ELECTRONICS WORKSHOP 02
PROJECT 02 REPORT

Project Name:
MOSFET-Based H-Bridge DC Motor Drive Circuit

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Contents

1 Video Recording of the whole project with explanation

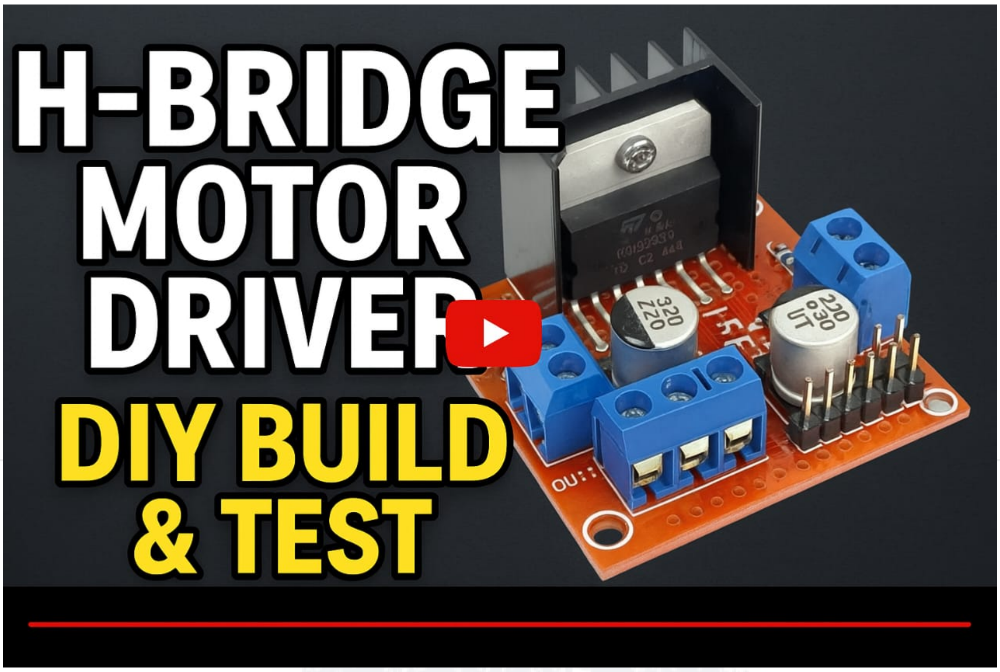


Figure 1: Click the image to watch the video

In this video, we take you through everything we've learned, created, and implemented while working on our **H-Bridge motor driving circuit using MOSFETs**. This isn't just a demonstration — it's a complete walkthrough of the knowledge we've gained and the challenges we've overcome throughout the project.

What's Inside the Video?

- Full explanation of how an H-Bridge works
- Step-by-step assembly of the circuit
- How MOSFETs are used for efficient motor control
- New techniques we applied to improve performance
- Troubleshooting common issues
- Real-time testing and working demonstration
- Insights into what we did differently and why

Key Takeaways

- We built the entire circuit ourselves
- We tested and debugged it independently
- We share honest lessons and what worked best
- We explain each and every component and decision

2 Detailed Analysis of the NE555P-Based PWM Circuit

2.1 System Function

- The circuit generates a **Pulse Width Modulation (PWM)** signal using the **NE555P timer IC** in **astable multivibrator mode**.
- The **duty cycle** (ON/OFF time ratio) of the output waveform is adjustable via **R1, R2, and C1**.
- **Diodes D1 and D2** ensure independent control of charge/discharge paths for precise duty cycle tuning.

2.2 System Purpose

- Designed to **control power delivery** to a load (e.g., motor, LED, heater) efficiently.
- Enables **speed control** (for motors) or **brightness control** (for LEDs) without excessive heat dissipation.

2.3 Why This Design is Better

- **Precise Duty Cycle Control**: The diode network (**D1, D2**) allows independent adjustment of charge/discharge times, improving PWM accuracy.
- **Stable Frequency**: The NE555P ensures consistent oscillation, reducing jitter.
- **Low Cost & Simplicity**: Uses minimal components while maintaining reliability.
- **High Efficiency**: PWM reduces power loss compared to linear control methods.

2.4 What It's Doing

- **Oscillation**: The NE555P generates a square wave whose frequency is set by R1, R2, and C1.
- **Duty Cycle Adjustment**:
  - D1 shortens the charging path (via R1 only), speeding up the rise time.
  - D2 shortens the discharging path (via R2 only), speeding up the fall time.
- **Output (PWM)**: The OUT pin delivers a variable-duty-cycle signal to drive external components (e.g., MOSFETs in an H-bridge).

2.5 Limitations & Considerations

- **Voltage Limits**: NE555P typically operates at 4.5 V to 16 V.
- **Current Sourcing**: Limited to 200 mA max; requires a buffer (e.g., MOSFET) for high-current loads.
- **Noise Sensitivity**: Unfiltered power supply noise may affect stability.

2.6 Circuit Overview

The circuit is an **astable multivibrator** using the NE555 timer to generate a square wave. Key components include resistors (R_{in}, R_{out}, R_4), capacitors (C_1, C_3, C_5), a diode (D_4), and a 12 V supply. The parameters R_{in} and R_{out} are varied to adjust frequency and duty cycle.

2.7 Component Roles and Calculations

2.7.1 NE555 Timer (U1)

- **Role**: Generates a square wave in astable mode.
- **Configuration**:
  - **TRIG** (Pin 2) and **THRS** (Pin 6) are connected to the timing capacitor C_1.
  - **DIS** (Pin 7) discharges C_1 through R_{out} and D_4.

