Simulation of an Ultra-Compact Leaky Integrate-and-Fire Neuron using eSim

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Abstract:

This work presents the simulation of an ultra-compact Leaky Integrate-and-Fire (LIF) neuron circuit using eSim. The circuit, based on the model proposed by Rozenberg et al. (2019), employs an SCR as the threshold switching element alongside MOSFET transistors for spike amplification. A PWL input voltage ranging from 2V to 7V was applied to observe sub-threshold integration, threshold-triggered firing, and repetitive spiking behaviour. The simulation results validate the biological analogy of integrate-and-fire operation, with output spikes of ~4.8V observed from 4V input onwards.

Theory:

Biological neurons are the fundamental processing units of the brain. They receive input signals through dendrites, integrate these signals in the cell body (soma), and generate an output spike when a certain threshold is reached. This spike is then transmitted through the axon to other neurons. One of the key characteristics of neurons is that information is not only encoded in the signal amplitude, but also in the timing and frequency of these spikes.

Traditional computing systems (based on the von Neumann architecture) separate memory and processing, which leads to limitations in speed and energy efficiency, especially for tasks like pattern recognition and learning. In contrast, the human brain performs such tasks efficiently using massively parallel, event-driven processing. This has led to the development of **neuromorphic computing**, which aims to design electronic systems that mimic the behaviour of biological neural networks.

To implement such systems, simplified neuron models are required. One of the most widely used models is the **Leaky Integrate-and-Fire (LIF) neuron model**. In this model, incoming signals are integrated over time (integration), while simultaneously leaking through a resistive path (leak). When the accumulated potential reaches a threshold, the neuron “fires” and resets. Despite its simplicity, the LIF model captures essential neuron behaviour and is widely used in hardware and simulation.

In electronic implementations, the LIF behaviour can be reproduced using basic circuit elements. A capacitor represents the membrane potential by storing charge, while resistors model the leakage of this charge. A nonlinear switching element is required to implement the firing mechanism. In the ultra-compact neuron (UCN) model, this is achieved using a silicon-controlled rectifier (SCR), which switches ON when a threshold voltage is reached and allows rapid discharge of the capacitor, generating a spike .

This project focuses on simulating a **Ultra Compact LIF neuron** using eSim. The aim is to observe the fundamental neuron behaviour—namely integration, threshold-triggered firing, and spike generation—using a minimal circuit. The simulation results demonstrate how the membrane voltage builds up over time and produces output spikes once the threshold is exceeded, validating the LIF model in an electronic circuit form.

Circuit Diagram:

