PES UNIVERSITY

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Report on

Non-Inverting DC-DC Buck-Boost Converter

Submitted by

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under the guidance of

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PROGRAM B. TECH

CERTIFICATE

This is to certify that the Report entitled

'Non-Inverting DC-DC Buck-Boost Converter'

is a bonafide work carried out by

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In partial fulfillment for the completion of 7th-semester course work in the Program of Study B.Tech in Electronics and Communication Engineering under rules and regulations of PES University, Bengaluru during the period Jan – Dec 2023. It is certified that all corrections/suggestions indicated for internal assessment have been incorporated in the report. The report has been approved as it satisfies the academic requirements in respect of project work.

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DECLARATION

We, **Vishwanath V Tirakapadi, Akhilesh, Amogh Mudakavi**, and **Keshavadithya S** hereby declare that the report entitled, ***'Non-Inverting Buck-Boost Converter',*** is an original work done by us under the guidance of **Prof. Sunita M S, Associate Professor, Department of ECE,** is being submitted in partial fulfillment of the requirements for completion of project work in the Program of Study B.Tech in Electronics and Communication Engineering.

PLACE: Bengaluru

DATE: 2nd December, 2023

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ABSTRACT

To adjust the output voltage to the required level, a mixed-ripple Adaptive On-time (MRAOT) Controlled Buck-Boost Converter is proposed. To achieve high conversion efficiency, the non-inverting buck-boost DC-DC converter only works in the buck or boost modes, not the buck-boost mode. The output voltage of this converter is regulated to 1V for the input voltage ranging from 0.8V to 1.3V. The switching frequency of the designed converter is 1MHz. As per the simulation results obtained, the maximum load current is found to be around 500mA. The efficiency obtained for buck operation is 75% and for boost operation is 95%. This converter is implemented using 45nm CMOS technology in the Cadence Virtuoso tool.

CHAPTER 1

INTRODUCTION

1.1 Introduction to PMIC:

A power management integrated circuit (PMIC) is used to control power on an electronic device or in modules on devices that may have a range of voltages. This means that a chip can have multiple components like a memory unit, I/O Unit, and a Control Unit, and each of these modules may require a different voltage to function and a PMIC does the job of delivering the proper Voltage to all these modules.

Applications of PMIC:

Some areas where PMICs are used are as follows

- Battery Power Charging
- DC to DC conversions
- Voltage Regulation

  A voltage regulator is a circuit that produces and maintains a steady output voltage regardless of changes in the input voltage or load conditions. Maintaining power supply voltages within a range that is suitable for the other electrical components is the goal of voltage regulators, or VRs.
- Power Sequencing
- Energy Harvesting
- Dynamic Voltage Scaling and in many more diverse areas.

1.1.1 DC-DC Converters:

What does a DC-DC converter do?

DC-to-DC converters are devices that temporarily hold electrical energy in order to change the voltage level of direct current (DC).

Two varieties of DC-to-DC converters include:

Linear Converters: A linear DC-to-DC converter generates and controls an output voltage via a resistive voltage drop as shown in Fig 1.1.

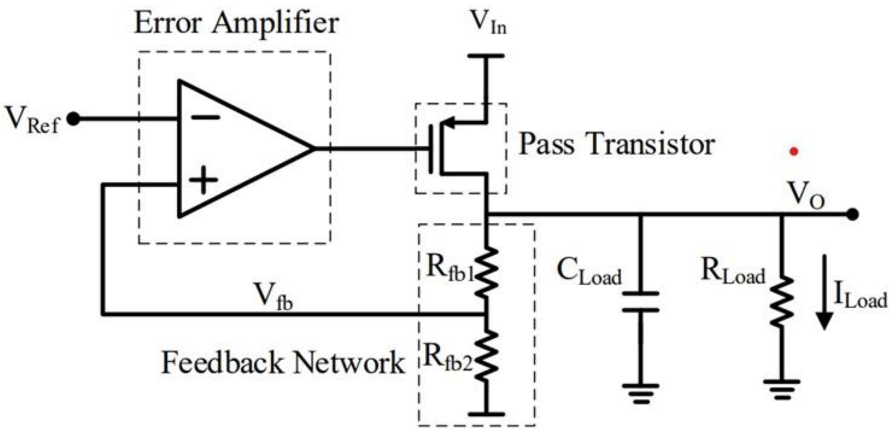


Fig 1.1 General Linear Converter Circuit

Advantages of Linear Converters:

- Low noise
- Used in low-output power applications

Switching Converters: When a DC-to-DC converter is in switched mode, energy from the input is periodically stored and released to the output at a varying voltage. Switching converters consist of an inductor, an output capacitor, and MOSFETs used as switches.

The converter operates in 3 modes and this is achieved by simultaneously switching these MOSFETs ON and OFF in different configurations.
There are three modes available:

- Buck
- Boost
- Buck-Boost

Advantages of Switching converters:

- High power efficiency
- Used to produce Outputs higher or lower than input instead of using multiple batteries to achieve the same thereby saving chip area.
- The inductor and Capacitor can be smaller in size as the switching frequency increases

i. Buck Converter: Stepping down or lowering the DC voltage level to obtain a lower DC voltage at the output is the purpose of this converter.

For Ex: Input Voltage = 1.3V Required Output Voltage = 1V

$Vout = D * V_{in}$

The duty cycle or ON time of the switching signal is represented by the letter D.

Here, the value of D ranges from 0 to 1.

ii. Boost Converter: The purpose of this converter is to raise the DC voltage level and produce a higher DC voltage at the output.

For Ex: Input Voltage = 0.8 V Required Output Voltage = 1 V

$$V_{out} = \frac{V_{in}}{(1 - D)}$$

The duty cycle or ON time of the switching signal is represented by the letter D.

Here, the value of D ranges from 0 to 1.

iii. Buck-Boost Converter: To obtain the necessary voltage at the output, this converter can step up and step down the DC voltage.

$$V_{out} = \frac{-V_{in} * D}{(1 - D)}$$

For a non-inverting Buck-Boost Converter:

$$V_{out} = \frac{V_{in} * D}{(1 - D)}$$

The duty cycle or ON time of the switching signal is represented by the letter D.

Here, the value of D ranges from 0 to 1.

1.2 INTRODUCTION TO BUCK-BOOST CONVERTER

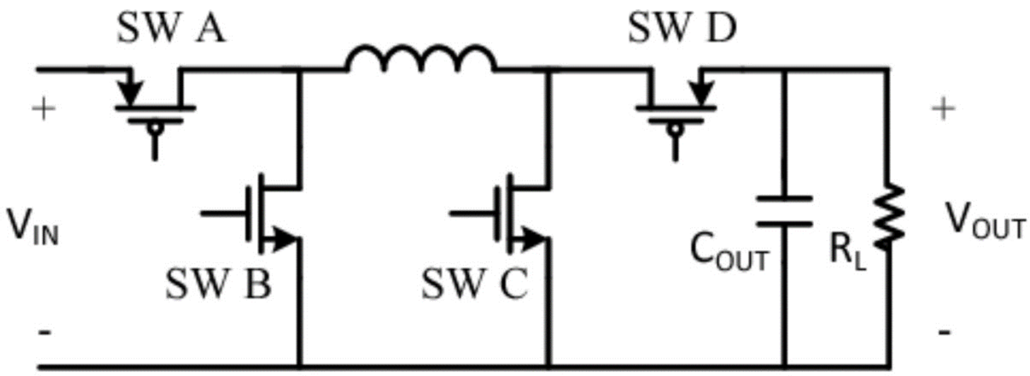


Fig 1.2 General DC-DC Buck-Boost Converter

Fig 1.2 depicts the circuit diagram of a 4 switch DC-DC buck-boost converter. A DC output voltage generated by a buck-boost converter may differ in value from its DC input voltage. It combines the capabilities of a buck converter, which lowers DC voltage, and a boost converter, which raises DC voltage, as the name implies.