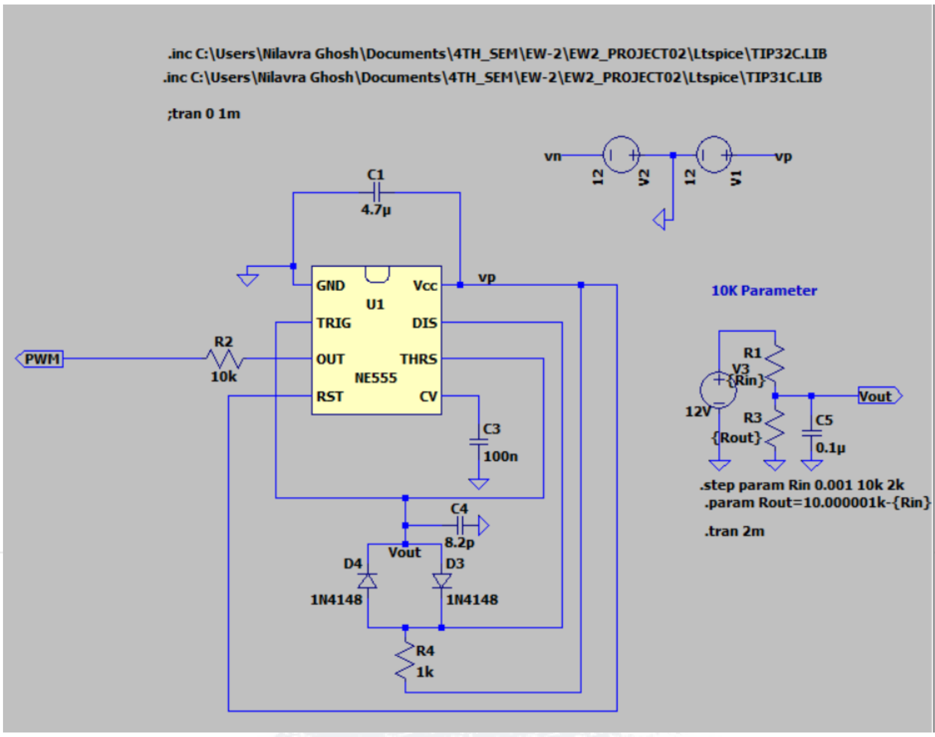


Figure 2: LTSPICE CIRCUIT OF THE 555-TIMER AND POTENTIOMETER

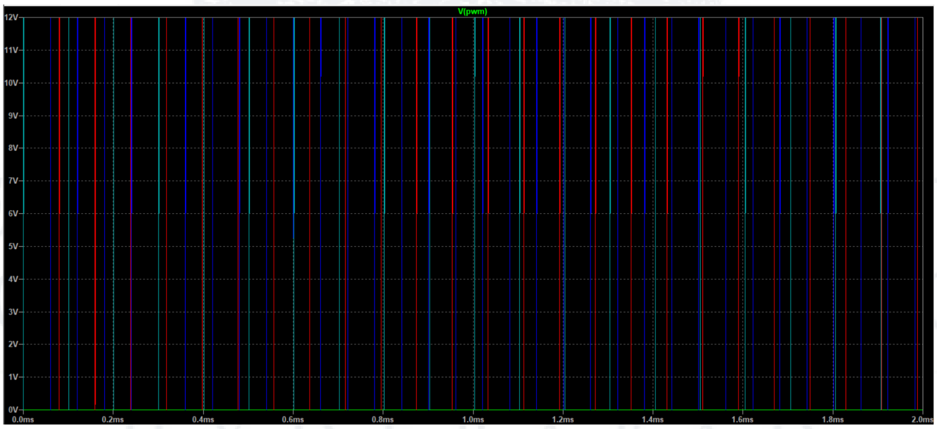


Figure 3: LTSPICE OUTPUT OF THE 555-TIMER AT PWM OUTPUT IN THE CIRCUIT

2.7.2 Timing Resistors (R_{in} and R_{out})

- **Relationship**: $R_{out} = 10.000\,001\,\text{k}\Omega - R_{in}$ (ensures $R_{in} + R_{out} \approx 10\,\text{k}\Omega$).
- **Role**:
  - R_{in}: Charging path resistor (between V_{cc} and DIS).
  - R_{out}: Discharging path resistor (between DIS and GND).
- **Frequency Formula**:

$$f = \frac{1.44}{(R_{in} + 2R_{out}) \cdot C_1}$$

Substituting $R_{out} = 10\,\text{k}\Omega - R_{in}$:

$$f = \frac{1.44}{(20\,\text{k}\Omega - R_{in}) \cdot 4.7\,\mu\text{F}}$$

- **Example Calculations**:

- **Case 1**: $R_{in} = 0\,\Omega$, $R_{out} = 10\,\text{k}\Omega$:

$$f = \frac{1.44}{(20\,\text{k}\Omega)(4.7\,\mu\text{F})} = \frac{1.44}{0.094} \approx 15.3\,\text{Hz}$$

- **Case 2**: $R_{in} = 5\,\text{k}\Omega$, $R_{out} = 5\,\text{k}\Omega$:

$$f = \frac{1.44}{(15\,\text{k}\Omega)(4.7\,\mu\text{F})} = \frac{1.44}{0.0705} \approx 20.4\,\text{Hz}$$

- **Case 3**: $R_{in} = 10\,\text{k}\Omega$, $R_{out} \approx 0\,\Omega$:

$$f = \frac{1.44}{(10\,\text{k}\Omega)(4.7\,\mu\text{F})} = \frac{1.44}{0.047} \approx 30.6\,\text{Hz}$$

2.7.3 Timing Capacitor ($C_1 = 4.7\,\mu\text{F}$)

- **Role**: Determines the charging/discharging time with R_{in} and R_{out}.
- **Value Justification**: A larger capacitance (4.7 µF) allows lower frequencies (15 Hz to 30 Hz range), suitable for applications like LED blinking or tone generation.

2.7.4 Diode D_4 (1N4148) and Resistor R_4 (1 kΩ)

- **Role**:
  - D_4 creates a separate discharge path through R_4, bypassing R_{out} during discharge.
  - R_4 limits discharge current and adjusts the duty cycle.
- **Duty Cycle Formula**:

$$\text{Duty Cycle} = \frac{R_{in} + R_{out}}{R_{in} + 2R_{out}} = \frac{10\,\text{k}\Omega}{20\,\text{k}\Omega - R_{in}}$$

  - **Case 1**: $R_{in} = 0\,\Omega \rightarrow 50\%$.
  - **Case 2**: $R_{in} = 5\,\text{k}\Omega \rightarrow 10k/15k \approx 66.7\%$.
  - **Case 3**: $R_{in} = 10\,\text{k}\Omega \rightarrow 10k/10k = 100\%$ (theoretical limit).

2.7.5 Capacitors C_3 (100 nF) and C_5 (0.1 µF)

- C_3: Connected to the **CV** (Control Voltage) pin to stabilize the threshold voltage and reduce noise.
- C_5: Power supply decoupling capacitor to filter high-frequency noise.

2.7.6 Power Supply (12 V)

- **Role**: Provides stable voltage for the NE555. The 555 operates optimally between 4.5 V to 15 V; 12 V is a common choice for robust output.

2.8 Summary of Component Choices

Component	Value	Role
R_{in}	0.001 kΩ to 10 kΩ	Adjusts charging resistance to vary frequency and duty cycle.
R_{out}	10 kΩ - R_{in}	Balances total resistance to 10 kΩ for consistent frequency range.
C_1	4.7 µF	Sets base timing for low-frequency oscillation.
D_4	1N4148	Enables asymmetric discharge path for duty cycle ¿50%.
R_4	1 kΩ	Limits discharge current through D_4.
C_3	100 nF	Stabilizes the control voltage pin (noise reduction).
C_5	0.1 µF	Decouples the power supply.
V_{CC}	12 V	Optimal supply voltage for NE555.

Table 1: Component Summary

2.9 Simulation Commands

- **.step param Rin 0.001 10k 2k**: Sweeps R_{in} from $0.001\,\Omega$ to $10\,\mathrm{k}\Omega$ in $2\,\mathrm{k}\Omega$ steps to analyze frequency/duty cycle variation.
- **.tran 2m**: Runs a transient analysis for 2 ms to observe waveform behavior.

