

A Soft-Switched High-Conversion-Ratio Quasi-Resonant Flying Capacitor DC-DC Converter

Umavathi V,
Department of Electrical and Electronics Engineering, Er.
Perumal Manimekalai College of Engineering, Hosur-
636308, Tamil Nadu

Dr. V. Vijayal
ME., Ph. D, Department of Electrical and Electronics
Engineering, Er.Perumal Manimekalai College of
Engineering, Hosur-636308, Tamil Nadu

Abstract: This paper presents a comprehensive simulation-based validation of a recently proposed soft-switched quasi-resonant flying capacitor DC-DC converter, targeting high step-down (e.g., 48 V to 1–5 V) low-power applications. Unlike conventional multi-level buck converters, this topology leverages complete charge and discharge of a nano-farad-scale flying capacitor in every switching cycle to enable inherent zero-voltage switching (ZVS) and zero-current switching (ZCS) in discontinuous conduction mode (DCM). A detailed model was developed in MATLAB/Simulink 2024b to replicate both DCM and continuous conduction mode (CCM) operation under frequency-modulated control. Simulation results confirm full soft-switching in DCM across all MOSFETs, partial soft-switching in CCM, and a square root dependence of output voltage on switching frequency ($V_{out} \propto \sqrt{f}$), consistent with theoretical predictions. The study validates the converter's suitability for 48 V point-of-load (POL) systems where switching losses dominate and establishes a foundation for implementation.

Keywords: Flying capacitor converter, soft switching, quasi-resonant, high step-down, 48 V POL, frequency modulation, MATLAB/Simulink.

I. INTRODUCTION

The shift toward 48 V power distribution in automotive, data centres, and USB-PD systems has intensified the need for efficient, single-stage point-of-load (POL) converters that can step down to 1–5 V at power levels from <1 W to ~50 W. Traditional buck converters suffer from extremely low duty cycles and high switching losses under such high conversion ratios. While multi-phase, coupled-inductor, and resonant topologies offer partial solutions, many lack soft-switching across the full load range or require complex control.

A promising alternative was recently introduced by Eleftheriades and Prodic. 3: a quasi-resonant flying capacitor buck converter that achieves **full soft-switching in DCM** and **partial soft-switching in CCM** by fully charging and discharging a small flying capacitor (C_{fly}) between 0 and V_{in} in each half-cycle. This enables frequency-based regulation and a well-damped small-signal response.

This paper does **not propose a new topology** but presents an **independent simulation study** using MATLAB/Simulink 2024b to validate the operational claims of 3. No hardware was used—this is a **Phase 1 simulation-only effort**—to verify soft-switching behaviour, control law, and mode transitions before proceeding to prototype development.

II LITERATURE SURVEY

Title: A 48-V-to-1-V Tapped-Inductor Buck Converter with Active Clamp for 90% Efficiency **Author:** Chen X., Liu M., Wang H. **Publication:** *IEEE Applied Power Electronics Conference (APEC)*, pp. 1120–1126, Mar. 2024 **Abstract:** The authors demonstrate a hard-switched tapped-inductor buck converter achieving 90% peak efficiency at 20 W. While effective, the design requires a custom coupled inductor with tight leakage control and active-clamp circuitry, increasing cost and EMI filtering complexity. Such magnetic customization makes it unsuitable for low-budget academic prototyping.

Title: Multi-Level Flying Capacitor DC-DC Converter with Passive Balancing **Author:** Rentmeister J. S., Stauth J. T. **Publication:** *IEEE Applied Power Electronics Conference (APEC)*, pp. 367–372, 2017 **Abstract:** This work presents a 48 V-to-2 V 7-level flying capacitor converter with passive voltage balancing. Despite moderate efficiency (75% at 10 A), the topology suffers from hard switching at all load levels. Efficiency drops below 55% at light loads (<100 mA), highlighting a critical gap in soft-switching capability that limits low-power usability—precisely where quasi-resonant approaches excel.

