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Design of Bipolar Dickson DC-DC Converter for Renewable Energy Applications

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A B S T R A C T :

In recent years, the demand for compact, efficient, and high-voltage power conversion solutions has significantly increased, driven by the growing adoption of renewable energy systems, electric vehicles, and high-density power electronic devices. Traditional switched-capacitor (SC) converters, especially the Dickson voltage multiplier, are widely known for their ability to achieve voltage step-up without magnetic components. These converters offer high power density and ease of integration into on-chip applications. However, conventional Dickson-based topologies suffer from high voltage stress on the capacitors and switches, significant output voltage ripple, and large energy storage requirements, which limit their scalability and suitability for high-power applications. To address these limitations, this paper investigates and analyses a novel Bipolar Dickson DC-DC converter topology that enhances the original Dickson structure by introducing two interconnected Dickson chains. The motivation behind this topology stems from the necessity to minimize component voltage stress and reduce energy storage demand while maintaining a high step-up voltage gain. The proposed configuration reduces the voltage stress on capacitors and switches by nearly 50% compared to the original and modified Dickson multipliers.

Keywords: Bipolar Dickson DC-DC Converter, Electric Vehicles, High Step-Up Voltage Gain, Renewable Energy Systems, Switched-Capacitor.

1. Introduction

Modern power electronic systems are increasingly required to deliver high voltages from low-voltage sources while maintaining compact size, low electromagnetic interference (EMI), and high power density. Applications such as renewable energy systems, battery-powered electric vehicles (EVs), portable electronics, and telecommunications demand efficient DC-DC converters with minimal size and cost. Traditionally, magnetic-based converters such as boost and flyback converters have been widely used. However, these converters involve inductors and transformers, which increase system bulk, introduce EMI, and are less favorable for integration into miniaturized platforms. As an alternative, Switched-Capacitor Converters (SCCs) have emerged as promising candidates due to their inductor-less design, inherent simplicity, and ease of integration. SCCs use capacitors and switches to perform voltage conversion through controlled charge transfer. Among various SCC topologies, voltage multipliers play a crucial role in achieving high voltage gain, with the Dickson charge pump being a widely recognized configuration for voltage boosting applications. As power electronics evolve to support emerging technologies such as electric vehicles (EVs), smart grids, aerospace systems, and Internet-of-Things (IoT) devices, there is a growing demand for compact, efficient, and lightweight power converters that can operate at high voltages without compromising reliability. Traditional magnetic-based converters, though effective, face limitations in size, noise, and integration. The industry is steadily shifting towards non-magnetic converters like Switched Capacitor Converters (SCCs), which promise high power density, reduced electromagnetic interference (EMI), and compatibility with modern semiconductor processes.

The Dickson charge pump, a well-known switched-capacitor voltage multiplier, is often used for stepping up low input voltages to higher levels. While efficient in low-voltage domains, it becomes less suitable for high-voltage applications due to increasing capacitor and switch voltage stress, ripple effects, and power losses. These stresses not only reduce efficiency but also require high-voltage-rated components, increasing cost and design complexity.

There is thus a strong motivation to design a converter that maintains the advantages of the Dickson structure—such as simplicity and inductor-less operation—while mitigating its limitations. Specifically, a topology is needed that:

- Reduces component voltage stress
- Minimizes output ripple
- Requires less energy storage
- Achieves high voltage gain with the same number of stages

This project proposes and analyses such a converter—the Bipolar Dickson DC-DC Converter—which significantly improves upon the original Dickson topology through a dual-chain configuration. This approach aligns well with modern design goals of energy efficiency, miniaturization, and cost-effectiveness. Voltage multipliers are indispensable in power electronic systems where a high DC voltage is required from a relatively low DC input source, particularly in systems where transformers and inductors are not feasible due to constraints in size, cost, or integration. They are commonly used in applications such as photomultiplier tubes, high-voltage biasing circuits, plasma generators, sensor networks, and battery management systems.