Non-inverting buck-boost converters take a positive(negative) voltage at the input and step it down or up using an inductor to store and dissipate energy to return a positive(negative) voltage at the output, either smaller or larger than the DC input.

1.2.1 OPERATING PHASES

The Buck-Boost Converter operates in three phases, which are,

A. Initial Phase
B. Buck Phase
C. Boost Phase

A. INITIAL PHASE:

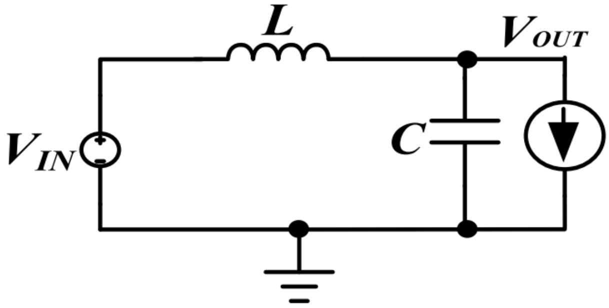


Fig 1.3 Buck-Boost Converter state during the initial phase

Fig 1.3 depicts the converter's state during the initial phase. In this phase, the inductor is charged by switching the MOSFETs accordingly that is, SW A and SW D are turned on and SW B and SW C are turned off.

B. BUCK PHASE:

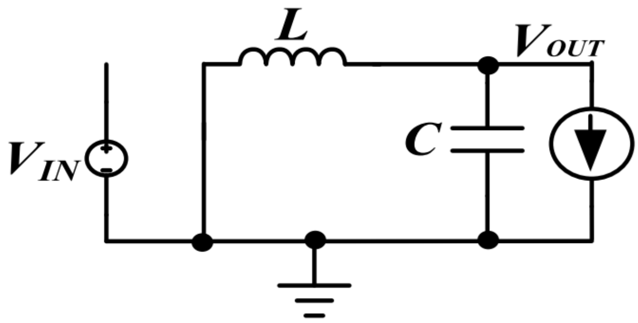


Fig 1.4 Buck-Boost Converter state during buck phase

Fig 1.4 depicts the converter's state during the buck phase. In this phase, after the inductor has been charged SW A is turned off and the inductor behaves like a source and charges the capacitor.
When the required output voltage is lower than the output voltage, the converter alternates between the initial and buck phases.

C. BOOST PHASE:

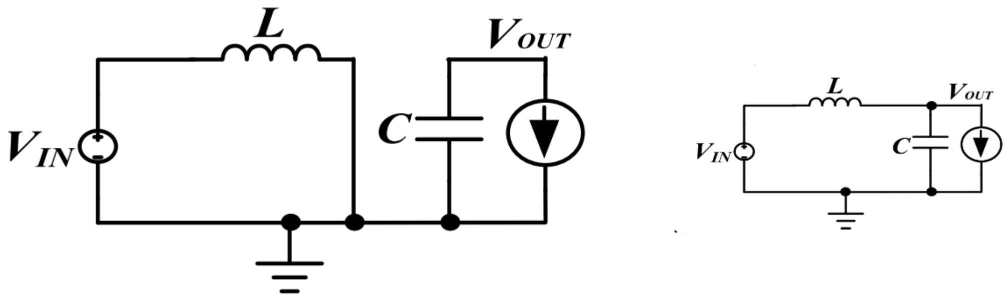


Fig 1.5 Buck-Boost Converter state during the boost phase

Fig 1.5 depicts the converter's state during the boost phase. In this phase, the voltage source and the inductor behave as two sources in series and are used to obtain a higher voltage when the converter transitions from the boost phase to the initial phase. The inductor is charged to a specific voltage during this phase.

