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A Hybrid Leaky Integrate-and-Fire Neuron with Tunable Reset Behavior in 7 nm Fin Field-Effect Transistor Technology

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A Hybrid Leaky Integrate-and-Fire Neuron with

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List of Abbreviations

ASAP7	7 nm Predictive FinFET Process Design Kit
CMOS	Complementary metal–oxide–semiconductor
DC	Direct current
f–I	Firing frequency versus input current
FinFET	Fin field-effect transistor
ISI	Inter-spike interval
LIF	Leaky integrate-and-fire
PVT	Process, voltage, and temperature
VDD	Positive supply voltage

Abstract

This thesis presents the design and simulation study of a compact hybrid leaky integrate-and-fire (LIF) CMOS neuron derived from a Besrour-style baseline and augmented with a minimal reset/timing branch. The proposed neuron introduces an auxiliary branch comprising Ctref, Npchg, Nbleed, and Nreset to improve control over post-spike reset while preserving the original neuron's compact structure. The central goal of this work is to determine whether a small reset-aware modification can provide a more useful tradeoff among reset behavior, firing frequency, and energy than the baseline Besrour neuron.

The circuit was implemented in Xschem and evaluated in ngspice using ASAP7 predictive FinFET device models. Reference neurons and the proposed hybrid neuron were analyzed within a common simulation workflow to enable a normalized comparison. The study focused on three primary evaluation metrics: reset behavior, firing frequency, and energy per spike, with additional consideration of static power and operating robustness. Transient simulations and parameter sweeps were used to examine how the added reset/timing branch modifies the membrane trajectory, internal spike formation, output response, and recovery behavior after firing.

The results show that the proposed hybrid neuron exhibits stable integrate-and-fire operation and that the added branch introduces a tunable reset mechanism strongly influenced by the bleed bias. Two practically important operating regions were identified. Near $V_{\text{bleed}} \approx 0.22$ V, the hybrid neuron achieved its best performance-oriented operating point, providing the most favorable nominal frequency/energy tradeoff among the tested hybrid points. Near $V_{\text{bleed}} \approx 0.24$ V, the neuron exhibited its best robustness-oriented operating point, with stronger reset control and broader clean-operation coverage across the tested sweeps. Compared with the Besrour baseline, the hybrid neuron provides an additional degree of control over reset and timing, enabling a more explicit study of how reset quality influences firing frequency and energy, while incurring a higher static power cost.

Overall, this work demonstrates that a compact Besrour-derived neuron can be extended with a minimal reset/timing branch to create a reset-aware hybrid LIF architecture with tunable operating regimes. The results support the view that reset is not merely a secondary waveform

detail, but a central design variable that directly shapes frequency, energy, and robustness in compact neuromorphic neurons.

Chapter 1: Introduction

1.1 Purpose and Motivation

Neuromorphic computing continues to attract attention as a hardware approach for implementing brain-inspired information processing with improved energy efficiency and event-driven operation compared with conventional von Neumann systems [1]. Within this area, compact spiking neuron circuits remain important because they influence the area, power, and scalability of larger neuromorphic systems. For this reason, there is continued value in studying neuron circuits that are simple enough to be practical while still offering meaningful control over their operating behavior.

Among neuron models, the leaky integrate-and-fire (LIF) neuron is especially attractive for circuit implementation because it captures the essential sequence of integration, threshold crossing, spike generation, and reset using relatively few devices [2]. In compact CMOS implementations, however, reset is often treated mainly as a consequence of the firing event rather than as a primary design target. This can be limiting because the reset state determines the starting condition of the next integration cycle and therefore directly affects spike timing, firing frequency, and energy consumption.

This thesis is motivated by the idea that reset deserves more explicit attention in compact spiking neurons. Rather than replacing a simple neuron architecture with a much larger one, this work investigates whether a small architectural addition can provide more useful control over post-spike behavior while preserving the compact character of the original design. The baseline chosen for this study is a Besrour-style compact spiking neuron, selected because it is easy to reason about and already capable of clean spiking operation [3].

The problem addressed in this thesis is therefore the following: can a compact Besrour-derived LIF neuron be usefully extended with a minimal reset/timing branch, and can the effect of that branch be quantified in terms of reset behavior, firing frequency, and energy? This question is important because it addresses a practical engineering tradeoff: whether a small increase in circuit complexity is justified by measurable improvement in operating control.

1.2 Thesis Objective and Research Questions

The objective of this thesis is to design, simulate, and evaluate a Besrour-derived hybrid LIF neuron with an added reset/timing branch and to compare it directly against the original Besrour reference neuron.

More specifically, this thesis aims to:

1. design a compact hybrid neuron that preserves the core spiking behavior of the Besrour baseline while adding an explicit reset/timing mechanism;
2. interpret the role of the added branch at the circuit and node level;
3. quantify how the added branch changes reset behavior relative to the baseline;
4. determine how those reset changes affect firing frequency and energy;
5. identify useful operating regions of the hybrid neuron, especially the performance-oriented region near $V_{\text{bleed}} \approx 0.22$ V and the robustness-oriented region near $V_{\text{bleed}} \approx 0.24$ V.

The main research questions are:

1. Does the added reset/timing branch improve control of post-spike reset relative to the Besrour reference neuron?
2. How does V_{bleed} affect reset, firing frequency, and energy per spike?
3. Can distinct performance-oriented and robustness-oriented operating regimes be identified for the hybrid neuron?
4. Does the added branch justify its extra circuit complexity relative to the original compact baseline?

1.3 Main Contributions

The main contributions of this thesis are as follows:

1. A Besrour-derived hybrid LIF neuron was proposed by extending a compact baseline with an added reset/timing branch composed of Ctref, Npchg, Nbleed, and Nreset.

2. A node-level interpretation of the modified firing cycle was developed, showing how the added branch participates in spike recovery and reset shaping.

3. A direct comparison was carried out between the proposed hybrid neuron and the original Besrour baseline in a common simulation flow.

4. The hybrid neuron was characterized using reset, frequency, and energy as the main evaluation metrics, rather than treating reset as a secondary waveform detail.

5. Two practically important operating regions were identified:

   a. $V_{\text{bleed}} \approx 0.22$ V as a performance-oriented operating point, and

   b. $V_{\text{bleed}} \approx 0.24$ V as a robustness-oriented operating point.

Together, these contributions position the proposed circuit as a reset-aware compact hybrid neuron rather than merely a modified version of the baseline schematic.

1.4 Scope and Limitations

This thesis is limited to simulation-based circuit analysis. All designs were implemented and evaluated using Xschem, ngspice, ASAP7 predictive device models, and Python-based waveform post-processing. The conclusions are therefore based on simulated behavior within the selected environment and operating ranges.

Several limitations should be stated clearly. First, the study does not include fabricated silicon measurements. Second, it does not attempt a full system-level or array-level neuromorphic demonstration. Third, the conclusions are limited to the tested sweep ranges and do not yet include full corner analysis, mismatch analysis, or post-layout parasitic extraction. Finally, not all reference neurons are equally suitable for the same style of direct quantitative comparison. In particular, the Xiangyu-inspired neuron is treated mainly as a pulse-driven qualitative reference rather than as the primary quantitative baseline.

These limitations do not reduce the value of the work. Rather, they define its proper scope as a compact circuit-design and simulation study focused on reset-aware tradeoffs in a Besrour-derived hybrid LIF neuron.

Chapter 2: Background and Related Work

2.1 Neuromorphic Computing and Spiking Neurons

Neuromorphic computing seeks to implement information-processing systems inspired by the event-driven and energy-efficient behavior of biological nervous systems. In hardware, this makes compact spiking circuits attractive because the area, power, and timing behavior of the neuron and synapse blocks directly influence the usefulness of larger neuromorphic systems [1]. For the purposes of this thesis, the main interest is not in broad neuromorphic theory, but in the design of compact spiking neurons whose circuit-level behavior can be controlled and interpreted.

Among neuron abstractions, the leaky integrate-and-fire (LIF) model remains especially attractive for hardware implementation because it captures the essential spiking cycle with relatively low circuit complexity [2]. In its basic form, the membrane state integrates input current while leaking toward a resting level. When the membrane reaches a threshold, a spike event is produced and the membrane is reset before the next integration phase begins. A simple continuous-time form of the model may be written as

$$C_m \frac{dV_m}{dt} = I_{\text{in}} - \frac{V_m - V_{\text{rest}}}{R_m}, \tag{2.1}$$

where V_m is the membrane voltage, C_m is the membrane capacitance, R_m is the effective leak resistance, and I_{in} is the input current. Once V_m reaches a threshold V_{th}, the neuron emits a spike and the membrane returns to a reset value V_{reset}. The attraction of the LIF model is that it preserves the essential timing structure of spiking computation without requiring a large or biologically elaborate circuit. This makes it a natural starting point for studies of compact neuron design, including the present work.

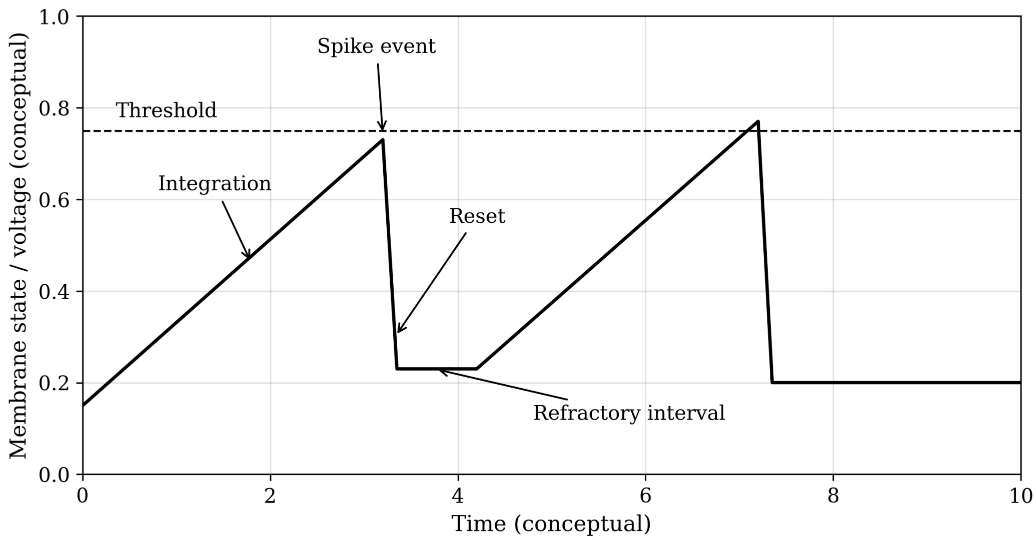

Figure 2.1: Conceptual LIF waveform

2.2 Why Reset Deserves Separate Attention

In a simplified discussion of the LIF cycle, reset is often treated as the last stage of the waveform. In practice, however, reset is a first-order circuit design variable. The post-spike reset state determines where the next integration cycle begins, which directly influences the next inter-spike interval and therefore the firing frequency. Because repeated charge and discharge behavior also determines how much energy is spent per cycle, reset is tightly coupled not only to timing but also to energy consumption.

This viewpoint is supported by prior silicon-neuron literature. Indiveri's review of silicon neuron circuits explicitly discusses reset and refractory behavior as circuit-level functions rather than merely incidental consequences of spiking [6]. Likewise, time-domain neurons such as the Xiangyu design use feedback to restore the membrane state as part of the firing sequence [5]. These examples support the idea that reset can be treated as a deliberate design target rather than only as a waveform artifact.

This perspective is central to the present thesis. The proposed hybrid neuron is not motivated by a desire to make the baseline waveform more complicated. Instead, it is motivated by the engineering idea that a compact neuron may benefit from a more explicit and tunable reset mechanism, and that such a mechanism is likely to affect both frequency and energy.