Traditional multipliers like the Cockcroft-Walton, Fibonacci, and ladder topologies offer high gain but often suffer from excessive component count or complexity in regulation and switching. The Dickson voltage multiplier, on the other hand, is simpler and more suited for integration using modern CMOS processes. It utilizes a series of capacitors and switches or diodes to transfer charge in a timed manner, producing a cumulative voltage gain with each stage.

However, increasing the number of stages in the Dickson converter can lead to higher parasitic losses, diode forward voltage drops, and output ripple, limiting its applicability in high-voltage scenarios. The capacitor sizing also becomes more critical to reduce ripple and maintain load stability. Consequently, there is a strong need for advanced multiplier topologies that offer the same high-gain benefits but with lower capacitor stress, better ripple performance, and improved energy efficiency. This paper addresses this need by adopting a bipolar Dickson configuration, which strategically reduces the ripple and stress on each component while preserving the step-up gain, thus making it highly suitable for power-dense and efficient voltage boosting applications.

2. Illustrations

DC-DC converters are power electronic devices that transform direct current (DC) from one voltage level to another. These circuits are fundamental in ensuring that electronic systems receive the proper voltage level required for their operation, especially when powered by a single DC source such as a battery or photovoltaic (PV) module. DC-DC conversion is not only about voltage step-up or step-down—it also involves regulating output voltage under varying input conditions and load demands. This function becomes increasingly critical in modern power systems where multiple loads operate at different voltage levels, and energy efficiency is paramount. Moreover, DC-DC converters are essential in renewable energy integration, electric mobility, portable electronics, industrial automation, and aerospace electronics. At the heart of DC-DC conversion are various converter topologies, each optimized for specific input/output voltage relations, isolation requirements, switching frequencies, and power handling capacities. Understanding these classifications is crucial to appreciate the role of voltage multipliers within the broader family of DC-DC converters. Fig. 1 illustrates the comprehensive classification of DC-DC converters based on their operational principles. The converters are broadly divided into three categories: Linear Mode, Hard Switching Mode, and Soft Switching (Resonant) Mode. Voltage multipliers form a subset of SCCs designed for high-voltage generation using only capacitors and switches (or diodes), making them highly attractive for applications requiring lightweight, integral solutions.

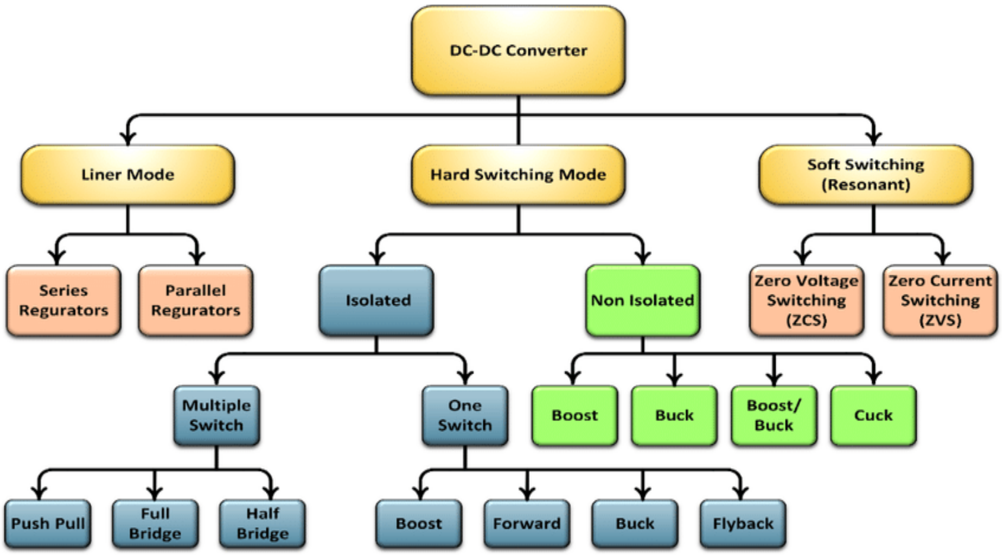

Fig. 1 - Comprehensive classification of DC-DC converters.

