Lecture 45: Use of UJT as relaxation oscillator

Oscillators

DI02011011: Electronics Circuit and Application (ECA)

Lecture Agenda: UJT Relaxation Oscillators

- 1. Circuit Configuration & Terminal Topology of UJT Relaxation Oscillator
- 2. Step-by-Step Operational Mechanics & Waveform Cycles (V_E, V_{B1}, V_{B2})
- 3. Mathematical Derivation of Period (T) & Oscillation Frequency (f_o)
- 4. Derivation of Upper ($R_{T,max}$) and Lower ($R_{T,min}$) Resistance Design Bounds
- 5. Numerical Design Example & Component Parameter Selection
- 6. Industrial Application: SCR Phase-Control Triggering & Line Synchronization
- 7. Constant Current Charging for Linear Sawtooth Ramp Generation

Circuit Topology & Component Roles

- Core Circuit Architecture: Timing resistor R_T connected between V_{CC} and Emitter (E); timing capacitor C_T connected between Emitter (E) and Ground.
- Base Terminal Bias Connections: Base 2 (B_2) connected to V_{CC} via temperature compensation resistor R_2; Base 1 (B_1) connected to Ground via small output load resistor R_1 ($50\ \Omega - 100\ \Omega$).
- Output Waveform Terminals: Sawtooth exponential ramp wave taken across capacitor C_T (V_E); sharp positive gate trigger spikes taken across R_1 (V_{B1}); sharp negative spikes taken across R_2 (V_{B2}).
- Dual-Function Capability: Generates timing sweep signals while simultaneously serving as an isolated, high-current trigger pulse generator for power thyristors.

Step-by-Step Operational Mechanics & Cycles

- Phase 1: Capacitor Charging (OFF State): Initially $V_E = 0 < V_P$. Diode D_E is reverse biased. C_T charges exponentially from valley voltage V_V toward V_{CC} through R_T with time constant $\tau = R_T C_T$. Emitter current $I_E \approx 0$. Charging equation: $V_E(t) = V_{CC} - (V_{CC} - V_V)e^{-t/R_T C_T}$.
- Phase 2: UJT Firing & Rapid Discharge (ON State): When $V_E(t)$ reaches peak firing voltage $V_P = \eta V_{BB} + V_D$, UJT fires ON. Resistance R_{B1} collapses to $R_{B1,sat} \approx 20\ \Omega$. C_T rapidly discharges through $R_{B1,sat}$ and R_1 with small time constant $\tau_{dis} = (R_{B1,sat} + R_1)C_T \ll \tau_{charge}$, producing a sharp voltage spike across R_1.
- Phase 3: Turn-OFF & Cycle Reset: When V_E drops down to valley voltage V_V and $I_E < I_V$, UJT turns OFF, restoring high R_{B1} impedance and repeating the cycle.

Derivation of Oscillation Frequency (f_o)

- Charging Period Approximation: Because discharge time constant $\tau_{dis} \ll \tau_{charge}$, total oscillation period $T \approx t_{charge}$.
- Setting Boundary Voltage Conditions: $V_E(T) = V_P = \eta V_{CC} + V_D$. Assuming initial voltage $V_V \approx 0$ and $V_D \ll V_{CC}$:
- Voltage Equation: $\eta V_{CC} = V_{CC}(1 - e^{-T/R_T C_T}) \Rightarrow 1 - \eta = e^{-T/R_T C_T}$.
- Taking Natural Logarithm: $\frac{T}{R_T C_T} = \ln\left(\frac{1}{1-\eta}\right) \Rightarrow T = R_T C_T \ln\left(\frac{1}{1-\eta}\right)$.
- Oscillation Frequency (f_o): $f_o = \frac{1}{T} = \frac{1}{R_T C_T \ln\left(\frac{1}{1-\eta}\right)}$.
- Standoff Ratio Simplification: For typical UJT with $\eta = 0.632$, $\ln\left(\frac{1}{1-0.632}\right) = \ln(2.718) = 1.00 \Rightarrow f_o \approx \frac{1}{R_T C_T}$.

