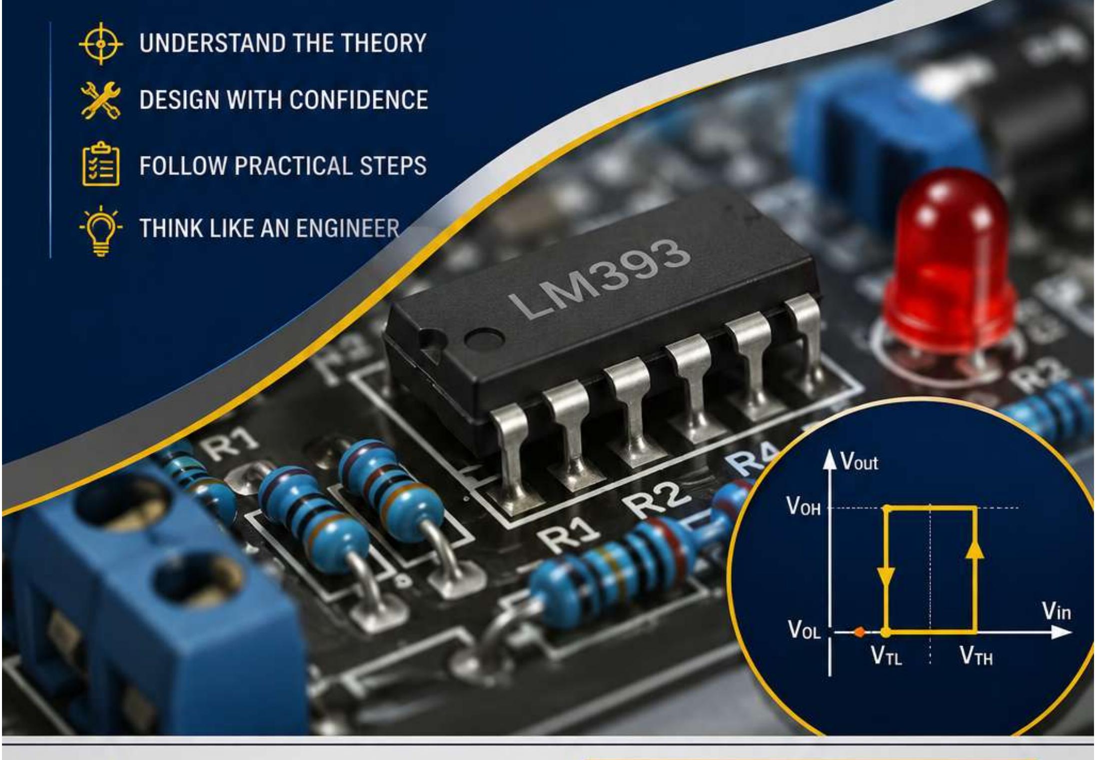
ELECTRONICS PRACTICAL HANDBOOK

USING THE LM393 IN HYSTERESIS MODE

THE PRACTICAL GUIDE WITH EXAMPLE

- UNDERSTAND THE THEORY
- DESIGN WITH CONFIDENCE
- FOLLOW PRACTICAL STEPS
- THINK LIKE AN ENGINEER



DESIGNED FOR ENGINEERS
BUILT FOR PRACTICE

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FIRST EDITION

A Practical Guide to Using the LM393 Comparator in Hysteresis Mode

Simplifying and understanding the design

Acknowledgment

This handbook is the result of many years of practical engineering experience combined with a sincere desire to present technical knowledge in a clear, logical, and accessible manner.

The author gratefully acknowledges the assistance of **ChatGPT**, developed by **OpenAI**, in the editorial development, educational structuring, and refinement of this handbook. Through numerous technical discussions, careful review of explanations, and thoughtful organization of the material, this collaboration contributed significantly to improving the clarity, consistency, and educational value of the handbook while preserving the author's engineering knowledge and practical experience.

The engineering concepts, analyses, practical design methods, and final technical judgments presented throughout this handbook remain the responsibility of the author.

It is the author's hope that this handbook will help students and practicing engineers not only learn how to design LM393 comparator circuits with hysteresis, but also develop a logical approach to engineering analysis, problem-solving, and practical circuit design.

Engineer

Khalid Basyouni

Preface

"…And say, 'My Lord, increase me in knowledge.'"
(Qur'an 20:114)

Engineering is not merely a collection of equations, formulas, or electronic components. It is a disciplined way of thinking, a process of observing, analyzing, understanding, and finally transforming ideas into practical solutions.

Among the many fundamental building blocks of analog electronics, the comparator occupies a special place. Although LM393 is one of the simplest and most widely used comparator integrated circuits, its behavior in hysteresis mode is often introduced in a way that appears mathematically complicated or disconnected from practical design. As a result, many students learn the equations without fully understanding the engineering principles behind them.

This handbook was written to bridge that gap.

Rather than presenting mathematics as an end by itself, every equation in these pages is introduced only after the underlying engineering concept has been established. In this way, mathematics becomes what it is meant to be precise language for describing engineering decisions and verifying design choices.

The approach adopted throughout this handbook follows a consistent philosophy. Each topic begins with the practical problem that must be solved, continues with the theoretical explanation required to understand it, develops the necessary mathematical relationships, and finally applies those relationships in a complete engineering design. In this manner, the reader is guided not only toward obtaining the correct answer, but also toward understanding why that answer is correct.

Special attention has been given to the practical aspects of circuit design. Component selection, threshold calculation, resistor-value considerations, common design mistakes, and troubleshooting techniques are discussed alongside the theoretical analysis. The objective is not simply to explain how an LM393 comparator works, but to help the reader develop the habits of thought that characterize sound engineering practice.

This handbook is intended for engineering students, technicians, hobbyists, and practicing engineers who wish to gain both a clear theoretical understanding and practical confidence in designing comparator circuits with hysteresis.

If, after reading these pages, the reader feels more confident in analyzing circuits, making design decisions, and approaching engineering problems logically and systematically, then this handbook will have fulfilled its purpose.

I pray that Allah places benefit in this work and makes it a source of useful knowledge for everyone who studies it.

Engineer

Khalid Basyouni

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Chapter 1

Introduction

Electronic circuits are expected to produce stable and predictable outputs, even when their input signals contain noise, small fluctuations, or slow transitions. In practice, however, real-world signals are rarely ideal. Electrical noise, interference, and measurement uncertainties can cause an input voltage to oscillate around a decision level, leading to unstable circuit operation if no preventive measures are taken.

A comparator is one of the simplest devices used to determine whether an input voltage is above or below a reference level. Under ideal conditions, its output changes state precisely when the input crosses the reference voltage. In practical applications, however, this ideal behavior can become a disadvantage. When the input voltage changes slowly or contains electrical noise, the comparator may switch repeatedly between its two output states, producing unwanted oscillations and unreliable operation.

The solution to this problem is **hysteresis**.

By introducing positive feedback, hysteresis creates two different switching thresholds instead of one. One threshold determines the output transition when the input voltage is rising, while the other determines the transition when the input voltage is falling. This small but powerful modification greatly improves circuit stability and immunity to noise.

Understanding hysteresis is therefore not merely a matter of learning another circuit technique. It is an excellent example of an important engineering principle: **a well-designed system anticipates imperfections instead of reacting to them.**

This handbook explains how hysteresis is implemented using the LM393 comparator, beginning with the engineering concepts before moving to mathematical analysis and practical circuit design. Each chapter builds upon the previous one, allowing the reader to develop both theoretical understanding and practical design skills in a logical and progressive manner.

1.1 Why Hysteresis?

Imagine a comparator whose reference voltage is exactly **5.00 V**.

If the input voltage rises steadily from **4.90 V** toward **5.10 V**, an ideal comparator would switch once when the input reaches **5.00 V**.

Unfortunately, practical signals are rarely perfectly smooth.

Suppose that electrical noise of only a few millivolts is superimposed on the input signal while it is near the switching point. Instead of crossing the threshold cleanly, the input voltage may move slightly above and below the reference several times within a very short period.

As a result, the comparator output repeatedly changes state.

This phenomenon is commonly known as **output chatter**, and it can lead to serious problems in practical circuits, including:

- False triggering of digital logic.
- Relay or switch instability.
- Multiple counts in digital counters.
- Unstable sensor outputs.
- Oscillating control systems.

Clearly, the comparator itself is not malfunctioning. It is responding correctly to every tiny variation in its input. The real problem is that the circuit treats every small fluctuation as though it were a meaningful signal.

Hysteresis solves this problem by introducing **memory** into the switching process.

Instead of using a single threshold voltage, the comparator operates with two different thresholds:

- **Upper Threshold (UT):** The input voltage required to change the output from LOW to HIGH.
- **Lower Threshold (LT):** The input voltage required to change the output from HIGH to LOW.

Because these thresholds are separated by a finite voltage difference, small fluctuations around either threshold no longer cause repeated switching. The input must move a significant distance before the output changes state again.

This simple concept dramatically improves noise immunity and switching stability, making hysteresis one of the most valuable techniques in analog and mixed-signal circuit design.

Engineering Insight

A comparator with hysteresis does not ignore noise; it distinguishes between **noise** and a **genuine change in the input signal**. Good engineering often depends more on making intelligent decisions than on increasing circuit complexity.

1.2 Why the LM393?

Among the many comparator integrated circuits available, LM393 has earned a reputation as one of the most practical and versatile devices for both educational and industrial applications.