Table 1: Functional Objective of converters and multipliers

Aspect	Boost Converter	Multiplier-Based SCC
Energy Transfer	Magnetic (Inductor)	Electric (Capacitor)
Components	Inductor, Switch, Diode	Capacitors, Switches/Diodes
EMI	High (due to inductors)	Low
Integration	Difficult	Easy (especially in CMOS)
Efficiency at High Gain	Drops	Maintained with ripple reduction techniques
Voltage Gain Scalability	Limited	Scalable with added stages

Thus, ***multiplier-based SCCs are considered inductor-less step-up converters***, ideal for applications requiring miniaturization, low EMI, and integration with semiconductor processes.

Multiplier-based converters offer numerous benefits over traditional inductor-based converters, especially for low to moderate power levels:

- *Inductor-less Design: Eliminates bulky magnetic components, enabling compact and lightweight systems.*
- *Low EMI: No inductor switching means minimal electromagnetic noise.*

- *High Power Density: Suitable for on-chip and high-frequency applications.*
- *Ease of Integration: Can be fabricated in CMOS for memory and display drivers.*
- *Scalable Voltage Gain: Gain increases linearly with the number of stages.*
- *Simple Clock Control: Uses phase-shifted signals for operation—no complex PWM required*

3. Proposed Converter Design and Operation

This project proposes a novel converter to reduce the voltage stress across the switches in the conventional Dickson converter while using the same number of components. The voltage stresses are reduced by a factor of 0.5. One of the main advantages of this converter is that the voltage ripple is also reduced by a factor of 2 and the capacitor voltage rating is also reduced all by half. The circuit diagram of this converter is shown in Fig. 2 which consists of five stages. Each stage contains two capacitors and two diodes. Figure 3.4 shows the proposed circuit realized with MOSFETs and diodes. It consists of two chains of Dickson charge pumps; the upper chain is labeled A, and the lower chain is labeled B. The output load will be fed by the sum of the two chain outputs.

The Bipolar Dickson converter builds upon the traditional Dickson charge pump, which typically uses a series of capacitors and diodes or switches driven by phase-shifted clock signals. In the proposed converter, **two Dickson chains are connected in parallel**, but with opposite polarities and synchronized, complementary switching phases.

- **Chain A and Chain B,** each consist of multiple stages (typically 3 to 5), and both chains are driven by two non-overlapping clock signals, Φ1 and Φ2.
- The output voltage is derived as the **sum of voltages** generated by both chains, effectively doubling the voltage gain compared to a single chain.
- The **floating output structure** means that the negative output terminal is not connected to the system ground, which helps in achieving symmetrical operation and ripple cancellation.

This topology reduces:

- Voltage stress across individual capacitors by **50%**
- Voltage stress across diodes and switches
- Required total energy storage (about **30%** of the original Dickson)
- Output voltage ripple due to opposite-phase operation.

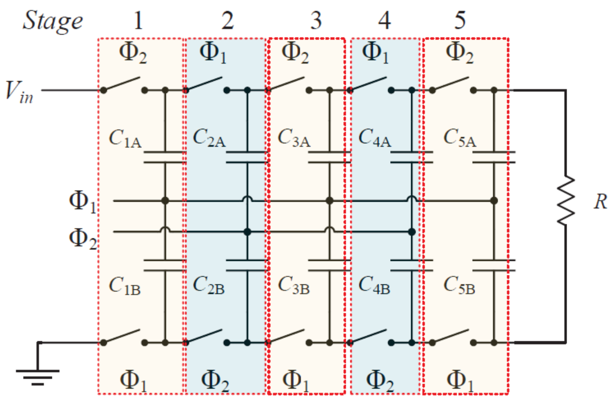

Fig. 2: The proposed switched capacitor converter.

