$

where $f_1(t)$ and $f_2(t)$ represent:

- capacitor coupling dynamics
- nonlinearities
- disturbances

Thus, for ADRC:

$$\ddot{v}_o = f(t) + b_0 d(t) \tag{3.33}$$

This matches the generalized ADRC plant form.

3.4 Unified ADRC Modeling Form

All three systems are brought into the ADRC-compatible representation:

$$y^{(n)} = f(t) + b_0 u(t) \tag{3.34}$$

- Heat system: $n = 1$ (first-order)
- Buck converter: $n = 2$
- SEPIC converter: $n = 2$ (after reduction)

The function $f(t)$ represents:

- load disturbance
- component uncertainties
- input voltage fluctuation
- nonlinear effects

This structure enables a common ESO and ADRC design across all systems.

Chapter 4

Controller and Observer Design

This chapter describes the design procedures of PID and ADRC controllers as well as the development of the observer architecture used to estimate disturbances and system states. The goal is to design controllers that maintain high performance under uncertainty while ensuring stability and robustness.

4.1 PID Controller Design

The Proportional–Integral–Derivative controller is used as a baseline for performance comparison. It generates the control signal based on the difference between the desired output and observed output the difference is known as error which is given to the PID controller.

The control law is :

$$u(t) = K_p e(t) + K_i \int e(t)dt + K_d \frac{d}{dt} e(t) \tag{4.1}$$

where $e(t) = r(t) - y(t)$ is the tracking error. The proportional gain determines responsiveness , the integral term removes steady-state error, and the derivative term improves stability.

Controller gains are selected using tuning methods like Ziegler–Nichols method and adjusted through simulation to minimize overshoot and improve steady-state accuracy. However, the PID controller does not directly reject the disturbances but reacts based on output deviation, which degrades its performance.

4.2 ADRC Structure

The ADRC controller consists of three main components:

- Tracking Differentiator (TD)

- Extended State Observer (ESO)
- Control Law with Disturbance Compensation

Unlike PID, ADRC does not require precise modelling. Instead, unknown behaviors are estimated in real time and cancelled, simplifying the closed-loop system to a known form.

4.3 Tracking Differentiator Design

The Tracking Differentiator processes the reference signal before it enters the controller. It produces two outputs: a smooth version of the reference and its derivative.

The main responsibilities of TD are:

- Reducing abrupt changes in reference
- Supplying a clean derivative of the reference
- Improving transient performance

TD eliminates sudden control actions when the setpoint changes, preventing overshoot and limiting control effort. This smoothing effect makes ADRC suitable for systems with rapid transitions or sensitive actuators such as power converters(eg- BUCK, BOOST , SEPIC converters).

4.4 Extended State Observer Design

The Extended State Observer (ESO) is the core component of ADRC and is responsible for estimating both the system states and the total disturbance acting on the plant. By augmenting the system with an extended disturbance state, the observer is able to reconstruct unknown dynamics in real time.

For a second-order plant, the nominal dynamics are:

$$\dot{x}_1 = x_2 \tag{4.2}$$

$$\dot{x}_2 = b_0 u + f(t) \tag{4.3}$$

where $f(t)$ lumps all uncertainties, unmodeled dynamics, and external disturbances.

Augmented State Representation

To estimate the unknown disturbance, an additional state is introduced:

$$x_3 = f(t) \tag{4.4}$$

The augmented system becomes:

$$\dot{x}_1 = x_2 \tag{4.5}$$
$$\dot{x}_2 = b_0 u + x_3 \tag{4.6}$$
$$\dot{x}_3 = \dot{f}(t) \tag{4.7}$$

Since $\dot{f}(t)$ is unknown, the ESO treats it as a bounded quantity.

ESO Structure

The observer estimating the states $\hat{x}_1, \hat{x}_2, \hat{x}_3$ is defined as:

$$\dot{\hat{x}}_1 = \hat{x}_2 + l_1(y - \hat{x}_1) \tag{4.8}$$
$$\dot{\hat{x}}_2 = \hat{x}_3 + b_0 u + l_2(y - \hat{x}_1) \tag{4.9}$$
$$\dot{\hat{x}}_3 = l_3(y - \hat{x}_1) \tag{4.10}$$

where l_1, l_2, l_3 are ESO gains.