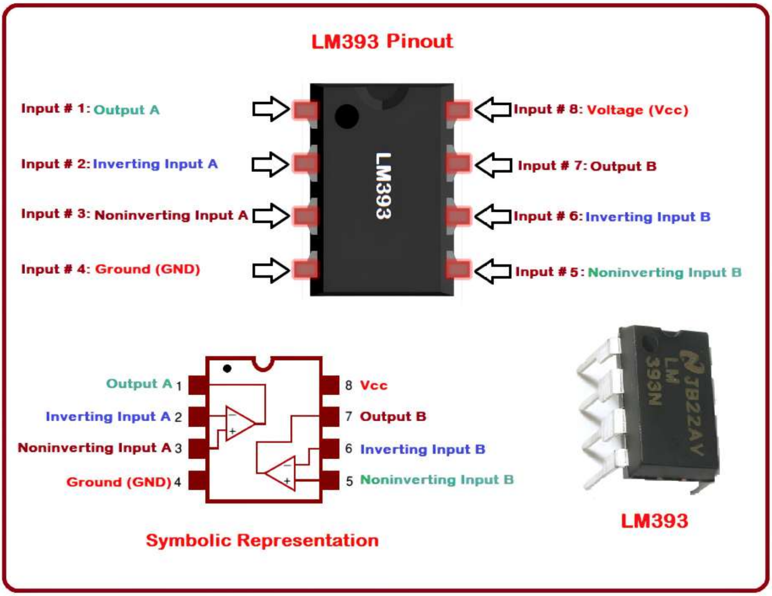
Its popularity is not accidental.

The LM393 combines simplicity, reliability, low power consumption, wide supply-voltage capability, and open-collector outputs, making it suitable for a wide range of analog and digital interface circuits.

From an educational perspective, it offers another important advantage.

Its internal operation is straightforward enough that the designer can focus on understanding the behavior of the external circuit rather than becoming distracted by unnecessary internal complexity. This makes the LM393 an ideal platform for learning the principles of comparator design and positive feedback.

LM393 contains 2 separate comparators instead of one.



Throughout this handbook, the LM393 will serve not merely as an electronic component, but as a practical example through which broader engineering principles can be explored. Once these principles are understood, they can be applied to many other comparator devices with only minor modifications.

About Mathematics

You will notice that this chapter contains **no equations**.

This is intentional.

Engineering design should begin with understanding the problem before introducing the mathematics used to describe it. Equations are valuable tools, but they become meaningful only after the physical behavior of the circuit is clearly understood.

In the chapters that follow, every mathematical relationship will be introduced only after its engineering purpose has become evident.

Think Like an Engineer

When a circuit behaves unexpectedly, resist the temptation to ask,

"What equation did I use incorrectly?"

Instead, ask,

"What behavior is the circuit trying to tell me?"

Measurements describe what a circuit is doing.

Understanding explains **why** it is doing it.

The best engineers learn to interpret both.

Transition to Chapter 2

Now that we understand **why hysteresis is necessary** and **why the LM393 is an excellent device for implementing it**, the next step is to understand **how** the comparator operates internally and how positive feedback creates two distinct switching thresholds.

This foundation will prepare us for the mathematical analysis and practical circuit designs presented in the following chapters.

Chapter 2

Operating Principles

Understanding a circuit begins long before any calculations are performed. Before selecting resistor, or deriving equations, an engineer should first understand **how the circuit behaves**. Once the behavior becomes clear, mathematic operations become a natural description rather than a collection of unrelated formulas.

The LM393 comparator is an excellent example of this principle. Although its operation is fundamentally simple, the addition of positive feedback transforms it from an ordinary comparator into a circuit capable of making stable and reliable decisions in the presence of noise and slight varying in input signals.

This chapter explains the operating principles that make hysteresis possible and establishes the physical understanding upon which all subsequent mathematical analysis will be built.

2.1 The Comparator as a Decision-Making Device

There are two ways a comparator can be used. That is the inverting comparator and the non-inverting comparator. The main difference between an inverting and a non-inverting comparator lies in **where the input signal is connected**, which reverses their output behavior. In an **inverting comparator**, the input goes to the negative pin, and the reference goes to the positive pin. In a **non-inverting comparator**, the input goes to the positive pin, and the reference goes to the negative pin.

A comparator continuously compares two input voltages.

- The **non-inverting input (+)** receives one voltage.

- The **inverting input (–)** receives another.

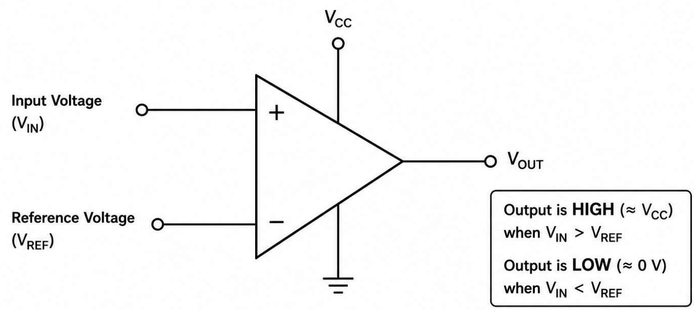
Its output simply indicates which voltage is greater.

When the voltage at the non-inverting input exceeds the voltage at the inverting input, the output changes to one state. When the opposite condition exists, the output changes to the other state.

Unlike a linear amplifier, the comparator is not concerned with *how much* the two voltages differ. It is only interested in **which one is larger**.

For this reason, a comparator can be regarded as an electronic decision-making device.

Figure 2-1. Basic Comparator Operating Principle



The comparator compares the input voltage (V_{IN}) with the reference voltage (V_{REF}).
The output switches between HIGH and LOW states.

V_{IN} = Input voltage applied to the non-inverting (+) input
V_{REF} = Reference voltage applied to the inverting (−) input
V_{OUT} = Comparator output voltage
V_{CC} = Positive supply voltage

2.2 The Limitation of a Single Threshold

An ordinary comparator has only one switching threshold.

Whenever the input voltage reaches that value, the output changes state.

At first glance this seems ideal.

However, practical signals rarely move cleanly through the threshold voltage. Electrical noise, sensor ripple, supply disturbances, and electromagnetic interference cause the input voltage to fluctuate continuously.

If these fluctuations occur near the switching point, the comparator repeatedly changes state.

The comparator is not making incorrect decisions.

It is making **too many correct decisions**.

Every tiny fluctuation is interpreted as a new input condition.

This repeated switching is known as **output chatter**, and in many practical systems it is unacceptable.

2.3 Positive Feedback Changes the Rules

The solution is remarkably elegant.

Instead of keeping the reference voltage fixed, a small portion of the output voltage is fed back to one of the comparator inputs through a resistor network.

This arrangement is known as **positive feedback**.

Unlike negative feedback, which attempts to reduce changes in circuit behavior, positive feedback reinforces the present output state.

Consequently, the reference voltage is no longer constant.

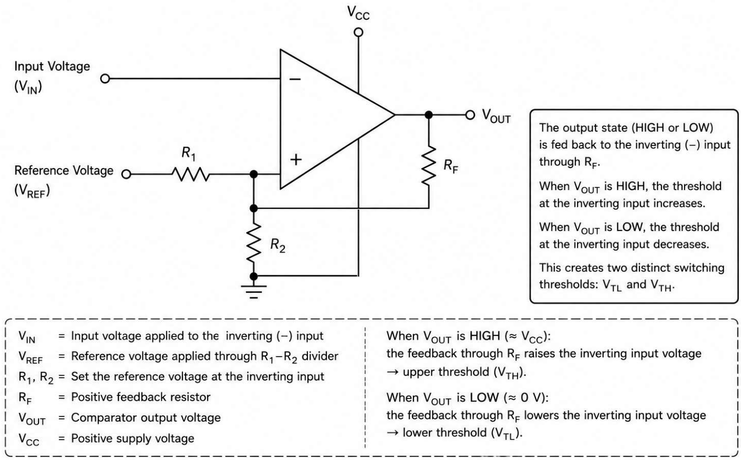
It depends upon the current output state of the comparator.

Whenever the output changes, the switching threshold also changes.

Therefore, the circuit no longer operates with one threshold.

It operates with two.

Figure 2-2. Positive Feedback Creating Two Switching Thresholds



2.4 Two Thresholds Instead of One

The introduction of positive feedback creates two distinct switching levels.

- **Upper Threshold Voltage (UT):**
  The input voltage required to change the output from LOW to HIGH.

- **Lower Threshold Voltage (LT):**
  The input voltage required to change the output from HIGH to LOW.

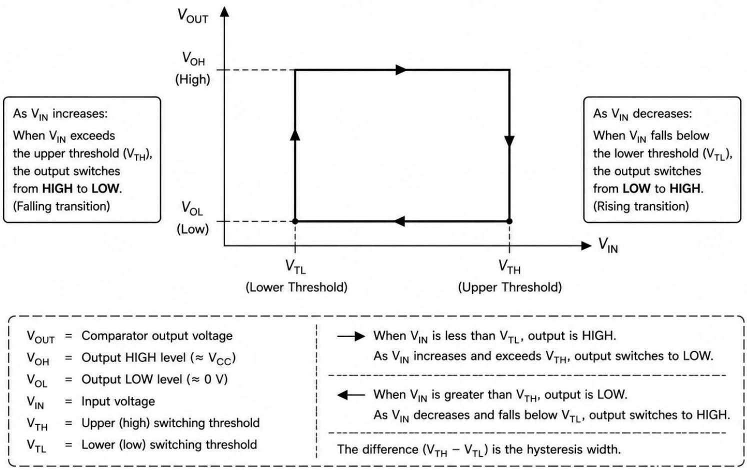
The voltage difference between these two thresholds is called hysteresis **width**.