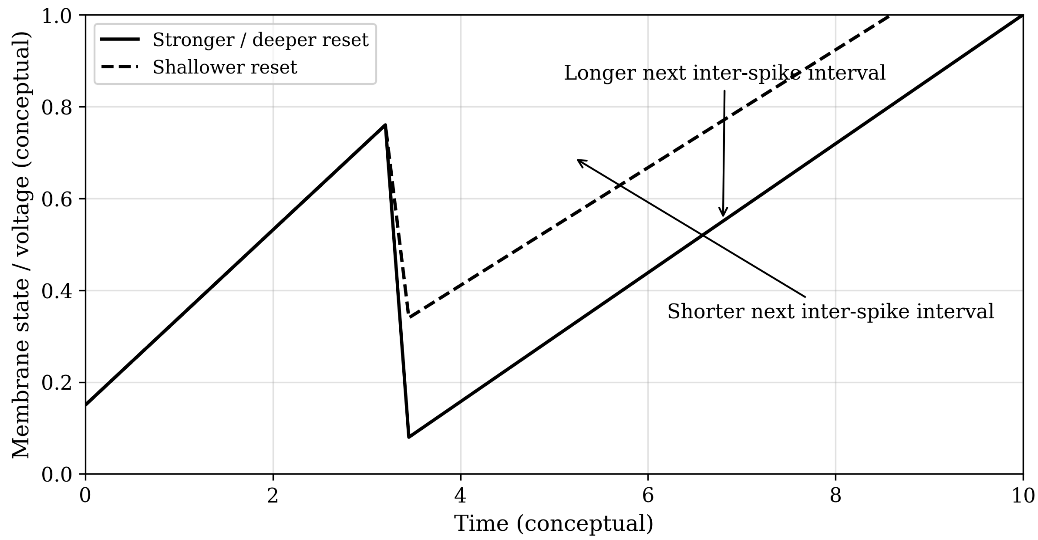

Figure 2.2: Conceptual effect of reset depth on the next spike cycle

2.3 CMOS Neuron Implementation Styles

Silicon neuron circuits can be grouped into several broad implementation styles. For the purposes of this thesis, three styles are especially relevant: compact LIF and axon-hillock circuits, biophysically inspired analog neurons, and time-domain or pulse-driven neurons.

2.3.1 Compact LIF and Axon-Hillock Circuits

Compact LIF and axon-hillock style circuits are attractive because they use relatively few devices to implement repeated spiking behavior. In these circuits, the main priorities are usually compactness, controllability, and low energy. Besrour et al. provide an especially important example for this thesis because their compact analog spiking neuron combines low energy with a clear LIF-style operating loop, making it a strong baseline for derivative design work [3]. Danneville's axon-hillock neuron represents a related compact tradition in which reset and discharge structure strongly influence ultra-low-power operation [7].

2.3.2 Biophysically Inspired Analog Neurons

A second implementation style seeks to reproduce more of the dynamics of biophysical neuron models. The Sourikopoulos neuron is a useful example because it is inspired by the Morris-Lecar model rather than by a minimal LIF abstraction [8]. This broadens the design context of the present thesis by showing that compact spiking circuits can also be approached from a richer nonlinear perspective, even though that perspective is not the main direction adopted here.

2.3.3 Time-Domain and Pulse-Driven Neurons

A third implementation style is the time-domain or pulse-driven neuron. Xiangyu Chen et al. presented a neuron structure in which pulse timing and delayed feedback play a central role in spike formation and reset [5]. This style is particularly relevant because it shows that reset and spike timing can be embedded into the firing sequence explicitly through compact feedback-driven subcircuits, rather than only through a conventional current-driven LIF loop.

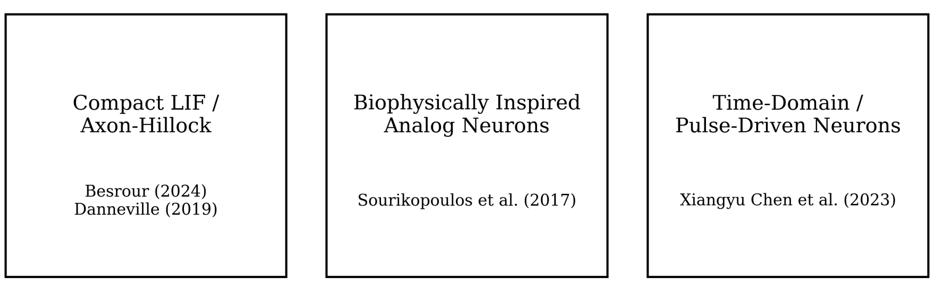

Figure 2.3: Taxonomy of neuron implementation styles

2.4 Reference Designs That Motivate This Thesis

The proposed hybrid neuron was not developed in isolation. It emerged from the study of several compact neuron designs, each of which contributed a different lesson.

2.4.1 Besrour as the Main Baseline

The Besrour neuron is the most important reference design in this thesis because it serves as the direct baseline for the proposed hybrid circuit. It is compact, LIF-oriented, and easy to interpret at the circuit level. Most importantly, it already provides a clear and functional integrate-and-fire loop, which makes it an ideal reference for asking whether a small architectural addition can create a meaningful new degree of control rather than merely adding complexity [3].

2.4.2 Danneville as an Efficiency and Simplicity Reference

The Danneville axon-hillock neuron is useful mainly as an efficiency- and simplicity-oriented reference. Its importance in this thesis is not that it directly defines the proposed architecture, but that it reinforces the idea that reset and discharge behavior strongly affect compact-neuron efficiency. This makes it a valuable secondary context for interpreting the cost of added reset/timing control [7].

2.4.3 Sourikopoulos as an Alternative Compact Spiking Reference

The Sourikopoulos neuron provides another compact spiking reference from a different design philosophy. Because it is influenced by the Morris-Lecar model, it shows that compact spiking can be pursued through a more nonlinear and biophysically inspired path than a simple LIF baseline. In this thesis, its main role is to broaden the comparison mindset rather than to serve as the main benchmark [8].

2.4.4 Xiangyu as a Time-Domain Reference

The Xiangyu neuron is treated as a secondary time-domain reference. Its relevance lies in the fact that reset and spike timing are built into the firing sequence in a very explicit way through pulse-driven feedback [5]. That makes it useful as a conceptual reference for reset-aware design, even though its pulse-driven operating philosophy differs from the current-driven Besrour-derived hybrid neuron developed here.

2.4.5 The "Simply Sufficient" Perspective

A final conceptual influence comes from Koçyigit's thesis, which frames neuron design in terms of what is "simply sufficient" rather than maximally elaborate [4]. This perspective is closely aligned with the present work. The proposed hybrid neuron does not attempt to become a fully elaborate or highly biomimetic design. Instead, it asks whether a small reset/timing branch is sufficient to produce a meaningful and useful operating tradeoff.

Table 2.1 summarizes the main reference works in [3, 5, 7, 8, 4] and shows how each one informs the present thesis.

Table 2.1: Summary of the main reference works that informed the proposed hybrid neuron and the comparison framework used in this thesis

Reference	Main model/style	Main motivation	Why it matters to this thesis	Role in this thesis
Besrour (2024)	Compact LIF / analog spiking neuron	Ultra-low-energy compact LIF baseline	Main architectural baseline for the proposed hybrid neuron	Primary quantitative comparison
Danneville (2019)	Axon-hillock compact neuron	Very low standby power and efficient compact spiking	Provides efficiency / simplicity context for reset-oriented compact design	Secondary quantitative context
Sourikopoulos et al. (2017)	Morris-Lecar-inspired analog neuron	Energy-efficient compact spiking with biophysical inspiration	Shows an alternative compact neuron philosophy beyond simple LIF	Secondary quantitative context
Xiangyu Chen et al. (2023)	Time-domain / pulse-driven neuron	Pulse-based accumulation and delayed spike generation	Useful contrast to current-driven LIF-style neurons; relevant for reset/feedback thinking	Secondary qualitative reference
Koçyigit thesis	"Simply sufficient" LIF design philosophy	Question of how much complexity is actually necessary	Supports the thesis framing of a compact but sufficient hybrid neuron	Conceptual framing reference

2.5 Thesis Positioning and Selected Metrics

The literature reviewed above shows that compact neuron circuits have been developed from several perspectives: compact LIF baselines, axon-hillock designs, biophysically inspired analog neurons, and pulse-driven time-domain neurons [3, 5, 7, 8]. The present thesis is positioned within this landscape as a simple reset-aware hybrid extension of a compact Besrour-derived LIF neuron.

This positioning is important because it defines the expected contribution correctly. The proposed circuit is not intended to replace every other neuron architecture or to claim universal superiority. Instead, it is intended to examine whether a minimal added branch can make reset more explicit and tunable within a compact LIF-style neuron.

For that reason, the evaluation in this thesis is organized around three tightly coupled metrics:

1. reset behavior
2. firing frequency
3. energy

These three metrics were selected because they directly reflect the purpose of the added branch. The branch is not meant only to alter the waveform shape. Its purpose is to modify the post-spike recovery process, and the most direct consequences of that modification are changes in reset behavior, firing frequency, and energy consumption.

This focus leads directly into the next chapter, which presents the Besrour baseline and the proposed hybrid architecture in detail.

Chapter 3: Reference Besrour Neuron and Proposed Hybrid Neuron

3.1 Baseline Besrour Architecture

The main baseline used in this thesis is a Besrour-style compact spiking neuron [3]. This baseline was selected because it combines a relatively small transistor count with a clear integrate-and-fire operating loop, making it a suitable reference for studying whether a minimal structural modification can introduce a useful new degree of control. In particular, the Besrour baseline already exhibits the essential sequence of membrane integration, threshold approach, spike generation, and reset. This makes it an appropriate starting point for a design study focused on the effect of an added reset/timing mechanism.

At a functional level, the Besrour neuron can be interpreted as a compact feedback-driven LIF-like spiking loop. An input stimulus charges the main membrane-related node, while the transistor network around the internal nodes shapes the transition from slow integration to rapid switching. Once the internal state reaches a critical region, regenerative activity produces a spike event, and the circuit enters a reset and recovery phase before the next cycle begins [3].

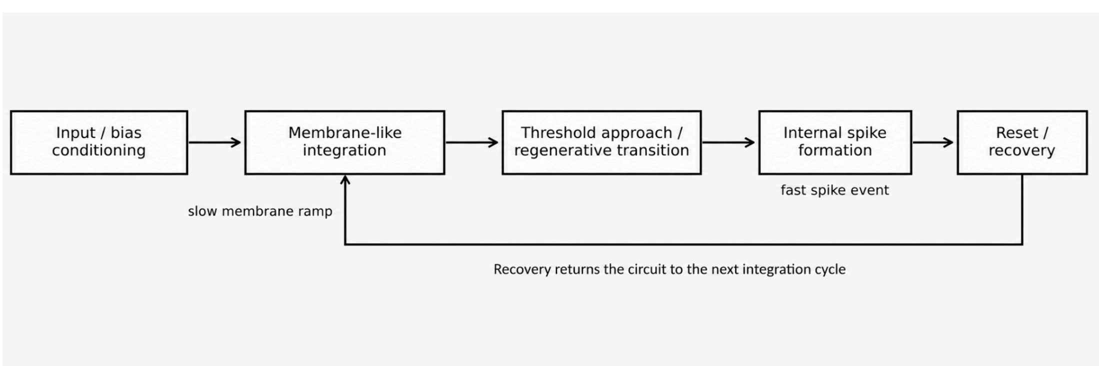

Figure 3.1: Simplified Besrour operating flow from input/bias conditioning through membrane integration, internal spike formation, and reset/recovery

Figure 3.1 summarizes the functional operating flow of the Besrour baseline. The main point to note is that integration, spike formation, and reset are all embedded within the original compact loop, without a separate tunable reset branch. This is the architectural feature that later motivates the hybrid modification.

The value of this baseline is that it is compact and already functional, but it does not expose reset/timing control as a separate and tunable branch. Reset exists in the baseline, but it is embedded in the natural operation of the compact feedback loop rather than being promoted to an explicit design knob. This limitation is the main reason the Besrour neuron is a strong baseline for the present work.

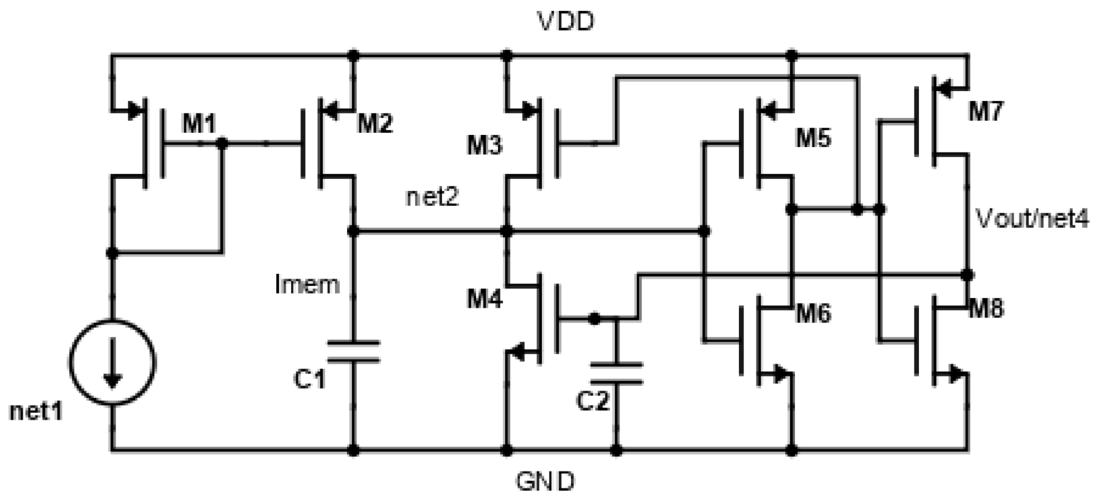

Figure 3.2: Besrour baseline schematic

Figure 3.2 shows the baseline Besrour schematic used throughout the architecture discussion in this chapter.