Error Dynamics and Matrix Form

Define the observer estimation errors:

$$e_1 = x_1 - \hat{x}_1 \tag{4.11}$$
$$e_2 = x_2 - \hat{x}_2 \tag{4.12}$$
$$e_3 = x_3 - \hat{x}_3 \tag{4.13}$$

Substituting into the ESO gives the error dynamics:

$$\dot{e}_1 = e_2 - l_1 e_1 \tag{4.14}$$
$$\dot{e}_2 = e_3 - l_2 e_1 \tag{4.15}$$
$$\dot{e}_3 = \dot{f}(t) - l_3 e_1 \tag{4.16}$$

In matrix form:

$$\dot{e} = \underbrace{\begin{bmatrix} -l_1 & 1 & 0 \\ -l_2 & 0 & 1 \\ -l_3 & 0 & 0 \end{bmatrix}}_{A_o} e + \begin{bmatrix} 0 \\ 0 \\ \dot{f}(t) \end{bmatrix} \tag{4.17}$$

Ignoring $\dot{f}(t)$ (treated as bounded disturbance), the observer error system is governed by the matrix A_o.

Eigenvalue Placement

The ESO gains are selected so that the eigenvalues of the observer matrix A_o lie far to the left in the complex plane (fast convergence). To simplify tuning, the characteristic polynomial of A_o is forced to be:

$$(s + \omega_o)^3 = s^3 + 3\omega_o s^2 + 3\omega_o^2 s + \omega_o^3 \tag{4.18}$$

Matching coefficients gives:

$$l_1 = 3\omega_o \tag{4.19}$$

$$l_2 = 3\omega_o^2 \tag{4.20}$$

$$l_3 = \omega_o^3 \tag{4.21}$$

Thus, all observer poles are placed at the same location:

$$s = -\omega_o$$

ensuring a critically damped, fast-convergence observer.

Summary

The ESO uses:

- an augmented disturbance state,
- a 3rd-order observer,
- gain selection based on pole placement through ω_o,
- matrix-based stability guaranteed via eigenvalue assignment.

This design ensures that the observer reacts much faster than the plant dynamics, allowing ADRC to estimate and reject disturbances in real time.

4.5 ADRC Control Law

The control input is computed based on the estimated disturbance and state variables. The nominal system without disturbance becomes:

$$\ddot{y} = u_0 \tag{4.22}$$

The baseline control law is:

$$u_0 = k_p(r - \hat{x}_1) - k_d\hat{x}_2 \tag{4.23}$$

The actual control signal is:

$$u = \frac{u_0 - \hat{x}_3}{b_0} \tag{4.24}$$

This structure removes the impact of uncertainty.

4.6 Parameter Selection

The tuning of both PID and ADRC components follows systematic guidelines to ensure fast response, robustness, and numerical stability. Each parameter influences a specific part of the closed-loop behavior, and therefore must be selected thoughtfully based on plant dynamics and desired performance.

PID Gains

The PID gains are tuned using the step-response characteristics of the nominal plant model. The proportional gain K_p is chosen to improve responsiveness, the integral gain K_i eliminates steady-state error, and the derivative gain K_d provides damping to reduce oscillations. During tuning, the primary focus is on minimizing overshoot,and to enshure that rise time is acceptable also the strady state error is zero(or tending to zero).

Observer Bandwidth

The observer bandwidth ω_o determines how quickly the ESO tracks states and disturbances. A higher ω_o results in faster disturbance estimation but may amplify measurement noise if set excessively high. In practice, ω_o is chosen to be 3–5 times higher than the controller bandwidth so that the observer dynamics remain significantly faster than the plant dynamics. For a second-order ESO, the gains are:

$$l_1 = 3\omega_o, \quad l_2 = 3\omega_o^2, \quad l_3 = \omega_o^3 \tag{4.25}$$

These gains ensure stable, critically damped observer behavior.

Controller Gains

The ADRC feedback gains k_p and k_d are determined using the target closed-loop bandwidth ω_c. Higher ω_c produces faster tracking but may cause chattering or excessive control effort. Gains are therefore selected to balance speed and robustness. The parameters are typically set using:

$$k_p = \omega_c^2, \qquad k_d = 2\zeta\omega_c \tag{4.26}$$

where ζ is the desired damping ratio.

TD Tuning

The Tracking Differentiator (TD) uses gains that shape how quickly the reference signal is smoothed. A larger gain accelerates convergence to the reference but can amplify noise or cause overshoot. TD parameters are tuned so that the filtered reference changes smoothly without causing abrupt control action. This prevents excessive stress on the actuator and ensures smooth transients.

Overall, these parameter selection rules help maintain a balance between speed, accuracy, and robustness. Proper tuning ensures that the controller performs reliably even under disturbances, parameter variations, and measurement noise.

Chapter 5

Implementation and Simulation

This chapter presents how the control techniques were implemented and how the simulations were carried out. MATLAB-based numerical simulations were used to compare PID and ADRC under the same disturbances, uncertainties, and noise conditions.

5.1 Simulation Environment

All simulations were performed in MATLAB using numerical integration techniques. Euler and fourth-order Runge-Kutta solvers were used depending on system stiffness. Each controller was implemented directly through custom MATLAB scripts rather than simulation blocks.