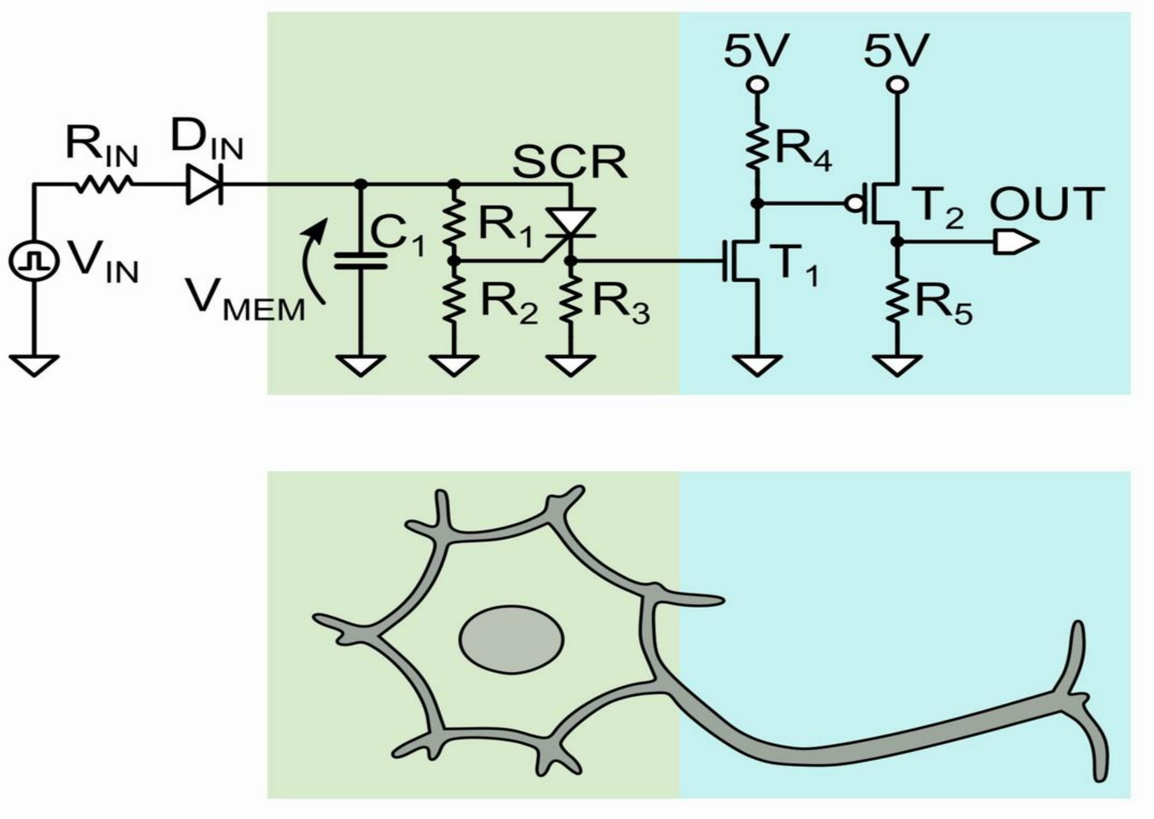

Fig. 1: An Ultra-compact LIF neuron circuit and its analogy to a biological neuron. The left section represents the soma (integration and firing), while the right section represents the axon (signal propagation).

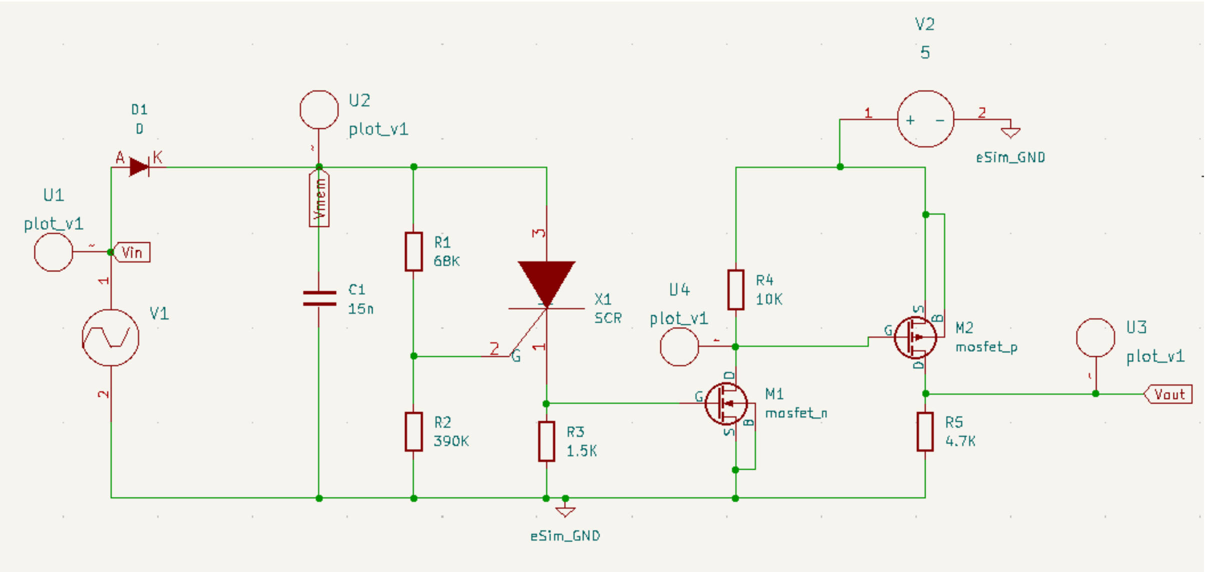

Fig. 2: eSim schematic of the ultra-compact leaky integrate-and-fire (LIF) neuron circuit used for simulation.

The circuit implements an ultra-compact LIF neuron model using basic electronic components. The input voltage source (Vin) provides pulse signals that are passed through the diode (D1), which ensures unidirectional signal flow and protects the circuit. The capacitor C1 acts as the membrane by integrating incoming input signals over time, while resistors R1 and R2 provide a leakage path that models the gradual decay of membrane potential.

The silicon-controlled rectifier (SCR) serves as the nonlinear threshold switching element. When the membrane voltage reaches a critical threshold, the SCR switches to a low-resistance state, allowing rapid discharge of the capacitor through R3. This sudden discharge produces a spike-like response.

The transistor stage (M1 and M2) acts as the output or axon stage, amplifying and shaping the spike signal for clear output. Resistors R4 and R5 provide proper biasing for the transistors. Overall, the circuit successfully emulates the key operations of a biological neuron, including signal integration, leakage, threshold-based firing, and spike propagation.