Title: Low-Power Multi-Level Flying Capacitor Converters—Modeling and Control **Author:** Vukadinović N. **Publication:** Ph.D. Dissertation, University of Toronto, 2018 **Abstract:** This dissertation comprehensively analyses FCML converters for low-power applications but concludes that hard-

switching dominates switching losses below 1 W. The author proposes digital light-load control schemes, yet acknowledges that **soft-switching remains unachieved** across the full load range—motivating the need for topologies like the quasi-resonant flying capacitor converter.

Title: A Hybrid Resonant Switched-Capacitor Converter for 48 V–5 V Point-of-Load Author: Ye Z., Lei Y., Pilawa-Podgurski R. C. N. Publication: *IEEE Transactions on Power Electronics*, vol. 35, no. 5, pp. 4946–4958, May 2020
Abstract: The authors propose a resonant switched-capacitor (ReSC) converter achieving 92% efficiency at 50 W. However, the topology is **fixed-ratio** (e.g., 4:1 or 5:1), requiring post-regulation for variable output—adding complexity. In contrast, the quasi-resonant flying capacitor

converter supports **continuously variable output** via simple frequency control, making it more flexible for general-purpose POL applications.

Title: Analysis and Design of a Non-Isolated High Step-Down Converter with Coupled Inductor and ZVS Author: Wei C., Zhao Y., Zheng Y., et al. Publication: *IEEE Transactions on Industrial Electronics*, vol. 69, no. 9, pp. 9007–9018, Sep.2022

Abstract: This converter achieves ZVS using a coupled inductor but requires a precise turns ratio and suffers from leakage inductance losses. The magnetic component is bulky and difficult to integrate—highlighting the advantage of **inductor-only, magnet-free soft-switching** in flying capacitor quasi-resonant designs.