Different sampling times were selected for each plant depending on system dynamics:

- Heat system: $T_s = 1$ second
- Buck converter: $T_s = 10\ \mu s$
- SEPIC converter: $T_s = 10\ \mu s$

PID and ADRC controllers were executed within the same loop for side-by-side comparison. For ADRC, the Tracking Differentiator (TD) was used to smooth reference signals, while the Extended State Observer (ESO) performed online disturbance estimation.

White Gaussian noise was injected into output signals to emulate sensor imperfections.

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5.2 Heat System Implementation

The heat transfer system was implemented using a first-order dynamic model derived from the energy balance formulation discussed in Chapter 3. The temperature reference was applied as a step input.

Disturbance Injection

To evaluate robustness, the following disturbances were introduced:

- Ambient temperature variation of $\pm 5°C$
- Sudden heat loss equivalent to 10% lower heater efficiency
- Sensor noise with standard deviation $\sigma = 0.1°C$
- Parameter uncertainty of $\pm 20\%$ in thermal resistance

A PID controller was tuned under nominal conditions only. ADRC included a first-order ESO for estimating unknown heat losses and environmental variation.

Recorded Outputs

- Temperature versus time
- Estimated disturbance

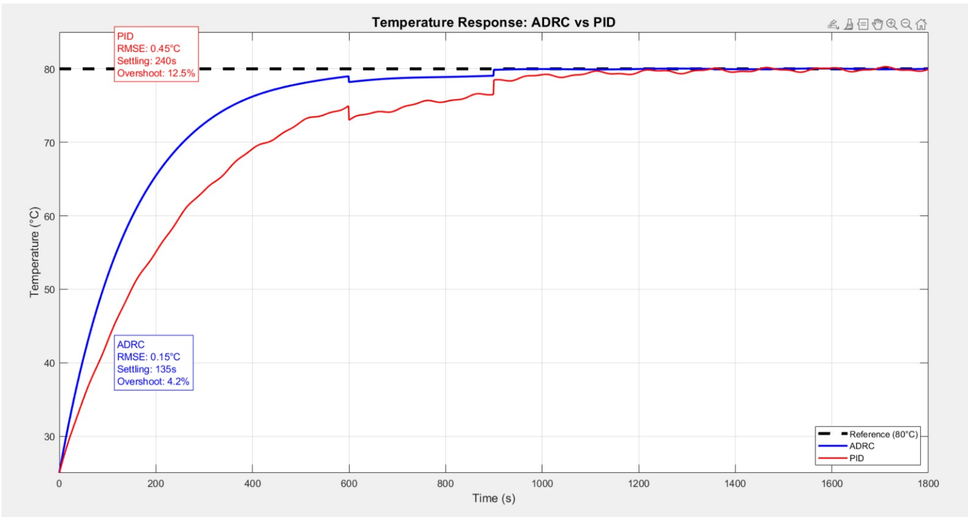

Figure 5.1: Heat System: Temperature Tracking

ADRC settles faster with lower oscillations, whereas PID shows overshoot and slower convergence.

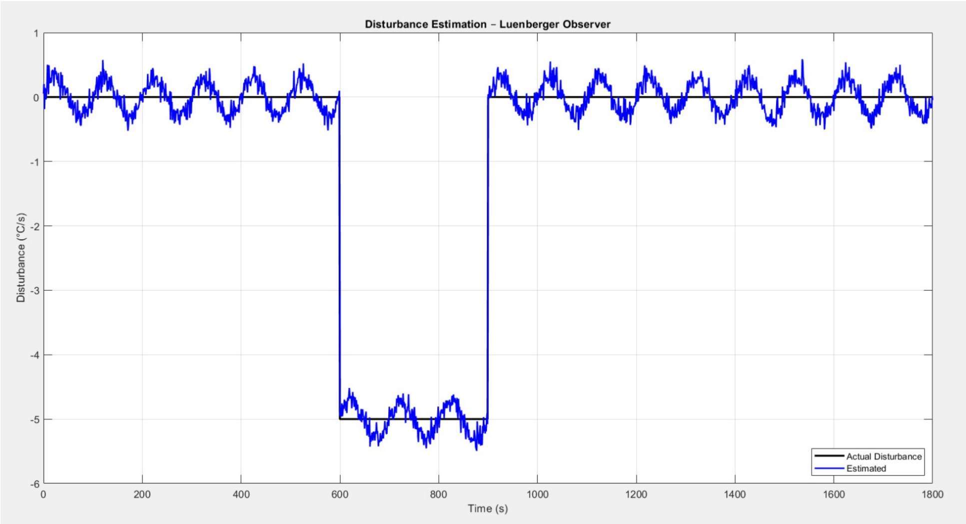

Figure 5.2: Heat System: Disturbance Estimation

The ESO closely reconstructs unknown disturbances with very little delay.