Detailed Justification of Component Values in NE555 Astable Multivibrator

2.10 Timing Capacitor $C_1 = 4.7\,\mu\mathrm{F}$

- **Design Requirement**: Achieve low-frequency oscillation (15 Hz to 30 Hz) for LED blinking/audio tones.
- **Calculation**:

$$f = \frac{1.44}{(R_{in} + 2R_{out}) \cdot C_1}$$
$$\text{Given } R_{out} = 10\,\mathrm{k}\Omega - R_{in} \Rightarrow R_{in} + 2R_{out} = 20\,\mathrm{k}\Omega - R_{in}$$
$$\text{For } f \approx 15.3\,\mathrm{Hz}:$$
$$C_1 = \frac{1.44}{f \cdot (20\,\mathrm{k}\Omega)} = \frac{1.44}{15.3 \times 20,000} \approx 4.7\,\mu\mathrm{F}$$

- **Standardization**: $4.7\,\mu\mathrm{F}$ is a common E6-series electrolytic capacitor value.

2.11 Resistors R_{in} and R_{out} (Total $\approx 10\,\mathrm{k}\Omega$)

- **Current Limiting**:

$$I_{max} = \frac{V_{CC}}{R_{total}} = \frac{12\,\mathrm{V}}{10\,\mathrm{k}\Omega} = 1.2\,\mathrm{mA} \quad \text{(Safe for NE555)}$$

- **Frequency Range**:

$$\text{When } R_{in} = 0\,\Omega: \quad f = \frac{1.44}{20\,\mathrm{k}\Omega \times 4.7\,\mu\mathrm{F}} \approx 15.3\,\mathrm{Hz}$$
$$R_{in} = 10\,\mathrm{k}\Omega: \quad f = \frac{1.44}{10\,\mathrm{k}\Omega \times 4.7\,\mu\mathrm{F}} \approx 30.6\,\mathrm{Hz}$$

- **Duty Cycle Control**:

$$\text{Duty} = \frac{R_{in} + R_{out}}{R_{in} + 2R_{out}} = \frac{10\,\mathrm{k}\Omega}{20\,\mathrm{k}\Omega - R_{in}}$$
$$R_{in} = 5\,\mathrm{k}\Omega \Rightarrow \text{Duty} = \frac{10\,\mathrm{k}\Omega}{15\,\mathrm{k}\Omega} \approx 66.7\%$$

2.12 Diode D_4 (1N4148) and Resistor R_4 ($1\,\mathrm{k}\Omega$)

- **Diode Selection**:
  - Reverse recovery time = 4 ns (fast enough for 30 Hz operation)
  - Forward voltage $V_f \approx 0.7\,\mathrm{V}$ (minimizes duty cycle error)
- **Discharge Current Protection**:

$$I_{dis} = \frac{V_{CC} - V_f}{R_4} = \frac{12\,\mathrm{V} - 0.7\,\mathrm{V}}{1\,\mathrm{k}\Omega} \approx 11.3\,\mathrm{mA}$$
$$\ll 200\,\mathrm{mA} \text{ (NE555 discharge pin rating)}$$

2.13 Capacitors C_3 (100 nF) and C_5 (0.1 µF)

- **Control Voltage Stabilization** (C_3):
  - Filters noise on internal voltage divider (Pin 5)
  - $X_C = \frac{1}{2\pi fC} = \frac{1}{2\pi \times 1\,\mathrm{MHz} \times 100\,\mathrm{nF}} \approx 1.6\,\Omega$ at 1 MHz
- **Power Decoupling** (C_5):
  - Standard 0.1 µF ceramic capacitor
  - Effective for frequencies >10 MHz ($X_C \approx 0.16\,\Omega$ at 10 MHz)

2.14 Power Supply $V_{CC} = 12\,\mathrm{V}$

- **Operating Range**:
  - NE555 specified for 4.5 V to 15 V operation
  - 12 V provides 20% margin from both limits
- **Output Swing**:

$$V_{out} = V_{CC} - 1.5\,\mathrm{V}\ \text{(typical)} = 10.5\,\mathrm{V}$$

2.15 Simulation Parameters

- **.step param Rin 0.001 10k 2k**:
  - Resolution: 2 kΩ steps cover all operating regions
  - Minimum $R_{in} = 0.001\,\Omega$ avoids division by zero
- **.tran 2m**:
  - Captures ≈30 cycles at lowest frequency (15 Hz)
  - $\frac{2\,\mathrm{ms}}{1/15\,\mathrm{Hz}} = 30$ cycles

Table 2: Component Selection Rationale

Component	**Value**	**Design Considerations**
Timing Capacitor	4.7 µF	• Frequency formula: $f = \frac{1.44}{(R_{in}+2R_{out})C_1}$ • For 15 Hz to 30 Hz range with $R_{total} \approx 10\,\text{k}\Omega$: – Calculated: $C_1 = \frac{1.44}{20\,\text{k}\Omega \times 15\,\text{Hz}} = 4.8\,\mu\text{F}$ – Selected standard 4.7 µF (E6 series) • Larger capacitance enables lower frequencies
Timing Resistors	R_{in}: 0 kΩ to 10 kΩ R_{out} = 10 kΩ - R_{in}	• Total resistance ≈10 kΩ provides: – Safe current: $I_{max} = \frac{12\,\text{V}}{10\,\text{k}\Omega} = 1.2\,\text{mA}$ – Target frequency range with 4.7 µF • Mathematical relationship ensures: – Linear frequency adjustment – Precise 50-100% duty cycle control – $R_{in} + R_{out}$ always ≈10 kΩ
Diode D4	1N4148	• Key specifications: – 4 ns reverse recovery time – 0.7 V forward voltage – 200 mA max current • Benefits: – Precise discharge control – Minimal duty cycle distortion

3 Circuit Analysis for the Gate Driver Circuit

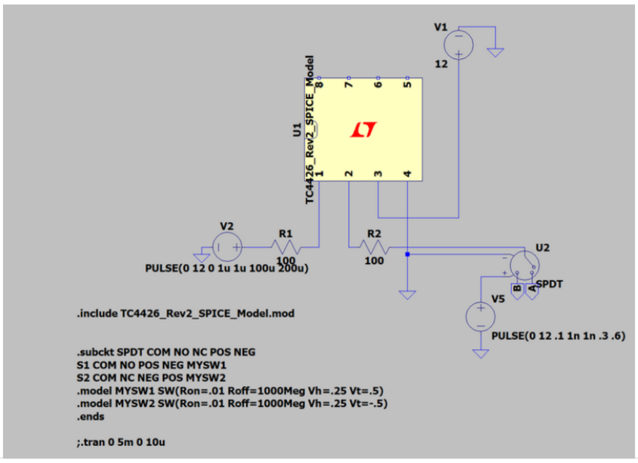


Figure 4: The gate-driver LTspice circuit with SPDT switch

3.1 Voltage Source V1 (12 V DC)

- **Value**: 12 V
- **Purpose**: This is the main DC power supply for the circuit.
- **Rationale**:
  - 12 V is a common voltage for automotive and many electronic systems.
  - The value was likely chosen based on the system requirements being simulated.
- **Calculation**: No calculation needed as this is a defined input voltage.

