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Developing and Evaluating a High Gain Sheppard-Taylor DC-DC Converter for Renewable Energy Application

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ABSTRACT
This paper introduces an innovative high step-up converter featuring average mode control tailored for power generation applications. A comprehensive steady-state analysis of the system is provided, yielding transfer functions for input voltage versus output voltage and duty cycle versus output voltage. The study includes simplifications and design rules to streamline feedback loop design. The Sheppard Taylor Converter, designed to emulate non pulsing input and output currents akin to the Cuk Converter, operates with forward energy transfer. Employing two inductors to shape input currents and feed the output load, this converter minimizes input and output current ripple. Compared to the Cuk Converter, the Sheppard Taylor converter demonstrates superior regulation of output voltage with less variation in the duty cycle. This paper explores the Sheppard Taylor converter, its state space average model, and its application in high step-up converters crucial for renewable energy application.

Keywords: *DC-DC, Converter, Boost converter, PI controller, High gain*

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I. INTRODUCTION

The growing importance of renewable resources in distribution systems is evident, driven by the depletion of conventional energy sources. Renewable sources like fuel cells and photovoltaic (PV) cells generate low DC voltage. In DC microgrid applications, a high-gain DC-DC converter is essential to elevate this minimal DC voltage to a higher value. The literature references numerous high-gain DC-DC converters, both isolated and non-isolated. A converter employing a voltage lift technique is discussed in [1], [3], emphasizing simultaneous switching of both switches to achieve high voltage gain. Despite its advantages, this topology is limited to low voltage applications. Another novel high-gain converter utilizing a switched inductor (SL) for boosting applications is proposed in [2], [6]. This design, while requiring fewer components, achieves high voltage gain at a lower duty cycle, but introduces high voltage stress. The Switched Capacitor (SC) converter presents advantages such as the absence of a high-frequency transformer, continuous input current, and high voltage gain with minimal voltage and current stress. However, increasing the number of boosting cells makes the circuit bulkier. An alternative approach is explored in [5], where a switched inductor-capacitor divided network converter attains high gain with a single switch. Although it reduces voltage across switches compared to output voltage, it incurs higher conduction losses due to the increased number of diodes. DC-DC switch-mode boost converters operating with LUO converter [10-11], [23], [28] achieve four times higher voltage gains with only half the voltage stress on transistors and diodes. A review of topological evolution in boost converters using switching capacitors is presented in [13], [38]. Highlighting a common ground feature, the evolution on a SC with a double-switch configuration is discussed, along with four enhanced voltage gain boost topologies and their drawbacks. A new technique utilizing two DC-DC converters with different connections, producing either positive or negative output voltages, is proposed in [8]. However, such voltage lifting strategies, relying on boosting gain cells, introduce control complexities. Traditional CUK and SEPIC converters inspire a new dual-output converter in [22], [25], [27], with a trade-off between increased output and higher volume, price, and losses due to transformers.

To enhance static gain with lower switch stress, a voltage multiplier technique is employed for typical non-isolated DC-DC converters. A step-up DC-DC converter combining SL, SC, and a voltage multiplier cell is introduced in [4]. Various extreme gain DC-DC converters using multilevel inverters are discussed in literature [14], with [15], [31], [35] addressing a high gain topology for renewable applications. A SEPIC topology based on a quasi-Z source structure with SC cell in boost mode for electric vehicle applications is reported in [12], [30], [34], [39]. An active switched LC network-based DC-DC converter maximizing solar power using a fuzzy controller type MPPT is presented in [7], [9], [26], [29]. Additionally, a high step-up converter with SC structure suitable for solar PV applications is explored in [20], [32]. Unlike fossil fuels, renewable energy sources generate intermittent power. Step-up DC-DC power converters efficiently control energy flow through power management [16-17], [19]. A quadratic boost structure DC-DC converter is introduced [], achieving less output voltage ripple and increased efficiency. PV systems, sensitive to power consumption, require improved performance for higher power and efficiency. A SEPIC converter with PV as the input source is detailed in [18], [21], demonstrating high gain with minimal duty cycle. Finally, an analysis of a DC-DC converter with SL and SC structure, along with outcomes, is presented in [24], [31]. An advanced neuro-adaptive fuzzy logic-based PI controller for tracking the maximum power point is introduced in [36-40].