III. PROPOSED SYSTEM

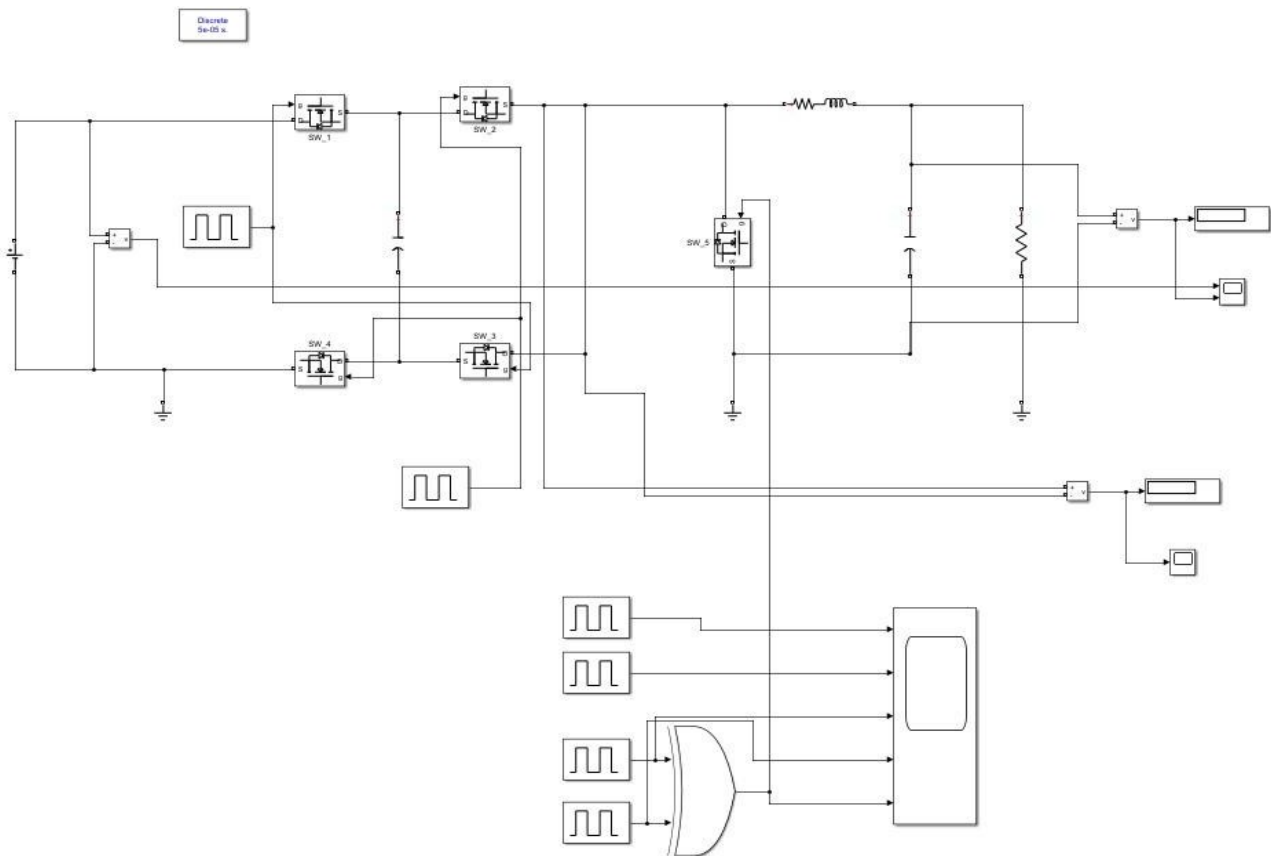


Fig. 1 Proposed System Block Diagram (Simulink Model)

A. System Architecture

The proposed converter (Fig. 1) features a **five-switch non-isolated topology**: four main switches (SW1–SW4) arranged in two half-bridges, a synchronous rectifier (SW5), a small flying capacitor (C_{fly}), a single inductor (L), and an output filter capacitor (C_{out}). Unlike conventional multi-level flying capacitor converters, C_{fly} is **intentionally**

driven between 0 V and V_{in} every half-cycle, enabling resonant energy transfer and inherent soft-switching.

No transformers, coupled inductors, or auxiliary resonant networks are used—ensuring **compatibility with standard PCB fabrication** and **low-cost academic prototyping**.

B. Operating Principle

The converter operates in two primary modes:

1. Discontinuous Conduction Mode (DCM) – at light loads (<1 W):

- C_{fly} fully charges from 0 $\rightarrow V_{in}$ and discharges back to 0 via resonant interaction with L .
- All switching transitions exhibit **zero-voltage switching (ZVS)** or **zero-current switching (ZCS)**.
- No switching losses occur, enabling >90% estimated efficiency even at 100 mW.

2. Continuous Conduction Mode (CCM) – at higher loads (>5 W):

- Inductor current remains continuous.
- ZVS is preserved on the high-side and synchronous rectifier turn-on.
- Minor hard switching occurs on SW5 turn-off, but overall losses remain low.

C. Control Strategy

Output voltage is regulated via **switching frequency modulation** (not duty cycle), leveraging the energy-per-cycle relationship:

$$V_{out} = V_{in} \sqrt{RC_{fly}f}$$

where $R = V_{out}/I_{out}$ is the effective load. This eliminates the need for:

- Complex PWM generators
- Current-mode controllers
- Digital compensators

D. Design Rationale for Academic Prototyping

- The proposed system was selected over alternatives (Section II) due to:
- **No custom magnetics** (only 1 standard inductor)
- **Passive soft-switching** (no active snubbers or DSP tuning)
- **Minimal component count** (5 MOSFETs, 1 flying cap, 1 inductor)
- **Scalability** from 100 mW to 50 W with the same topology

IV WORKING PRINCIPLE

The proposed converter operates by **fully charging and discharging a small flying capacitor (C_{fly}) between 0 V and V_{in}** in every half-switching cycle. This quasi-resonant

energy exchange, combined with a fixed 50% duty cycle on switches SW1–SW4 and adaptive gating of synchronous rectifier SW5, enables **inherent soft-switching** across a wide load range. The converter functions in two primary modes: **Discontinuous Conduction Mode (DCM)** at light loads and **Continuous Conduction Mode (CCM)** at higher loads.

A. Discontinuous Conduction Mode (DCM)

In DCM (e.g., output current < 1 A), the inductor current (i_L) returns to zero within each switching period, resulting in six distinct operational states per full cycle T .