Component Values:

Component	Value
R1	68 kΩ
R2	390 kΩ
R3	1.5 kΩ
R4	10 kΩ
R5	4.7 kΩ
C1	15 nF
D1	1N4148
SCR	Thyristor (SCR)
M1	NMOS transistor
M2	PMOS transistor
Input Voltage (Vin)	Pulse / PWL (2 V – 7 V)
Supply Voltage	5 V

The table lists the values of all components used in the simulation of the ultra-compact LIF neuron circuit. The resistor and capacitor values are selected to control the integration and leakage behaviour of the membrane voltage. The diode ensures proper input signal direction, while the SCR acts as the threshold switching element responsible for spike generation. The MOSFET transistors form the output stage, amplifying the spike signal. The input voltage is varied from 2 V to 7 V to observe different neuron firing regimes, and a constant supply voltage of 5 V is used for circuit operation.

Results:

The simulation results illustrate the key behaviour of the LIF neuron, including integration, threshold-based firing, and spike generation.

1. **Input Voltage (Vin):**

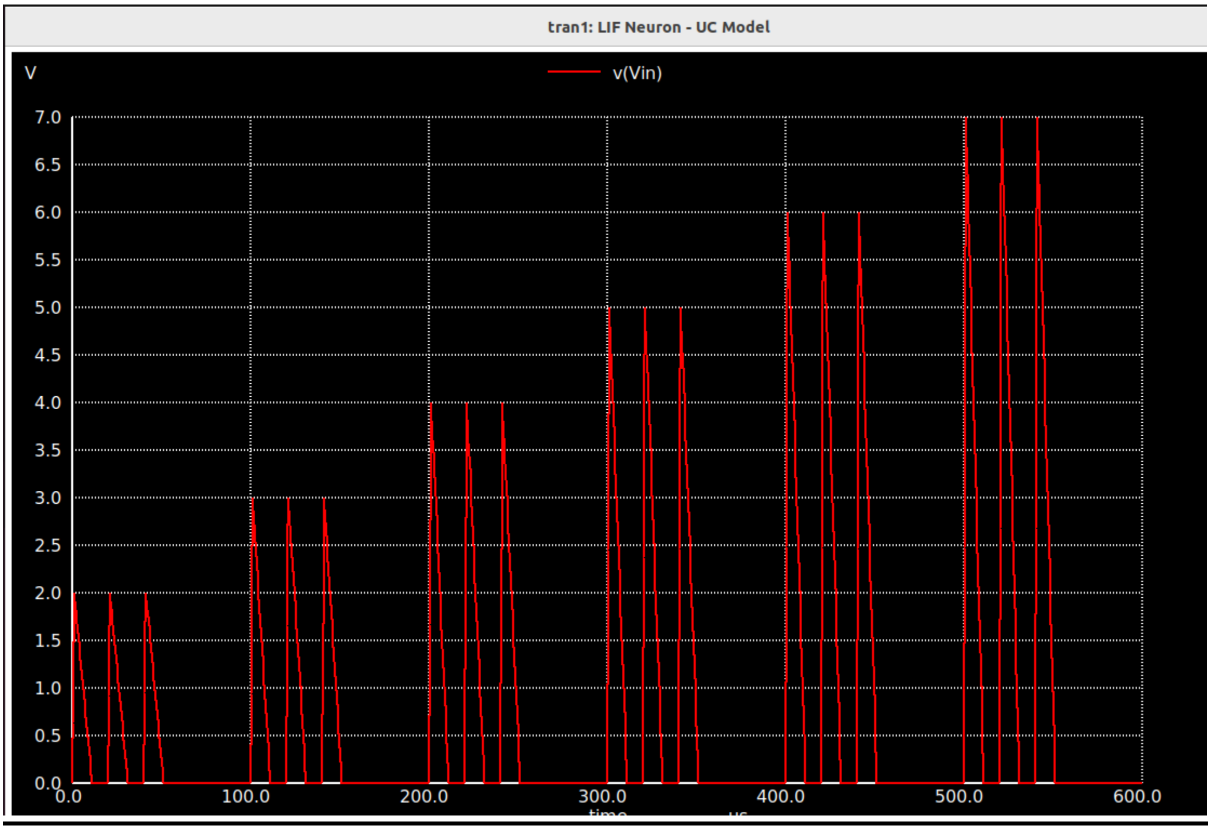

Fig. 3: Input Voltage Waveform (Vin)

The input voltage waveform consists of a sequence of pulse signals whose amplitude increases gradually with time. These pulses act as external stimuli applied to the neuron circuit. The step-wise increase in amplitude allows observation of how the neuron transitions from inactive to active firing states. At lower voltage levels, the input is insufficient to trigger any response, while higher amplitudes provide enough excitation to drive the neuron into spiking behaviour. This controlled variation of input enables analysis of the neuron's threshold and dynamic response characteristics.