As long as the input voltage remains between these two limits, the output retains its previous state.

In effect, the comparator acquires a simple form of memory. It remembers its last output until the input changes by a sufficiently large amount.

This memory is what makes hysteresis so effective in rejecting unwanted noise.

Figure 2-3. Hysteresis Transfer Characteristic



2.5 Understanding the Circuit Behavior

At first encounter, many students assume that positive feedback somehow makes the comparator "more sensitive."

The opposite is true. The comparator becomes **more selective**.

Small input variations are ignored because they are insufficient to force the input voltage across the opposite threshold. Only a genuine change in the input signal produces a change in output state.

This distinction is fundamental. The purpose of hysteresis is not to increase sensitivity. Its purpose is to improve **decision quality**.

About Mathematics

No mathematical derivations have been introduced in this chapter.

This is intentional.

Before equations can be used correctly, the engineer must first understand what the circuit is doing physically.

In the next chapter we shall convert these operating principles into mathematical relationships that allow the switching thresholds to be calculated accurately.

The equations will therefore become a natural consequence of the circuit behavior rather than isolated mathematical expressions.

Engineering Insight

Many successful engineering designs are based on a simple principle:

Do not allow a system to react to insignificant changes.

Whether designing an electronic comparator, a motor controller, or an industrial automation system, introducing an appropriate decision margin often produces a system that is more stable, more reliable, and easier to troubleshoot.

Hysteresis is one practical implementation of this universal engineering principle.

Think Like an Engineer

When analyzing any electronic circuit, always ask two questions:

1. **What determines the present state of the circuit?**
2. **What event is capable of changing that state?**

If you can answer these two questions, mathematical analysis usually becomes straightforward.

Good engineers learn to understand the behavior first and derive the equations afterward.

Transition to Chapter 3

Now that we understand how positive feedback creates two switching thresholds and why hysteresis improves circuit stability, we are ready to examine a practical implementation using LM393.

In the next chapter we will analyze the **non-inverting comparator with hysteresis**, derive the design equations step by step, and develop a systematic procedure for selecting component values to meet any required switching thresholds.

Chapter 3

Configuration 1: Non-Inverting Comparator with Hysteresis

3.1 Mathematical Analysis

The operation of the non-inverting comparator with hysteresis can now be translated into mathematical relationships that allow the circuit to be designed accurately.

As explained in the previous chapter, the comparator has two distinct switching thresholds. The upper threshold determines the voltage at which the output changes from LOW to HIGH, while the lower threshold determines the voltage at which the output returns from HIGH to LOW.

The purpose of this analysis is to derive the equations that describe these two thresholds and to determine how the resistor values influence the hysteresis width.

Circuit Conditions

The circuit must be analyzed under two operating conditions.

Case 1 – Output LOW

When the output is LOW, the feedback voltage is approximately zero. The switching threshold is therefore determined by the reference voltage together with the resistor network.

This condition produces the **Upper Threshold Voltage (V_{UT}).**

Case 2 – Output HIGH

When the output becomes HIGH, a portion of the output voltage is fed back through the feedback resistor. This additional voltage shifts the switching threshold.

This condition produces the **Lower Threshold Voltage (V_{LT}).**

The difference between these two threshold voltages is called hysteresis width.

Final Design Equations

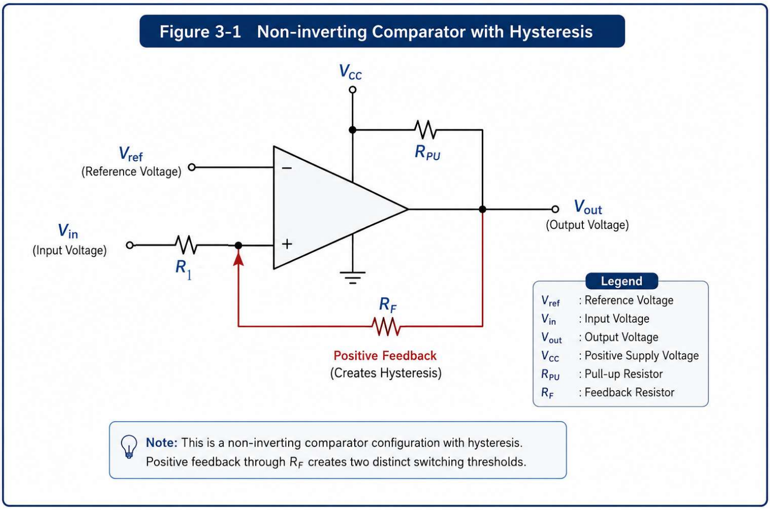


Figure 3-1 Non-inverting Comparator with Hysteresis

$$V_{UT} = V_{REF} \cdot \left(1 + \frac{R_1}{R_F}\right)$$

The upper threshold V_{UT} is the input voltage that must be exceeded before the comparator output changes from LOW to HIGH as V_{IN} rises.

$$V_{LT} = V_{REF} \cdot \left(1 + \frac{R_1}{R_F}\right) - V_{CC} \cdot \left(\frac{R_1}{R_F}\right)$$

The lower threshold V_{LT} is the input voltage below which the comparator output changes from HIGH to LOW as V_{IN} falls.

$$\Delta V_{HYS} = V_{UT} - V_{LT} = V_{CC} \cdot \left(\frac{R_1}{R_F}\right)$$

The hysteresis width depends on the supply voltage and the feedback resistor ratio. The reference voltage determines the position of the switching window, whereas the resistor ratio determines its width.

3.2 Practical Design Procedure

Once the required switching thresholds have been specified, the circuit can be designed using the following sequence.

1. Determine the required Upper Threshold Voltage.
2. Determine the required Lower Threshold Voltage.
3. Calculate the required hysteresis width.
4. Select the desired reference voltage.
5. Calculate the resistor ratio using the design equations.
6. Choose the nearest preferred resistor values.
7. Verify the resulting threshold voltages.
8. Construct and test the circuit.

This systematic procedure avoids trial-and-error design and ensures that the completed circuit satisfies the original specification.

Practical Design Notes

When selecting resistor values, remember the following recommendations:

- R_{PU} value is usually chosen from 1 to 10 KΩ.
- R_F Should be $>>$ R_{PU} So, the pull up drop is negligible. Ex: R_F = 50 → 100 R_{PU}

- Avoid excessively small resistor values, as they increase current consumption unnecessarily.
- Avoid excessively large resistor values, since they increase the effect of leakage currents and electrical noise.
- Select standard resistor values whenever possible.
- Verify the calculated thresholds after rounding resistor values to the nearest preferred values.
- Whenever practical, confirm the final design by measurement before incorporating it into a larger system.

Common Design Mistakes

The following mistakes are frequently encountered during comparator design.

- Choosing resistor values before defining the required thresholds.
- Ignoring the effect of resistor tolerances.
- Assuming the comparator output reaches the exact supply voltage.
- Forgetting that the LM393 requires an external pull-up resistor.
- Omitting verification measurements after construction.

Avoiding these common mistakes greatly increases the likelihood of obtaining the required switching characteristics on the first prototype.

Think Like an Engineer

Successful engineers rarely begin a design by selecting components.

They begin by defining the required performance.

The circuit is then designed to satisfy those requirements.

Whenever a design problem appears to be difficult, first define the desired behavior clearly.

Only then begin the mathematical calculations.

Engineering is not the process of solving equations.

Engineering is the process of solving problems.

Chapter Summary

In this chapter, the mathematical relationships governing the non-inverting hysteresis comparator have been established.

The design equations provide a direct method for determining the resistor values required to obtain any specified switching thresholds.

The next chapter applies the same engineering philosophy to the inverting comparator configuration, demonstrating how a different circuit arrangement leads to a different set of design equations while preserving the same principles of hysteresis operation.

Chapter 4

Configuration 2: Inverting Comparator with Hysteresis

4.1 Introduction

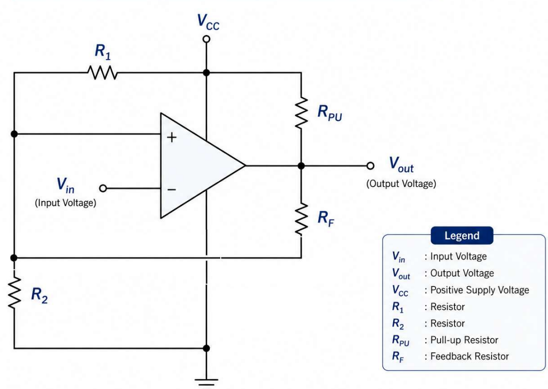
The non-inverting comparator discussed in the previous chapter demonstrated how positive feedback creates two distinct switching thresholds, thereby improving noise immunity and eliminating output instability around the reference voltage.

The same principle can also be applied to the **inverting comparator** configuration. Although the circuit arrangement differs, the objective remains the same: to produce a well-defined hysteresis window with predictable switching thresholds.

This chapter explains the operation of the inverting configuration, develops the corresponding design equations, and presents a systematic design procedure suitable for practical engineering applications.

4.2 Circuit Description

Figure 4-1 Inverting Comparator with Hysteresis



In this configuration, the input signal is applied to the **inverting input** of the LM393 comparator, while the reference voltage and the positive feedback network are connected to the non-inverting input. R_1 & R_2 act as a voltage divider to adjust the reference voltage required at IN+.