3.2 Motivation for the Hybrid Modification

The proposed hybrid neuron was developed from the observation that, in a compact LIF-like circuit, reset is not merely the final portion of the waveform. Reset influences the starting condition of the next integration cycle and therefore directly affects spike timing, firing frequency, and energy consumption. If the reset is too shallow, the neuron may return too quickly into the next cycle or become sensitive to unintended retriggering. If the reset is too aggressive, the firing frequency may be reduced and extra energy may be spent in the recovery process. This makes reset a design variable rather than only a passive consequence of the firing event.

The Besrour baseline provides a compact and efficient foundation, but it does not provide an explicit bias parameter whose primary role is to shape reset/timing behavior. The proposed hybrid neuron addresses this by adding a small auxiliary branch that introduces an internal timing/reset state. This branch is designed to remain small enough that the overall neuron still qualifies as a compact hybrid design rather than a large architectural departure from the baseline.

The central architectural question is therefore whether a small added branch can create a more controllable reset mechanism and expose a useful tradeoff among reset, frequency, and energy while preserving the essential compact behavior of the Besrour-derived spiking loop.

3.3 Proposed Hybrid Neuron Architecture

The proposed hybrid neuron retains the main Besrour-style spiking core and introduces an added reset/timing branch composed of four elements:

- Ctref
- Npchg
- Nbleed
- Nreset

These elements create an auxiliary internal state that is not present in the baseline in the same explicit form. Conceptually, a timing/reset node is introduced and stored on Ctref. This node is charged via Npchg in response to spike/output activity and discharged via Nbleed, whose strength is governed by V_{bleed}. The resulting timing/reset-node voltage then controls Nreset, which helps shape the post-spike trajectory.

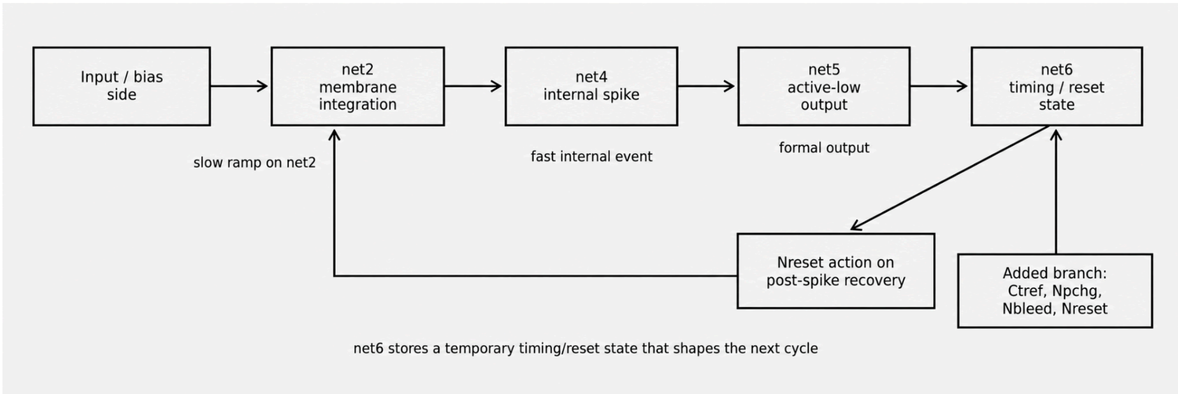

Figure 3.3: Simplified hybrid operating flow showing the Besrour-derived spiking path together with the added timing/reset branch that influences post-spike recovery through net6 and Nreset

Figure 3.3 summarizes the operating flow of the proposed hybrid neuron. In addition to the original Besrour-derived spiking path, the hybrid includes an added timing/reset branch whose stored state on net6 influences post-spike recovery through Nreset. This added path is what creates the tunable reset behavior studied in the later chapters.

For this reason, the firing cycle is no longer governed only by the original compact spiking loop. It is now influenced by an auxiliary timing/reset state whose evolution can be tuned externally. This is the main reason the neuron is described as hybrid in this thesis. The circuit remains fundamentally a compact Besrour-derived LIF-style spiking neuron, but it now includes a second functional sub-mechanism that explicitly participates in the reset/timing phase.

Structurally, the proposed neuron can therefore be viewed as having two layers of behavior:

- The original Besrour-derived spiking core, which provides the main integrate-and-fire loop, and
- The added reset/timing branch, which shapes how the neuron recovers from each spike and enters the next cycle.

This architecture preserves the baseline's compactness and interpretability while providing a direct design path for studying reset-aware behavior.

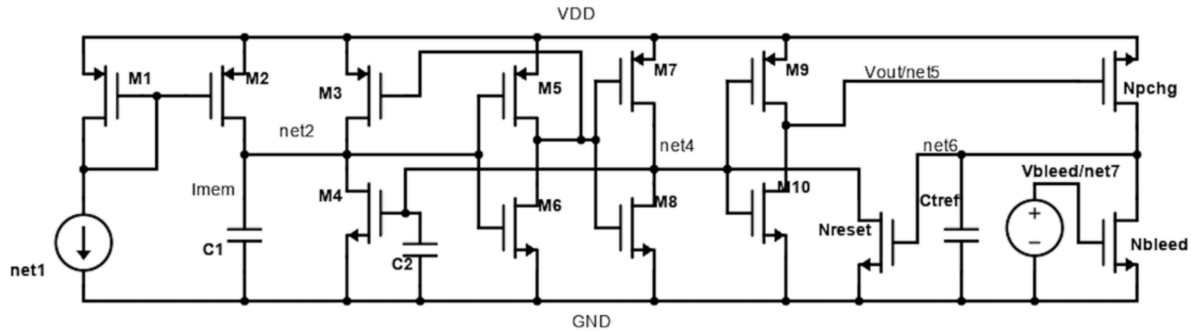

Figure 3.4: Proposed hybrid neuron schematic

Figure 3.4 shows the proposed hybrid schematic, including the added Ctref, Npchg, Nbleed, and Nreset branch discussed throughout the rest of this thesis.

3.4 Node Dictionary and Added Branch Elements

To make the later waveform interpretation and measurement definitions consistent, the following node meanings are used throughout this thesis.

Table 3.1: Hybrid node dictionary

Node	Functional role	Expected waveform behavior	Why it matters in analysis
net2	Hybrid membrane node	Repeated integrate-and-fire sawtooth trajectory	Primary node for reset depth and recovery analysis
net4	Internal spike node	Fast internal spike event	Useful for locating internal firing transition
net5	Official active-low output	Buffered active-low output pulse	Formal output node for reporting spike waveform
net6	Timing/reset node	Pulse-like timing/reset activity	The main indicator that the added branch is active

Among these nodes, net2 and net6 are the most important for interpreting the added branch. net2 captures the membrane recovery trajectory, while net6 captures the explicit internal timing/reset behavior introduced by the hybrid modification. net5 remains the official active-low output of the proposed neuron, even though some frequency interpretation is more safely derived from the membrane cycle and internal spike behavior.

The functional roles of the added elements are summarized below.

Table 3.2: Added branch element roles

Element	Functional purpose	Main expected effect
Ctref	Stores the timing/reset-node voltage	Creates a temporary dynamic reset state
Npchg	Charges the timing/reset node during spike-related activity	Activates the reset/timing branch
Nbleed	Discharges the timing/reset node under control of V_{bleed}	Tunes reset/timing duration and strength
Nreset	Applies timing/reset-node influence back into the main loop	Shapes post-spike recovery

Ctref provides the dynamic memory of the added branch. Npchg couples branch activation to actual firing activity. Nbleed and V_{bleed} provide the main tuning path. Nreset acts as the point through which the branch influences the main spiking loop. Together, these elements convert reset into a more explicit and tunable function than in the plain baseline.

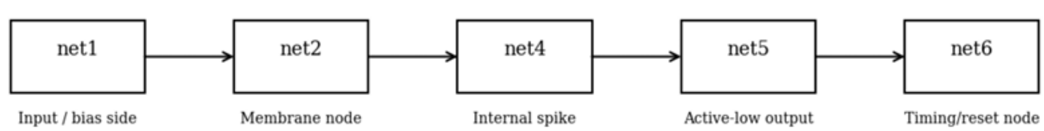

Figure 3.5: Hybrid node map

3.5 Operating Principle of the Proposed Hybrid Neuron

The firing cycle of the proposed hybrid neuron can be interpreted in four phases. The exact transistor currents are nonlinear and device-dependent, but the observed waveforms support the following simplified operating sequence.

3.5.1 Integration and Threshold Approach

During the integration phase, the membrane node net2 rises gradually. In this phase, the main Besrour-derived spiking loop dominates the neuron's behavior. The input-side branch establishes the charging condition, and net2 follows a slow upward trajectory toward the firing condition.

As net2 continues to rise, the internal transistor network enters a more sensitive region in which the neuron becomes increasingly susceptible to regenerative switching. This threshold-approach behavior marks the transition from slow membrane integration to rapid internal spike formation.

3.5.2 Internal Spike Formation and Active-Low Output Event

Once the neuron reaches the firing threshold, net4 undergoes a sharp internal spike. This is the point at which the circuit leaves the slow-integration regime and enters the rapid-switching regime. The spike event at net4 is the clearest internal marker that firing has occurred.

At the same time, the official active-low output net5 responds to the firing event. In the hybrid neuron, net5 provides the externalized output waveform, whereas the internal spike is more directly observed at net4.

3.5.3 Timing/Reset-Node Activation and Reset Action

The firing event also activates the timing/reset node net6. Through Npchg, spike-related activity causes net6 to charge and create a temporary internal timing/reset state. This is the key architectural distinction between the hybrid neuron and the plain Besrour baseline.

As net6 evolves, it controls Nreset, which participates in the post-spike recovery of the main spiking loop. At the waveform level, this phase corresponds to the downward excursion of net2 after firing. The depth and timing of that excursion are influenced by the added branch and are therefore tunable through V_{bleed}.

3.5.4 Recovery and Return to Integration

After the reset phase, the stored timing/reset state on net6 decays through the bleed path. The circuit then returns to its next integration cycle. net2 begins rising again, net4 leaves its internal spike state, and net5 returns from the active-low output event.

This final phase is important because it shows why reset matters. The next cycle does not begin from an arbitrary condition. It begins from a state shaped by the previous spike and by the hybrid reset/timing branch. This is why a reset directly affects the next inter-spike interval and, therefore, both firing frequency and energy.

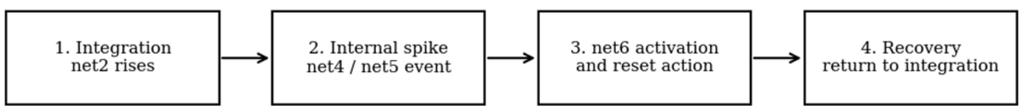

Figure 3.6: Conceptual phase-by-phase operating diagram

3.6 Design Hypothesis and Expected Tradeoffs

The proposed hybrid neuron is based on the hypothesis that a compact Besrour-derived LIF neuron can be improved in a useful way by adding a small reset/timing branch that provides more explicit and tunable post-spike control.

More specifically, the design hypothesis is that:

1. The added branch will create an active internal timing/reset state that is absent in the plain baseline in the same explicit form.
2. That internal state will influence the post-spike reset of the membrane trajectory.

3. The bleed-bias parameter V_{bleed} will provide a practical tuning knob for shaping the reset/timing tradeoff.

4. The resulting reset changes will affect firing frequency and energy, not only waveform shape.

This hypothesis is deliberately modest. The intent is not to claim that the added branch will improve every metric simultaneously or that it will dominate every other neuron architecture in the literature. Instead, the intent is to determine whether a small branch can create a meaningful and useful tradeoff in a compact hybrid neuron.