2. Membrane Voltage (Vmem):

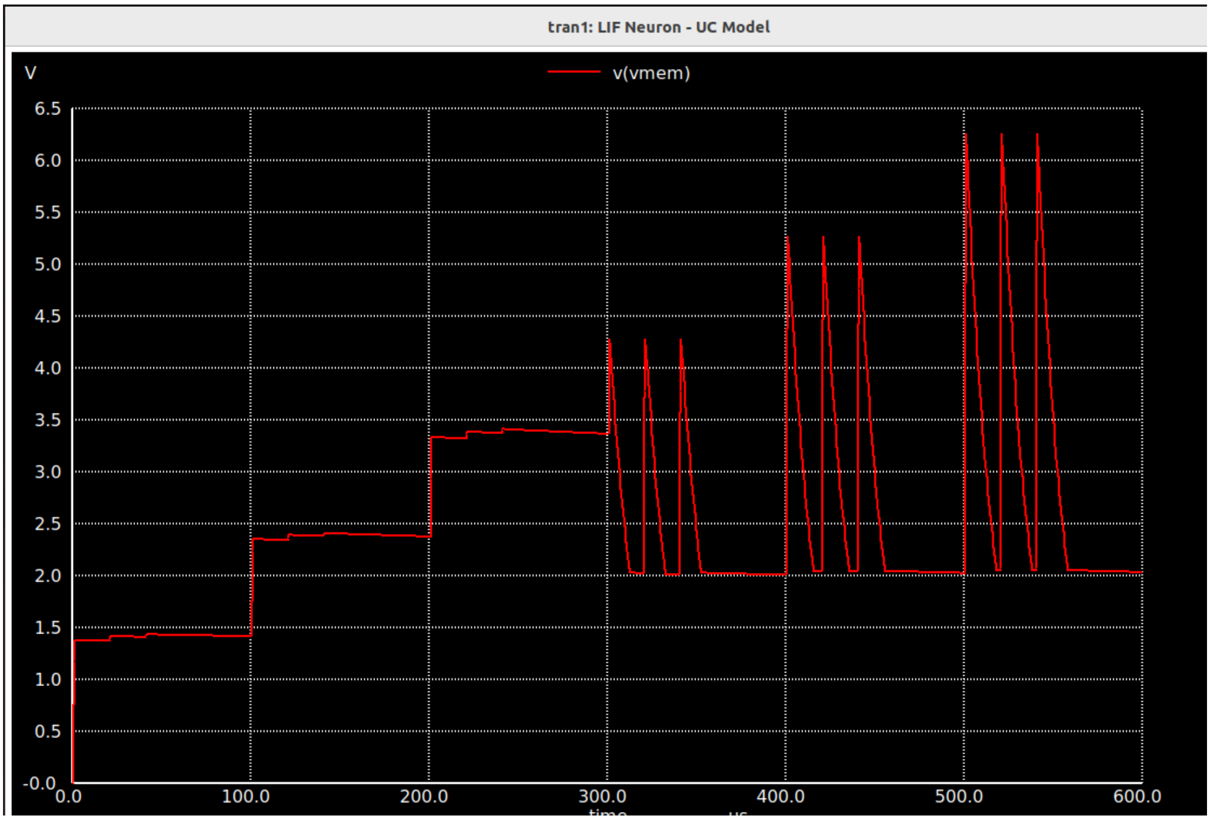

Fig. 4: Membrane Voltage (Vmem)

The membrane voltage (Vmem), measured across capacitor C1, represents the internal state of the neuron. As input pulses are applied, the capacitor gradually accumulates charge, causing the voltage to increase over time. Between pulses, the voltage slightly decreases due to leakage through resistors, mimicking the natural decay observed in biological neurons. When the membrane voltage approaches a critical threshold, a sudden drop is observed, indicating rapid discharge through the SCR. This repeated charging and discharging cycle reflects the integrate-and-fire behaviour of the neuron.

