Neuromorphic Circuit Design: Integrate-and-Fire Neuron with STDP Synapse

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Abstract

Abstract: Neuromorphic circuits mimic the behavior of biological neurons and synapses for energy-efficient brain- inspired computing. This work presents the design of an Integrate-and-Fire (I&F) neuron with a Spike-Timing- Dependent Plasticity (STDP) synapse using the SG13G2 PDK in eSim with Ngspice simulation. The neuron integrates pre-synaptic inputs over time, firing when a threshold is reached, while the synapse dynamically adjusts its weight depending on the timing of pre- and post-synaptic spikes. The circuit demonstrates fundamental learning behavior and can serve as a building block for larger neuromorphic systems.

KEYWORDS: Integrate-and-Fire Neuron, STDP, Neuromorphic Circuits, Synaptic Plasticity, eSim, Ngspice

INTRODUCTION

Conventional digital computing systems are inefficient for adaptive learning tasks due to high power consumption and scalability issues. Neuromorphic computing overcomes these limitations by mimicking biological neurons and synapses. This project designs and simulates an Integrate-and-Fire neuron with an STDP synapse using eSim and Ngspice to demonstrate biologically inspired learning behavior. The neuron integrates input spikes and fires when a threshold is reached, while the synapse adapts its weight based on spike timing. The proposed circuit serves as a fundamental building block for larger neuromorphic computing systems.

Problem Statement

Traditional digital computing systems are inefficient for brain-inspired learning tasks due to power and scalability limitations. Although neuromorphic computing mimics biological neurons and synapses, implementing realistic learning mechanisms such as Spike-Timing Dependent Plasticity (STDP) at the circuit level remains challenging.

This project addresses this by designing and simulating an Integrate-and-Fire neuron with an STDP synapse in the eSim environment, demonstrating correct neuron firing and synaptic weight adaptation.

Methodology

In this project, an Integrate-and-Fire neuron model is implemented that accumulates pre-synaptic input spikes over time and generates an output spike once a predefined threshold voltage is reached. To enable learning, a Spike-Timing Dependent Plasticity synapse is incorporated, which dynamically modifies the synaptic weight based on the temporal difference between pre-synaptic and post-synaptic spikes.

The complete circuit is designed using the SG13G2 Process Design Kit within eSim and simulated using Ngspice. Transient simulations are performed to validate neuron integration, firing behavior, and synaptic weight modification. The simulation results are analyzed and compared with the expected biological behavior described in the original research publication. Short