Any architectural modification that changes reset behavior is expected to introduce tradeoffs. A stronger or more explicit reset mechanism may improve control of post-spike recovery, but it may also reduce firing rate by forcing the membrane node to recover from a deeper post-spike condition. Likewise, adding a timing/reset branch introduces extra capacitance and device activity, which may increase energy or static overhead even if it improves control. Finally, introducing V_{bleed} as a tuning parameter adds flexibility but also introduces bias dependence.

For these reasons, the hybrid neuron should not be judged only by whether reset becomes deeper or whether nominal speed becomes higher. It should be judged by the overall tradeoff created among reset, frequency, and energy. That tradeoff is the main subject of the later results and discussion chapters.

3.7 Chapter Summary

This chapter introduced the Besrour baseline and the proposed hybrid neuron architecture. The Besrour neuron was established as the main compact reference because it already provides a clear and efficient integrate-and-fire loop. The proposed hybrid neuron was then presented as a Besrour-derived extension that adds a small reset/timing branch composed of Ctref, Npchg, Nbleed, and Nreset. The key hybrid nodes net2, net4, net5, and net6 were defined, and the functional roles of the added elements were summarized. A phase-by-phase interpretation of the firing cycle showed how the added branch becomes active during the spike and reset sequence. The central hypothesis that emerges from this chapter is that a small added branch can make reset behavior more explicit and tunable, and that this tunability should influence both frequency and energy. The next chapter presents the simulation methodology used to test that hypothesis.

Chapter 4: Simulation Methodology

4.1 Simulation Environment and Circuits Under Test

All circuits in this thesis were implemented schematically in Xschem, simulated in ngspice, and analyzed in Python/Google Colab using exported waveform files. This workflow was selected because it allowed the baseline and proposed neurons to be represented in the same schematic environment, simulated under the same transient-analysis framework, and analyzed using the same extraction scripts and metric definitions.

The transistor models used in the main comparison flow were based on the ASAP7 predictive device model environment. In this thesis, the model flow is therefore treated as a common ASAP7 predictive FinFET simulation environment rather than as an attempt to reproduce every original literature result at its original technology node [9]. This is important because the reference works considered in the thesis span multiple original process nodes and different intended operating regimes. The purpose of the common ASAP7 flow was to provide a normalized basis for design comparison rather than a literal process-node reproduction of each source design.

Five neuron implementations were considered during the work:

1. the Besrour reference neuron,
2. the proposed hybrid neuron,
3. the Danneville reference neuron,
4. the Sourikopoulos reference neuron, and
5. a Xiangyu-inspired pulse-driven neuron.

However, the thesis is centered on the first two. The Besrour neuron serves as the primary baseline because the proposed hybrid neuron is directly derived from that structure. Danneville and

Sourikopoulos provide secondary comparison context, while the Xiangyu-inspired neuron is treated mainly as a pulse-driven qualitative reference [3, 7, 8, 5].

For the proposed hybrid neuron, the key nodes used throughout the analysis are:

- net2 = hybrid membrane node
- net4 = internal spike node
- net5 = official active-low output
- net6 = timing/reset node

These node definitions are used consistently in waveform interpretation and metric extraction.

4.2 Nominal Operating Points and Sweep Strategy

The main nominal comparison in this thesis was performed between the hybrid neuron and the Besrour baseline under matched operating conditions chosen to isolate the effect of the added reset/timing branch.

For the matched nominal point:

- $V_{DD} = 0.30$ V
- $I_{syn} = 100$ nA
- $C_1 = 2$ fF
- $C_2 = 2$ fF

For the hybrid neuron, the added branch also used:

- Ctref = 1 fF
- V_{bleed} as the primary tuning parameter

The two most important hybrid operating points identified in the full dataset are:

- $V_{bleed} \approx 0.22$ V, interpreted as the performance-oriented operating point

- $V_{\text{bleed}} \approx 0.24$ V, interpreted as the robustness-oriented operating point

The Danneville and Sourikopoulos reference neurons were also simulated at representative nominal points chosen to produce stable operation in the same common flow. The Xiangyu-inspired reference was ultimately characterized as a pulse-driven neuron and therefore treated separately from the current-driven f–I style comparisons used for Hybrid and Besrour [7, 8, 5].

The main sweep types used in the thesis were:

- nominal waveform sweeps,
- current sweeps,
- supply-voltage sweeps,
- capacitance sweeps,
- static-power sweeps,
- and, for the hybrid only, V_{bleed} and Ctref sweeps.

For the Xiangyu-inspired neuron, the main sweeps were instead:

- excitatory pulse-period sweep,
- excitatory pulse-width sweep,
- V_{DD} sweep,
- and C_1 sweep.

The sweep ranges used in the study are summarized in Table 4.1.

Table 4.1: Sweep summary table

Neuron	**Sweep type**	**Values used**	**Purpose**
Hybrid	Representative waveform sweep vs V_{bleed}	0.18, 0.20, 0.22, 0.24 V	Show waveform and reset/timing change with V_{bleed}
Hybrid	Current sweep	10 nA, 20 nA, 50 nA, 100 nA, 200 nA, 500 nA, 1 uA	Determine operating-frequency range and onset of sustained spiking

Table 4.1 continued from previous page

Neuron	Sweep type	Values used	Purpose
Hybrid	V_{DD} sweep	0.22, 0.25, 0.28, 0.30, 0.32, 0.35, 0.40 V	Examine voltage sensitivity and robustness
Hybrid	C_1/C_2 main-cap sweep	2, 5, 10, 20, 50 fF	Study time-scale/frequency scaling
Hybrid	Ctref sweep	0.5, 1, 2, 5 fF	Evaluate timing-branch usefulness across storage strengths
Hybrid	Static-power sweep	I_{syn} = 1 pA; V_{DD} = 0.22 to 0.40 V	Separate static power from active spiking power
Besrour	Current / V_{DD} / C_1C_2 / static sweeps	Matched to Hybrid where applicable	Primary baseline comparison
Danneville	Current / V_{DD} / C_1 / static sweeps	Representative ranges	Secondary quantitative context
Sourikopoulos	Current / V_{DD} / C_1C_2 / static sweeps	Representative ranges	Secondary quantitative context
Xiangyu	Pulse-period sweep	5, 10, 20, 40 ns	Pulse-driven operating-frequency study
Xiangyu	Pulse-width sweep	20, 50, 100, 200 ps	Pulse-strength / accumulation study
Xiangyu	V_{DD} sweep	0.40, 0.50, 0.60, 0.70 V	Pulse-driven supply sensitivity
Xiangyu	C_1 sweep	10, 20, 50, 100 fF	Pulse-driven membrane-capacitance sensitivity

A key practical outcome of the sweep strategy was that the hybrid neuron could not be described by a single globally best operating point. Instead, the sweeps revealed distinct operating regions, which are among the main findings of the thesis.

4.3 Data Export and Post-Processing

All transient waveform files were exported from ngspice in ASCII form using wrdata. Each file contained a time column and the requested waveform columns. Unique filenames were assigned to each sweep point so that the neuron type, sweep category, and sweep value could be identified directly from the filename. This was essential for later batch analysis.

During development, it was found that the correct use of ngspice reset and alter commands was critical for reproducible sweeps. In particular:

- .ic had to be specified as a netlist statement, not as a .control command,
- reset reloads the circuit,
- and therefore all required alter values had to be re-applied after every reset.

Waveform files were then processed in Python/Google Colab. The post-processing scripts were used to:

- read waveform files,
- identify valid operating windows,
- detect spike times,
- extract membrane peaks and troughs,
- compute average power and energy per spike,
- and classify runs as clean, sustained but nonideal, or boundary/unstable.

This workflow made it possible to evaluate a large number of sweep points consistently while still preserving the original transient traces for visual inspection.

4.4 Measurement Definitions

The main thesis metrics are reset, frequency, and energy. These were measured as described below.

4.4.1 Reset Metrics

The primary reset metric for the hybrid neuron is the post-spike minimum of net2. This is the deepest point reached by the membrane node after a spike and before the next integration phase begins. In this thesis, it is referred to as the membrane trough or reset level.

A second reset-related metric is the timing-node pulse width on net6. This is the duration for which the timing/reset node remains active above a chosen threshold after a spike event. In practice, this metric was extracted from the pulse on net6 and used as an indicator of how long the reset/timing branch remains dynamically engaged.

Conceptually, membrane reset depth may be written as

$$\Delta V_{\text{reset}} = V_{\text{peak,pre}} - V_{\text{min,post}}, \tag{4.1}$$

where $V_{\text{peak,pre}}$ is the membrane value before the spike and $V_{\text{min,post}}$ is the post-spike membrane minimum.

In this thesis, reset quality is therefore discussed mainly in terms of:

- how deep the membrane reset becomes,
- how repeatable that trough is across cycles,
- and how the timing-node activity changes with V_{bleed}.

4.4.2 Frequency Metrics

For the hybrid neuron, the official output node is net5, but net5 is an active-low output and in some long-run cases it can show output chatter or extra narrow output events. For this reason, the principal hybrid firing cycle was interpreted mainly from the repeated membrane cycle on net2, with support from the internal spike behavior at net4 when needed.

For the Besrour neuron, frequency was determined from its main repetitive spiking cycle using the corresponding membrane/output behavior of that topology. For Danneville and Sourikopoulos, the output-like node most clearly representing the repeated spiking event was used. For the Xiangyu-inspired neuron, output-event timing was extracted from Vspike because the neuron was characterized as a pulse-driven circuit.

The nominal firing frequency was calculated as

$$f = \frac{1}{\overline{\text{ISI}}}, \tag{4.2}$$

where ISI is the mean inter-spike interval over the selected steady-state window.

To reduce startup effects, the first transient portion of the run was excluded from the main frequency extraction when necessary.

4.4.3 Power and Energy Metrics

Supply current was measured from i(Vvdd) in every dynamic run used for quantitative comparison. Instantaneous power was therefore computed as

$$P(t) = -V_{\mathrm{DD}} \cdot i(\mathrm{Vvdd}), \tag{4.3}$$

where the negative sign compensates for the source-current sign convention in ngspice.

The average dynamic power over the selected steady-state window was computed as

$$P_{\mathrm{avg}} = \frac{1}{T}\int_{t_1}^{t_2} P(t)\,dt, \tag{4.4}$$

and the dynamic energy per spike was then computed as

$$E_{\mathrm{spike}} = \frac{P_{\mathrm{avg}}}{f}, \tag{4.5}$$

for runs that exhibited sustained periodic or quasi-periodic behavior.

Static power was extracted separately from near-idle runs by reducing I_{syn} to 1 pA, allowing the circuit to settle, and averaging the final region of the supply-current waveform. Static power is treated separately from active dynamic power because it reflects leakage and bias overhead rather than the energy of repeated spiking.

4.4.4 Robustness Classification

Not every sweep point should be treated as equally valid for the same type of interpretation. During analysis it became clear that some operating points were clean and periodic, some were sustained but nonideal, and some were clearly boundary or unstable cases.

For this reason, runs were classified into the following categories:

- clean: one-to-one repeated operating cycle with stable membrane behavior and no obvious output chatter,
- sustained but nonideal: repeated activity persists, but with extra sub-pulses, clustered events, or ambiguous output behavior,
- boundary / unstable: the run locks up, dies out, fails to reach a clean repeated regime, or aborts early.

This classification was especially important for the hybrid neuron because the added reset/timing branch created a meaningful operating tradeoff rather than a single universally best regime.

4.5 Fair Comparison and Methodological Limits

Because the proposed hybrid neuron is derived from the Besrour baseline, fairness in that comparison is central to the methodology. The comparison was made fair in the following ways:

- both circuits were simulated in the same Xschem/ngspice/ASAP7 environment,
- the main nominal operating point used the same V_{DD}, input current, and main capacitance values,
- the same transient-analysis and post-processing workflow was applied,
- and dynamic power and energy were extracted from the same supply-current method.

The key difference is that the hybrid includes the added reset/timing branch and therefore the additional parameter V_{bleed}. The purpose of the methodology is therefore not to eliminate the architectural difference, but to isolate and quantify what that difference changes.