When the output voltage is less than the needed output voltage, the converter alternates between the boost and initial phases.

Two conduction modes:

a) **Continuous Conduction Mode (CCM):**
In this mode, charging and discharging take place without allowing the inductor's current to entirely drop to zero. The inductor's current never reaches zero while switching (charging and discharging) is happening as depicted in Fig 1.6.

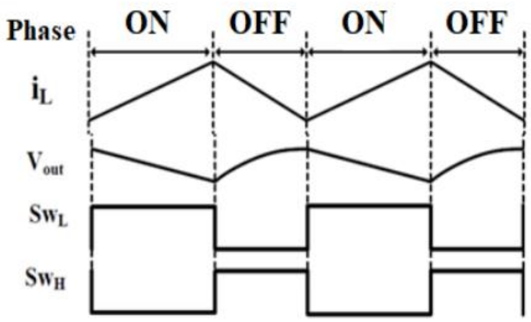


Fig 1.6 CCM mode of operation

b) **Discontinuous Conduction Mode (DCM):**
In this mode, the current goes to zero that is complete discharging of the inductor takes place. Once the inductor is charged to a certain voltage it completely discharges during the inductor discharging phase and current through the inductor becomes zero as depicted in Fig 1.7.

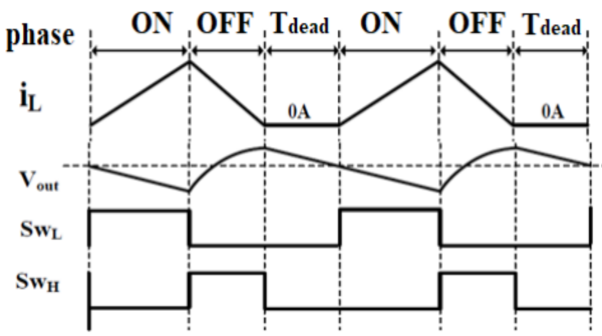


Fig 1.7 DCM mode of operation

1.2.2 Performance Parameters of the Buck-Boost Converter:

i) Input voltage range:

The range of input voltages for which the output voltage must be accurately regulated to the specified voltage level is referred to as the input voltage range.

ii) Output voltage:

It is the constant voltage that has to be maintained at the output of the circuit.

iii) Switching frequency:

The frequency of the clock signal generated, which is utilized to control the power switches is referred to as the switching frequency.

iv) Load Current:

It refers to the amount of electric current that a device or circuit draws from a power source.

v) Output voltage ripple:

It is the part of the direct current (DC) output voltage that is in the alternating current (AC) domain.

vi) Inductor current ripple:

It is the variation in the current flowing through the inductor during the switching process.

vii) Efficiency:

It refers to the ratio of the useful output power to the total input power. In other words, it is the percentage of the input power that is converted into output power.

CHAPTER 2

LITERATURE SURVEY

[1] C. Xu and L. Liu, "A Four Modes and Smooth Transition Non-inverting Buck-Boost Converter," 2021 IEEE 14th International Conference on ASIC (ASICON), Kunming, China, 2021, pp. 1-4, doi:10.1109/ASICON52560.2021.9620338.

- A DC-DC converter circuit with four operating modes has been suggested.
- The large variance in input voltage does not affect the circuit's ability to seamlessly transition between modes.
- The converter runs in Boost mode when the input voltage is sufficiently lower than the output voltage. On the other hand, if the VIN is sufficiently higher than the VOUT, the converter enters Buck mode.
- The E-Boost and E-Buck modes are two more modes that are introduced when the input and output voltage are near or equal.
- The converter features a switching frequency of 1MHz, an output voltage of 1.8V, and a maximum load current of 100mA. It can operate between 0.4V and 3.3V, which is a wide input voltage range.
- The converter that was used has a 78% efficiency. E-Buck and E-Boost are more efficient than Buck-Boost when VIN is near VOUT.
- This circuit is appropriate for low-power and voltage applications since it generates a steady output voltage at a greater switching frequency.
- SMIC 0.18 um CMOS technology has been used to implement the circuit.