II. MODELING AND ANALYSIS

CIRCUITDIAGRAM

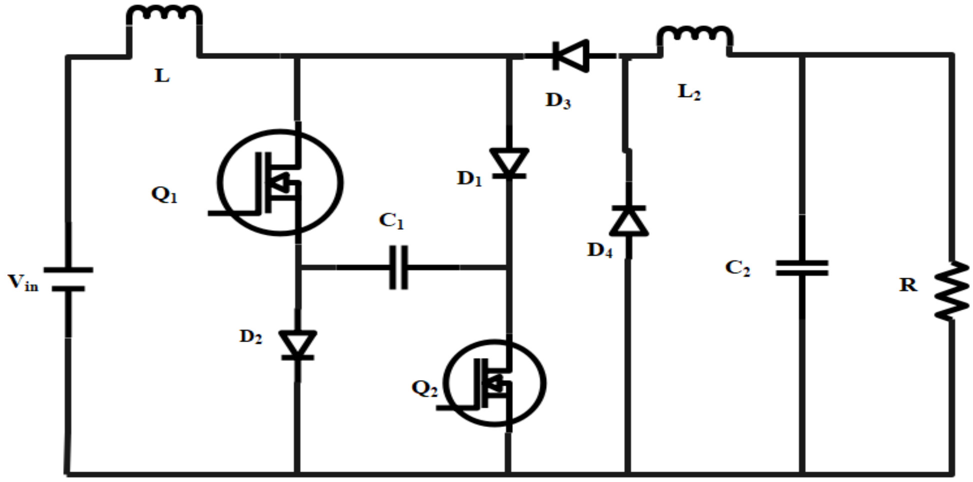

Figure 1: Sheppard-Taylor existing circuit

The circuit is in a steady-state operation, with continuous inductor current and a very large capacitor ensuring a constant output voltage. The voltage across the components switches periodically with a period denoted as T, and a duty cycle represented by D. The switch is closed for a duration of DT and opened for a period of (1-D)T. The components in the figure include two switches, three diodes, an inductor, and two capacitors, all assumed to be ideal. The circuit maintains continuous current at both the input and output throughout its operation.