The positive feedback resistor causes the reference voltage at the non-inverting input to change according to the output state. As a result, the comparator switches at two different input voltages depending on whether the output is presently HIGH or LOW.

This behavior creates the hysteresis window required for stable switching.

4.3 Principle of Operation

The circuit operates in two stable conditions.

Case 1 – Output LOW

When the output is LOW, the feedback voltage is also LOW.

The reference voltage therefore assumes its lower value.

As the input voltage falls below this level, the comparator output switches HIGH.

Case 2 – Output HIGH

When the output switches HIGH, positive feedback raises the reference voltage.

The input voltage must now rise above this new threshold before the output returns LOW.

The difference between these two threshold voltages is the hysteresis window.

4.4 Mathematical Analysis

The mathematical derivation of the switching thresholds is presented below.

- Upper Threshold Voltage (V_{UT}) occurs when the output is HIGH ($\approx V_{CC}$), putting R_F effectively in parallel with R_1

$$V_{UT} = V_{CC} \cdot \left(\frac{R_2}{(R_1 \parallel R_F) + R_2} \right)$$

Where the parallel resistance $(R_1 \parallel R_F) = \frac{R_1 \,.\, R_F}{R_1 + R_F}$

- Lower Threshold Voltage (V_{LT}) occurs when the output is LOW ($\approx$ 0 V), putting R_F effectively in parallel with R_2.

$$V_{LT} = V_{CC} \cdot \left(\frac{(R_2 \parallel R_F)}{R_1 + (R_2 \parallel R_F)} \right)$$

Where the parallel resistance $(R_2 \parallel R_F) = \frac{R_2 \,.\, R_F}{R_2 + R_F}$

- **Hysteresis width**:

$$\Delta V_{HYS} = V_{UT} - V_{LT}$$

4.5 Practical Design Procedure

Design the circuit according to the following sequence.

1. Specify the required Upper Threshold Voltage.
2. Specify the required Lower Threshold Voltage.
3. Calculate the required hysteresis width.
4. Select the reference voltage.
5. Determine the resistor ratio using the design equations.
6. Select the nearest preferred resistor values.
7. Verify the calculated threshold voltages.
8. Construct and test the circuit.

Following this sequence minimizes design errors and avoids unnecessary trial-and-error calculations.

Practical Design Notes

- Choose resistor values that provide an appropriate compromise between current consumption and noise immunity.
- R_F should be >> R_{PU}.
- Use preferred resistor values whenever practical.
- Recalculate the thresholds after rounding resistor values to standard values.
- Consider resistor tolerances where "switching accuracy" is important.

- Verify the completed circuit experimentally before final installation.

Common Design Mistakes

- Confusing the upper and lower switching thresholds.
- Reversing the comparator inputs.
- Ignoring resistor tolerances.
- Forgetting the LM393 pull-up resistor.
- Failing to verify the final switching voltages experimentally.

Think Like an Engineer

The circuit configuration may change, but the engineering method does not.

Always begin by defining the required switching behavior.

Then derive the necessary resistor values.

Finally, verify that the completed circuit satisfies the original design specification.

A successful engineer cares about performance first in designs and selects components second.

Chapter Summary

This chapter introduced the inverting LM393 comparator with hysteresis and demonstrated how positive feedback produces two distinct switching thresholds.

Although the circuit configuration differs from that of the non-inverting comparator, the same design philosophy applies. By following a systematic design procedure, predictable switching characteristics can be achieved with confidence.

Now it is time to clarify something that relates to both chapters three and four. What is the Difference between non-inverting and inverting configurations? When to use any? Well, in non-inverting configuration, V_{in} is fed to the IN+ of the comparator. In hysteresis mode, this configuration makes output LOW when:

1- V_{in} is lower than V_{TH1} and,
2- V_{in} is between (V_{TH1} and V_{TH2}) if V_{in} started LOW.

This configuration on the other side, makes output HIGH when:

1- V_{in} is higher than V_{TH2} and,
2- V_{in} is between (V_{TH1} and V_{TH2}) if V_{in} started HIGH.

While in inverting mode, Vin is fed to the IN- of the comparator. In hysteresis mode, this configuration makes output HIGH when:

1- V_{in} is lower than V_{TH1} and,
2- V_{in} is between (V_{TH1} and V_{TH2}) if V_{in} started LOW.

This configuration on the other side, makes output LOW when:

1- V_{in} is higher than V_{TH2} and,
2- V_{in} is between (V_{TH1} and V_{TH2}) if V_{in} started HIGH.

The next chapter presents a complete worked design example, illustrating how the principles developed in the previous chapters are applied to solve a practical engineering problem.

Chapter 5

Complete Worked Design Example

5.1 Introduction

The previous chapters established the operating principles and mathematical design equations for both the non-inverting and inverting comparator configurations. In this chapter, these principles are brought together in a complete engineering design example.

Rather than studying individual equations in isolation, the reader will follow the same sequence used by practicing engineers: beginning with a design specification and progressing systematically toward a finished circuit.

The purpose of this chapter is not only to obtain the correct resistor values, but also to demonstrate an organized design methodology that can be applied to future engineering projects.

5.2 Design Specification

Assume that a comparator circuit is required to monitor an analog voltage with the following design specifications:

- Supply Voltage: **(**$V_{CC} = 15\ V$**)**
- Upper Threshold Voltage: **(**$V_{UT} = 7.25V$**)**
- Lower Threshold Voltage: **(**$V_{LT} = 6V$**)**

The objective is to determine suitable resistor values that satisfy these requirements.

5.3 Step 1. Select Circuit Topology

To generate independent thresholds using a single supply source without relying on an external reference voltage generator, deploy the **Inverting Comparator with Hysteresis** topology because it allows the reference voltage to be determined using voltage divider resistors.

- The input voltage V_{IN} connects to the inverting pin IN-.
- A fixed divider network R_1 and R_2 powered by V_{CC} sets the reference, and the feedback resistor Rf alters the reference node at the non-inverting pin IN+.

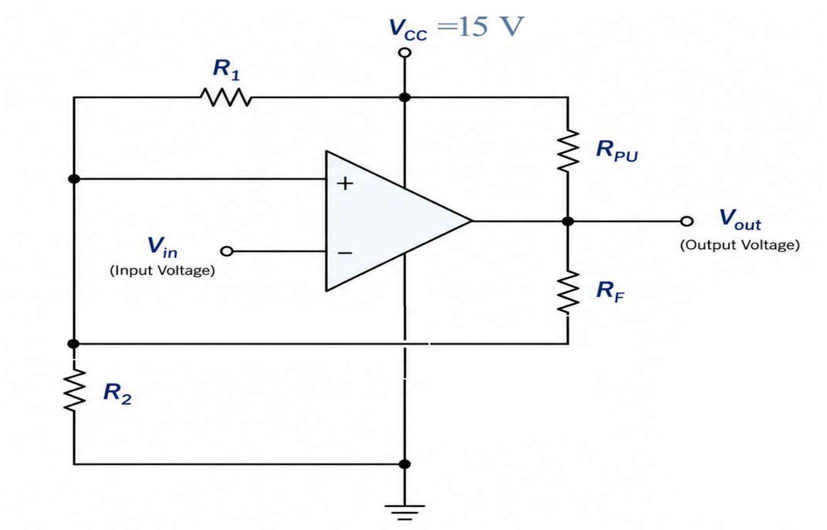


Fig 5 - 1

5.4 Step 2 – Determine R_{PU} & R_F

- Select R_{PU} first: Pick a value like 4.7 **KΩ** or 10 **KΩ** to keep the output sink current well within the LM393's safe limits (< 5 mA).

- Keep feedback resistor much larger than pull up resistor: choose R_F value in the range of 100 to 1000 **KΩ.** This will minimize the loading effect on the open-collector output network.
- Account for input limits: Ensure your input signals and V_{REF} do not exceed the common-mode input voltage limit, which is (V_{CC} – 1.5V) for standard operations.

5.5 Step 3 – Calculations for Finding resistors

When the comparator output is HIGH, the output is pulled to V_{CC} via R_{PU}. Because R_F >> R_{PU}, we can safely approximate the output as V_{CC}, putting R_F in parallel with R_1. So...

$$V_{UT} = V_{CC} \cdot \left(\frac{R_2}{(R_1 \parallel R_F) + R_2} \right)$$

When the comparator output trips LOW, the output stage conducts to ground (0 V), Putting R_F in parallel with R_2. So...

$$V_{LT} = V_{CC} \cdot \left(\frac{(R_2 \parallel R_F)}{R_1 + (R_2 \parallel R_F)} \right)$$

By simultaneously solving these equations with a goal of matching standard commercial E24 series components (with a tolerance of 1%), we find optimal balance of power efficiency and signal accuracy:

- R_1 (Pull-up divider resistor) = 39 K Ohm.
- R_2 (Pull-down divider resistor) = 30 K Ohm.
- R_F (Positive feedback resistor) = 180 K Ohm.
- R_{PU} (Output Pull-up resistor) = 4.7 K Ohm.

So,

For a **(15 V) power supply** (V_{CC}), an **Inverting Schmitt Trigger configuration** delivers your exact thresholds using highly standard E24 resistor values: **(R_1 = 39 k Ohm)**, **(R_2 = 30 K Ohm)**, and **(R_F = 180 k Ohm)**. Pair these with a standard **(R_{PU} = 4.7 k Ohm) pull-up resistor** on the open-collector output of the **LM393 comparator** to secure an upper switching threshold (V_{UT}) of **(7.25 V)** and a lower switching threshold (V_{LT}) of **(5.96 V)**.