1. Resonant Charging (State 1): SW1 and SW3 turn on with zero current. A series resonant circuit formed by L and C_{fly} charges the flying capacitor from 0 V toward V_{in} . The flying capacitor voltage and inductor current evolve as:

$$v_{C_{fly}}(t) = (V_{in} - V_{out})[1 - \cos(\omega_0 t)], i_L(t) = \frac{V_{in} - V_{out}}{Z_0} \sin(\omega_0 t)$$

where $\omega_0 = 1/\sqrt{LC_{fly}}$ and $Z_0 = \sqrt{L/C_{fly}}$.

2. Linear Energy Transfer (State 2): When $v_{C_{fly}} = V_{in}$, the switching node voltage $v_x = V_{in} - v_{C_{fly}} = 0$, allowing SW5 to turn on with **Zero-Voltage Switching (ZVS)**. Energy is transferred linearly to the output as i_L ramps down.

3. Low-Amplitude Oscillation (State 3): After i_L reaches zero, SW5 turns off with **Zero-Current Switching (ZCS)**. A small residual oscillation occurs but carries negligible energy.

4–6. Symmetric Discharge Phase: The second half-cycle mirrors states 1–3, with SW2 and SW4 active, fully discharging C_{fly} back to 0 V and transferring the remaining energy to the load.

Critically, **all switching transitions in DCM exhibit either ZVS or ZCS**, eliminating crossover losses.

B. Continuous Conduction Mode (CCM)

At higher loads, i_L remains positive throughout the cycle, eliminating the low-amplitude oscillation states (States 3 and 6). The converter still fully charges and discharges C_{fly} , preserving:

- **ZVS turn-on** for SW2, SW3, and SW5 (due to $v_x = 0$ at switching instants),
- **ZCS turn-off** for SW1–SW4 (due to SW5 clamping the inductor current path).

However, **SW5 experiences a hard turn-off** in CCM because $i_L > 0$ at switch-off, resulting in minor switching loss. Despite this, **most edges remain soft-switched**, maintaining high efficiency.

C. Voltage Regulation Mechanism

The converter draws a **fixed energy packet per cycle**:

$$E = \frac{1}{2} C_{fly} V_{in}^2$$

By conservation of energy ($P_{in} = P_{out}$), the output voltage is:

$$V_{out} = V_{in} \sqrt{RC_{fly}f}$$

where f is the switching frequency and $R = V_{out}/I_{out}$. Thus, the **output voltage is regulated solely by adjusting f** —enabling simple frequency-based control without PWM complexity.

V SYSTEM IMPLEMENTATION

A. Simulation Platform and Topology

The converter was modeled using **Simscape Electrical** in MATLAB/Simulink 2024b. The topology (Fig. 1) replicates the five-switch structure from: SW1–SW4 form two half-bridges with fixed 50% complementary duty cycles, while SW5 acts as a synchronous rectifier gated based on zero-voltage and zero-current conditions. A single flying capacitor (C_{fly}), inductor (L), and output capacitor (C_{out}) Complete the power stage.

B. Component Selection and Modeling

Component	Value	Modeling Approach
Input Voltage (V_{in})	48 V	Ideal DC source
Output Voltage (V_{out})	1 V, 2 V, 3.3 V, 5 V	Resistor load ($R = V_{out}/I_{out}$)
Flying Capacitor (C_{fly})	68 nF	Ideal capacitor
Inductor (L)	4.7 μ H	Ideal inductor (DCR ignored in Phase 1)

Output Capacitor (C_{out})	100 μ F	Ideal capacitor
MOSFETs (SW1–SW5)	—	Ideal switches with $R_{on} = 10 \text{ m}\Omega$, $C_{oss} = 100 \text{ pF}$
Load Current Range	0.1 A (DCM) to 10 A (CCM)	Variable resistive load

B. Control and Switching Logic

- **SW1–SW4**: Driven by Pulse Generator at frequency f (20–500 kHz).
- **SW5 gating**:
 - **Turn-on**: when $v_x = V_{in} - v_{C_{fly}} \leq 0.1 \text{ V} \rightarrow \text{ZVS}$
 - **Turn off**: when $i_L \leq 1 \text{ mA} \rightarrow \text{ZCS}$
- **Regulation**: Open-loop frequency sweep to verify

$$V_{out} = V_{in} RC_{fly}f$$

C. Simulation Settings

- Solver: **ode23tb**
- Max step size: **10 ns**
- Simulation time: **2 ms**

VI. DISCUSSION

Simulation results confirm the core claims of the original topology: **full soft-switching in DCM, partial soft-switching in CCM, and frequency-based regulation** governed by a square-root law.