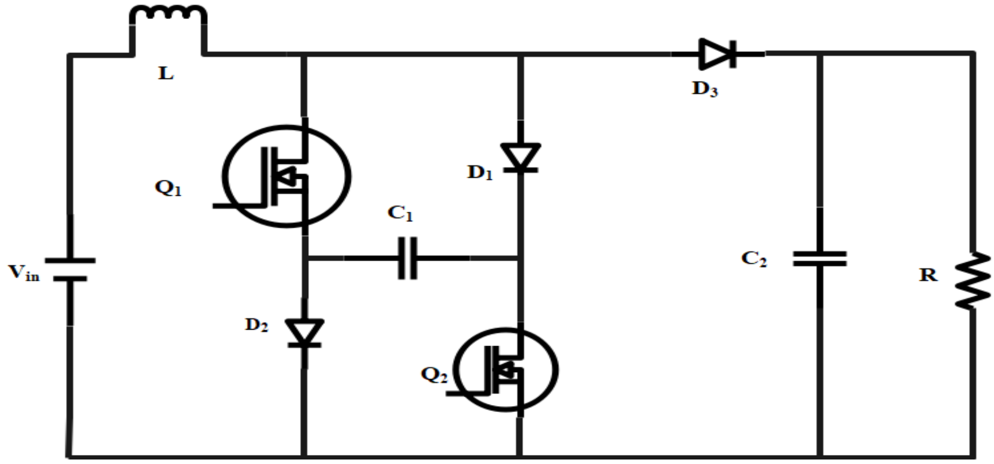

Figure 2: Proposed Topologies

The proposed converter showcases several commendable features. The development of this innovative converter design stems from the aim to preserve the advantageous characteristics of the S-T converter. Notably, it exhibits the capability to regulate voltage effectively amidst wide variations in both load and input voltage. The new topology stands out for its streamlined implementation with fewer components, thereby simplifying circuit analysis for engineers. Additionally, the design results in a small input line current ripple, simplifying the design of the input filter or rendering it unnecessary altogether. The performance of this novel switching power supply design permits the utilization of a lower switching frequency and uncomplicated circuits for both the drive and feedback systems. Other notable advantages include a constant switching frequency and a limited duty ratio excursion, which is less than half. These features collectively contribute to the enhanced efficiency and simplicity of the proposed converter design

Mode of operation
MODE1:Q1,Q2turnon

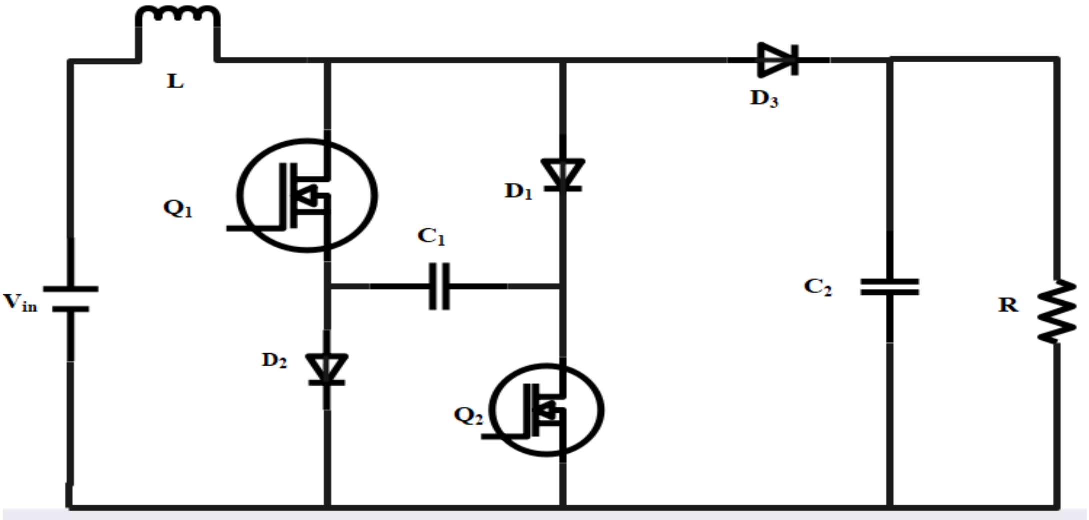

Figure 3: Mode 1 operation

The switches Q1and Q2are turned on, voltage across theinductor, capacitor. inductor current is a positive constant. The current increaseslinearly. C1is discharged through Q1and Q2, reverse biasing D1and D2.outputcurrentissuppliedentirelyfromC1.theoutputfiltercapacitorisassumedtobeverylargetoconstantoutput voltage.

$$V_1=V_{in}+V_{c1} \tag{1}$$

$$\frac{di_l}{dt}=\frac{V_{in}+V_{c1}}{L} \tag{2}$$

$$V_{c2}=V_o \tag{3}$$

MODE2:Q1,Q2turnoff, D3isnot conducting:
WhenQ1,Q2areturned off,C1ischarged throughthe diodesD1,D2theenergy frombothinputandinductor.InductorcurrentIdecreases,D3isturnedoff,becauseVc1isoff.