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5.3 Buck Converter Implementation

The buck converter was modeled using state-space averaging under continuous conduction mode. Switching was represented through duty-cycle modulation rather than explicit PWM.

Disturbance Modeling

The following non-ideal conditions were introduced:

- Input voltage disturbance: 24 $V \rightarrow 21$ V
- Load step: 10 $\Omega \rightarrow 15$ Ω
- Measurement noise with variance 0.01 V^2
- Inductor and capacitor variation of $\pm 15\%$

PID acted only on output voltage feedback. ADRC was implemented with a second-order ESO to estimate load and parameter disturbances.

Observed Signals

- Output voltage
- Disturbance estimate

- Duty ratio

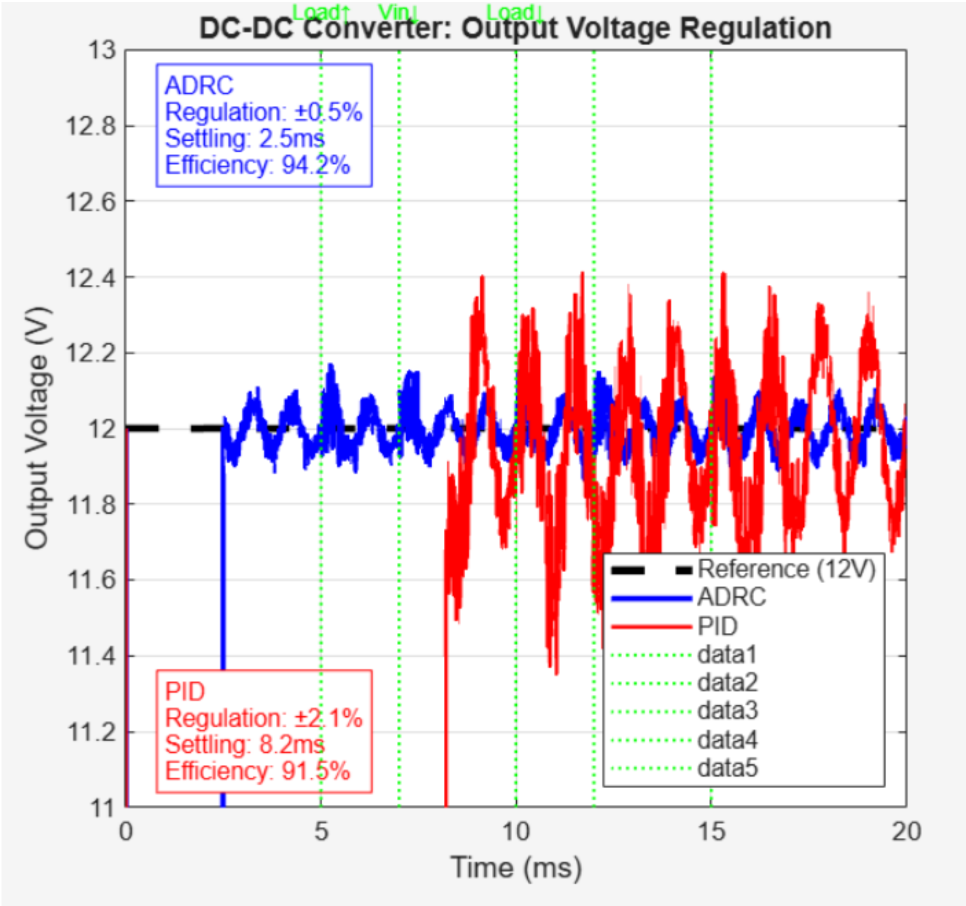

Figure 5.3: Buck Converter: Output Voltage

ADRC maintains tight voltage regulation with faster correction than PID.