Several limitations should also be stated clearly. First, the study is simulation-based and does not include fabricated silicon measurements. Second, the ASAP7/ngspice environment produced model warnings related to ignored BSIM parameters and missing library components, which means that absolute quantitative values should be interpreted with caution. Third, one low-current hybrid point at $V_{\text{bleed}} = 0.24$ V, $I_{\text{syn}} = 20$ nA remained numerically difficult and was treated as a boundary/unstable operating case rather than a clean periodic point. Fourth, the Xiangyu-inspired neuron differs fundamentally from the current-driven compact LIF comparisons because it is pulse-driven, and it is therefore analyzed separately. Finally, the present methodology does not include full PVT coverage, mismatch analysis, post-layout parasitics, or array-level behavior.

These limitations do not invalidate the study. They define its level: a compact circuit-design and simulation thesis focused on reset-aware tradeoffs in a Besrour-derived hybrid LIF neuron.

4.6 Chapter Summary

This chapter described the simulation methodology used to evaluate the proposed hybrid neuron and the reference circuits. All designs were implemented in Xschem, simulated in ngspice using a common ASAP7 model flow, and analyzed in Python-based post-processing. The methodology emphasized matched comparison between the hybrid and Besrour neurons, with reset, frequency, and energy as the primary metrics. Parameter sweeps over current, supply voltage, capacitance, and branch-specific variables were used to characterize operating behavior and robustness. Formal definitions were given for membrane reset level, timing-node activity, firing frequency, average power, energy per spike, static power, and operating-state classification. With the architecture and methodology now defined, the next chapter presents the simulation results and the direct comparison between the Besrour baseline and the proposed hybrid neuron.

Chapter 5: Results

5.1 Baseline Besrour Nominal Behavior

The Besrour reference neuron was used as the main compact baseline because it already exhibits a clear integrate-and-fire cycle while maintaining a relatively compact architecture. At the matched nominal operating point used in this thesis (V_{DD} = 0.30 V, I_{syn} = 100 nA, $C_1 = C_2$ = 2 fF), the Besrour neuron showed stable periodic spiking. The membrane-related node displayed a repeated sawtooth trajectory consistent with integrate-and-fire operation, while the internal output-like spike node showed a corresponding fast transition for each cycle.

At this nominal point, the Besrour neuron achieved a firing frequency of approximately 300.17 MHz, with an average dynamic power of approximately 215.41 nW, a dynamic energy per spike of approximately 717.61 aJ/spike, and a static power of approximately 4.45 nW. These values make the Besrour neuron a strong compact baseline because it offers clean nominal spiking behavior with low dynamic energy in the same general range as the proposed hybrid neuron, while avoiding the extra overhead of the hybrid reset/timing branch.

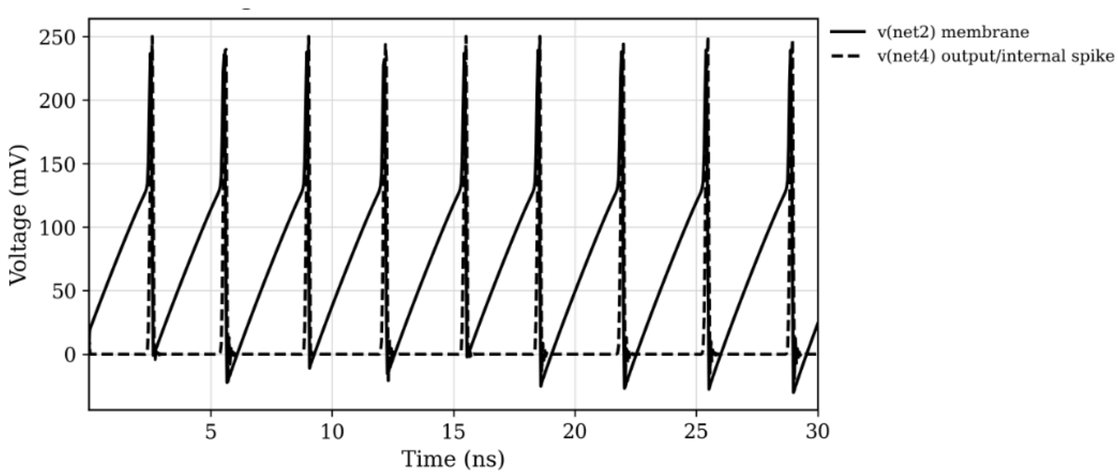

Figure 5.1: Besrour nominal waveforms

5.2 Proposed Hybrid Nominal Behavior

The proposed hybrid neuron preserves the Besrour-derived compact spiking core but adds the reset/timing branch composed of Ctref, Npchg, Nbleed, and Nreset. Under nominal operating conditions, the hybrid neuron exhibits a repeated firing cycle in which the membrane node net2, the internal spike node net4, the official active-low output net5, and the timing/reset node net6 all participate in a coordinated manner.

At the waveform level, net2 rises during integration, net4 undergoes a rapid internal spike event, net5 responds as the official active-low output, and net6 becomes active through the added hybrid branch. This makes the hybrid neuron qualitatively different from the baseline: it no longer behaves only as a compact spiking loop, but also includes a second internal state that shapes the post-spike recovery.

Two operating points are especially important in the full dataset:

- $V_{\text{bleed}} \approx 0.22$ V as the performance-oriented operating point
- $V_{\text{bleed}} \approx 0.24$ V as the robustness-oriented operating point

These points are used repeatedly throughout the remainder of the chapter because they summarize the main operating tradeoff introduced by the added branch.

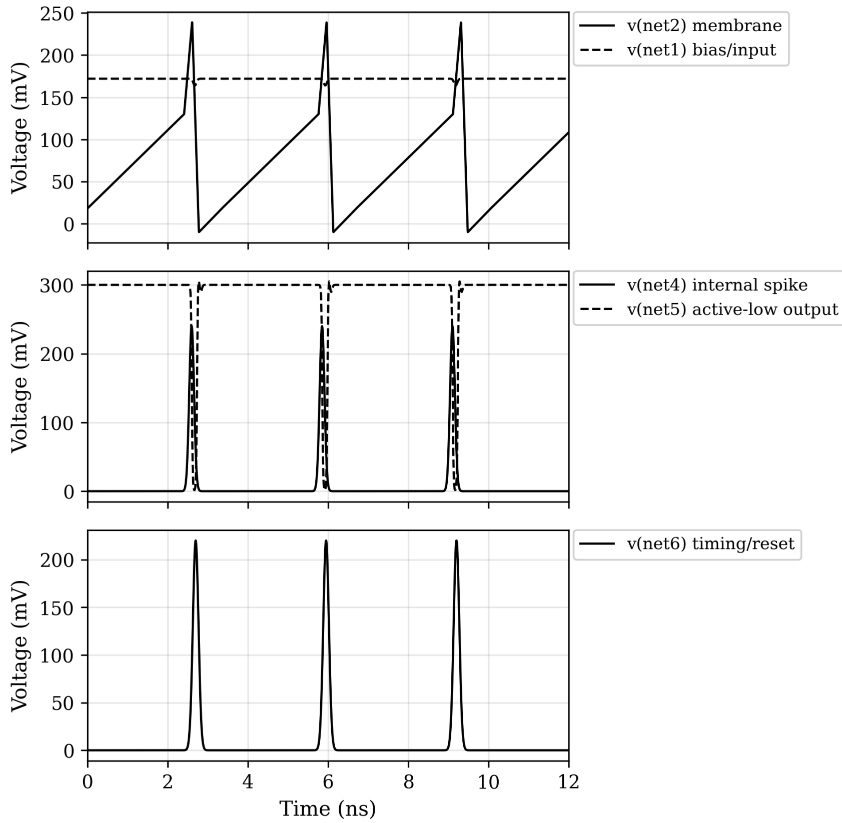

Figure 5.2: Hybrid nominal waveforms ($V_{\text{bleed}} = 0.22$)

5.3 Reset Analysis

Reset behavior is one of the central contributions of this thesis. The purpose of the added branch was not only to produce a different waveform shape, but to create a more explicit and tunable reset mechanism whose influence could be measured and interpreted.

For the hybrid neuron, the most useful reset-related quantity is the post-spike minimum of net2. This trough indicates how far the membrane state is driven down after firing and therefore how the next integration cycle begins. A second key quantity is the pulse width of the timing/reset node net6, because net6 is the internal state introduced by the hybrid branch and directly reflects how long the reset/timing branch remains active.

Across the representative V_{bleed} sweep, the post-spike trough of net2 shifted from approximately +12.82 mV at $V_{\text{bleed}} = 0.18$ V to approximately -5.78 mV at $V_{\text{bleed}} = 0.24$ V. Over the same range, the net6 timing width shrank from approximately 313.52 ps to approximately 147.11 ps. This indicates that increasing V_{bleed} does not merely rescale the waveform; instead, it deepens reset while shortening the timing-node excursion. The added branch is therefore creating a genuine reset/timing tradeoff rather than a single monotonic "better reset" effect.

A deeper reset gives the next cycle a more conservative starting condition, which is consistent with the observation that the $V_{\text{bleed}} \approx 0.24$ V region later emerges as the strongest robustness-oriented operating point. By contrast, lower V_{bleed} values lead to shallower reset and longer timing-node activity, which may support higher nominal speed but can also be associated with more fragile operating behavior in longer runs.

Table 5.1: Hybrid reset/timing sweep summary

V_{bleed}	**net2 trough**	**net6 timing width**	**Interpretation**
0.18 V	+12.82 mV	313.52 ps	Shallower reset, longer timing excursion
0.20 V	+4.45 mV	239.77 ps	Intermediate reset/timing behavior
0.22 V	-0.37 mV	181.51 ps	Stronger reset with favorable performance tradeoff
0.24 V	-5.78 mV	147.11 ps	Deepest reset and strongest robustness-oriented behavior