3.2 Component U1 (TCM-32_Rw2_SPICE_Model)

- **Model**: TCM-32_Rw2_SPICE_Model
- **Purpose**: This appears to be a custom SPICE model (possibly a relay coil or other component).
- **Rationale**:
  - The ".include" statement shows this model is defined in an external file "TCA426_Rw2_SPICE_Model.mod".
  - The naming suggests it might be a relay coil model (TCM could stand for "Telephone Circuit Module" or similar).

3.3 Voltage Source V2 (Pulse Source)

- **Value**: PULSE(0 12 0 1u 1u 100u 280u)
- **Purpose**: This generates a pulsed waveform to simulate switching behavior.
- **Parameters**:
  - Initial value: 0 V
  - Pulsed value: 12 V
  - Delay time: 0 s
  - Rise time: 1 µs
  - Fall time: 1 µs
  - Pulse width: 100 µs
  - Period: 280 µs
- **Rationale**:

- The pulse is likely driving the relay coil (U1).
- 12 V matches the coil's operating voltage (from V1).
- The 100 µs ON time and 180 µs OFF time (280 µs period - 100 µs pulse) create a duty cycle of ∼35.7%.
- Fast rise/fall times (1 µs) simulate realistic but not instantaneous switching.

- **Calculations**:

$$\begin{aligned} \text{Duty cycle} &= \left(\frac{\text{Pulse width}}{\text{Period}}\right) \times 100 \\ &= \left(\frac{100\,\mu\text{s}}{280\,\mu\text{s}}\right) \times 100 \approx 35.7\% \\ \text{Frequency} &= \frac{1}{\text{Period}} = \frac{1}{280\,\mu\text{s}} \approx 3.57\,\text{kHz} \end{aligned}$$

3.4 Resistor R2

- **Value**: 100 Ω
- **Purpose**: Likely a current limiting resistor for the relay coil.
- **Rationale**:
  - With 12 V supply, this limits coil current to $I = V/R = 12\,\text{V}/100\,\Omega = 120\,\text{mA}$.
  - This is a reasonable current for many relay coils.
  - Prevents excessive current draw from the pulse source.
- **Calculation**:

$$\begin{gathered} I = \frac{V}{R} = \frac{12\,\text{V}}{100\,\Omega} = 120\,\text{mA} \\ P = I^2R = (0.12\,\text{A})^2 \times 100\,\Omega = 1.44\,\text{W} \\ \text{(would need a 2 W resistor for safety margin)} \end{gathered}$$

3.5 Component U2 (PSPDT)

- **Model**: SPDT (defined in the subcircuit)
- **Purpose**: Simulates a Single Pole Double Throw (SPDT) relay or switch.
- **Subcircuit Analysis**:

```
subckt SPDT CON NO NC POS NEG
S1 CON NO POS NEG MYSW1
S2 CON NC NEG POS MYSW2
.model MYSW1 SW(Ron=.01 Roff=1000Meg Vh=.25 Vt=.5)
.model MYSW2 SW(Ron=.01 Roff=1000Meg Vh=.25 Vt=-.5)
.ends
```

- **Parameters**:
  - Two switches (S1 and S2) implement the SPDT functionality
  - CON: Common terminal
  - NO: Normally Open contact
  - NC: Normally Closed contact
  - POS/NEG: Control terminals
- **Switch Models**:
  - Ron = 0.01 Ω (very low ON resistance)
  - Roff = 1000 MΩ (very high OFF resistance)

  - Vh = 0.25 V (hysteresis voltage)
  - Vt = ±0.5 V (threshold voltage, opposite signs for the two switches)

- **Rationale**:
  - The switch models create realistic switching behavior:
    * Low ON resistance simulates good contact closure
    * High OFF resistance simulates proper isolation
    * Hysteresis prevents chatter during switching
  - Opposite Vt values ensure only one switch is on at a time

3.6 Commented Transient Analysis

- **Command**: `; .tran 0 5m 0 10u`
- **Purpose**: Would perform a transient analysis if uncommented
- **Parameters**:
  - Start time: 0 s
  - Stop time: 5 ms
  - Step time: 10 µs
- **Rationale**:
  - 5 ms duration would show multiple cycles of the 280 µs pulse
  - 10 µs step provides adequate resolution for the 1 µs rise/fall times

System Operation Analysis

3.7 Power Supply:

- V1 provides 12 V DC to the system
- V2 provides a pulsed 12 V signal with 35.7% duty cycle at ∼3.57 kHz

3.8 Relay Operation:

- The pulse signal through R2 (100 Ω) drives the relay coil (U1)
- Coil current peaks at 120 mA during ON periods
- The SPDT switch (U2) changes state based on the coil activation

3.9 Switching Behavior:

- When control voltage is above +0.5 V:
  - S1 turns ON (Ron=0.01 Ω)
  - S2 turns OFF (Roff=1000 MΩ)
- When control voltage is below -0.5 V:
  - S2 turns ON
  - S1 turns OFF
- Between -0.25 V and +0.25 V (hysteresis band), switches maintain their state

Design Considerations

3.10 Relay Coil Parameters:

- The 100 Ω resistor suggests the coil resistance is either:
  - Part of the U1 model (external definition)
  - Or the total coil circuit resistance is 100 Ω

3.11 Switching Speed:

- The 1 µs rise/fall times are realistic for solid-state relays
- Mechanical relays would typically have slower switching (ms range)

3.12 Power Dissipation:

- During ON state:
  - Switch power = I^2Ron
  - For 1 A current: $1^2 \times 0.01\,\Omega = 10\,\text{mW}$ per switch
- During OFF state:
  - Leakage current = V/R_{off}
  - For 12 V: $12/1000\,\text{M}\Omega = 12\,\text{pA}$ (negligible)