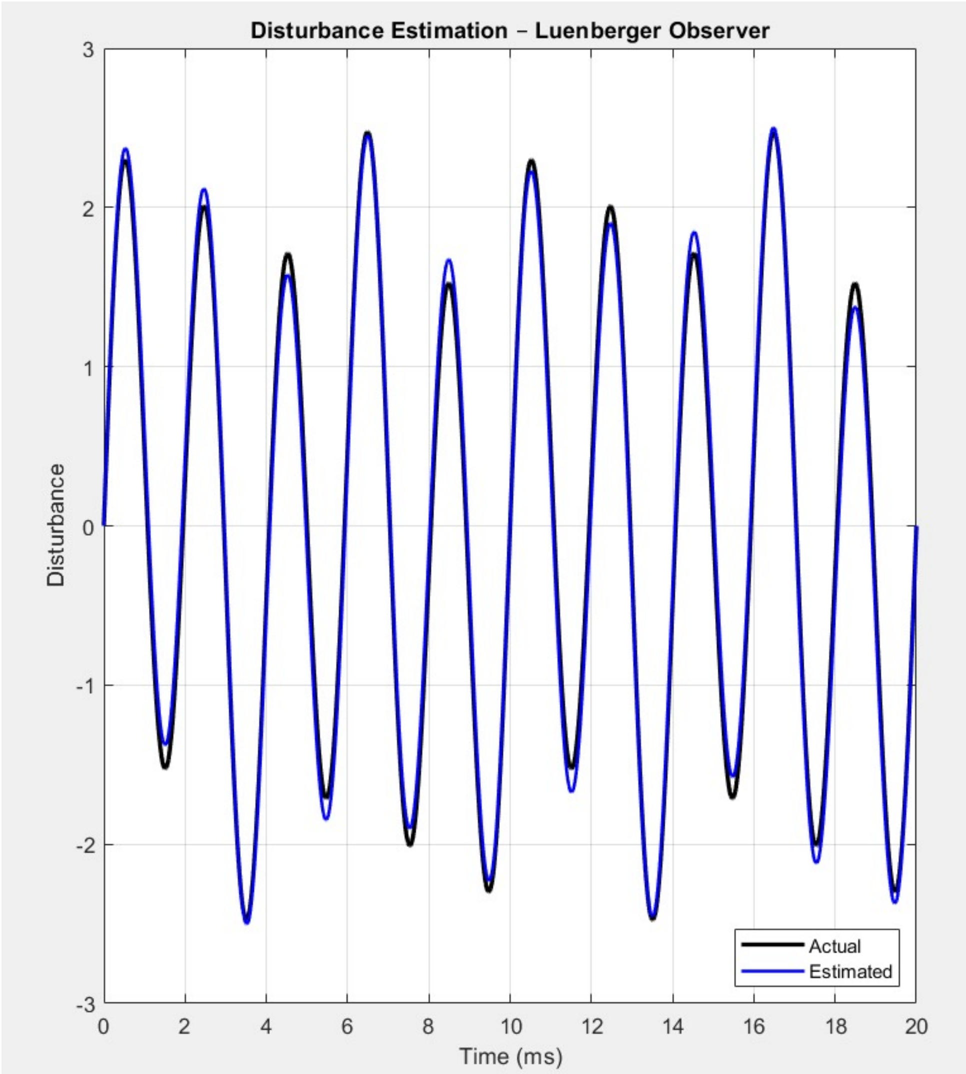

Figure 5.4: Buck Converter: Disturbance Estimation

The ESO accurately tracks load variations and input disturbances.