3. <u>Output Voltage (Vout):</u>

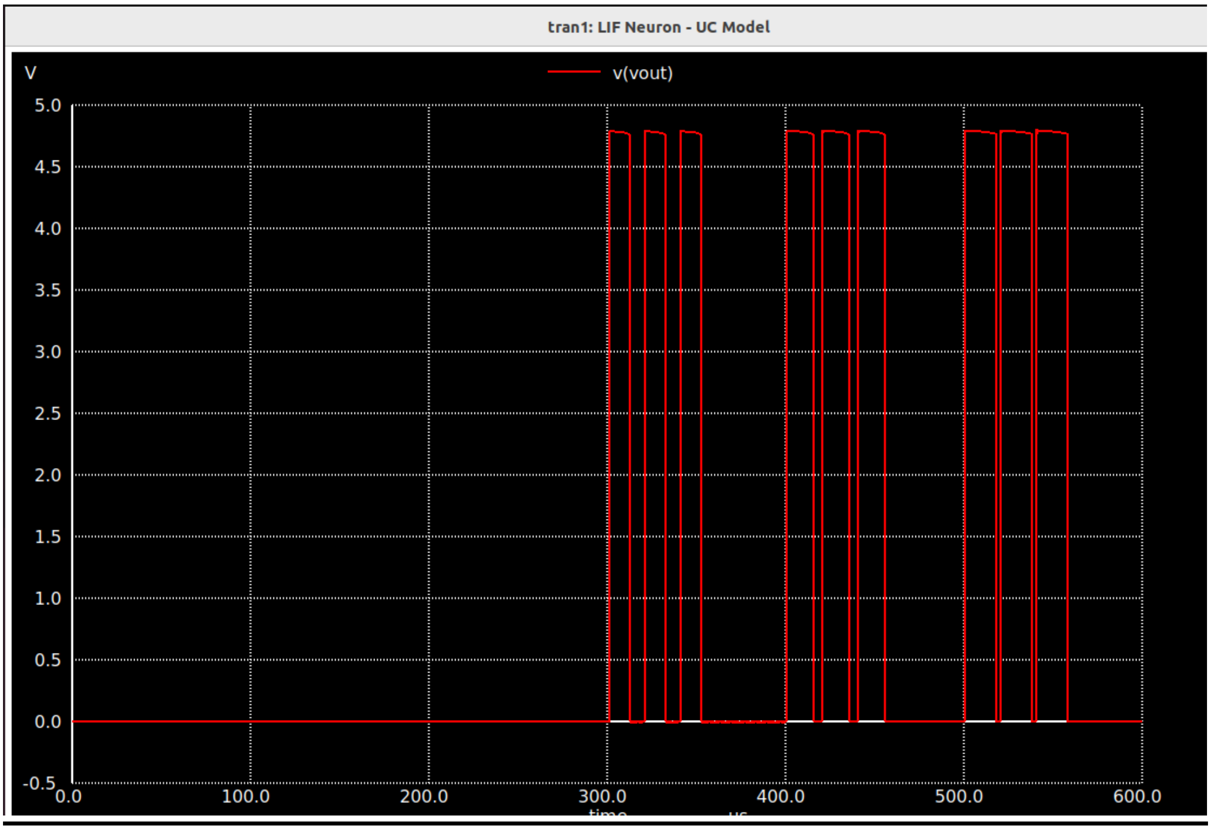

Fig. 5: Output Voltage (Vout)

The output voltage (Vout) represents the firing response of the neuron. At low input levels, no spikes are observed, confirming sub-threshold operation. As the input amplitude increases, distinct voltage spikes begin to appear, indicating that the neuron has reached its firing threshold. With further increase in input strength, the frequency of these spikes increases, demonstrating the ability of the neuron to encode input intensity in terms of firing rate. The sharp and well-defined spikes reflect the rapid switching behaviour of the SCR and the amplification provided by the transistor stage.