[2] G. -G. Kang, J. -H. Lee, S. -U. Shin, G. -H. Cho and H. -S. Kim, "A Boost-Oriented SIDO (BO-SIDO) Step-Up/Down DC–DC Converter Embedding Buck Conversion With an Energy-Balancing Capacitor," in IEEE Solid-State Circuits Letters, vol. 5, pp. 296-299, 2022, doi:10.1109/LSSC.2022.3229253.

- To increase power efficiency, a step-up/down DC-DC converter called a BO-SIDO (boost-oriented single-inductor dual-output) converter has been developed.
- To recycle leftover inductive energy for powering the buck output, the converter topology incorporates an energy-balancing capacitor.
- The power switches' lower conduction loss and use of PFM improve the converter's efficiency during buck conversion.
- The proposed BO-SIDO converter's operational concept involves four independent behavioural phases: energizing the inductor, delivering the inductor energy to the boost output, delivering the inductor energy to the buck output, and de-energizing the inductor.
- The converter has an operating voltage range of 2.8V to 4V for input voltage, 1.5V to 5V for output voltage, 50-400mA for load current, and 1MHz for switching frequency.
- The implemented converter has an efficiency of 93.5%.
- A 0.5-µm CMOS technology was used to implement the circuit.

[3] K. -C. Wu, H. -H. Wu and C. -L. Wei, "Analysis and Design of Mixed-Mode Operation for Noninverting Buck–Boost DC–DC Converters," in IEEE Transactions on Circuits and Systems II: Express Briefs, vol. 62, no. 12, pp. 1194-1198, Dec. 2015, doi: 10.1109/TCSII.2015.2469032.

- A noninverting buck-boost DC-DC converter's analysis and design, with an emphasis on mixed-mode operation.
- As the input voltage gets closer to the output voltage, the converter switches between the buck and boost modes, a phenomenon known as the "mixed mode," which is discussed in this work.
- To reduce output ripples and minimize the mixed mode's operating range, the article suggests a symmetric dual-ramp generating circuit.
- A full-cycle low-noise current sensing circuit has been introduced in order to suppress the switching noise on the measured current signal.
- The converter suggested in this paper has an input voltage range of 2.5–5 V and an output voltage of 3.3 V, respectively.
- This converter has a maximum load current and switching frequency of 300mA and 500KHz respectively.
- The implemented converter has an efficiency of 93.5%.
- The circuit has been implemented in a 350nm CMOS process.

[4] S. Wen, W. -L. Zeng, C. -S. Lam, F. Maloberti and R. P. Martins, "An Analog Multiplier Controlled Buck-Boost Converter," in IEEE Transactions on Circuits and Systems II: Express Briefs, vol. 69, no. 10, pp. 4173-4177, Oct. 2022, doi: 10.1109/TCSII.2022.3189537.

- In this converter, a novel analog multiplier-based controller has been developed which is capable of working either in buck mode or in boost mode.
- This simplifies design, conserves power, and reduces the controller's footprint.
- To achieve optimal performance, the analog multiplier controller has the ability to automatically switch between buck and boost modes based on the input and needed output voltage.
- By facilitating a seamless transition between the buck and boost modes, the developed analog multiplier controller reduces overshoot and undershoot problems.
- To enable smooth transitioning between buck and boost modes, the above-mentioned analog multiplier-based controller is used which is necessary for maintaining stable output voltages.
- The suggested paper's converter has an input voltage range of 0.7V to 1.4V, a regulated output voltage of 0.9V, a maximum load current range of 50-200mA, and a switching frequency of 600KHz.
- The implemented converter has an efficiency of 95.1%.
- The circuit has been implemented in a 65nm CMOS process.