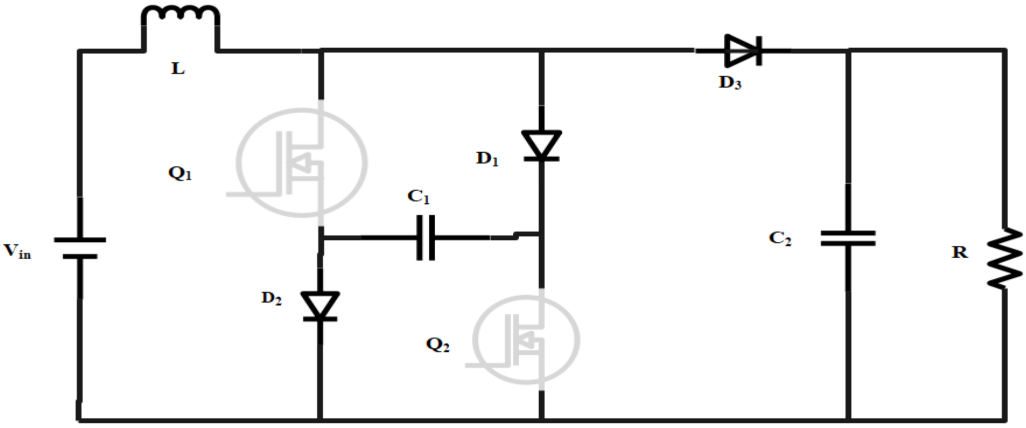

Figure 4: Mode 2 operation

$$V_L = V_{in} - V_{c1} \quad (4)$$

$$\frac{d_{il}}{dt} = \frac{V_{in} - V_{c1}}{L} \quad (5)$$

$$V_{c2} = V_O \quad (6)$$

MODE3:Q1,Q2turnoff, D3isconducting:
When the voltage of capacitor C1is larger than voltage ofcapacitor att=d1T,diodeD3willbeconductingoutputvoltageisequaltocapacitor voltage.

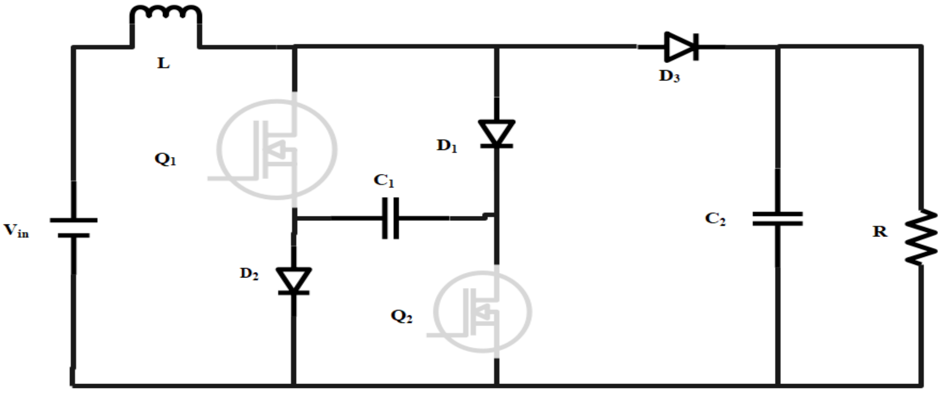

Figure 4: Mode 2 operation

$$V_o = V_{c1} = \frac{V_{in}}{1-2d} \quad (7)$$

$C_2 = C_1(1-2d)$ (8)

The measured gate and collector voltages of switches Q1, Q2 ; the measured voltageWaveformsofdiodesD1,D2andD3duringoneswitchingperiod.ThemeasuredwaveformsofGate voltage, inductor voltage, capacitor voltage, output voltage. Measured gate voltage, switch current, diode currents. Switches are turned off,C1is charged through the diodes D1,D2withTheenergyfromboththeinputand L,inductordecreases,D3isturnedoff,becauseVc1>Vo.