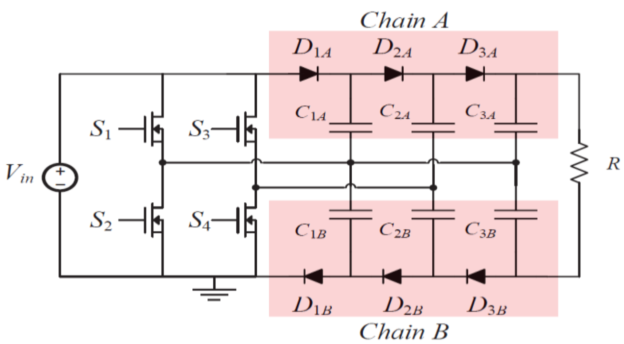

Fig. 3: The proposed converter with actual components.

The converter is composed of:

- **Capacitors:** Each stage includes two capacitors, one from Chain A and one from Chain B. For N stages, there are **2N capacitors**.
- **Diodes:** Diodes are used to control the direction of current flow during each switching phase. Each chain uses **N diodes**, alternating between charge and discharge cycles.
- **Switches (or Synchronous MOSFETs):** Controlled by clock signals to alternate conduction states between Φ1 and Φ2.
- **Clock Generator:** Produces two non-overlapping control signals to ensure that switches from both chains operate in complementary phases.

Modes of Operation

The operation of the Bipolar Dickson DC-DC Converter revolves around two distinct non-overlapping switching phases: Phase 1 (Φ1) and Phase 2 (Φ2). The converter operates based on the charge-pump principle, where capacitors are alternately charged and discharged through controlled switches (or diodes), transferring energy from the input to the output in stages.

In this topology, two symmetrical Dickson chains—Chain A (upper) and Chain B (lower)—are operated in complementary fashion. This means when capacitors in one chain are charging, the capacitors in the other chain are discharging and transferring energy to the load.

Each stage contains:

- Two capacitors (e.g., C1A, C1B)
- Two diodes (e.g., D1A, D1B)

Switches controlled by two clock signals Φ1and Φ2.

Phase 1 Operation (Φ1 Active)

In **Phase 1**, the switches controlled by the clock signal **Φ1** are turned ON, while the switches controlled by **Φ2** are turned OFF. This causes a specific set of diodes in **Chain A** and **Chain B** to conduct in a pre-defined pattern. The operation can be understood as follows:

a. Switch States:

- **ON:** Even-numbered switches in **Chain A** (e.g., S2A, S4A)
- **ON:** Odd-numbered switches in **Chain B** (e.g., S1B, S3B)
- **OFF:** All other switches (complementary to above)

b. Charging and Discharging:

- **Chain A:** Capacitors are in their **charging** phase.
  - Input voltage is applied to the first capacitor (C1A) via a conducting switch.
  - Charges propagate forward through the chain in a staircase fashion using active switches and conducting diodes.
  - Diodes in Chain A (e.g., D1A, D2A, D3A) conduct to allow energy flow.
- **Chain B:** Capacitors are in their **discharging** phase.
  - Previously charged capacitors (e.g., C1B, C2B, C3B) discharge their energy forward to the load.
  - Energy is transferred stage-by-stage to the output through conducting diodes (e.g., D1B, D2B, D3B).

c. Energy Transfer Direction:

- For both chains, energy flows **from left to right**, but their actions are opposite:
  - Chain A: **charging** from the input
  - Chain B: **discharging** to the output

d. Resulting Output Voltage:

- The load receives energy **only from Chain B** in this phase.
- Since this chain was pre-charged in the previous phase, it now boosts the voltage toward the load.