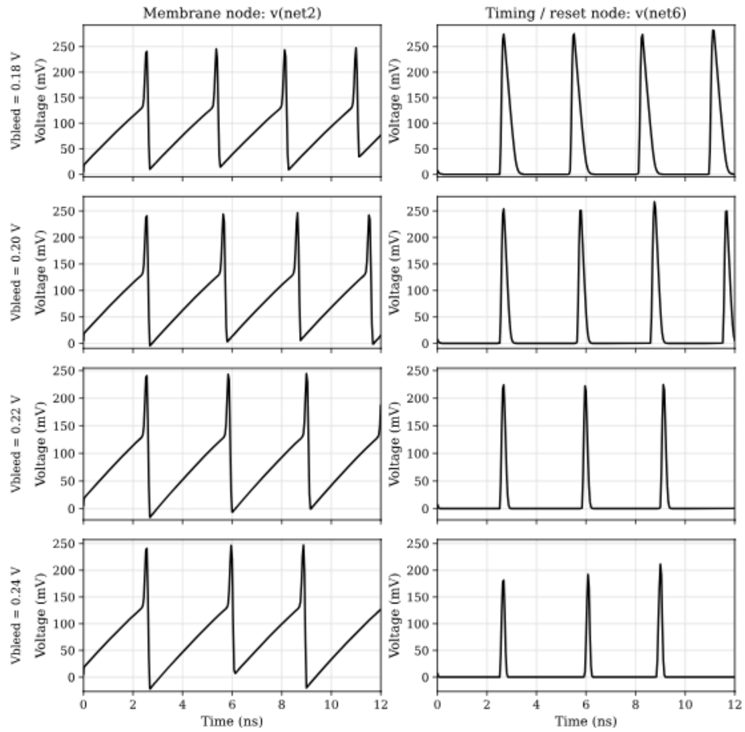

Figure 5.3: net2 and net6 versus V_{bleed}

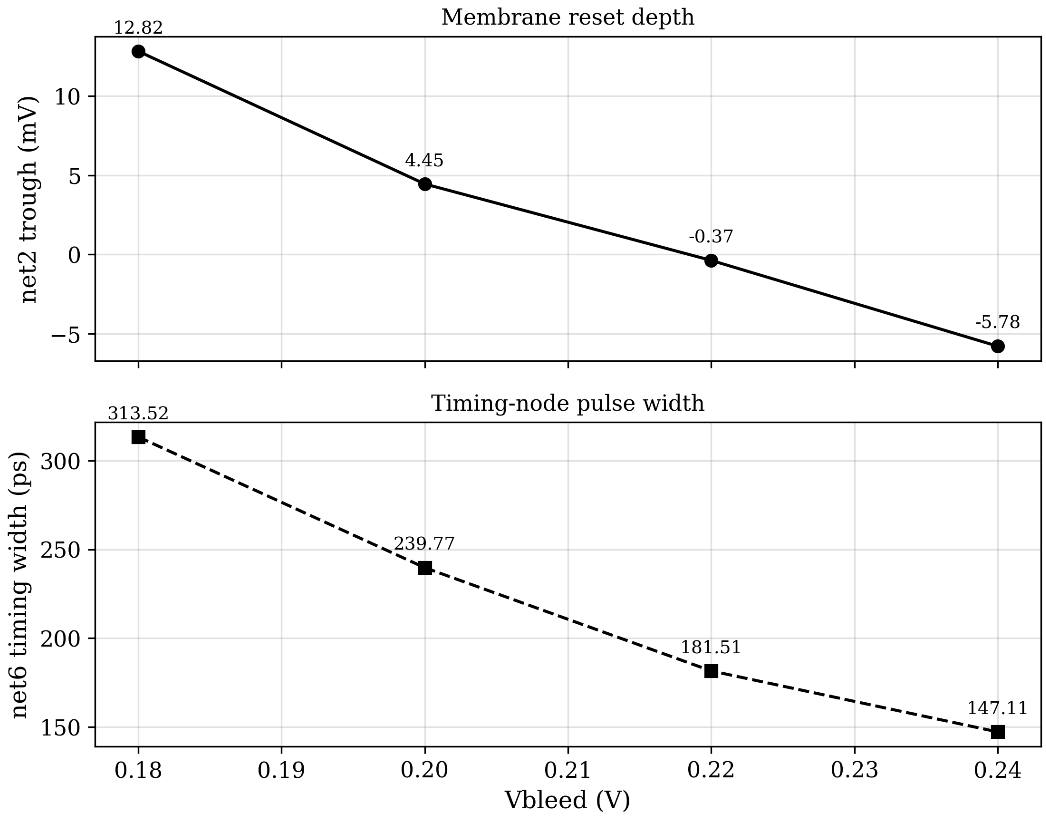

Figure 5.4: Reset trough and timing width versus V_{bleed}

5.4 Frequency Analysis

Frequency is the second major focus of the thesis, and it is tightly linked to reset. In the hybrid neuron, changes in reset depth and reset timing alter the time required for the next cycle to return to its firing condition. Frequency therefore provides a direct quantitative consequence of the reset changes introduced by the added branch.

At the representative nominal waveform operating point, the Besrour baseline fired at approximately 300 MHz, while the hybrid fired at approximately 323 MHz at $V_{\text{bleed}} \approx 0.22$ V and approximately 322 MHz at $V_{\text{bleed}} \approx 0.24$ V. These nominal waveform results indicate that the hybrid preserves compact integrate-and-fire behavior, but they do not by themselves support the much larger nominal-frequency advantage.

The full sweep set shows that the hybrid supports a broad tunable operating-frequency range, but not all points are equally clean. Over the clean operating points in the final dataset, the hybrid spans roughly 52.68 MHz to 1797.44 MHz, while the Besrour baseline spans roughly 36.77 MHz to 1571.36 MHz. This means the hybrid does not simply shift the nominal frequency upward; it also expands the upper end of the clean operating-frequency range. However, that benefit comes with a cost: the hybrid is more bias-dependent and exhibits a narrower robust region than the more consistently stable Besrour sweep behavior.

This bias dependence is especially clear in the robustness counts. The $V_{\text{bleed}} \approx 0.24$ V hybrid point gave the best overall coverage across the tested sweeps, with clean operation at 5/7 current-sweep points, 6/7 supply-sweep points, 5/5 main-capacitance points, and 4/4 Ctref points. This is the strongest evidence that the 0.24 V region is the most robust hybrid operating point, even though it is not the fastest.

The low-current boundary further shows why the hybrid must be discussed in terms of operating regions rather than a single globally best point. The file `hybrid-fi-vb-0.24-isyn-20n-all.txt` remained numerically difficult and exhibited clustered and irregular behavior near the lower operating boundary. This point is therefore best interpreted as a boundary/unstable case rather than as a clean steady-state frequency point.

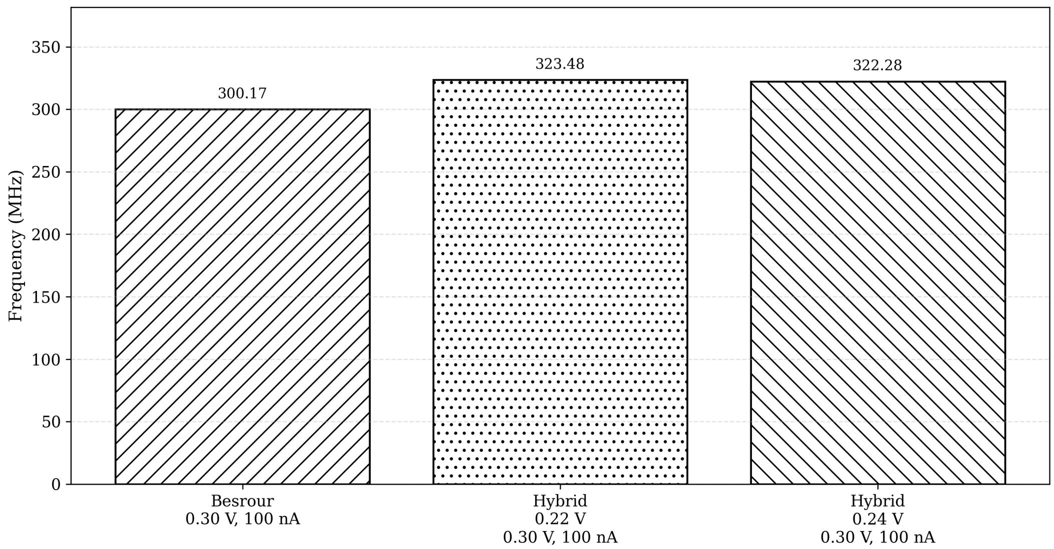

Figure 5.5: Representative nominal frequency comparison

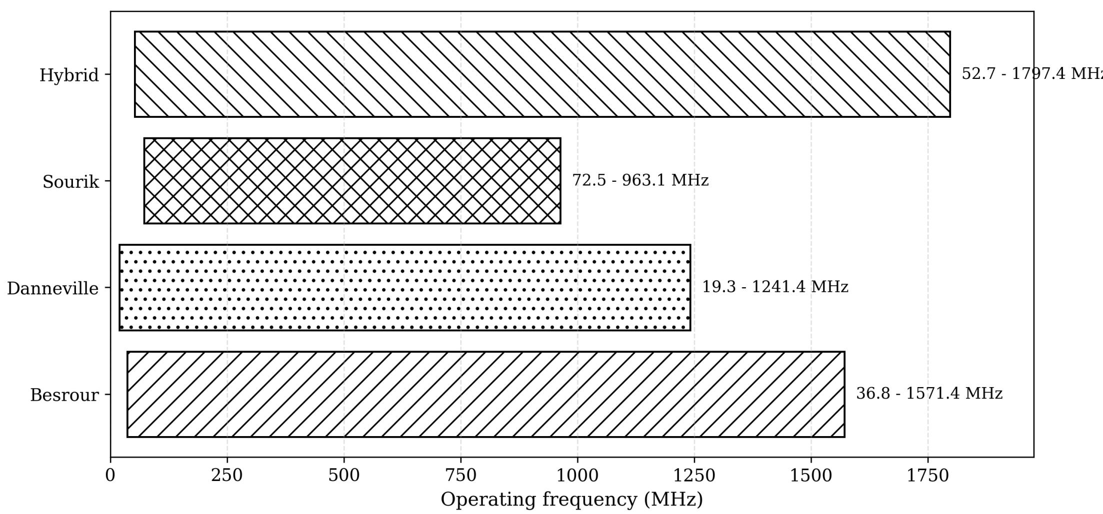

Figure 5.6: Stable operating-frequency window comparison

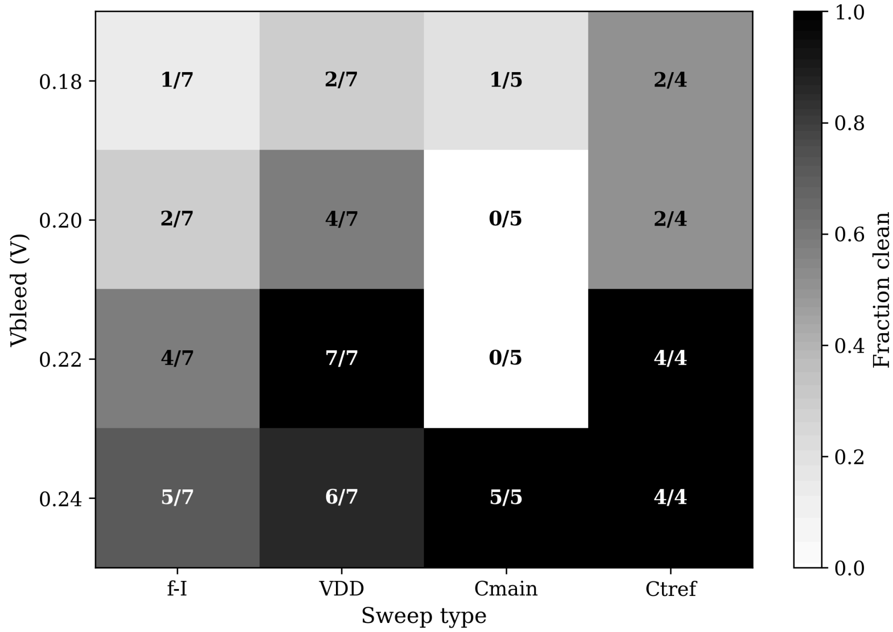

Figure 5.7: Hybrid robustness map across sweeps

5.5 Energy Analysis

The third main metric of the thesis is energy. In compact spiking neurons, energy must be discussed together with both dynamic energy per spike and static power, because a design may appear favorable under one measure and less favorable under another.

At the matched nominal point, the Besrour baseline achieved approximately 717.61 aJ/spike with an average dynamic power of approximately 215.41 nW and a static power of approximately 4.45 nW. By comparison, the hybrid neuron at $V_{\text{bleed}} \approx 0.22$ V achieved approximately 876.82 aJ/spike with an average dynamic power of approximately 283.63 nW, and the hybrid at $V_{\text{bleed}} \approx 0.24$ V achieved approximately 888.82 aJ/spike with an average dynamic power of approximately 286.45 nW. In both hybrid cases, the static power was approximately 6.30 nW.

These results show that the hybrid neuron does not achieve its benefit by reducing all forms of power. Instead, it operates at higher dynamic activity and higher static cost than the Besrour baseline, while still keeping dynamic energy per spike in the same overall order of magnitude. This defines the nature of the hybrid tradeoff: the hybrid should not be presented as a universally lower-power neuron, but as a higher-speed, reset-aware compact neuron whose dynamic energy per spike remains competitive with the baseline at the cost of additional static overhead.

The Danneville and Sourikopoulos nominal points help contextualize this tradeoff. Danneville is lower in both average dynamic power and static power but also lower in nominal frequency. Sourikopoulos achieves high nominal frequency but at substantially higher dynamic energy per spike. This places the hybrid in a useful middle region of the comparison space.