4. All Waveforms Plotted Together:

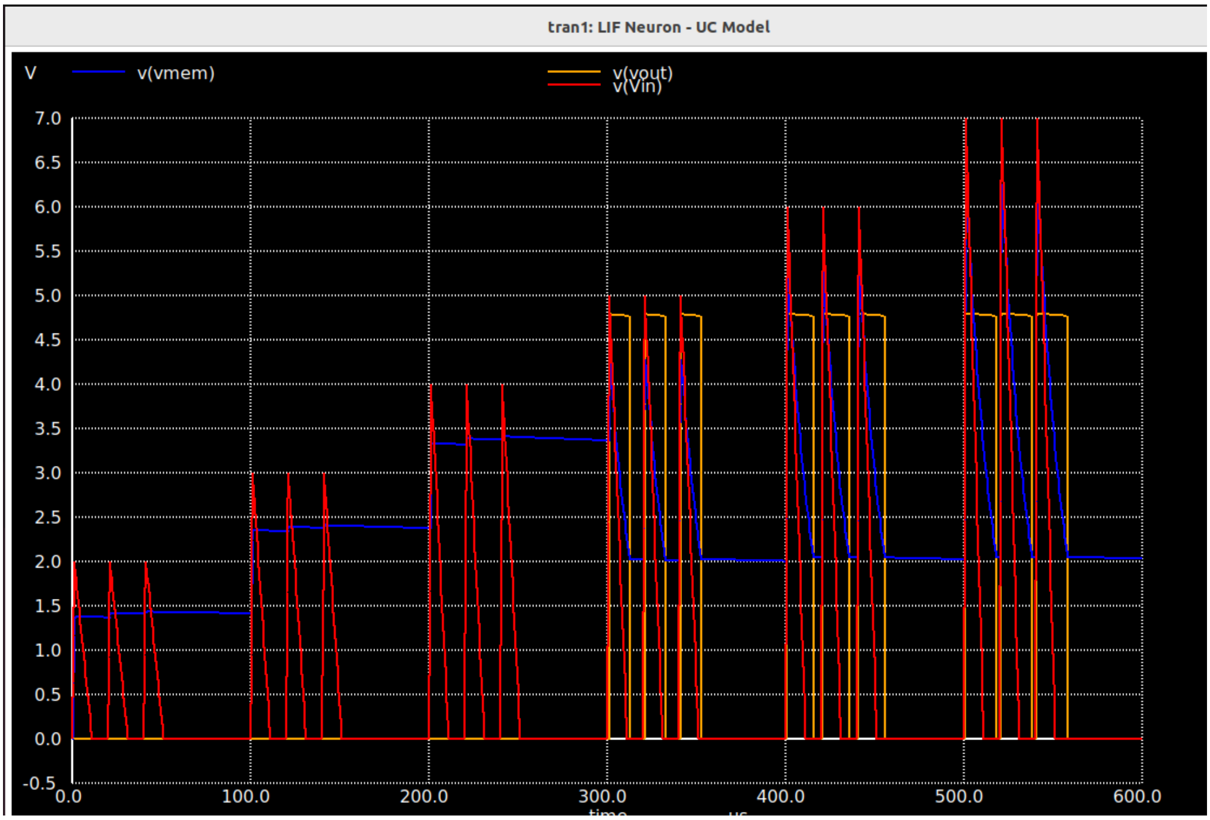

Fig. 6: Combined Waveforms (Vin, Vmem, Vout)

This figure provides a comprehensive view of the interaction between input, membrane voltage, and output response. The input signal (Vin) drives the gradual rise in membrane voltage (Vmem), which integrates the incoming pulses over time. Once the membrane voltage reaches the threshold level, a rapid discharge occurs, resulting in an output spike (Vout). Each spike corresponds to a sudden drop in membrane voltage, clearly showing the cause-and-effect relationship between the internal state of the neuron and its output. As the input amplitude increases, the time taken to reach the threshold decreases, leading to more frequent spikes. This confirms the expected behaviour of the LIF neuron model.

5. Sub-Threshold Region:

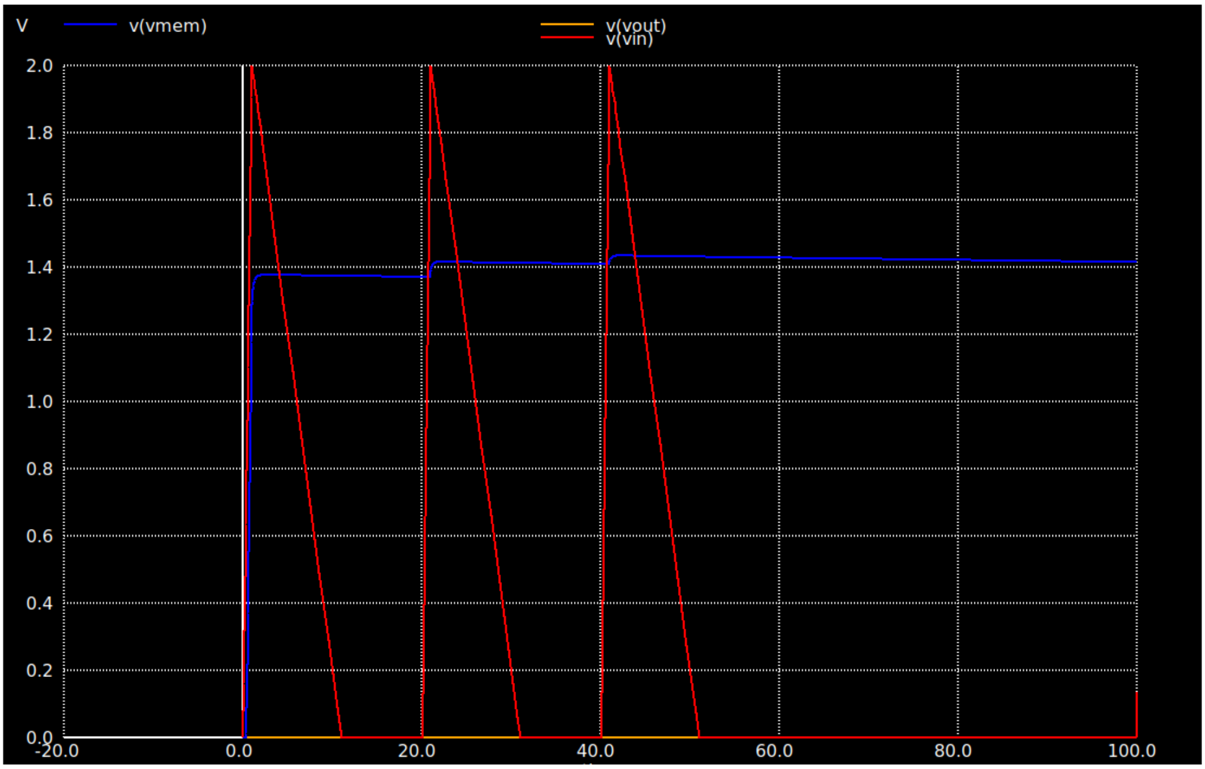

Fig. 7: Sub-threshold Region (0–100 µs)

This figure illustrates the sub-threshold region of operation, where the input signal is not strong enough to trigger neuron firing. Although input pulses are present, the membrane voltage increases only slightly and remains well below the threshold level required for activation of the SCR. As a result, no output spikes are observed. This behaviour confirms that the neuron remains inactive under weak stimulation and highlights the importance of threshold conditions for spike generation.