Phase 2 Operation (Φ2 Active)

In **Phase 2**, the roles are reversed. The clock signal **Φ2** is active, turning ON the switches controlled by it, while the Φ1-controlled switches are turned OFF. The result is complementary behavior to Phase 1.

a. Switch States:

- **ON:** Odd-numbered switches in **Chain A** (e.g., S1A, S3A)
- **ON:** Even-numbered switches in **Chain B** (e.g., S2B, S4B)
- **OFF:** All other switches

b. Charging and Discharging:

- **Chain A:** Capacitors now **discharge** energy toward the output.
  - Previously charged capacitors C1A, C2A, C3A begin to transfer energy toward the load.
  - The corresponding diodes (e.g., D1A, D2A, D3A) in Chain A conduct.
- **Chain B:** Capacitors begin to **charge** using the input voltage.
  - The input source charges C1B, C2B, C3B through switches and conducting diodes.

c. Energy Transfer Direction:

- As in Phase 1, energy flows left to right.
  - Chain A: **discharging**
  - Chain B: **charging**

d. Resulting Output Voltage:

- The load receives energy **from Chain A** in this phase.
- Chain B prepares for the next phase by fully charging its capacitors.

To evaluate the performance of the proposed Bipolar Dickson DC-DC Converter, simulations were conducted using the MATLAB software environment. The simulation was designed to replicate real-world conditions as closely as possible by including non-idealities such as diode forward voltage drop, capacitor ESR, and finite switching frequency.

The converter was configured to operate at a switching frequency of 100 kHz, with three stages per chain (i.e., six capacitors in total across both chains). The input voltage was set to approximately 17.2 V to achieve a theoretical voltage gain close to 6, aiming for a target output voltage of 100 V. The table below summarizes the key parameters and components used in the simulation model.

Table I: List of Components and Parameters Used in Simulation

Parameter	Value
Switching Frequency	100 kHz
Number of Capacitors	6 (3 per chain)
Capacitor Value	44 µF (each)
Equivalent Series Resistance (ESR)	18 mΩ
Diode Forward Voltage Drop (VfV_fVf)	0.45 V
Input Voltage (Ideal)	16.67 V
Input Voltage (Simulated)	17.2 V
Target Output Voltage	100 V
Load Resistance	500 Ω

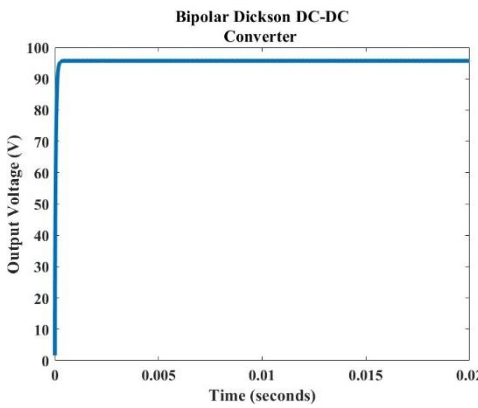

Fig. 4: Bipolar Dickson DC-DC Converter Output Voltage with Vin = 17.2V.

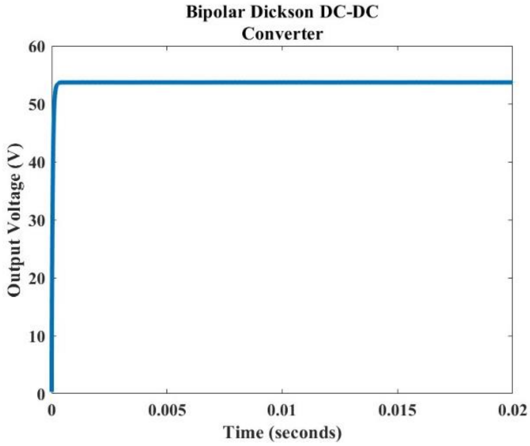

Fig.5: Bipolar Dickson DC-DC Converter Output Voltage with Vin = 10V.