5.6 Step 4 – Verify the Design

Substitute the selected resistor values into the threshold equations to verify the design.

$$(R_1 \parallel R_F) = \frac{39\ K\ .\ 180\ K}{39\ K + 180\ K} \cong 32.05\ KOhm$$

$$V_{UT} = 15\ V\ .\left(\frac{30\ K}{32.05\ K + 30\ K}\right) \cong 7.252\ V$$

(Error = 0.03%) Totally accepted.

$$(R_2 \parallel R_F) = \frac{30\ K\ .\ 180\ K}{30\ K + 180\ K} \cong 25.71\ KOhm$$

$$V_{LT} = 15\ V\ .\left(\frac{25.71\ K}{39\ K + 25.71\ K}\right) \cong 5.960\ V$$

(Error = 0.66%) Totally accepted.

Confirm that the calculated switching thresholds satisfy the original design specification.

If necessary, adjust the resistor values and repeat the verification until the desired performance is achieved.

5.7 Practical Considerations

To successfully deploy the LM393 with hysteresis, positive feedback must be routed back to the non-inverting input while explicitly including a pull-up resistor on the output pin to overcome its open-collector limitation.

After completing the mathematical design, several practical considerations should be evaluated before constructing the circuit.

- Component tolerances.
- Supply voltage variations.
- Electrical noise.
- Temperature effects.
- Measurement accuracy.

Considering these factors during the design stage increases the reliability and stability of the completed circuit.

Think Like an Engineer

A successful design is not achieved when the calculations are complete.

A successful design is achieved when the completed circuit performs exactly as intended.

Mathematics predicts circuit behavior.

Practical testing confirms it.

Professional engineering always relies on both.

Chapter Summary

This chapter demonstrated a complete design procedure for an LM393 comparator with hysteresis.

Beginning with a set of design specifications, the required resistor values were determined, verified, and evaluated using a systematic engineering approach.

The next chapter concludes this handbook by presenting practical implementation recommendations, troubleshooting techniques, and design guidelines that help engineers obtain reliable and repeatable results in real-world applications.

Chapter 6

Analytical View to The Circuit Design

6.1 Used circuit description

Fig. 6.1 shows the same circuit used in the example of chapter 5. For more flexibility and more control purposes, one tiny modification was made. The input voltage V_{in} is not directly fed into IN-. Instead, it's fed to a voltage divider and a percentage part of it is fed to IN-. This allows us to use a potentiometer to control the inverted input too. So, variables in this situation are:

- R_1 & R_2, pullup and pulldown divider resistors to IN+
- R_F, Positive feedback resistor
- $R_{\%}$, percentage of the pullup part of the resistor that feeds IN- and gives %age part of Vin to IN-

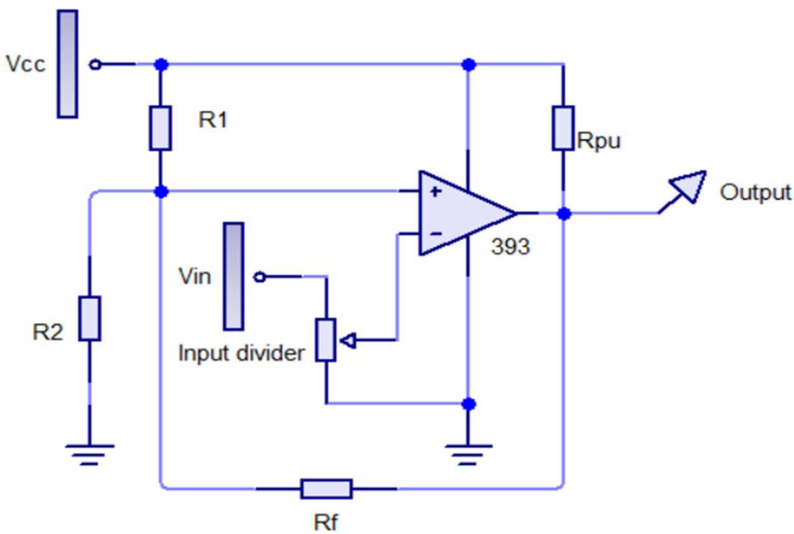


Fig 6-1

Studying this situation enables us to see the effect of each factor (R_1, R_2, R_F, $R_{\%}$, and V_{CC}) on the thresholds individually. It will give us the following resulted graphs from which we can obtain some very important relations as will be clarified hereunder. These relations will help us decide to increase/decrease which factor to:

- Increase/decrease V_{TH1} alone
- Increase/decrease V_{TH2} alone
- Increase/decrease Both V_{TH1} and V_{TH2}
- Increase/decrease the gap between V_{TH1} and V_{TH2} that means (enlarge/reduce hysteresis window)

This is a full control process.

Fig. 6-2, shows the relation between R_1 and (V_{UT} and V_{LT}). This figure tells us that the effect of R_1 on both thresholds goes with an inverse relationship. Also, the rate of V_{LT} drop is slightly more than it is in V_{UT} with the increase in R_1.

Fig. 6-3, shows the relation between R_2 and (V_{UT} and V_{LT}). This figure tells us that the effect of R_2 on both thresholds goes with a direct relationship. Also, the rate of V_{UT} rise is slightly more than it is in V_{LT} with the increase in R_2.

Fig. 6-4, shows the relation between R_F and (V_{UT} and V_{LT}). This figure tells us that the effect of R_F on V_{LT} goes with a direct relationship, while it goes with an inverse relationship with V_{UT}. Also, its effect fades when R_F is too high in value.

Fig. 6-5, shows the relation between V_{CC} and (V_{UT} and V_{LT}). This figure tells us that the effect of V_{CC} on both thresholds goes with a direct relationship. Also, the rate of V_{UT} rise is slightly more than it is in V_{LT} with the increase in V_{CC}. This means that the gap between the two thresholds increases with the increase in $V_{CC.}$

Fig. 6-6, shows the relation between $R_{\%}$ and (V_{UT} and V_{LT}). This figure tells us that the effect of $R_{\%}$ on both thresholds goes with an inverse relationship. Also, the rate of V_{LT} drop is slightly less than it is in V_{UT} with the increase in $R_{\%}$. The two curves meet at 100% ratio. In fact, the gap between the two thresholds (hysteresis window) is almost negligible at 15% or more.

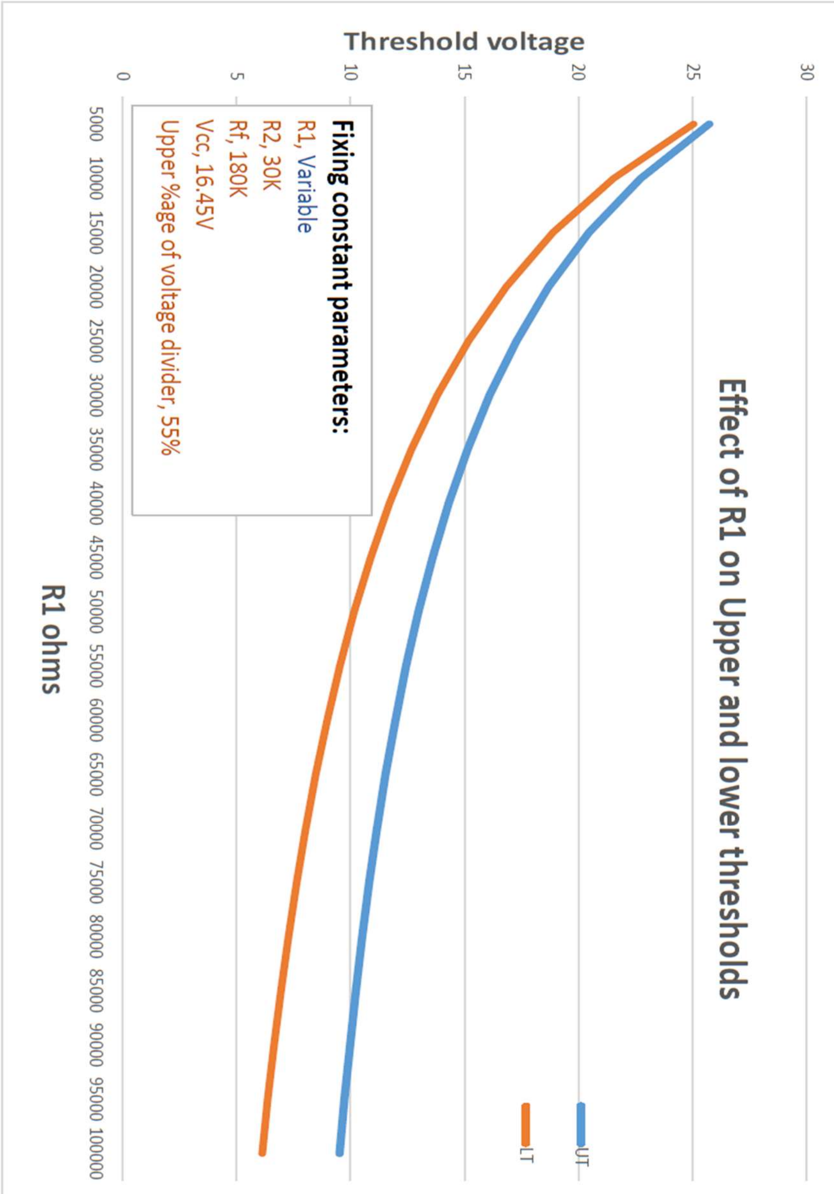

Effect of R1 on Upper and lower thresholds
Threshold voltage
R1 ohms
Fixing constant parameters:
R1, Variable
R2, 30K
Rf, 180K
Vcc, 16.45V
Upper %age of voltage divider, 55%
UT
LT