6. **Near-Threshold Region:**

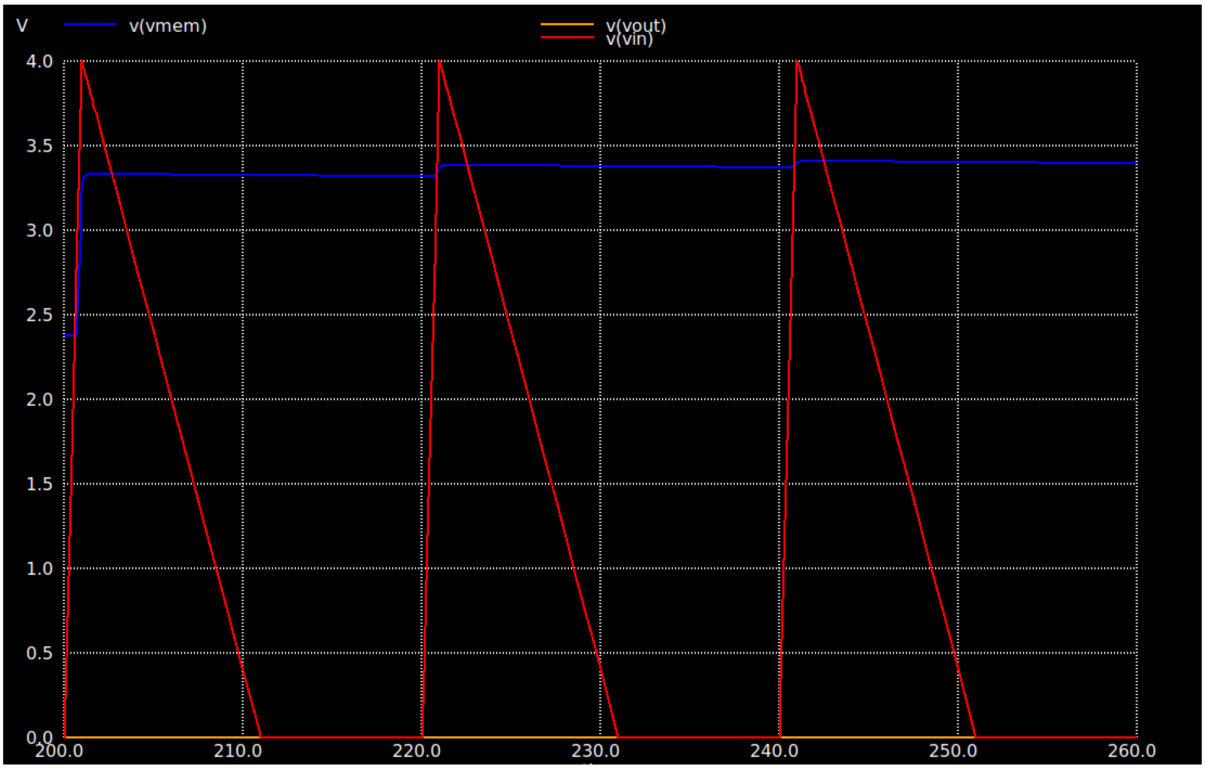

Fig. 8: Near-Threshold Behaviour (200–260 µs)

This figure shows the behaviour of the neuron as it approaches the firing threshold. The membrane voltage rises progressively with each input pulse and reaches values close to the threshold level. In this region, the neuron becomes highly sensitive to small changes in input amplitude. The absence or initial appearance of spikes in this region marks the transition between sub-threshold and active firing states. This demonstrates the critical role of threshold voltage in determining neuron activation.