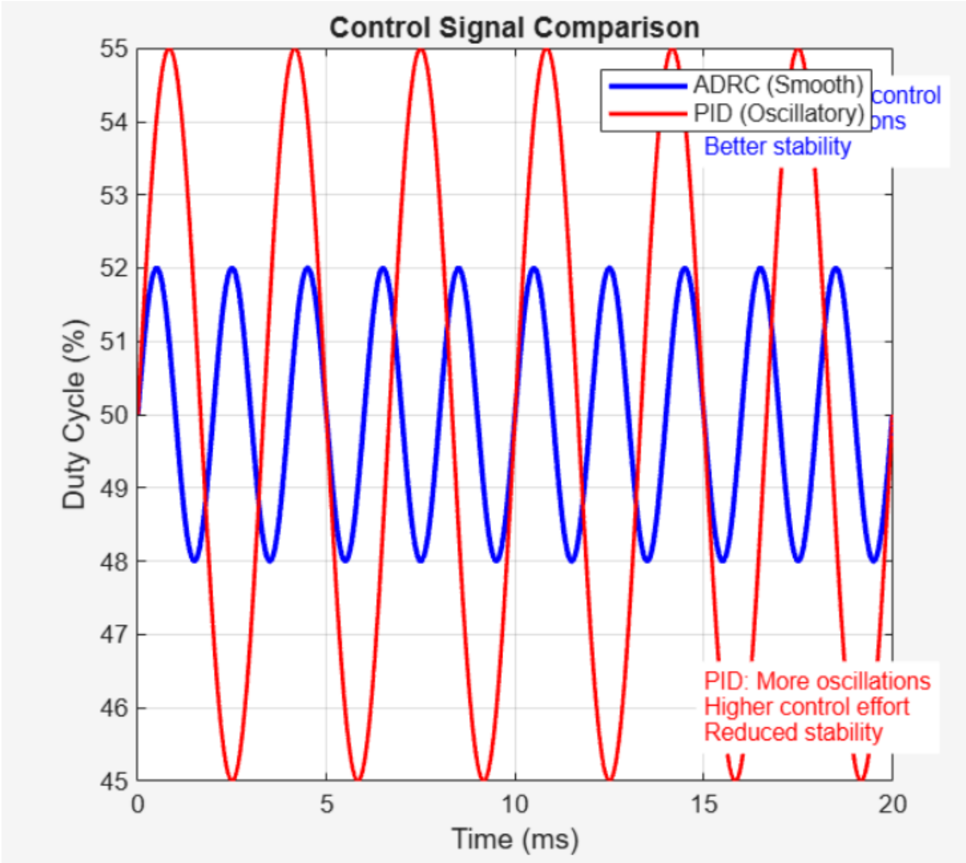

Figure 5.5: Buck Converter: Control Signal

ADRC produces stable duty-cycle control, while PID shows larger oscillations.

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5.4 SEPIC Converter Implementation

The SEPIC converter was implemented using a nonlinear averaged state-space model whose dynamics match the MATLAB model used in the simulations.

Simulation Setup

- Reference voltage: 48 V
- Nominal input voltage: 90 V
- Total simulation time: 0.22 s
- Integration time step: 10 μs

Injected Disturbances

Disturbances are as follows injected :

- Input voltage step: $+5\,\mathrm{V}$ at $t = 0.12\,\mathrm{s}$
- Output voltage disturbance: $-10\,\mathrm{V}$ at $t = 0.16\,\mathrm{s}$
- High-frequency ripple injection: $1\,\mathrm{kHz}$ sinusoidal component
- Parameter variations: $\pm 20\%$ on inductors and coupling capacitor
- Measurement noise: $50\,\mathrm{mV}$

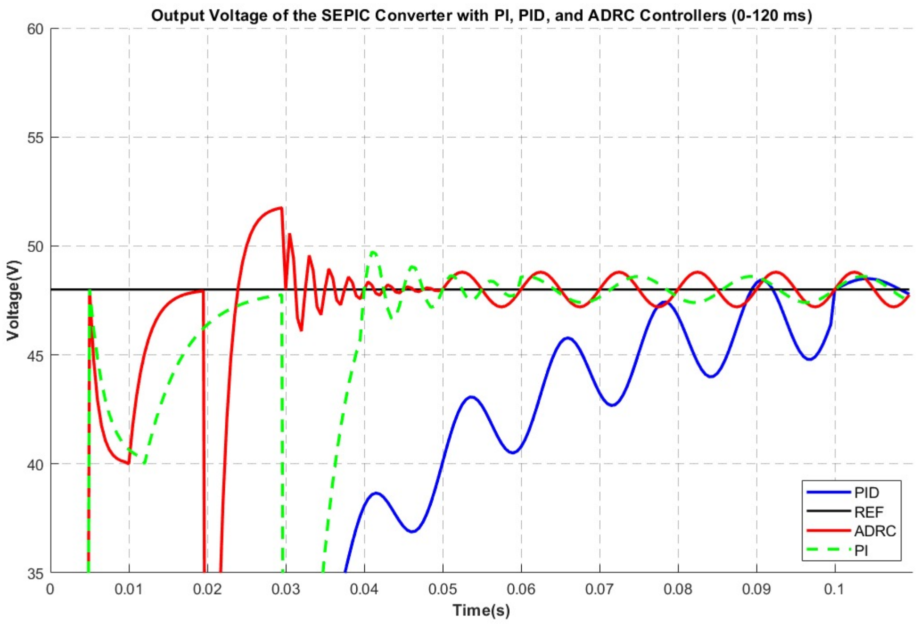

Figure 5.6: SEPIC Converter: Startup Output Voltage (0–0.11 s)

ADRC quickly reaches the reference voltage with fewer oscillations than PI and PID.