Design Limits & Bounds for Timing Resistor (R_T)

- Upper Bound ($R_{T,max}$ for Successful Turn-ON): Current supplied through R_T when $V_E = V_P$ must exceed Peak Point Current I_P to trigger negative resistance: $R_{T,max} = \frac{V_{CC}-V_P}{I_P}$. If $R_T > R_{T,max}$, capacitor C_T fails to reach V_P and UJT never fires.
- Lower Bound ($R_{T,min}$ for Successful Turn-OFF): Current supplied through R_T when $V_E = V_V$ must be less than Valley Point Current I_V to allow UJT to turn OFF: $R_{T,min} = \frac{V_{CC}-V_V}{I_V}$. If $R_T < R_{T,min}$, UJT remains latched ON continuously.
- Permissible Resistance Window: $\frac{V_{CC}-V_P}{I_P} > R_T > \frac{V_{CC}-V_V}{I_V}$.
- Design Selection Rule: Select R_T safely near the geometric mean of $R_{T,min}$ and $R_{T,max}$ to guarantee reliable oscillation.

UJT Oscillator Complete Design Example

- Problem Statement: Design a UJT relaxation oscillator operating at $f_o = 400$ Hz with $C_T = 0.1\ \mu$F. Given UJT parameters $\eta = 0.65$, $V_P = 13.7$ V, $V_V = 2.0$ V, $I_P = 5.0\ \mu$A, $I_V = 4.0$ mA, and supply $V_{CC} = 20.0$ V, calculate required timing resistor R_T and verify design bounds.
- Step 1: Calculate Target Oscillation Period (T): $T = \frac{1}{f_o} = \frac{1}{400\text{ Hz}} = 2.5\text{ ms} = 2.5 \times 10^{-3}$ s.
- Step 2: Calculate Required Timing Resistor (R_T): $T = R_T C_T \ln\left(\frac{1}{1-\eta}\right) \Rightarrow 2.5 \times 10^{-3} = R_T(0.1 \times 10^{-6}) \ln\left(\frac{1}{1-0.65}\right) = R_T(10^{-7}) \ln(2.857) = R_T(10^{-7})(1.0498) \Rightarrow R_T = \frac{2.5\times10^{-3}}{1.0498\times10^{-7}} \approx 23.81\text{ k}\Omega$ (standard 24 kΩ).
- Step 3: Calculate Upper Resistance Limit ($R_{T,max}$): $R_{T,max} = \frac{V_{CC}-V_P}{I_P} = \frac{20.0\text{ V}-13.7\text{ V}}{5.0\times10^{-6}\text{ A}} = \frac{6.3\text{ V}}{5.0\times10^{-6}\text{ A}} = 1.26\text{ M}\Omega$.
- Step 4: Calculate Lower Resistance Limit ($R_{T,min}$): $R_{T,min} = \frac{V_{CC}-V_V}{I_V} = \frac{20.0\text{ V}-2.0\text{ V}}{4.0\times10^{-3}\text{ A}} = \frac{18.0\text{ V}}{4.0\times10^{-3}\text{ A}} = 4.5\text{ k}\Omega$.
- Step 5: Verify Design Validity: $4.5\text{ k}\Omega < 23.81\text{ k}\Omega < 1.26\text{ M}\Omega$ (Design is fully valid and stable).

Output Pulse Characteristics across Base-1 (R_1)

- Peak Trigger Voltage (V_{p1}): Peak pulse voltage appearing across R_1 during discharge: $V_{p1} \approx \frac{R_1}{R_1+R_{B1,sat}}(V_P - V_V)$.
- Pulse Duration ($t_p|_{50\%}$): Determined by C_T discharge time constant: $t_p \approx (R_1 + R_{B1,sat})C_T$. Typically narrow ($1.0\ \mu$s $- 20.0\ \mu$s).
- Resistor Selection Guidelines: R_1 must be kept small ($20\ \Omega - 100\ \Omega$) to minimize quiescent DC voltage drop during OFF state while producing sufficient pulse amplitude (1.0 V $- 3.0$ V) to trigger SCR gates.
- Base-2 Resistor Selection: $R_2 \approx \frac{10000}{\eta V_{CC}}$ to stabilize peak firing voltage V_P across ambient temperature variations.

Application: SCR Phase-Control Triggering

- Synchronized Firing Topology: UJT relaxation oscillator powered by Zener-clamped full-wave rectified AC voltage (V_{zener}).
- Zero-Crossing Synchronization: At the end of each AC half-cycle, Zener voltage drops to zero, discharging C_T to zero and synchronizing oscillator timing with line frequency (50 Hz/60 Hz).
- Firing Angle Control (α): Adjusting variable timing resistor R_T alters capacitor charging rate, sweeping SCR trigger firing angle *lpha* smoothly from 0° to 180°.
- Industrial Applications: Light dimmers, motor speed control, electric heater regulators, and controlled AC-to-DC converters.