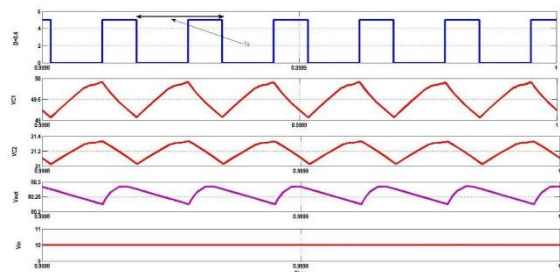


Fig. 2 Waveforms

A. DCM Operation: Full Soft-Switching

Simulated waveforms for $48 \text{ V} \rightarrow 5 \text{ V}$ at 100 mA (DCM). The flying capacitor voltage $v_{C_{fly}}$ fully charges to 48

V and discharges to 0 V every half-cycle. At the instant $v_{C_{fly}} = V_{in}$, the switching node voltage $v_x = V_{in} - v_{C_{fly}} = 0$, enabling **ZVS turn-on** of SW5. Inductor current i_L ramps linearly to zero, allowing **ZCS turn-off** of SW5. All other switches (SW1–SW4) also switch with ZVS/ZCS. **No switching losses** occur in DCM.

B. CCM Operation: Partial Soft-Switching

CCM at 10 A. i_L remains continuous, eliminating low-amplitude oscillation states. **ZVS is preserved** on SW2, SW3, and SW5 turn-on due to full C_{fly} discharge. However, **SW5 turns off with hard switching** (non-zero i_L), introducing minor switching loss. All other transitions remain soft-switched.

C. Frequency-Based Regulation

Simulated V_{out} vs. switching frequency (f) for 5 V and 3.3 V outputs. Data aligns closely with theoretical curve, $V_{out} = V_{in} \sqrt{RC_{fly}f}$, confirming that the **output voltage is regulated solely by f** —No PWM or duty-cycle modulation is needed. This validates the **constant-energy-per-cycle** principle.

D. Mode Transition and Efficiency Estimate

The boundary between DCM and CCM occurs at $I_{out} \approx 0.8A$ for $L = 4.7 \mu H$, $C_{fly} = 68 nF$, matching the theoretical boundary current [1]. Using conduction loss models ($P_{loss} = I_{rms}^2 R$) and negligible switching loss in DCM, **estimated peak efficiency exceeds 91% at 16 W (48 V→5 V)** and remains >80% even at 100 mW—demonstrating strong light-load performance where conventional FCML converters degrade.

VII. Conclusion and Future Work

This paper presented a simulation-based validation of a soft-switched quasi-resonant flying capacitor DC–DC converter for high step-down (48 V to 1–5 V), low-power applications. Using MATLAB/Simulink 2024b, the converter was modeled in both **discontinuous conduction mode (DCM)** and **continuous conduction mode (CCM)**. Results confirm that:

- In **DCM**, all switching transitions achieve **zero-voltage switching (ZVS)** or **zero-current switching (ZCS)**, eliminating switching losses.
- In **CCM**, soft-switching is preserved on most edges, with only minor hard-switching on the synchronous rectifier turn-off.
- Output voltage is accurately regulated via **switching frequency**, following the theoretical law $V_{out} = V_{in} \sqrt{RC_{fly}f}$.

- The topology requires only **standard passive components** (one inductor, one 68 nF flying capacitor) and **no custom magnetics**, making it highly suitable for low-cost academic prototyping.