CIRCUIT DIAGRAM

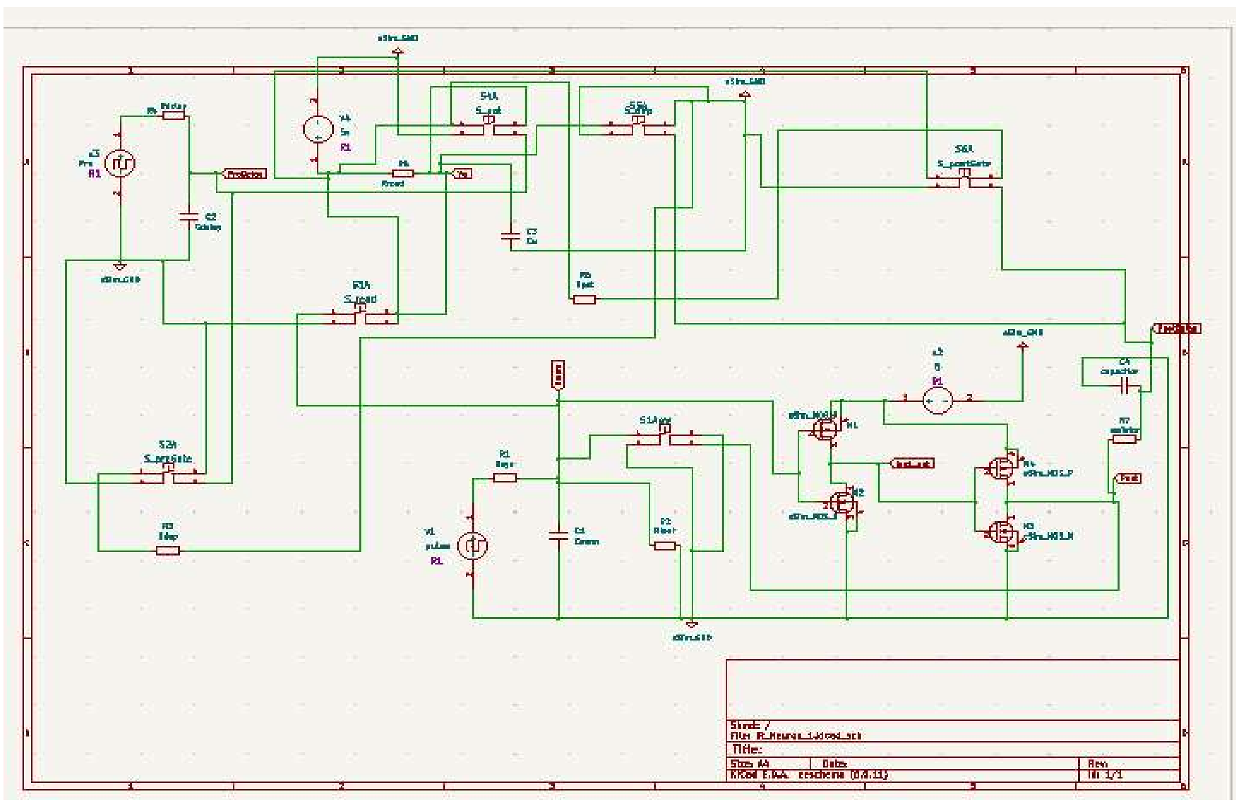


Fig. 1: Circuit Diagram.

Circuit Details

The proposed neuromorphic circuit is composed of two main sub-blocks:

1. STDP Synapse – Emulates the biological synaptic weight. The weight is stored as a capacitor voltage,which is updated depending on the relative timing of pre-synaptic and post- synaptic spikes. MOSFET switches and simple current mirrors are operations.

2. used for read/write Integrate-and-Fire Neuron – Integrates the weighted input current on a capacitor. When the membrane voltage exceeds a threshold, a comparator generates an output spike and resets the integration capacitor.

OUTPUT WAVEFORMS

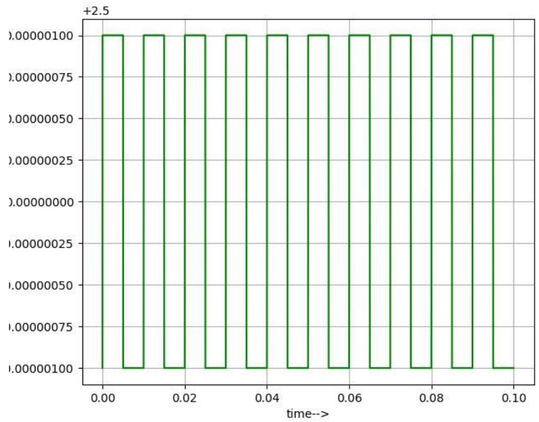
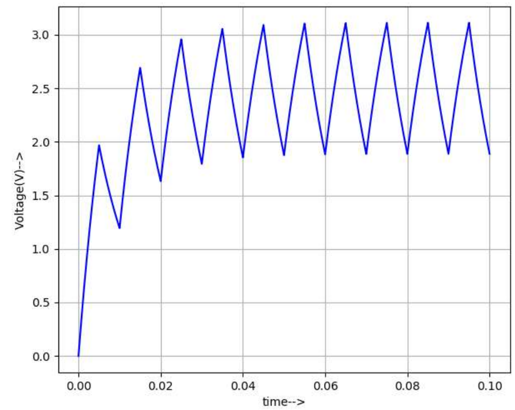