4 Detailed Circuit Analysis for the H-Bridge Circuit

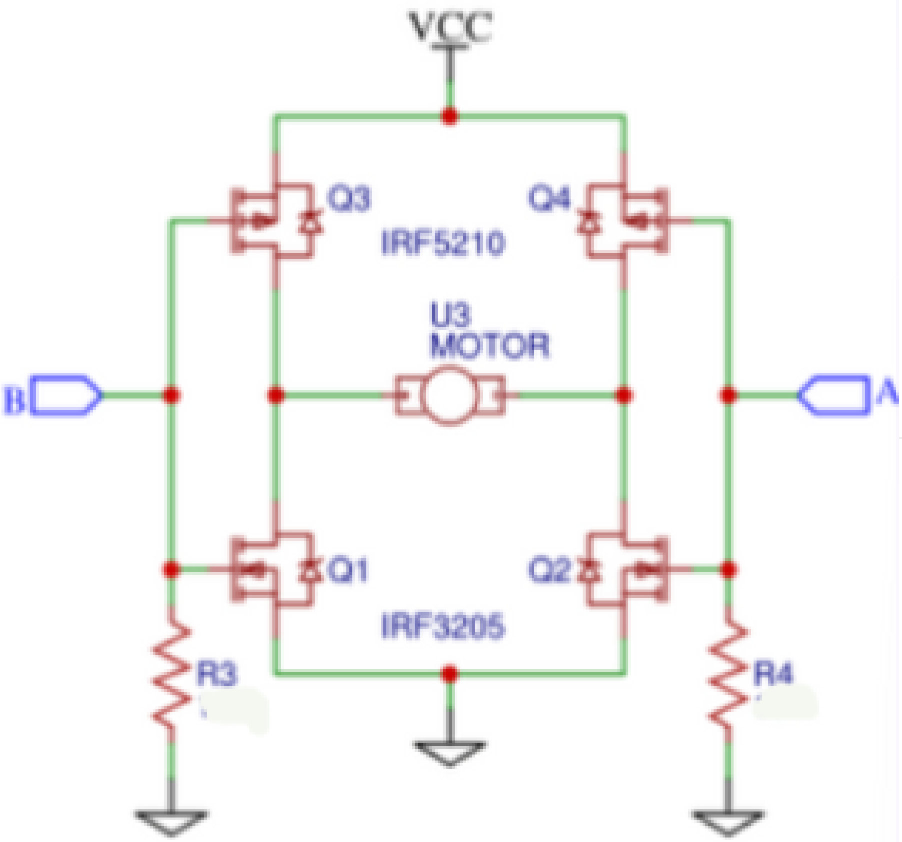


Figure 5: Initial Circuit plan for the H-bridge Circuit

4.1 Component Analysis

4.2 Circuit Analysis Calculations

1. **Base Current Calculations (for BC547)**:

$$\begin{aligned}
&\text{For Q4 with } R1 = 10\,\text{k}\Omega: \\
I_b &= \frac{V_{cc} - V_{be}}{R1} \\
&= \frac{12\,\text{V} - 0.7\,\text{V}}{10\,\text{k}\Omega} \\
&= 1.13\,\text{mA} \\
&\text{Assuming } h_{FE} = 100: \\
I_c &= I_b \times h_{FE} \\
&= 1.13\,\text{mA} \times 100 \\
&= 113\,\text{mA}
\end{aligned}$$

2. **Power Dissipation Calculations**:

$$\begin{aligned}
&\text{For transistors:} \\
P_{max} &= V_{CE} \times I_C \\
&\text{For 4 A current and } 2\,\text{V}V_{CE}: \\
P &= 4\,\text{A} \times 2\,\text{V} = 8\,\text{W} \\
&\text{(Requires heatsinking)}
\end{aligned}$$

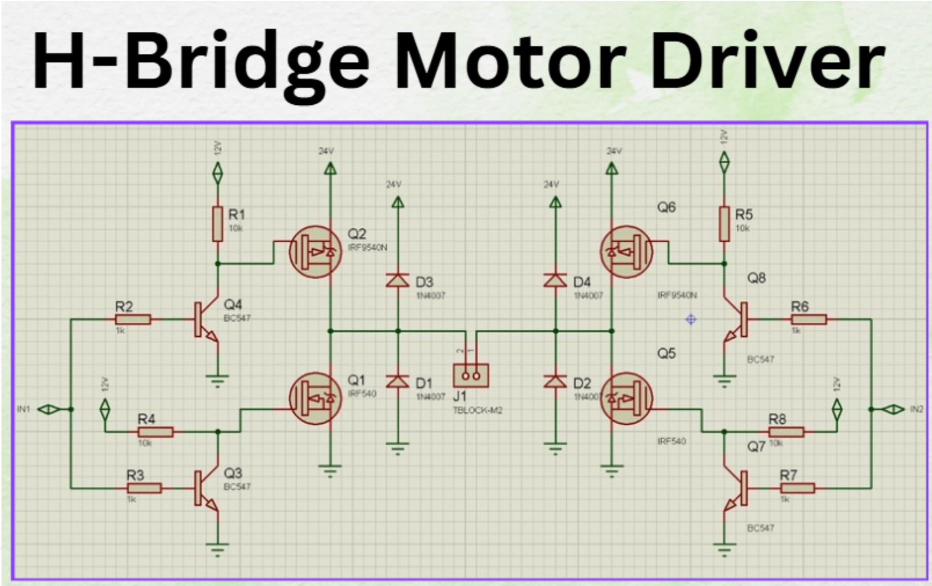


Figure 6: H-bridge circuit after redesigning

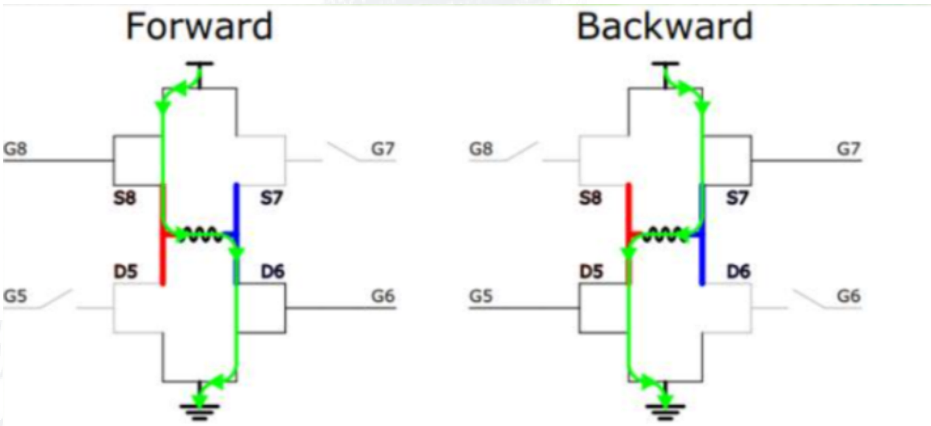


Figure 7: Bi-directional Flow Depicting in the H-bridge Circuit by the Motor

3. **Diode Current Handling**:
   - 1N4007 diodes:
     - Max continuous current = 1 A
     - Peak surge current = 30 A
4. **Switching Speed Considerations**:
   - For BC547:
     - Turn-on/off time ≈ 100 ns
     - Switching frequency limit ≈ 1 MHz

4.3 Design Rationale

- **Mixed Signal/Power Design**:
  - BC547 for control/logic functions
  - IRF540/IRF9540N for power switching
- **Complementary Topology**:
  - NPN/PNP combination enables push-pull operation
- **Protection Features**:

Table 3: Component Specifications and Functions (Part 1)

Component	**Value/Type**	**Purpose and Characteristics**
Resistor R1	$10\,\text{k}\Omega$	• Base current limiting resistor • Calculation: – $I_b = \frac{12\,\text{V}-0.7\,\text{V}}{10\,\text{k}\Omega} = 1.13\,\text{mA}$ – For $\beta = 100$: $I_c \approx 113\,\text{mA}$
Transistor Q2,Q6	IRF9540N	• Power MOSFET (N-channel) • V_{DS}: $40\,\text{V}$, I_D: $4\,\text{A}$ • $R_{DS(on)}$: $<0.1\,\Omega$
Resistor R2	1K	Placeholder for future modifications
Transistor Q4,Q4,Q7,Q8	BC547	• General purpose NPN • V_{CEO}: $45\,\text{V}$, I_C: $100\,\text{mA}$