Fig 6 - 2

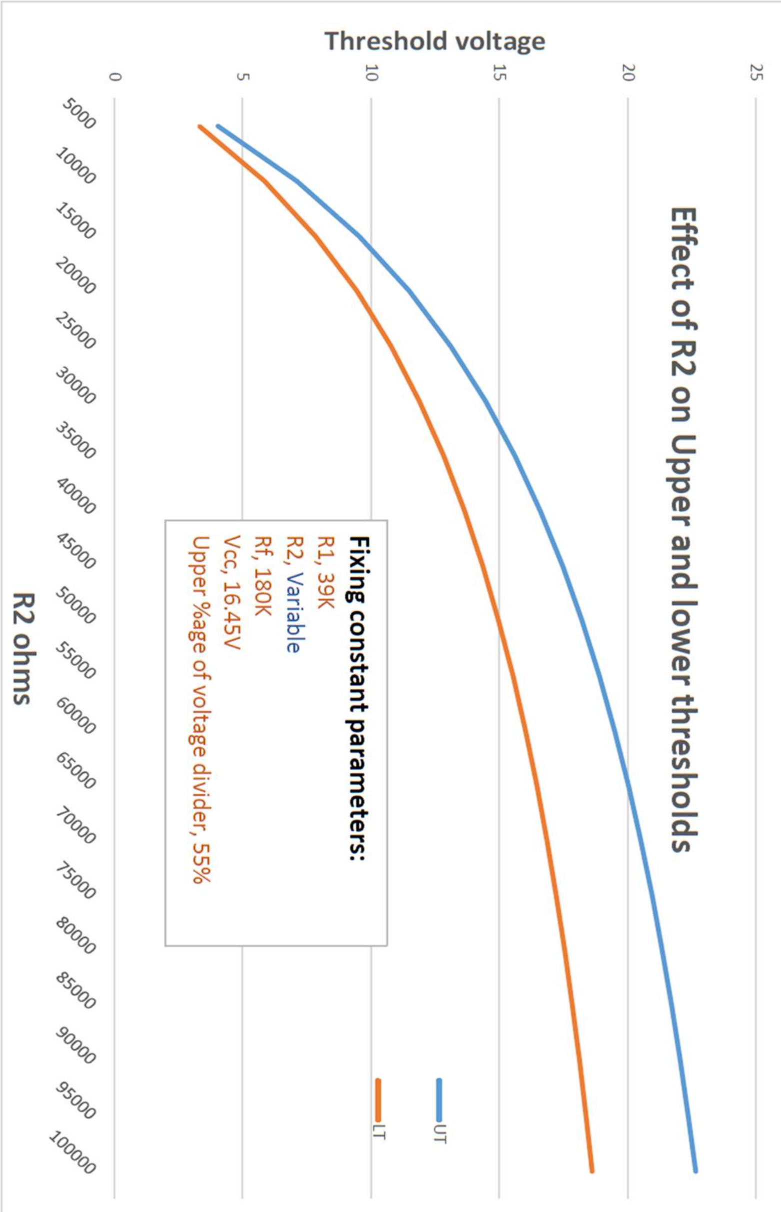
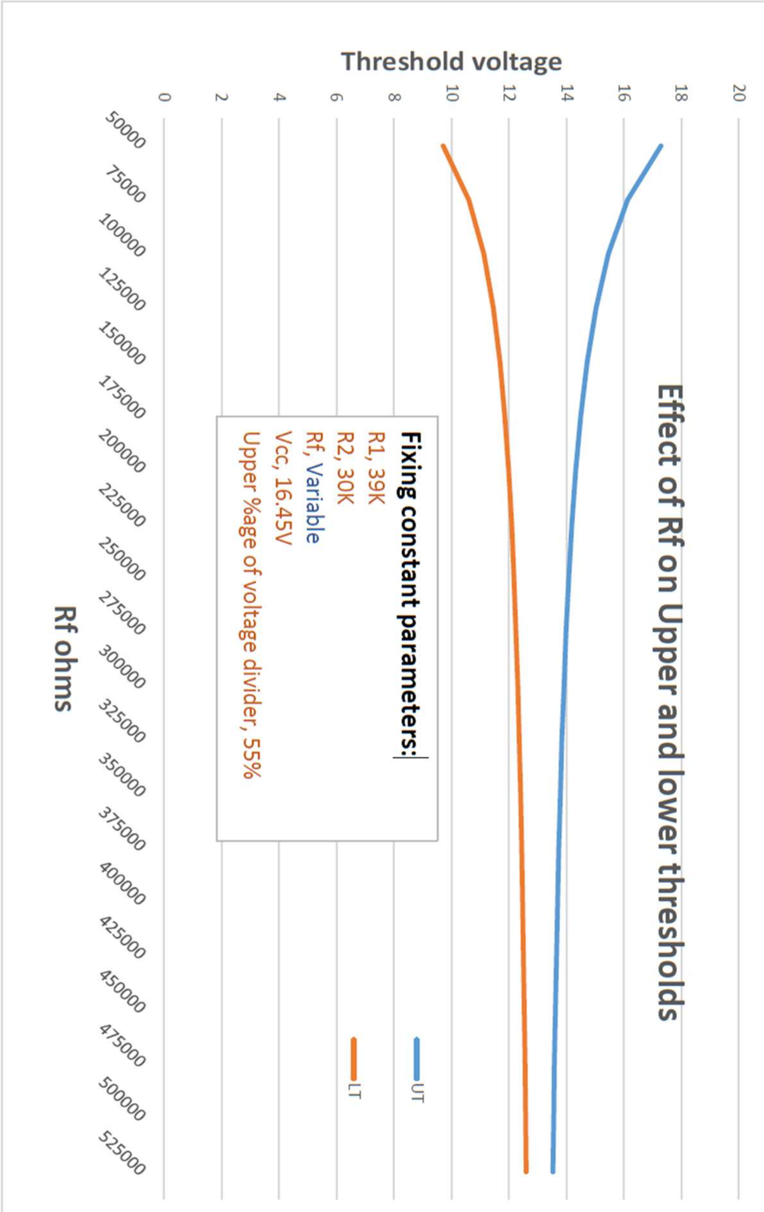

Effect of R2 on Upper and lower thresholds
Threshold voltage
0
5
10
15
20
25
5000
10000
15000
20000
25000
30000
35000
40000
45000
50000
55000
60000
65000
70000
75000
80000
85000
90000
95000
100000
R2 ohms
Fixing constant parameters:
R1, 39K
R2, Variable
Rf, 180K
Vcc, 16.45V
Upper %age of voltage divider, 55%
UT
LT

Fig 6 - 3



Effect of Rf on Upper and lower thresholds
Threshold voltage
0
2
4
6
8
10
12
14
16
18
20
50000
75000
100000
125000
150000
175000
200000
225000
250000
275000
300000
325000
350000
375000
400000
425000
450000
475000
500000
525000
Rf ohms
Fixing constant parameters:
R1, 39K
R2, 30K
Rf, Variable
Vcc, 16.45V
Upper %age of voltage divider, 55%
UT
LT

Fig 6 - 4

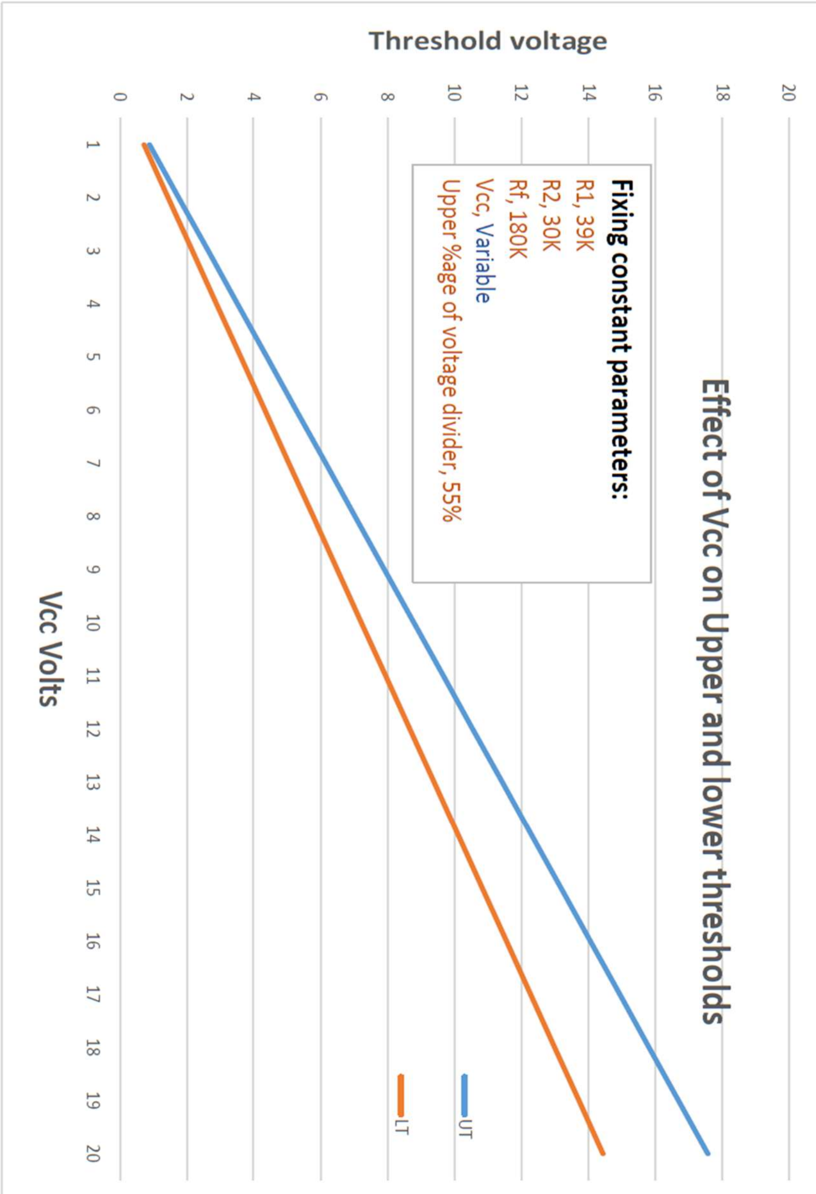

Effect of Vcc on Upper and lower thresholds
Fixing constant parameters:
R1, 39K
R2, 30K
Rf, 180K
Vcc, Variable
Upper %age of voltage divider, 55%
Threshold voltage
0
2
4
6
8
10
12
14
16
18
20
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
Vcc Volts
UT
LT