Table 5.2: Main nominal frequency and energy comparison

Neuron / operating point	**Frequency**	**Avg dynamic power**	**Energy per spike**	**Static power**
Besrour at 0.30 V, 100 nA	300.17 MHz	215.41 nW	717.61 aJ	4.45 nW
Danneville at 0.30 V, 100 nA	193.77 MHz	114.38 nW	590.31 aJ	1.85 nW
Sourikopoulos at 0.40 V, 100 nA	742.68 MHz	1034.46 nW	1392.89 aJ	4.20 nW
Hybrid at 0.30 V, 100 nA, $V_{\text{bleed}} = 0.22$ V	323.48 MHz	283.63 nW	876.82 aJ	6.30 nW
Hybrid at 0.30 V, 100 nA, $V_{\text{bleed}} = 0.24$ V	322.28 MHz	286.45 nW	888.82 aJ	6.30 nW

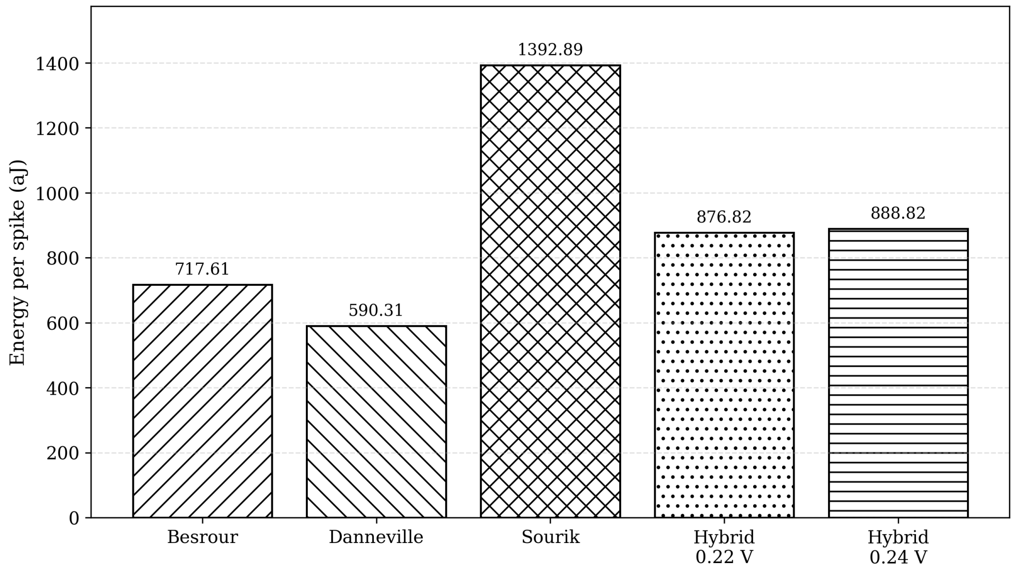

Figure 5.8: Energy per spike comparison

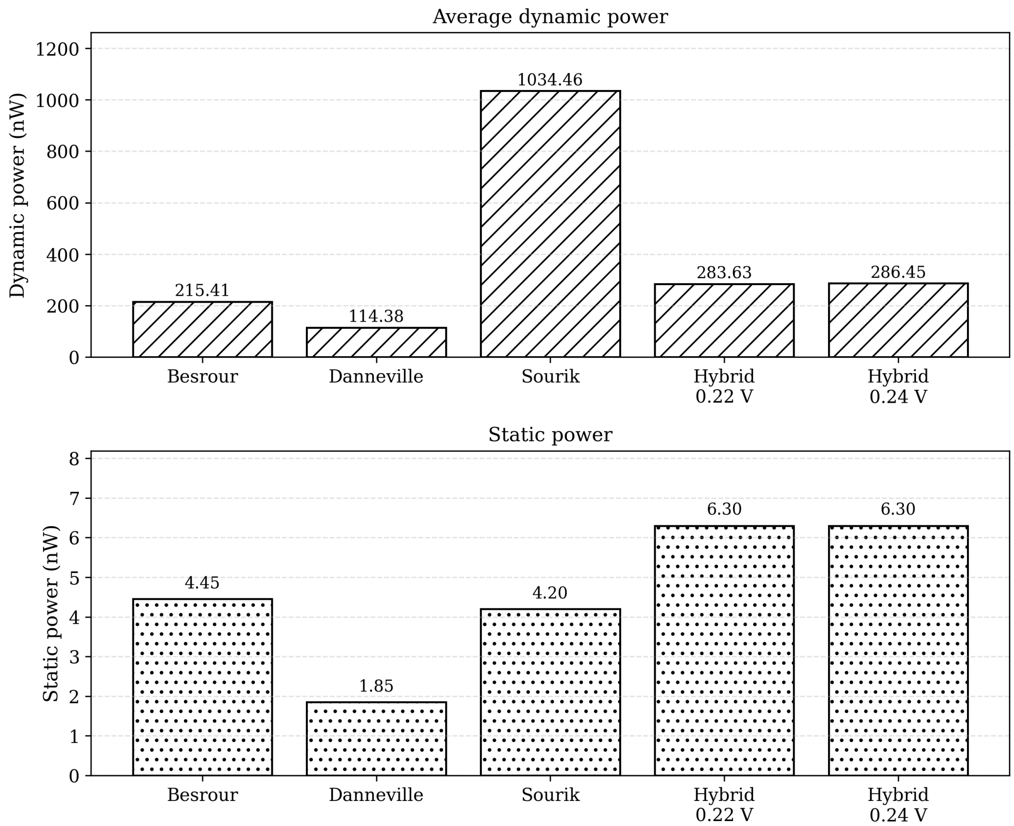

Figure 5.9: Average dynamic power and static power comparison

5.6 Performance-Oriented, Robustness-Oriented, and Baseline Comparison

One of the clearest outcomes of the full dataset is that the hybrid neuron does not have one single universally best operating point. Instead, two practically important operating regions emerge.

The first is the performance-oriented operating point near $V_{\text{bleed}} \approx 0.22$ V. At this point, the hybrid achieved the strongest nominal speed/energy tradeoff in the dataset. The firing frequency was highest among the main hybrid operating points, and the energy per spike remained competitive with the Besrour baseline.

The second is the robustness-oriented operating point near $V_{\text{bleed}} \approx 0.24$ V. This point was slightly slower and slightly less favorable in nominal dynamic energy per spike than the 0.22 V case, but it provided the strongest overall operating coverage across the hybrid sweep set and produced the deepest reset and shortest timing-node excursion among the main V_{bleed} values.

Together with the Besrour baseline, these two operating points provide the clearest summary of the thesis:

- Besrour baseline: compact and consistent reference, but no explicit reset/timing tuning
- Hybrid at $V_{bleed} \approx 0.22$ V: strongest nominal performance-oriented point
- Hybrid at $V_{bleed} \approx 0.24$ V: strongest robustness-oriented point

Table 5.3: Performance point versus robustness point

Case	Reset behavior	Frequency	Avg dynamic power	Energy per spike	Static power	Main advantage	Main limitation
Besrour baseline	Embedded reset only	300.17 MHz	215.41 nW	717.61 aJ	4.45 nW	Compact and consistent baseline	No explicit reset/timing tuning
Hybrid at $V_{bleed} = 0.22$ V	Tunable reset, moderate depth	323.48 MHz	283.63 nW	876.82 aJ	6.30 nW	Best performance-oriented point	Lower robustness than 0.24 V
Hybrid at $V_{bleed} = 0.24$ V	Deepest reset, shortest timing width	322.28 MHz	286.45 nW	888.82 aJ	6.30 nW	Best robustness-oriented point	Slightly reduced nominal performance

Compared with the Besrour baseline, the hybrid introduces a measurable and tunable reset/timing mechanism, provides a modest nominal-frequency increase at the matched operating point, and keeps dynamic energy per spike in the same general range, but it also incurs higher static power and requires more careful bias selection.

This is the main quantitative comparison of the thesis.

5.7 Secondary Reference Results

The other reference neurons provide useful context but do not displace the main Hybrid-versus-Besrour story.

The Danneville reference achieved approximately 193.77 MHz at the nominal point, with approximately 590.31 aJ/spike and approximately 1.85 nW static power. This makes it useful as an efficiency-oriented compact reference. Relative to the hybrid, Danneville is less aggressive in nominal frequency but more favorable in static power.

The Sourikopoulos reference achieved approximately 742.68 MHz at the nominal point but with approximately 1392.89 aJ/spike, which is substantially higher than the hybrid and Besrour nominal energies. It therefore serves mainly as a contrasting compact spiking topology rather than as the main baseline.

The updated Xiangyu-inspired reference was ultimately treated as a pulse-driven neuron rather than as a direct current-driven baseline. In its nominal pulse-driven configuration, repeated excitatory input pulses produced output spikes only after sufficient accumulation at Vmem. This supports its use as a qualitative time-domain reference rather than as a direct quantitative baseline in the same f–I style as the hybrid and Besrour neurons.

5.8 Failure Modes and Boundary Cases

The sweep results also revealed important limits and boundary behaviors. First, not all hybrid operating points are equally robust. Lower V_{bleed} values can produce nominally attractive spiking but are more fragile over longer runs. Conversely, $V_{\text{bleed}} \approx 0.24$ V is more conservative in nominal performance but more stable across the tested sweep dimensions.

Second, the point $V_{\text{bleed}} = 0.24$ V, $I_{\text{syn}} = 20$ nA remained numerically difficult even after targeted rerun attempts. The transient aborted at approximately 191 ns with irregular clustered behavior, so this point is treated as a lower-boundary or unstable operating case rather than as a clean steady-state point.

Third, in some long-run hybrid cases the official active-low output net5 showed output-like chatter even when the membrane cycle remained the more reliable indicator of the true firing cycle. For this reason, net5 was retained as the official output waveform, but the principal cycle interpretation for quantitative analysis relied on membrane and internal-spike behavior where appropriate.

These failure modes are important because they help define the actual operating boundary of the proposed design and prevent overclaiming.

5.9 Chapter Summary

This chapter presented the simulation results for the proposed hybrid neuron and the reference circuits, with the main emphasis placed on the comparison between the hybrid and the Besrour baseline. The Besrour neuron was shown to provide a compact and stable nominal reference with low energy per spike. The hybrid neuron was shown to preserve compact spiking behavior while adding an active timing/reset branch that changes post-spike recovery. The reset analysis demonstrated that increasing V_{bleed} deepens the membrane reset and shortens the timing-node excursion, confirming that the added branch is active and tunable. The frequency analysis showed that the hybrid can achieve a slight nominal firing-frequency increase over the matched Besrour baseline at the matched operating point while also supporting a broad operating-frequency range. The energy analysis showed that the hybrid keeps dynamic energy per spike in the same general range as the baseline but at a higher static-power cost. Finally, two practically important operating points were identified: $V_{\text{bleed}} \approx 0.22$ V as the best performance-oriented point and $V_{\text{bleed}} \approx 0.24$ V as the best robustness-oriented point. These results establish the main empirical foundation for the discussion chapter that follows.

Chapter 6: Discussion

6.1 What the Added Branch Changes

The most important question in this thesis is not whether the proposed hybrid neuron spikes. That question is already answered by the transient results. The more important question is what the added reset/timing branch changes relative to the plain Besrour baseline.

At the circuit level, the main structural change introduced by the proposed design is the addition of a second internal state associated with net6. In the Besrour baseline, the firing cycle is governed primarily by the compact interaction among the membrane-related and internal spike nodes. Reset exists, but it is embedded in the natural switching and recovery of that compact loop. In the proposed hybrid neuron, the branch composed of Ctref, Npchg, Nbleed, and Nreset creates a more explicit internal timing/reset state. This state is stored on Ctref, activated in connection with the spike/output event, shaped by the bleed path, and then translated back into the main loop through Nreset.

This change matters because it introduces a new control mechanism into the firing cycle. The circuit no longer has only the original compact spiking trajectory. It now has a second dynamic quantity that influences how the neuron leaves one spike and begins the next cycle. In the waveforms, this appears most clearly through the behavior of net6. Unlike a passive extra node or a purely buffered copy of an existing waveform, net6 exhibits its own pulse-like activity and changes substantially with V_{bleed}, confirming that the added branch is electrically active and functionally significant.

In practical terms, the added branch changes the neuron in three related ways. First, it makes the post-spike trajectory of net2 more tunable. Second, because the next firing cycle begins from that post-spike state, it changes the inter-spike timing and therefore the output frequency. Third, because changing the reset trajectory also changes how internal capacitances are repeatedly charged and discharged, it changes the energy behavior of the circuit. This is why reset, frequency, and energy cannot be treated as independent topics in this thesis. They are linked through the same architectural addition.

The strongest interpretation of the design is therefore not that the added branch simply "improves reset" in a vague sense. Rather, the branch converts reset into a tunable circuit variable, and that tunability propagates into both frequency and energy. This is the core design contribution of the proposed hybrid neuron.

6.2 Performance-Oriented and Robustness-Oriented Operating Regions

A central result of this thesis is that the hybrid neuron does not have one single universally best operating point. Instead, two practically useful operating regions were identified.

The first is the performance-oriented operating region near $V_{\text{bleed}} \approx 0.22$ V. This point is best described as performance-oriented because it gave the most favorable nominal combination of reset behavior, representative firing frequency, and energy per spike among the main hybrid operating points. At the matched nominal comparison point, the hybrid at $V_{\text{bleed}} \approx 0.22$ V achieved approximately 323.48 MHz, slightly higher than the Besrour baseline at approximately 300.17 MHz, while maintaining dynamic energy per spike in the same overall range. This indicates that the branch can be biased to improve reset control without forcing the neuron into an overly conservative operating mode.