Table 4: Component Specifications and Functions (Part 2)

Component	**Value/Type**	**Purpose and Characteristics**
Resistor R3	1K	Same as R2
Resistor R4	$10\,\text{k}\Omega$	• Pull-up/pull-down resistor • Base current limiting
Transistor Q5,Q1	IRF540	• Power Mosfet(P-channel) • V_{CEO}: $-40\,\text{V}$, I_C: $-4\,\text{A}$

  - 1N4007 diodes provide flyback protection
  - $10\,\text{k}\Omega$ resistors prevent excessive base current
- **Scalability**:
  - Multiple parallel transistors suggest high-current capability
  - Unpopulated resistors allow for circuit tuning
- **Voltage Requirements**:
  - Component ratings suggest $12\,\text{V}$ to $24\,\text{V}$ operation
  - 1N4007 diodes allow for high voltage spike handling

Component Analysis

4.4 Resistor R1 ($10\,\text{k}\Omega$)

- **Base Current Calculation for BC547 (Q4):**

$$\begin{aligned}
h_{FE} &= 100 \text{ (minimum guaranteed)} \\
I_C &= 100\,\text{mA} \text{ (max for BC547)} \\
I_B &= \frac{I_C}{h_{FE}} = \frac{100\,\text{mA}}{100} = 1\,\text{mA} \\
R1 &= \frac{V_{CC} - V_{BE}}{I_B} = \frac{12\,\text{V} - 0.7\,\text{V}}{1\,\text{mA}} = 11.3\,\text{k}\Omega \\
&\rightarrow \text{Standard } 10\,\text{k}\Omega \text{ chosen}
\end{aligned}$$

- **Purpose:** Limits base current to 1.13 mA (safe for BC547)
- **Trade-off:**
  - Higher values reduce drive capability
  - Lower values risk overdriving transistor

4.5 Transistor Q2 (IRF540N)

- **Parameters:**
  - $V_{DS} = 40\,\text{V}$ (matches 12 V system with margin)
  - $I_D = 4\,\text{A}$ (sufficient for power switching)
  - $R_{DS(on)} \approx 0.1\,\Omega$ (low conduction losses)
- **Selection Rationale:**
  - Handles 4× more current than BC547
  - Low gate drive requirements (compatible with BC547)
  - TO-220 package for heat dissipation

4.6 Resistors R2/R3 (1K)

- **Design Flexibility:**
  - Placeholders for current sensing (e.g., 1 Ω resistors)
  - Allow for gain adjustment in differential pairs
  - Potential base stopper resistors (100 Ω to 1 Ω-1 kΩ)

4.7 Transistors Q3/Q4 (BC547)

- **Technical Justification:**
  - $V_{CEO} = 45\,\text{V} > 12\,\text{V}$ system
  - $I_C = 100\,\text{mA}$ sufficient for control
  - $h_{FE} = 110 - 800$ provides good amplification
  - $f_T = 300\,\text{MHz}$ for fast switching
- **Cost Optimization:**
  - 0.02/unit vs 0.50 for similar FETs

Power Stage Design

4.8 Resistor R4 (10 kΩ)

- **Pull-up/Pull-down Calculation:**

$$\begin{aligned} &\text{For } 100\,\mu\text{A leakage:} \\ V_{drop} &= I \times R = 100\,\mu\text{A} \times 10\,\text{k}\Omega = 1\,\text{V} \\ P &= I^2 R = (100\,\mu\text{A})^2 \times 10\,\text{k}\Omega = 0.1\,\text{mW} \end{aligned}$$

- **Noise Consideration:**
  - Low enough to prevent floating inputs
  - High enough to not overload drivers

4.9 Power Transistors Q5/Q7/Q9/Q10

- **Current Sharing Calculation (4 parallel):**

$$
\begin{aligned}
I_{total} &= 4 \times 4\,\text{A} = 16\,\text{A} \\
\Delta I &= \pm 10\% \rightarrow 0.4\,\text{A} \\
R_e &= \frac{\Delta V_{BE}}{\Delta I} = \frac{0.05\,\text{V}}{0.4\,\text{A}} \approx 0.125\,\Omega \\
&\rightarrow \text{Standard } 0.1\,\Omega \text{ used}
\end{aligned}
$$