The output voltage waveform demonstrates the transient behaviour and steady-state performance of the converter under an input of 10V:

1. Start-up Transient (0 – 2 ms):
   - At the beginning, the output voltage is 0 V.
   - Capacitors in the Bipolar Dickson converter begin to charge in the first few switching cycles.
   - A rapid voltage rise occurs due to efficient charge pumping across the Dickson chains.
   - This is a characteristic fast transient response due to the absence of inductive components (unlike inductor-based converters which exhibit slower ramp-up due to energy accumulation in magnetic fields).
2. Steady-State Response (After ~2 ms):
   - The output voltage reaches a steady level slightly below 55 V.
   - This matches the theoretical expectation for a 1:5.4 to 1:5.5 step-up gain, taking into account practical losses like:
     - Diode forward voltage drop (typically ~0.45 V per stage)
     - Switching losses
     - Capacitor ESR (Equivalent Series Resistance)
   - The target gain for a 3-stage bipolar Dickson converter (with two chains) ideally would be:

$$V_o=2\cdot N*V_{in}=2*3*10=60\ V$$

     - The obtained ~55V indicates high efficiency, but minor loss due to non-idealises.
3. Ripple Observation:
   - The waveform is flat and stable in the steady state.
   - Ripple is minimal, validating one of the key design advantages of the Bipolar Dickson topology: ripple cancellation between the two complementary chains

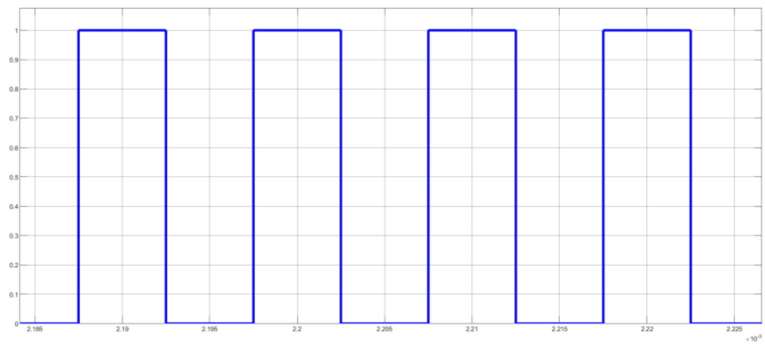

Fig. 6: Duty Cycle Phase A.

Fig. 6 shows a PWM-type square waveform, used as a clock signal for controlling switches in one of the two phases (Φ1 or Φ2). X-Axis: Time, focused around 2.19 to 2.225 milliseconds. Y-Axis: Logic Level (0 or 1), representing switch ON (1) or OFF (0). The waveform has a 50% duty cycle, indicating equal ON and OFF periods.

4. Conclusion

In this paper, a novel Bipolar Dickson DC-DC Converter was analyzed and evaluated for high step-up voltage applications. The converter is based on an enhancement of the traditional Dickson voltage multiplier topology, restructured into a bipolar dual-chain configuration to address key limitations found in existing switched-capacitor converters, particularly in high-voltage scenarios.

The converter was thoroughly studied using theoretical analysis and simulation modeling, with no experimental implementation. Its operation was divided into two complementary switching phases (Φ1 and Φ2), where two symmetrical Dickson chains (Chain A and Chain B) alternately charge and discharge, resulting in a cumulative voltage boost at the output. This unique configuration helped reduce voltage stress on capacitors and diodes, effectively cutting the maximum stress by nearly 50% when compared to the original Dickson topology.

Simulation results carried out in PLECS confirmed that the proposed converter achieves:

- A high voltage gain (approximately 1:5.5) with an input of 10 V yielding ~55 V at the output
- Minimal output ripple due to ripple cancellation between complementary chains
- Improved component stress profile, enabling the use of lower voltage-rated components
- Reduced energy storage requirements (only 30% compared to the original topology)
- High theoretical efficiency, simulated up to 94%, showcasing the converter's suitability for modern, high-efficiency applications

Additionally, a comparative analysis between the Original Dickson, Modified Dickson, and Bipolar Dickson converters highlighted the superiority of the proposed design in terms of:

- Voltage distribution
- Component count efficiency
- Output quality
- Energy optimization

This makes the Bipolar Dickson converter a promising candidate for use in renewable energy interfaces, compact electronic power supplies, battery-operated devices, and systems requiring high-voltage generation without magnetic components.

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