Fig 6 - 5

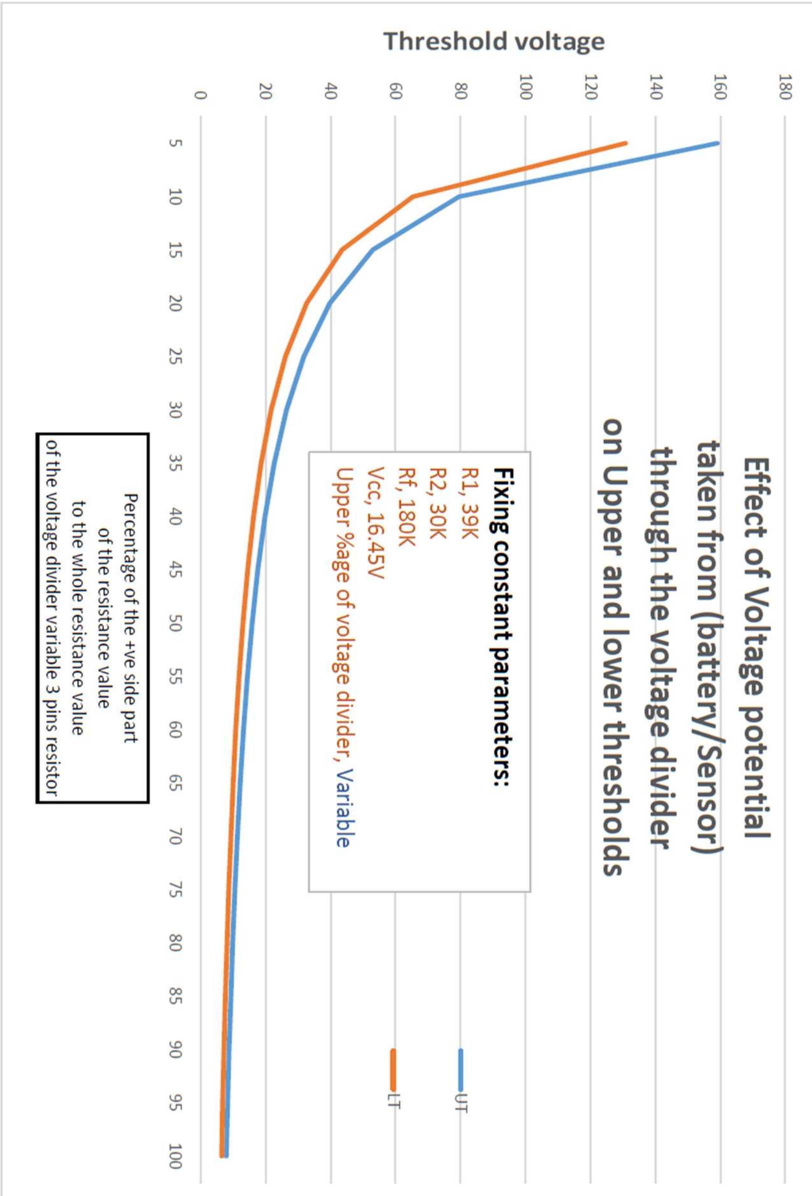

Effect of Voltage potential taken from (battery/Sensor) through the voltage divider on Upper and lower thresholds
Threshold voltage
0 20 40 60 80 100 120 140 160 180
5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100
Fixing constant parameters:
R1, 39K
R2, 30K
Rf, 180K
Vcc, 16.45V
Upper %age of voltage divider, Variable
UT
LT
Percentage of the +ve side part of the resistance value to the whole resistance value of the voltage divider variable 3 pins resistor

Fig 6 - 6

Chapter 7

Practical Design Guidelines and Troubleshooting

7.1 Introduction

A mathematically correct design does not always guarantee satisfactory performance in a practical circuit. Component tolerances, electrical noise, PCB layout, power supply quality, and environmental conditions all influence the behavior of a comparator.

This chapter summarizes the practical considerations that should be taken into account when implementing LM393 comparator circuits with hysteresis. It also presents common troubleshooting techniques that help identify and correct problems during testing and commissioning.

7.2 Good Design Practices

The following recommendations should be considered regarding every comparator design.

Use Stable Reference Voltages

The switching thresholds are directly related to the reference voltage. Any variation in the reference voltage shifts both switching thresholds.

Whenever high accuracy is required, use a stable, low-noise reference source.

Choose Resistor Values Carefully

Select resistor values that provide an appropriate balance between power consumption and noise immunity.

Very low resistance values increase current consumption unnecessarily, while excessively high resistance values make the circuit more susceptible to leakage currents, input bias current errors, and electrical interference.

Use Clean Power Supplies

Noise present on the supply voltage can influence the comparator inputs and affect the switching thresholds.

Place a bypass capacitor as close as possible to the LM393 supply pins to reduce supply noise and improve circuit stability.

Keep Signal Paths Short

Long PCB traces can collect electrical noise and increase the possibility of false switching.

Keep comparator input connections short and route sensitive analog signals away from high-current and high-frequency conductors.

7.3 Troubleshooting Guide

If the circuit does not perform as expected, verify the following items before modifying the design.

Symptom: Output Oscillates Near the Switching Point

Possible Causes

- Insufficient hysteresis.

- Excessive electrical noise.
- Poor PCB layout.
- Unstable reference voltage.

Recommended Action

Increase the hysteresis width if appropriate. Verify the stability of both the reference voltage and the power supply.

Symptom: Incorrect Switching Thresholds

Possible Causes

- Incorrect resistor values.
- Wiring errors.
- Component tolerance.
- Calculation errors.

Recommended Action

Measure each resistor, verify all wiring connections, and compare the measured switching thresholds with the calculated values.

Symptom: Output Does Not Switch

Possible Causes

- Missing pull-up resistor.
- Incorrect supply voltage.
- Faulty comparator.

- Input voltage outside the intended operating range.

Recommended Action

Verify the pull-up resistor, supply voltage, and input signal before replacing any component.

7.4 Practical Verification Procedure

Before approving the final circuit design, perform the following verification steps.

1. Verify the supply voltage.
2. Verify the reference voltage.
3. Measure the upper switching threshold.
4. Measure the lower switching threshold.
5. Compare the measured values with the calculated values.
6. Verify stable operation in the presence of small input disturbances.
7. Confirm reliable operation over the expected operating conditions.

Documenting these measurements provides confidence that the completed circuit satisfies the original design objectives.

7.5 Final Design Recommendations

Before placing the circuit into service, ensure that:

- The measured thresholds agree with the calculated values.

- Preferred resistor values have been used whenever practical.
- The power supply is properly decoupled.
- The PCB layout minimizes electrical noise.
- The circuit has been tested under its intended operating conditions.

A few additional minutes spent verifying the completed circuit can prevent many hours of troubleshooting after installation.

Think Like an Engineer

A good engineer is not judged by how quickly a circuit is designed.

A good engineer is judged by how reliably that circuit performs after it leaves the workbench.

Theory provides understanding.

Mathematics provides prediction.

Testing provides proof.

Professional engineering requires all three.

Chapter Summary

This handbook has presented the LM393 comparator as a practical engineering tool rather than simply an electronic component.

Beginning with the concept of hysteresis, progressing through circuit operation and mathematical design, and concluding with practical implementation and troubleshooting, the objective has been to provide a complete engineering methodology for designing reliable comparator circuits.

Although the examples focused on the LM393, the engineering principles discussed throughout this handbook can be applied to many other analog and mixed-signal designs.

Readers are encouraged to use these methods as a foundation for further study, experimentation, and practical circuit development.

Chapter 8

Common Mistakes and Frequently Asked Questions

8.1 Introduction

Even when the mathematical design is correct, practical implementation errors can prevent a comparator circuit from operating as intended. Many of these problems result from simple oversights rather than complex design errors.

This chapter summarizes the most common mistakes encountered when designing and testing LM393 comparator circuits with hysteresis. It also answers practical questions frequently raised by students and engineers.

8.2 Common Design Mistakes

Mistake 1 – Designing Before Defining the Requirements

One of the most common mistakes is selecting resistor values before determining the required switching thresholds.

A successful design always begins by defining the required circuit behavior.

Only after the design objectives have been established should the component values be calculated.

Mistake 2 – Ignoring Hysteresis

Some designers omit positive feedback because the comparator appears to operate correctly during initial testing.