The second is the robustness-oriented operating region near $V_{\text{bleed}} \approx 0.24$ V. This point was slightly slower and slightly less favorable in nominal energy per spike than the 0.22 V case, but it provided the strongest clean-operation coverage across the tested hybrid sweep set. It also produced the deepest reset and shortest timing-node excursion among the main V_{bleed} values. For this reason, 0.24 V is best understood as the point where the hybrid branch produces the most conservative and stable operating condition in the present dataset.

These two regions are one of the strongest outcomes of the thesis because they show that the added branch is not merely a fixed modification. It creates a meaningful design knob that allows the same compact hybrid neuron to be tuned toward different objectives. In practical terms, the proposed design can be biased toward:

- higher nominal performance, or
- safer reset-oriented robustness.

That tunability is one of the main reasons the design deserves to be called a successful hybrid neuron rather than only a small variant of the baseline.

6.3 Tradeoff Between Reset, Frequency, and Energy

The central thesis message is that reset, frequency, and energy are tightly coupled in the proposed hybrid neuron. They should therefore be interpreted as parts of one tradeoff rather than as separate independent metrics.

Reset appears first in that tradeoff. Through V_{bleed}, the added branch changes how deeply the membrane node net2 is driven after a spike and how long the timing/reset node net6 remains active. A deeper or more conservative reset changes the starting condition of the next cycle.

That change then becomes a frequency effect. If the neuron begins the next cycle from a deeper reset condition, more time is needed to integrate back toward threshold, and the firing rate tends to decrease. If the reset is shallower, the next cycle begins closer to threshold, and the neuron can fire again more quickly. This is why the hybrid frequency trend with V_{bleed} is not arbitrary. It is a direct consequence of reset tuning.

Finally, both reset and timing influence energy. A stronger reset can change how much charge is moved in each cycle and how much time the circuit spends recovering before the next spike. At the same time, the added branch itself introduces extra dynamic activity and extra leakage paths. This means that a stronger or more explicit reset/timing mechanism is not free. In the hybrid neuron, the benefit of reset control comes with both dynamic and static consequences.

This is the reason the thesis does not treat reset as a secondary waveform detail. The results support the opposite conclusion: in compact neuromorphic neurons, reset is a first-order design variable because it directly shapes both timing and energy.

6.4 Positioning of the Proposed Hybrid Neuron

The main comparison of this thesis is between the proposed hybrid neuron and the Besrour baseline. The strongest improvement relative to Besrour is the introduction of an explicit and tunable reset/timing mechanism. In the Besrour baseline, reset is embedded in the compact spiking loop. In the hybrid neuron, reset is elevated into a more visible and adjustable design feature through net6 and V_{bleed}. This is not a trivial difference. It gives the designer a way to move the neuron between distinct operating regions without abandoning the compact Besrour-derived core.

A second important difference appears at the main matched operating point. The hybrid at $V_{\text{bleed}} \approx 0.22$ V was slightly faster than the Besrour baseline at the representative nominal waveform point, while the two main hybrid operating points remained in the same general frequency range as the baseline. At the same time, the hybrid maintained dynamic energy per spike in the same overall order of magnitude. This means the added branch created a meaningful new operating regime rather than only adding overhead, even though the corrected nominal-waveform data do not support the much larger speed advantage.

However, the hybrid should not be described as strictly better in every respect. The design also introduces clear costs. Static power is higher than in the Besrour baseline, and the operating behavior is more bias-dependent. Besrour remains a more consistent all-around baseline across the tested sweeps. The hybrid is therefore best described as more tunable and capable of higher nominal performance, but at higher static cost and with more sensitivity to operating point selection.

The secondary references help place this result in a broader context. Relative to Danneville, the hybrid is not the more efficient or simpler neuron in terms of static cost, but it is more aligned with the goal of creating a compact LIF-style design with explicit reset/timing tunability. Relative to Sourikopoulos, the hybrid occupies a different part of the compact-neuron design space: less biophysically motivated, but more directly tied to a compact LIF baseline and a reset-aware design question. Relative to Xiangyu, the difference is more conceptual. The Xiangyu-inspired neuron demonstrates pulse-driven accumulation and delayed spike generation, and it is therefore valuable as a qualitative reference, but its operating philosophy is different enough that it should not be treated as the main quantitative benchmark.

Taken together, these comparisons show that the proposed hybrid neuron is a legitimate member of the compact-spiking-neuron design space, with its main distinguishing feature being explicit reset-aware tunability.

6.5 Supported Claims, Remaining Limits, and Final Interpretation

The current dataset supports several clear claims. First, the proposed hybrid neuron is a real functional circuit, not merely a conceptual modification. It exhibits repeated spiking behavior, and the added branch is electrically active. Second, the added branch provides a tunable reset mechanism, as shown by the measured changes in net2 and net6. Third, the hybrid branch changes the firing frequency in a meaningful and systematic way, and the two main operating points near 0.22 V and 0.24 V are not arbitrary biases but distinct regimes with different strengths. Fourth, the hybrid achieves dynamic energy per spike in the same general range as the Besrour baseline while providing a tunable reset mechanism and distinct operating regimes. The corrected nominal-waveform data support only a modest nominal-frequency increase at the performance-oriented point rather than a dramatic one.

These results are strong enough to support the main thesis claim: the proposed circuit is a successful simple hybrid neuron design whose added value lies in making reset an explicit and tunable design variable.

At the same time, the work does not yet establish full process-voltage-temperature robustness, statistical mismatch tolerance, post-layout parasitic sensitivity, or array-level behavior. These are meaningful future-work directions rather than weaknesses that invalidate the present contribution. The current thesis should therefore be interpreted as a compact circuit-design and simulation study that demonstrates a reset-aware hybrid neuron and its main operating tradeoffs, not as a full silicon-signoff study.

The final interpretation is therefore straightforward. The proposed neuron is not a universal replacement for every compact neuron architecture. It is a Besrour-derived compact LIF neuron that has been successfully extended with a small reset/timing branch. That branch creates a new design knob, changes reset behavior in a measurable way, and produces a tunable tradeoff among reset, frequency, and energy.

Although this thesis is limited to schematic-level circuit evaluation, the reset-aware tunability of the proposed hybrid neuron may still matter at the array and SNN levels. The performance-oriented operating region near $V_{\text{bleed}} \approx 0.22$ V may be attractive when higher spike throughput is desired, whereas the robustness-oriented region near $V_{\text{bleed}} \approx 0.24$ V may be more suitable for larger arrays where broader clean-operation coverage and more repeatable post-spike recovery are valuable. The tradeoff is added per-neuron overhead: relative to the Besrour baseline, the hybrid adds Ctref, Npchg, Nbleed, and Nreset, increasing structural complexity and static power. Because this thesis does not include layout extraction or network-level training experiments, these system-level implications should be interpreted as circuit-level design inferences rather than as proven SNN-level advantages.

6.6 Chapter Summary

This chapter interpreted the simulation results of the proposed hybrid neuron in relation to the Besrour baseline and the secondary reference neurons. The central conclusion is that the added branch changes the neuron in a specific and useful way: it makes reset an explicit and tunable design variable. That change propagates directly into spike timing, operating frequency, and energy behavior. Two important operating regions were identified. Near $V_{\text{bleed}} \approx 0.22$ V, the hybrid neuron exhibits its best performance-oriented behavior, while near $V_{\text{bleed}} \approx 0.24$ V, it exhibits its best robustness-oriented behavior. Compared with the Besrour baseline, the hybrid provides a new degree of reset/timing control together with a slight representative nominal-frequency increase, while incurring higher static power and stronger dependence on bias selection.

Chapter 7: Conclusion and Future Work

7.1 Conclusions

This thesis investigated whether a compact Besrour-derived leaky integrate-and-fire neuron could be usefully extended with a minimal reset/timing branch, and whether the effect of that branch could be quantified through reset behavior, firing frequency, and energy. The work began from the observation that in compact spiking neurons, reset is often present but not always treated as an explicit design variable. Because reset defines the starting condition of the next integration cycle, it directly influences spike timing and therefore also affects frequency and energy.

To address this problem, a compact hybrid neuron was developed by extending a Besrour-style baseline with a small reset/timing branch composed of Ctref, Npchg, Nbleed, and Nreset. The resulting circuit preserves the main Besrour-derived spiking core while introducing a second internal timing/reset state through net6. This state is controlled through the bleed-bias parameter V_{bleed}, which provides a practical tuning mechanism for post-spike behavior.

The simulation results showed that the proposed hybrid neuron is a functional compact spiking circuit and that the added branch is both active and measurable. In particular, the branch changes the post-spike membrane recovery trajectory and creates a clear link among reset, frequency, and energy. Compared with the Besrour baseline, the hybrid neuron achieved a slight nominal firing-frequency increase at the matched operating point while maintaining dynamic energy per spike in the same overall range. At the same time, the hybrid incurred a higher static-power cost and showed stronger dependence on operating-point selection.

A particularly important outcome of the work was the identification of two practically useful operating regions. Near $V_{\mathrm{bleed}} \approx 0.22$ V, the hybrid neuron exhibited its best performance-oriented operating point, providing the most favorable nominal reset/frequency/energy tradeoff among the tested hybrid operating points. Near $V_{\mathrm{bleed}} \approx 0.24$ V, the hybrid neuron exhibited its best robustness-oriented operating point, with deeper reset behavior and broader clean-operation coverage across the tested sweeps. This shows that the proposed circuit does not simply introduce one new fixed behavior. Instead, it creates a tunable design tradeoff between performance-oriented and robustness-oriented operation.

The main contribution of the thesis is therefore the demonstration that a compact Besrour-derived neuron can be transformed into a reset-aware hybrid LIF neuron through a minimal architectural addition. More broadly, the work shows that reset is not merely the last portion of a spike waveform. In compact neuromorphic neurons, reset is a first-order design variable because it directly shapes the next cycle and therefore shapes frequency, energy, and robustness.

7.2 Supported Claims and Remaining Limits

The present thesis directly supports several claims. First, the proposed hybrid neuron is a real and functional compact spiking circuit. Second, the added branch introduces a tunable reset mechanism that is visible through the behavior of net2 and net6. Third, the hybrid can be tuned into distinct operating regimes rather than having only one fixed nominal point. Fourth, compared with the Besrour baseline, the hybrid offers slightly higher representative nominal frequency together with more explicit reset/timing control while keeping dynamic energy per spike in a comparable range. These are strong enough results to support the thesis claim that the proposed circuit is a meaningful simple hybrid neuron design and not merely a cosmetic variation of the baseline.

At the same time, several broader questions remain outside the scope of the present work. The study does not include full process-voltage-temperature signoff-style validation, statistical mismatch analysis, post-layout parasitic extraction, or array-level system evaluation. In addition, one low-current hybrid operating point near the lower stability boundary remained numerically difficult and is best interpreted as a boundary case rather than a clean periodic operating point. These limitations do not undermine the thesis. Rather, they define it appropriately as a schematic-level, simulation-based circuit-design study focused on reset-aware tradeoffs in a compact hybrid neuron.

This thesis demonstrates functional reset-aware behavior and comparative tradeoffs at schematic level, but it does not yet establish manufacturability-grade robustness under full PVT, mismatch, or post-layout variation.

7.3 Future Work

Several natural directions follow from this work.

First, the hybrid neuron itself can be further optimized. Although the present thesis identified $V_{\text{bleed}} \approx 0.22$ V and $V_{\text{bleed}} \approx 0.24$ V as especially useful operating points, the design space has not been exhausted. Finer bias sweeps and additional device-sizing exploration could reveal better performance-versus-robustness tradeoffs.

Second, future work should broaden the validation methodology. Mismatch analysis, process-corner analysis, and temperature sweeps would provide a stronger understanding of how robust the proposed reset/timing branch remains under more realistic circuit variation.

Third, layout-aware evaluation is an important next step. Because this thesis remained at the schematic and netlist level, it did not capture post-layout parasitic effects. Extracted parasitics could influence the timing of the added branch, the effective reset behavior, and the stability of the highest-frequency operating points.

Fourth, the design philosophy itself can be extended. The present work examined one particular reset/timing branch added to a Besrour-derived base. Future studies could compare this strategy with alternative compact reset-aware or refractory-aware branches to determine whether the present design is one useful instance of a broader class of simple hybrid neurons.

Finally, the proposed neuron can be studied in larger neuromorphic contexts. Array-level simulation, neuron-synapse interaction, and small spiking-network demonstrations would help determine whether the reset-aware tradeoff observed here remains useful at the system level.

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