WAVEFORM:

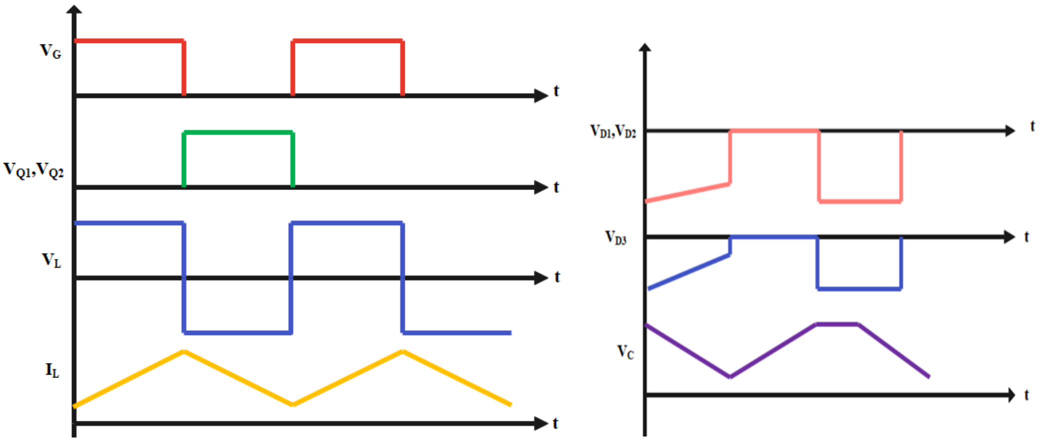

Figure 5: Switching waveforms

SIMULINKMODEL:

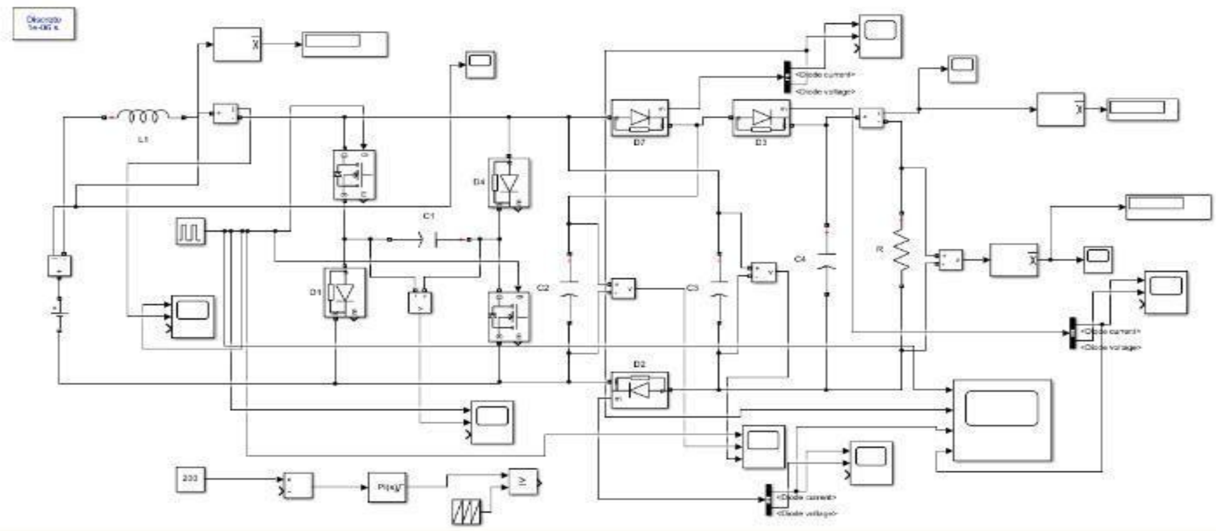

Figure 6: Simulink diagram

In the given schematic incorporating components such as MOSFET, PID controller, pulse generator, capacitor, inductor, and diode, the focus is on assessing both the output voltage and current. By manipulating the duty cycle and computing the resulting output voltage, efforts are made to minimize the output, achieved through a reduction in capacitor value. The observed constant output voltage suggests an effectively infinite capacitance. To determine the peak-to-peak output voltage ripple, scrutiny is placed on the capacitor current waveform. Measurements of capacitor current, inductor current, and diode current are conducted. Examining the variations in output voltage under different loads, a DC to DC converter employing proportional-integral voltage feedback control is employed to ensure the converter's stability, with PWM control being an integral part of the adopted approach.