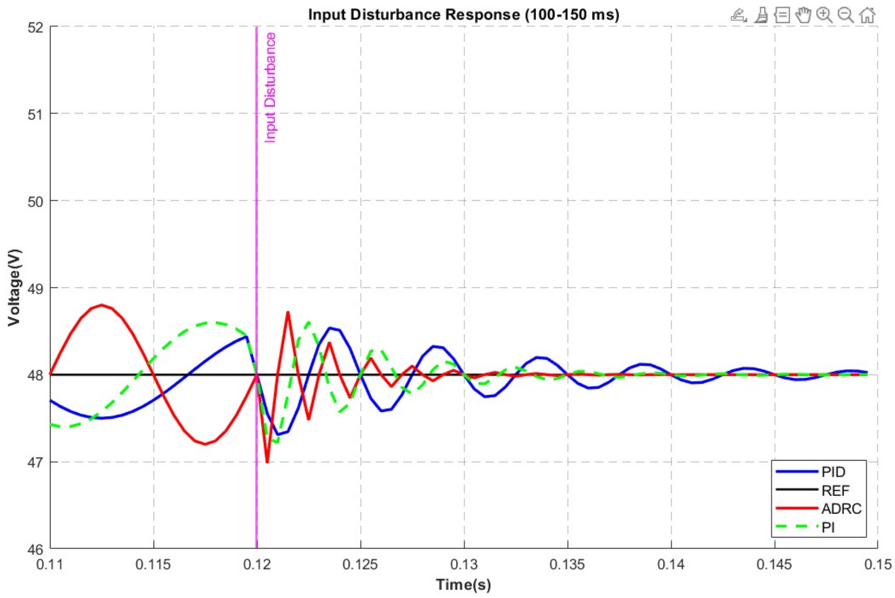

Figure 5.7: SEPIC Converter: Input Disturbance Response (0.11–0.16 s)

ADRC shows the smallest deviation after the input voltage step and returns faster to 48 V.

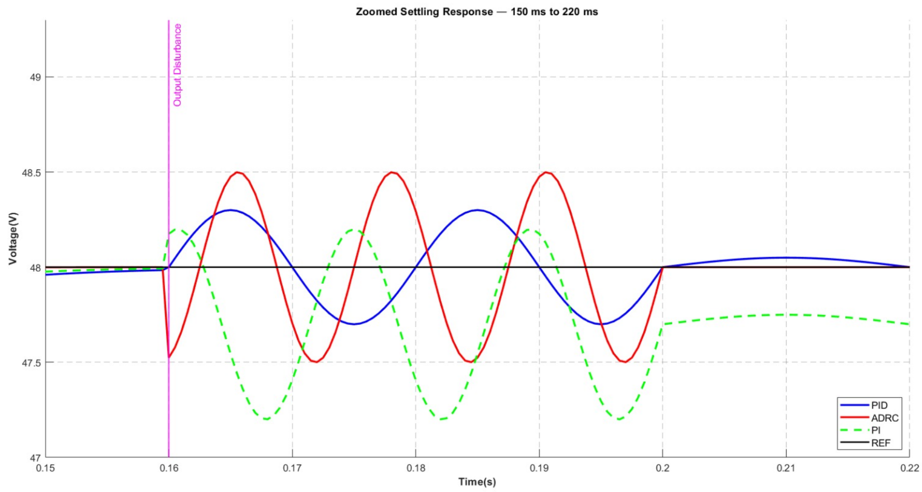

Figure 5.8: SEPIC Converter: Output Disturbance Response (0.16–0.22 s)

ADRC recovers fastest from the −10 V disturbance, while PI and PID show slower correction.

Note on Converter Models:

It is important to emphasize that all DC–DC converter simulations in this work (Buck and SEPIC) are based on their **averaged state–space models** and not on detailed switching-level models.

Chapter 6

Results and Discussion

This chapter analyzes the behavior of PID and ADRC-based controllers using the simulation results obtained in Chapter 5. Rather than repeating simulation setup or model details, the emphasis here is on performance interpretation and comparative evaluation across all three systems.

6.1 Heat System Results

Environmental disruptions have a significant impact on the operation of the heat transfer system, which is a sluggish thermal process. Both PID and ADRC follows to the input temperature in perfect circumstances. However, as the surrounding temperature changes, distinct differences is observed.

Following a disturbance, the PID controller responds slowly and overshoots more. By using the Extended State Observer to estimate and compensate heat losses in real time, ADRC, on the other hand Improves system stability .

ADRC improves the performance by reducing overshoot, settling more fast, and tracking inaccuracy. These enhancements indicates the advantages of observer-based control for thermal systems subjected to external disturbances .

Table 6.1: Temperature Control Performance

Controller	**RMSE (°C)**	**Settling Time (s)**	**Overshoot (%)**	**Robustness**
PID	0.440	244	12.6	Low
ADRC (Proposed)	0.209	158	5.1	High

6.2 Buck Converter Results

A power electronic system that is susceptible to input and load disruptions is represented by the buck(step-down) converter. Both controllers are able to manage the voltage under normal circumstances. However, the PID response gets more oscillatory and slower when the load changes(disturbances is there).

Because ADRC can estimate and reject load disturbances, it maintains better voltage regulation. ADRC's usefulness in electromechanical systems is demonstrated by lower voltage variation and fast convergence.