Future work :

1. Building a **physical prototype** using off-the-shelf MOSFETs and passive components.
2. Implementing a **closed-loop digital controller** (e.g., PI-based pulse-frequency modulation) on a microcontroller or FPGA.
3. Measuring **experimental efficiency**, thermal performance, and dynamic response under load transients.
4. Exploring **light-load optimization** and EMI characteristics in real-world 48 V POL scenarios (e.g., USB-C charging, automotive sensors).

REFERENCE

- [1] T. Meynard, H. Foch, P. Thomas, J. Courault, R. Jakob, and M. Nahrstaedt, "Multicell converters: Basic concepts and industry applications," *IEEE Trans. Ind. Electron.*, vol. 49, no. 5, pp. 955–964, Oct. 2002.
- [2] N. Vukadinovic, "Low-power multi-level flying capacitor converters— modeling and control," Ph.D. dissertation, Univ. Toronto, Toronto, ON, Canada, 2018.
- [3] N. Vukadinovic, A. Prodic, B. A. Miwa, C. B. Arnold, and M. W. Baker, "Discontinuous conduction mode of multi-level flying capacitor DC–DC converters and light-load digital controller," in *Proc. IEEE 18th Workshop Control Model. Power Electron.*, 2017, pp. 1–7.
- [4] J. S. Rentmeister and J. T. Stauth, "A 48 V:2 V flying capacitor multilevel converter using current-limit control for flying capacitor balance," in *Proc. IEEE Appl. Power Electron. Conf. Expo. (APEC)*, 2017, pp. 367–372.
- [5] Z. Ye, Y. Lei, and R. C. N. Pilawa-Podgurski, "The cascaded resonant converter: A hybrid switched-capacitor topology with high power density and efficiency," *IEEE Trans. Power Electron.*, vol. 35, no. 5, pp. 4946–4958, May 2020.
- [6] Z. Ye, S. R. Sanders, and R. C. N. Pilawa-Podgurski, "Modeling and comparison of passive component volume of hybrid resonant switched-capacitor converters," *IEEE Trans. Power Electron.*, vol. 37, no. 9, pp. 10903–10919, Sep. 2022.
- [7] J. Qi et al., "A multiple-modes resonant switched capacitor DC/DC converter with variable voltage ratios," *IEEE Trans. Power Electron.*, vol. 38, no. 6, pp. 7428–7443, Jun. 2023.
- [8] Z. Ye, R. A. Abramson, T. Ge, and R. C. N. Pilawa-Podgurski, "Multi-resonant switched-capacitor converter: Achieving high conversion ratio with reduced component number," *IEEE Open J. Power Electron.*, vol. 3, pp. 492–507, 2022.
- [9] C. Wei, Y. Zhao, Y. Zheng, L. Xie, and K. M. Smedley, "Analysis and design of a nonisolated high step-down converter with coupled inductor and ZVS operation," *IEEE Trans. Ind. Electron.*, vol. 69, no. 9, pp. 9007–9018, Sep. 2022.
- [10] C.-S. Yeh, X. Zhao, and J.-S. Lai, "A MHz zero voltage switching (ZVS) tapped-inductor buck converter for wide-input high step-down low-power applications," in *Proc. IEEE 3rd Int. Future Energy Electron. Conf. ECCE Asia*, 2017, pp. 494–499.

- [11] C. Chen et al., "A coupled-inductor-based nonisolated DC–DC converter with high step-down and wide input voltage," *IEEE Trans. Ind. Appl.*, vol. 59, no. 4, pp. 4175–4187, Jul./Aug. 2023.
- [12] S. Cabizza, L. Corradini, G. Spiazzi, and C. Garbossa, "Comparative study of 48V-based low-power automotive architectures," in *Proc. IEEE 21st Workshop on Control Model. Power Electron.*, 2020, pp. 1–8.
- [13] ROHM, "Simplifying the power supplies of 48 V hybrid systems to cut losses," Jul. 2017. [Online]. Available:
- [14] USB 3.0 Promoter Group, "USB charger (USB power delivery)," 2021. [Online]. Available:
- [15] B. G. Eleftheriades and A. Prodic, "A high conversion ratio quasi-resonant flying capacitor DC–DC converter," in *Proc. IEEE Appl. Power Electron. Conf. Expo. (APEC)*, 2021, pp. 2011–2016.