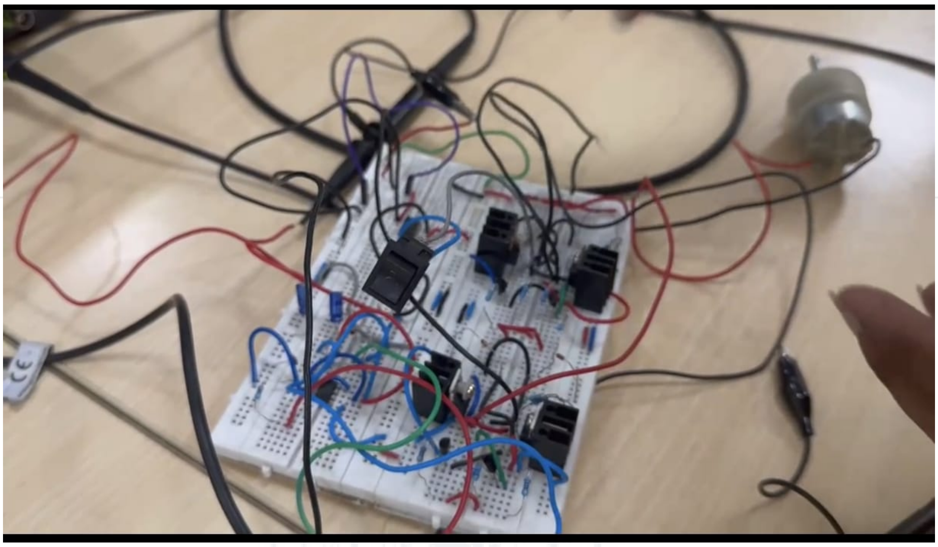


Figure 8: Final Hardware Implemention of the circuit

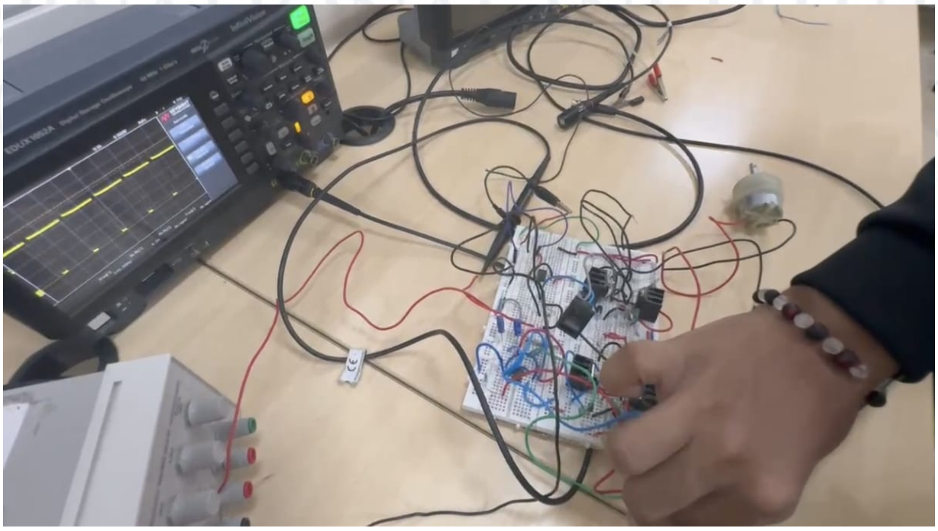
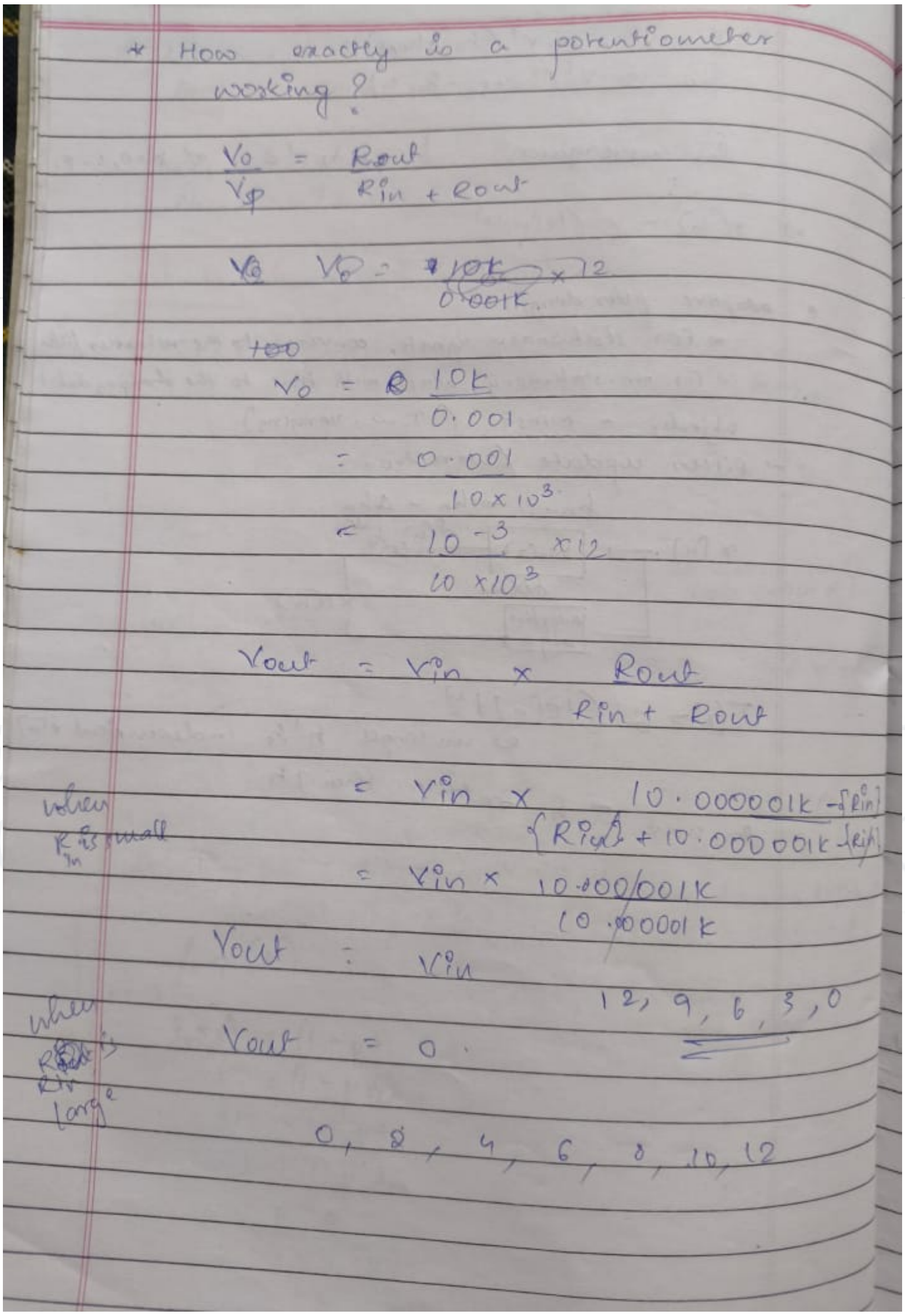


Figure 9: Duty Cycle changing with the Potentiometer



* How exactly is a potentiometer working?

$$\frac{V_o}{V_p} = \frac{R_{out}}{R_{in} + R_{out}}$$

$$V_o = \frac{10k}{0.001k} \times 12$$

$$V_o = \frac{10k}{0.001}$$

$$= \frac{0.001}{10 \times 10^3}$$

$$= \frac{10^{-3}}{10 \times 10^3} \times 12$$

$$V_{out} = V_{in} \times \frac{R_{out}}{R_{in} + R_{out}}$$

when R_{in} is small

$$= V_{in} \times \frac{10.000001k - \{R_{in}\}}{\{R_{in}\} + 10.000001k - \{R_{in}\}}$$