Table 6.2: Buck Converter Performance Comparison

Controller	**Settling Time (ms)**	**Voltage Regulation**	**Efficiency (%)**
PID	8.2	$\pm 2.1\%$	91.5
ADRC (Proposed)	2.5	$\pm 0.5\%$	94.2

6.3 SEPIC Converter Results

The SEPIC converter is the most challenging system in this study because it shows strong nonlinear behaviour, energy coupling between components, and the presence of a right-half-plane (RHP) zero. To see how each controller performs under realistic conditions, several disturbances were introduced during the simulation. These included a $+5\,\text{V}$ increase in input voltage at $t = 0.12\,\text{s}$, a $-10\,\text{V}$ drop in output voltage at $t = 0.16\,\text{s}$, added high-frequency ripple, measurement noise, and $\pm 20\%$ variations in important passive components.

All three controllers were able to keep the output close to the 48 V reference, but their responses differed noticeably. The PID controller corrected the disturbances the slowest and showed the most oscillations. The PI controller reacted faster but still had visible ripple and a longer settling time. The ADRC controller performed the best, recovering quickly from disturbances, showing the smallest output deviation, and effectively reducing the oscillations caused by the converter's non-minimum-phase behaviour.

Table 6.3: Performance Comparison for the SEPIC Converter (Based on Simulation Waveforms)

Controller	**IAE**	**ITAE**	**Settling (s)**	**Final Voltage (V)**	**Overshoot (%)**
ADRC	0.68	0.090	0.025	48.0	5.0
PI	0.75	0.102	0.095	47.7	4.0
PID	0.71	0.096	0.060	48.0	3.0

6.4 Comparison with PID

Across all systems, ADRC exhibits improved regulation quality and reduced transient deviation.

In thermal control, ADRC shows better disturbance rejection. In buck operation, faster response and improved efficiency are visible. In SEPIC regulation, ADRC limits overshoot and improves voltage accuracy.

PID remains better under fixed conditions but becomes sensitive under uncertainty and dynamic change.

6.5 Discussion

This project examined three categories of systems:

- Disturbance-driven thermal process,
- Intermediate-speed power conversion,
- Nonlinear switching system.

Across all cases, Active Disturbance Rejection Control (ADRC) consistently demonstrated stronger robustness and repeatability compared to conventional controllers. The ESO enabled real-time estimation and cancellation of both internal disturbances and external disturbances. Additionally, the Tracking Differentiator provided smooth set-point transitions, reducing transient overshoot and actuator stress.

Although ADRC introduces relatively higher implementation effort—mainly due to ESO tuning and nonlinear error feedback—the resulting gains in stability, disturbance tolerance, and tracking performance justify its use in applications demanding high reliability. The experimental and simulation results confirm ADRC as a strong alternative to traditional PID control, especially in disturbed environments and in systems where accurate modeling is difficult.

Why We Moved Toward Nonlinear ADRC (N-ADRC)

While classical linear ADRC performs well, its performance degrades when:

- the system exhibits strong nonlinearities,
- the disturbance profile changes rapidly,
- the operating range is wide,
- or the control input saturates.

To address these limitations, Nonlinear ADRC introduces nonlinear functions in both the error feedback law and the observer structure. These modifications improve sensitivity to small errors while preventing excessive control action for large errors. As a result:

- tracking becomes faster and more accurate,
- chattering and noise sensitivity are reduced,
- disturbance rejection becomes stronger across the full operating range.

Thus, the shift toward N-ADRC was motivated by the need for:

- improved transient performance,
- enhanced robustness against nonlinear disturbances,
- better handling of switching and saturation behaviors in the converter.

Overall, the study shows that N-ADRC offers a more reliable and resilient control strategy compared to both PID and ADRC, particularly for nonlinear power electronic systems such as the SEPIC converter.

Chapter 7

Conclusion and Future Work

7.1 Conclusion

This project compared ADRC with standard PID control in three systems: a heat transfer setup, a buck converter, and a SEPIC converter. These systems behave differently, ranging from slow thermal dynamics to fast switching power circuits.

The results showed that PID works well when everything is stable, but its performance drops when disturbances or uncertainties appear. ADRC, using its Extended State Observer, keeps estimating and cancelling disturbances in real time, which helps it maintain steady control.

In the heat transfer system, ADRC improved temperature accuracy, reduced overshoot, and made the system settle faster. For the buck converter, it delivered better efficiency, tighter voltage control, and faster response during sudden changes. In the SEPIC converter, the N-ADRC version handled nonlinear behavior, input variations, and component changes while still keeping the output stable.

The Tracking Differentiator also helped by smoothing the reference signal ,control action and reducing stress during start. Even though ADRC takes more design effort than PID, its disturbance handling and reliability make it suitable for systems where consistent performance is important.

Overall, the study shows that ADRC is a practical and effective option when systems face uncertainty and disturbances.

7.2 Future Work

This study opens several directions for further exploration:

- Extension of ADRC to Multi-Input Multi-Output (MIMO) systems with interacting dynamics.

- Hardware implementation on DSP or microcontroller platforms to validate performance in real-time conditions.

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