TABLE: 1DUTYCYCLEVsOUTPUTVOLTAGE

DUTYCYCLE	OUTPUTVOLTAGE	THEORTICAL VOLTAGE
0.1	12.7	13
0.2	17.3	16.9
0.3	22.4	22.4
0.4	27.7	27.5
0.5	33.6	33.6
0.6	38.2	38
0.7	43.56	42.9

OUTPUTVOLTAGEWAVEFORM:

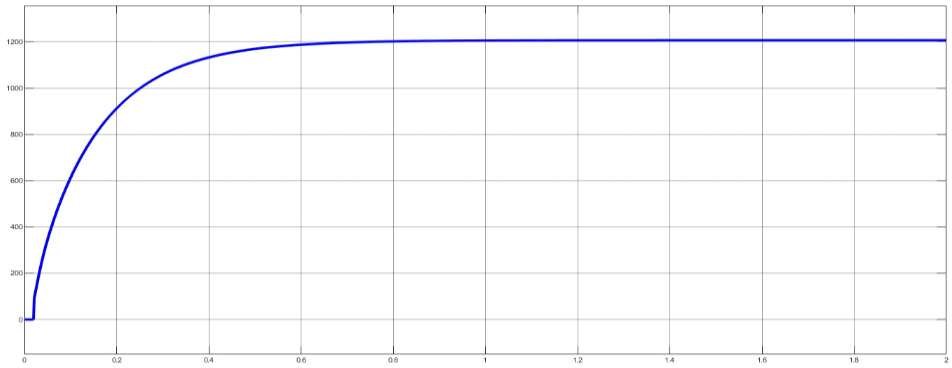

Figure 7: Output voltage waveforms

Measured voltage waveforms of diode D1, D2, D3during one switching period. outputvoltage variations with different loads, the dc to dc converter with proportional integral voltagefeedbackControlis utilizedtoensure the converters stability.

OUTPUTCURRENTWAVEFORM

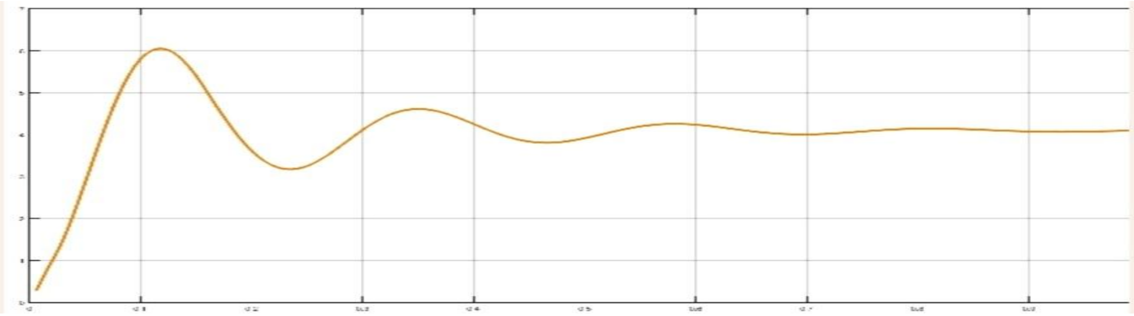

Figure 4: Mode 2 operation

Outputcurrentchangewithloadvariation.Currentisalwayspositive. The inductorCurrent is constant,the current is increase linearly. The inductor current is negative theCurrentisdecreaseslinearly.changein inductorcurrent overoneperiod iszero.

III. CONCLUSION

The genesis of the novel converter design was rooted in the objective of preserving the favorable characteristics of the S-T converter. The resulting circuit analysis is notably more straightforward, owing to the simplified topology. A small input line current ripple, inherent in this design, not only facilitates the ease of designing the input filter but also renders it potentially unnecessary. The converter boasts a constant switching frequency and limited duty ratio, both of which contribute to its stable performance. The analysis and simulation, conducted based on the small-signal model using the state-space averaging approach, provide insights into the converter's behavior. This methodology ensures the derivation of a high step-up voltage ratio and an optimal duty cycle, leading to minimal component stress. The converter's ability to achieve high efficiency across a broad load range further underscores its robust performance and suitability for diverse applications.

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