SCR Firing Angle Calculation Example

- Problem Statement: A UJT relaxation oscillator synchronized to a 50 Hz AC line ($T_{half} = 10.0$ ms) triggers an SCR. Given $C_T = 0.22\ \mu$F and $\eta = 0.632$, calculate timing resistor R_T required for firing angles: (a) $\alpha = 45°$, (b) $\alpha = 90°$.
- Step 1: Calculate Delay Time for $\alpha = 45°$: $t_{d1} = \frac{45°}{180°} \times 10.0\text{ ms} = 2.5\text{ ms}$.
- Step 2: Solve for R_{T1} at $\alpha = 45°$: Since $\eta = 0.632$, $\ln\left(\frac{1}{1-0.632}\right) = 1.00 \Rightarrow t_{d1} = R_{T1}C_T \Rightarrow R_{T1} = \frac{2.5\times10^{-3}\text{ s}}{0.22\times10^{-6}\text{ F}} \approx 11.36\text{ k}\Omega$.
- Step 3: Calculate Delay Time for $\alpha = 90°$: $t_{d2} = \frac{90°}{180°} \times 10.0\text{ ms} = 5.0\text{ ms}$.
- Step 4: Solve for R_{T2} at $\alpha = 90°$: $R_{T2} = \frac{5.0\times10^{-3}\text{ s}}{0.22\times10^{-6}\text{ F}} \approx 22.73\text{ k}\Omega$.

Linear Sawtooth Generation via Constant Current

- Non-Linearity Problem: Standard passive $R_T C_T$ charging produces an exponential curve ($V_E(t) = V_{CC}(1 - e^{-t/\tau})$), causing sweep non-linearity.
- Constant Current Charging Solution: Replace passive timing resistor R_T with a PNP transistor constant current source ($I_C = \frac{V_{CC} - V_B - V_{BE}}{R_E}$).
- Linear Voltage Ramp Equation: Capacitor charges linearly according to $V_E(t) = \frac{I_C}{C_T} \times t$.
- Linear Period Formula: $T = \frac{C_T(V_P - V_V)}{I_C} = \frac{C_T(\eta V_{CC} + V_D - V_V)}{I_C}$.
- Applications: Oscilloscope Cathode Ray Tube (CRT) time-base sweep generators and linear ramp analog-to-digital converters.

Comparison: UJT Relaxation vs. Op-Amp Astable

- Waveform Outputs: UJT (exponential/linear sawtooth across C_T + narrow trigger spikes across R_1); Op-Amp Astable (square wave output + exponential triangle across C).
- Component Count & Simplicity: UJT requires only 1 discrete 3-terminal transistor + 3 resistors + 1 capacitor; Op-Amp astable requires multi-transistor IC package.
- High Peak Current Discharge: UJT discharges C_T through collapsed channel ($R_{B1,sat} \approx 20\ \Omega$), delivering heavy peak current pulses (> 1 A) ideal for SCR triggering; Op-Amp output current is internally limited ($\sim 20 - 40$ mA).
- Frequency Range: UJT (up to ~ 500 kHz); Op-Amp Astable (up to several MHz).

Summary of UJT Relaxation Oscillator

- UJT Relaxation Oscillator converts DC supply into exponential sawtooth ramps (V_E) and sharp positive gate pulses (V_{B1}).
- Oscillation period $T = R_T C_T \ln\left(\frac{1}{1-\eta}\right) \approx R_T C_T$ (when $\eta \approx 0.632$).
- Timing resistance must be bounded within $\frac{V_{CC}-V_P}{I_P} > R_T > \frac{V_{CC}-V_V}{I_V}$ to ensure turn-ON and turn-OFF.
- Extensively applied in SCR/TRIAC phase control, linear time-base ramp generators, and pulse timing delays.

Formula Reference & Key Equations

- Oscillation Period: $T = R_T C_T \ln\left(\frac{1}{1-\eta}\right)$.
- Oscillation Frequency: $f_o = \frac{1}{T} = \frac{1}{R_T C_T \ln(1/(1-\eta))}$.
- Timing Resistance Bounds: $\frac{V_{CC}-V_P}{I_P} > R_T > \frac{V_{CC}-V_V}{I_V}$.
- Base-1 Peak Pulse Voltage: $V_{p1} \approx \frac{R_1}{R_1+R_{B1,sat}}(V_P - V_V)$.
- Linear Ramp Period (Current Source I_C): $T = \frac{C_T(V_P-V_V)}{I_C}$.