However, even a small amount of electrical noise can produce unstable switching if hysteresis is not provided.

Whenever the input signal changes slowly or is subject to electrical noise, hysteresis should be considered an essential part of the design.

Mistake 3 – Assuming Ideal Comparator Behavior

Practical comparators differ from ideal mathematical models.

Supply voltage limitations, output saturation voltage, propagation delay, input offset voltage, and resistor tolerances all influence circuit performance.

Design calculations should always be confirmed by practical measurements.

Mistake 4 – Poor PCB Layout

An excellent circuit design can perform poorly if implemented with an unsuitable PCB layout.

Keep signal paths short, separate sensitive analog signals from noisy switching circuits, and place the supply bypass capacitor as close as possible to the LM393.

8.3 Frequently Asked Questions

Why does the output oscillate near the switching point?

This behavior is usually caused by insufficient hysteresis, excessive electrical noise, or an unstable reference voltage.

Increasing the hysteresis width and improving the circuit layout generally eliminate this problem.

Can hysteresis be made too large?

Yes.

Increasing hysteresis width improves noise immunity but reduces switching sensitivity.

The hysteresis width should therefore be selected according to the requirements of the intended application.

Should resistor values always be as large as possible?

No.

Large resistor values reduce power consumption but increase the influence of leakage currents, input bias current, and electrical noise.

A balanced design usually provides the best overall performance.

Is simulation sufficient to verify the design?

Simulation is an excellent engineering tool, but it cannot replace practical measurements.

Component tolerances, temperature variations, and environmental conditions often produce effects that are not fully represented by simulation models.

Think Like an Engineer

Good engineers learn from mistakes before making them.

Study unsuccessful designs as carefully as successful ones.

Every problem discovered during testing provides an opportunity to improve future designs.

Engineering experience is built one lesson at a time.

Chapter Summary

This chapter reviewed common design mistakes and answered practical questions frequently encountered during comparator design.

Understanding these issues enables engineers to avoid unnecessary troubleshooting and develop reliable comparator circuits more efficiently.

The next chapter concludes this handbook with a concise engineering reference that summarizes the key principles presented throughout this work.

Chapter 9

Quick Reference

9.1 Introduction

The preceding chapters have developed the concepts, mathematical foundations, and practical design procedures required for implementing LM393 comparator circuits with hysteresis.

This final technical chapter provides a concise reference to the most important principles presented throughout the handbook. It is intended to serve as a practical guide that can be consulted during future circuit designs without rereading the complete text.

9.2 Design Workflow

For every new comparator design, follow the sequence below.

1. Define the application requirements.
2. Specify the upper switching threshold.
3. Specify the lower switching threshold.
4. Calculate the required hysteresis width.
5. Select the reference voltage.
6. Determine the required feedback resistor ratio.
7. Select the nearest preferred resistor values.
8. Verify the calculated switching thresholds.
9. Construct the circuit.
10. Measure and verify the actual switching thresholds.

Following this procedure significantly reduces design errors and minimizes troubleshooting during testing.

9.3 Practical Design Checklist

Before approving a completed design, verify the following items.

□ Application requirements are clearly defined.

□ Upper and lower switching thresholds specified.

□ Hysteresis width calculated.

□ Standard resistor values selected.

□ Pull-up resistor included.

□ Power supply adequately decoupled.

□ PCB layout reviewed.

□ Switching thresholds verified experimentally.

□ Circuit tested under intended operating conditions.

Completing this checklist before releasing a design greatly improves reliability and reduces commissioning problems.

9.4 Quick Troubleshooting Guide

Observed Problem	Most Likely Cause	Recommended Action
Output oscillates near threshold	Insufficient hysteresis	Increase hysteresis or reduce electrical noise
Incorrect switching thresholds	Incorrect resistor values	Verify resistor values and calculations
Output remains HIGH	Input never crosses threshold	Verify the input voltage range
Output remains LOW	Wiring or reference voltage error	Inspect wiring and reference voltage
Unstable operation	Poor supply decoupling or PCB layout	Improve bypassing and PCB layout

---

9.5 Key Engineering Principles

Throughout this handbook, several engineering principles have been emphasized.

- Start every design by defining the required circuit behavior.
- Use mathematics as a design tool rather than as the design objective.
- Positive feedback improves switching stability and noise immunity.

- Select practical component values instead of mathematically perfect values.
- Verify every design experimentally.
- Learn from every prototype and every test result.

Applying these principles consistently leads to more reliable designs and stronger engineering judgment.

Think Like an Engineer

Engineering knowledge becomes valuable only when it is applied.

The purpose of equations is not memorization.

The purpose of theory is not examination.

The purpose of engineering is to solve practical problems safely, efficiently, and reliably.

Never stop asking *why* a circuit behaves as it does.

Understanding remains the engineer's most valuable instrument.

Chapter Summary

This chapter presented a concise reference to the design methods, practical recommendations, troubleshooting techniques, and engineering principles developed throughout this handbook.

It is intended to remain a practical companion during future comparator designs, allowing the reader to review the essential concepts quickly whenever required.

The following Conclusion closes this handbook by reflecting on the engineering philosophy that guided its preparation and by encouraging readers to continue developing their practical design skills.

Conclusion

Engineering is far more than the application of formulas or the selection of electronic components. It is a disciplined process of observation, analysis, design, verification, and continuous improvement.

Throughout this handbook, the LM393 comparator has been used as a practical example to demonstrate that process. Beginning with the concept of hysteresis, progressing through circuit operation, mathematical analysis, practical design procedures, troubleshooting, and engineering guidelines, the objective has been to develop not only an understanding of a specific circuit, but also a method of thinking that can be applied to many engineering challenges.

A recurring theme throughout these pages has been that successful design begins with clearly defining the required behavior. Mathematics then becomes a powerful tool for achieving that objective, while practical testing confirms that the design performs as intended under real operating conditions.

Readers are encouraged to experiment with the circuits presented in this handbook, modify the design examples, evaluate the results, and continue building their own engineering experience. Every successful prototype increases confidence, while every unexpected result provides an opportunity for deeper understanding.

Although this handbook focuses on the LM393 comparator operating with hysteresis, the engineering principles discussed here extend well beyond a single integrated circuit. The same systematic approach can be applied to many analog, mixed signals, and control system designs.

Finally, remember that engineering is a lifelong journey of learning and improvement. Technology continues to evolve, but the value of careful analysis, sound design practice, and intellectual curiosity remains constant.

May this handbook serve not only as a technical reference, but also as an encouragement to approach every engineering challenge with confidence, discipline, and a desire to understand.

Keep learning.

Keep experimenting.

Keep building.

About the Author

Engineer Khalid Basyouni is an electronics engineer with extensive practical experience in electronic circuit design, industrial applications, and technical training. Throughout his career, he has combined engineering practice with teaching, focusing on simplifying complex electronic concepts and presenting them in a clear, practical manner.

His areas of interest include analog and digital electronics, comparator circuits, embedded systems, electronic measurement, and practical circuit design. He believes that a solid understanding of engineering fundamentals, supported by practical examples, is the key to successful electronic design.

This handbook is part of his effort to provide engineers, technicians, students, and electronics enthusiasts with concise, application-oriented references that bridge the gap between theoretical knowledge and real-world implementation.

"Engineering is not merely about making circuits work, it is about understanding why they work."

Basyouni considers teaching to be a continuous learning journey and hopes that every reader will gain not only technical knowledge but also the confidence to design, analyze, and improve electronic circuits independently. He hopes this work will help readers build confidence in designing reliable electronic circuits and encourage them to continue exploring the fascinating field of electronics.

This Book

Purpose & Audience: This handbook by Engineer Khalid Basyouni is a concise, practical guide for engineers, students, technicians, and hobbyists seeking to understand and design LM393 comparator circuits with hysteresis. It bridges the gap between theory and real-world application, emphasizing logical engineering thinking over rote memorization of formulas.

Key Concepts:

- **Comparator Basics:** The LM393 is a widely used comparator IC. Comparators determine if an input voltage is above or below a reference, but in noisy environments, this can cause unstable outputs (chatter).
- **Hysteresis Principle:** Adding positive feedback creates two switching thresholds (upper and lower), giving the circuit memory and greatly improving noise immunity and stability. This is essential for reliable analog-to-digital interfacing.

Design Approach:

- The book introduces both non-inverting and inverting comparator configurations with hysteresis, explaining their operation, mathematical analysis, and practical design steps.
- **Design Workflow:**
    - Define application requirements and switching thresholds.
    - Calculate hysteresis width and select reference voltage.
    - Use provided equations to determine resistor values.
    - Choose standard resistor values, verify calculations, and test the circuit.
- **Worked Example:** A step-by-step design is provided, showing how to select resistor values for specified thresholds using standard components, and how to verify the design experimentally.

Practical Guidance:

- Emphasizes the importance of stable reference voltages, careful resistor selection, clean power supplies, and good PCB layout.
- Includes troubleshooting tips for common issues (e.g., output oscillation, incorrect thresholds, missing pull-up resistor).
- Offers a quick reference checklist and troubleshooting table for rapid design and debugging.

Engineering Philosophy:

- Start with clear requirements, use mathematics as a tool, and always verify designs experimentally.
- Learn from mistakes and focus on understanding circuit behavior, not just calculations.

Conclusion: The handbook is both a technical reference and a guide to disciplined engineering thinking. It encourages readers to experiment, verify, and continuously improve their designs, applying these principles beyond the LM393 to broader engineering challenges.