$$= V_{in} \times \frac{10.000001k}{10.000001k}$$

$$V_{out} = V_{in}$$

12, 9, 6, 3, 0

when R_{in} is large

$$V_{out} = 0.$$

0, 2, 4, 6, 8, 10, 12

Figure 10: Some theoretical calculations while doing the project

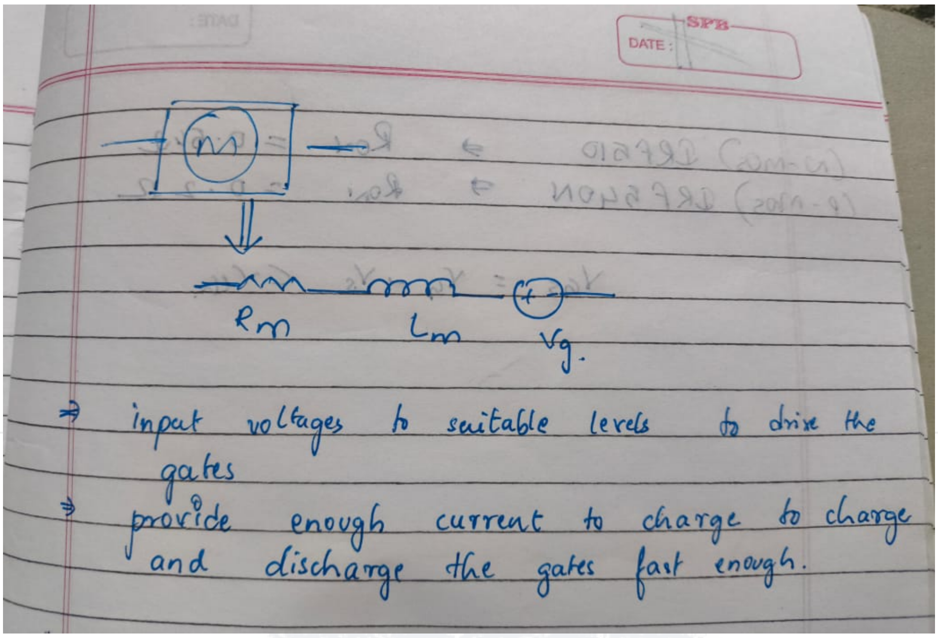


Figure 11: Some theoretical calculations while doing the project

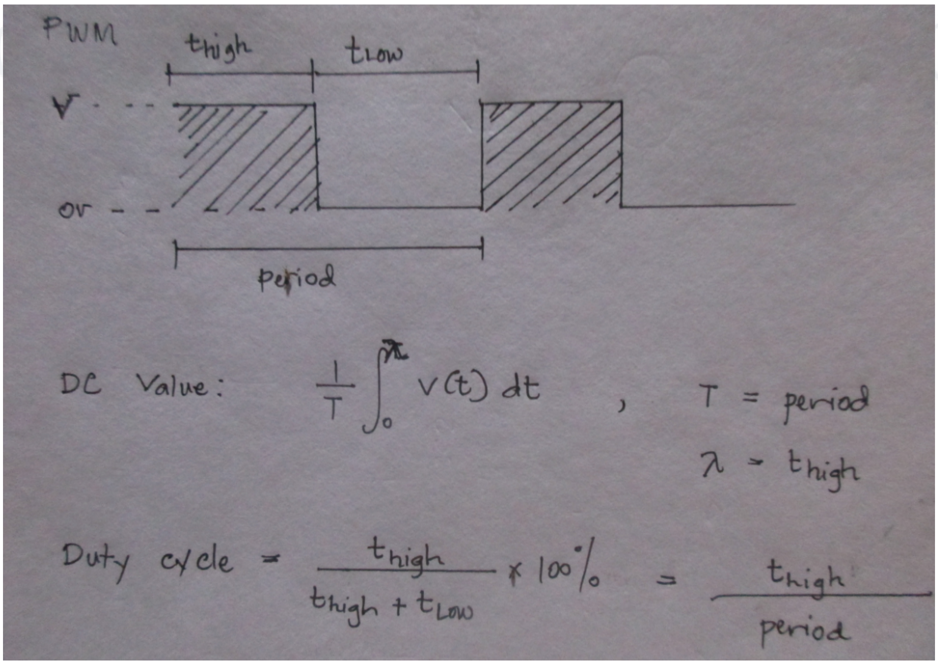


Figure 12: Duty cycle calculations

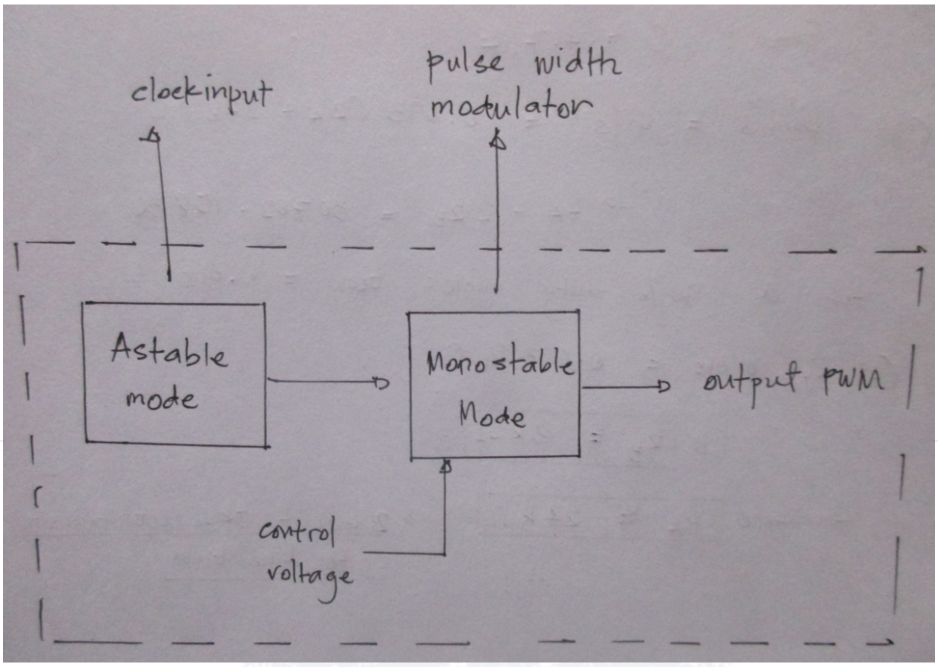


Figure 13: different 555 timer design motivation

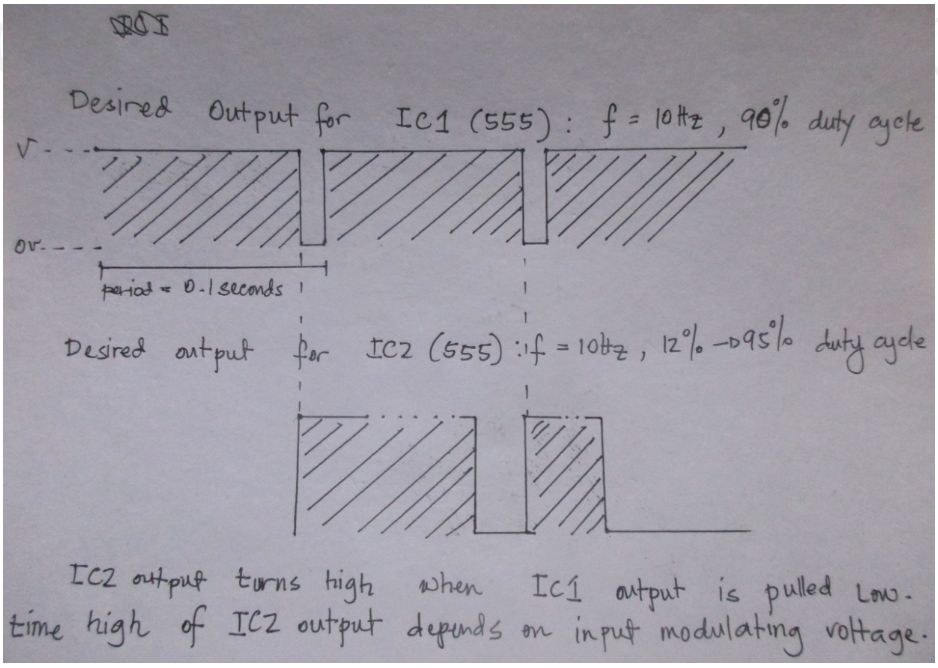


Figure 14: Some theoretical calculations