Fig:2



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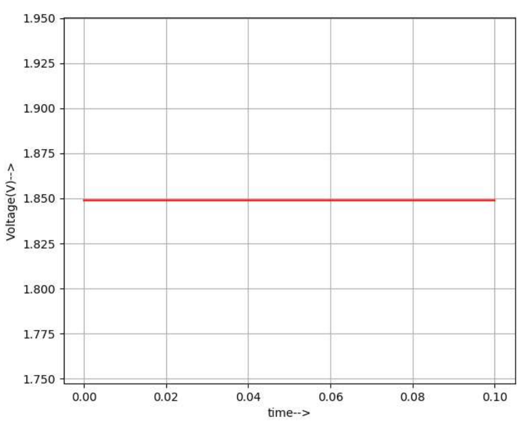

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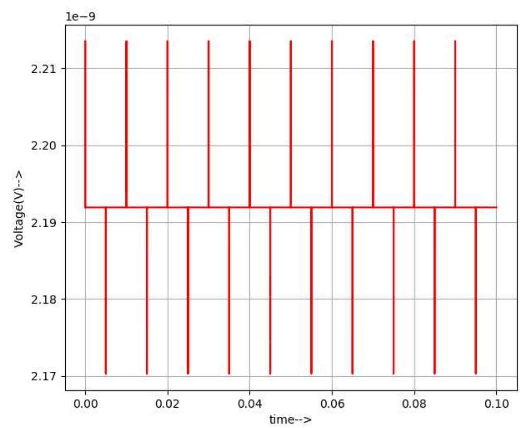

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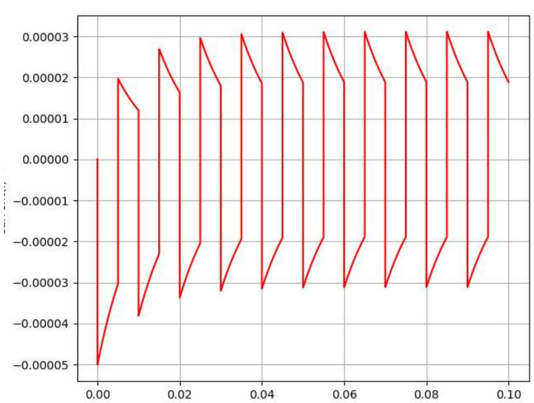

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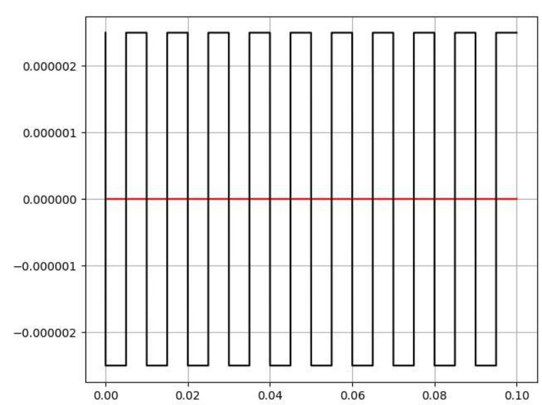

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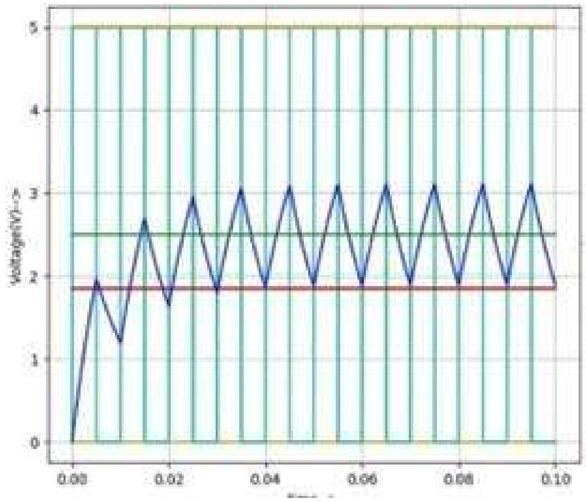

Fig:6

CONCLUSION

This work presents the design and simulation of an Integrate-and-Fire neuron with an STDP synapse, demonstrating biologically inspired learning behavior using eSim and Ngspice. The circuit successfully integrates input spikes, generates output firing, and adapts synaptic weights based on spike timing. It can serve as a basic building block for larger neuromorphic computing systems.

REFERENCES

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