7. Repetitive Spiking Behaviour:

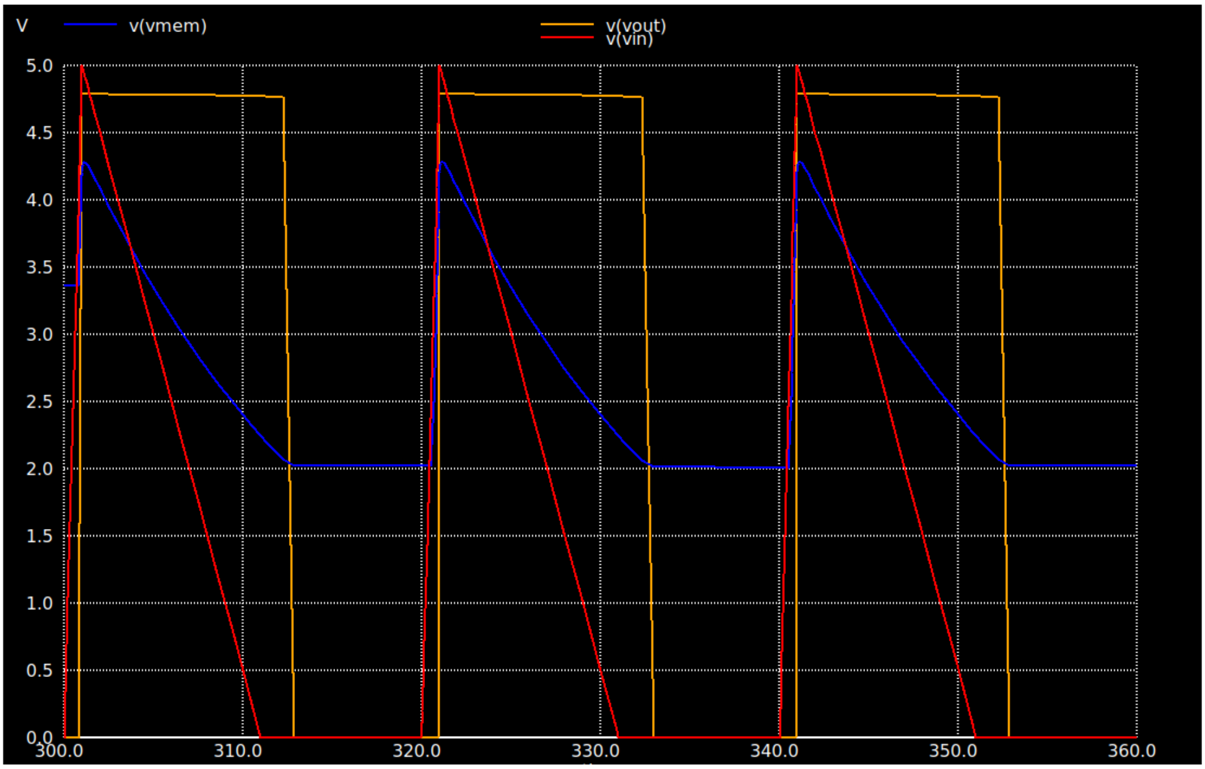

Fig. 9: Repetitive Spiking Behaviour (300–360 µs)

This figure demonstrates the repetitive spiking behaviour of the neuron under strong input stimulation. The membrane voltage repeatedly charges to the threshold and then rapidly discharges, producing periodic output spikes. Each cycle corresponds to an integrate-and-fire event. The consistent repetition of this cycle indicates stable neuron operation in the active firing region. Additionally, the reduced time between spikes at higher input levels reflects increased firing frequency, which is a key characteristic of LIF neurons.

8. **Signal Values (Vin, Vmem, Vout):**

1	Peak	Time in us	Vin	Vmem	Vout
2	1	1	1.269	0	0
3	2	21	1.39	0	0
4	3	41	1.419	0	0
5	4	101	2.24	0	0
6	5	121	2.363	0	0
7	6	141	2.392	0	0
8	7	201	3.228	0	0
9	8	221	3.368	0	0
10	9	241	3.401	0	0
11	10	301	4.184	0	4.788
12	11	321	4.207	0	4.796
13	12	341	4.207	0	4.797
14	13	401	5.189	0	4.791
15	14	421	5.192	0	4.78
16	15	441	5.192	0	4.779
17	16	501	6.179	0.001	4.803
18	17	521	6.179	0.001	4.803
19	18	541	6.179	0.001	4.805

Fig. 10: Signal Values Table

The table presents selected values of input voltage (Vin), membrane voltage (Vmem), and output voltage (Vout) at different time instances. At lower input voltages (approximately 1–3 V), the membrane voltage remains below the threshold and no output spikes are observed. As the input voltage increases beyond a certain level (around 4 V and above), output spikes begin to appear.

It can be seen that Vout rises to approximately 4.7–4.8 V during spiking events, while Vmem undergoes rapid discharge, indicating the firing of the neuron. This behaviour confirms the threshold-based operation of the LIF neuron, where spike generation occurs only when the membrane voltage exceeds a critical value.

Overall, the table supports the simulation results by quantitatively showing the relationship between input amplitude and neuron firing behaviour.

Conclusion:

The simulation successfully demonstrates LIF neuron behaviour in eSim. The SCR-based ultra-compact design achieves spike generation with minimal components, confirming its suitability for neuromorphic circuit design.

References:

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2. M. J. Rozenberg et al., *“An ultra-compact leaky-integrate-and-fire model for building spiking neural networks,”* Scientific Reports, 2019.
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