[5] K. -D. Kim, H. -M. Lee, S. -W. Hong and G. -H. Cho, "A Noninverting Buck–Boost Converter With State-Based Current Control for Li-ion Battery Management in Mobile Applications," in IEEE Transactions on Industrial Electronics, vol. 66, no. 12, pp. 9623-9627, Dec. 2019, doi: 10.1109/TIE.2018.2883257.

- It has been suggested to use a current-based state controller for mode switching in a state-based buck-boost (S3B) converter.
- The S3B control scheme adaptively adjusts mode boundaries for optimal mode decisions in varying load conditions.
- The transient response of the S3B converter is comparatively slow because of a lower loop bandwidth for stability.
- The S3B control strategy can be used to buck-boost converters, irrespective of their transient response capability, by giving priority to steady output regulation and smooth mode changeover.
- During the crossing period, the S3B control scheme enables fixed switching patterns.
- The converter operates within an input voltage range of 2.7V to 4.2V, producing an output voltage of 3.4V, a load current range of 0.5-1.1A, and a switching frequency of 1MHz.
- The implemented converter has an efficiency of 90.9%.
- A 0.18-µm BCD technique has been used to implement the circuit.

[6] J. Yang, B. Li, K. N. Leung, Z. Chen and Y. Zheng, "A Triple-Mode DC–DC Converter With Wide Input and Load Ranges for Energy Harvesting in IoT Edge Nodes," in IEEE Transactions on Circuits and Systems II: Express Briefs, vol. 69, no. 12, pp. 4694-4698, Dec. 2022, doi: 10.1109/TCSII.2022.3196029.

- The energy harvester exhibits MPPT and automatic buck-boost functioning, and it is intended for use with the Internet of Things edge nodes.
- There are three modes of operation for the energy harvester: strong energy harvesting mode (SEM), weak energy harvesting mode (WEM), and battery-assisted power-supply mode (BPM).
- The controller design utilizes output and input feedback to regulate power switching sequences and maintain energy harvester voltage.
- The recommended system ensures a steady operation in a suitable energy-distribution path with a quick load response of less than 450 µs, contingent on variations in the load and input source.
- With an output voltage range of 1-4V, a maximum load current of 50mA, and a switching frequency of less than or equal to 800KHz, the converter operates within an input voltage range of 1.2V to 4V.
- The implemented converter has an efficiency of 88.7%.
- A 0.18-µm CMOS technology was used to implement the circuit.

[7] Y. -Y. Tsai, Y. -S. Tsai, C. -W. Tsai and C. -H. Tsai, "Digital Noninverting-Buck–Boost Converter With Enhanced Duty-Cycle-Overlap Control," in IEEE Transactions on Circuits and Systems II: Express Briefs, vol. 64, no. 1, pp. 41-45, Jan. 2017, doi: 10.1109/TCSII.2016.2546881.

- A duty cycle overlap control method that uses a dual output digital compensator to generate an offset value for minimizing the switching loss and helps in dealing with stability issues during mode transition has been proposed.
- In this paper, duty cycle ranges have been established which indicate the mode in which the converter is supposed to function. This helps in obtaining a stable and precise output voltage for both buck and boost operations.
- The research suggests an improved duty cycle overlap control approach to obtain a stable and precise output voltage in order to address the issues of low efficiency and unpredictable ripple voltage.
- The suggested converter has an input voltage range of 2.5 V to 4.5 V and a regulated output voltage of 3.3 V. It was possible to reach a maximum load current of 0.5 A. The switching frequency used by the converter is ≤ 1MHz.
- The implemented converter has an efficiency of 85.5%.
- The circuit has been implemented through an FPGA platform.

[8] Y. -Y. Chen, Y. -C. Chang and C. -L. Wei, "Mixed-Ripple Adaptive On-Time Controlled Non-Inverting Buck-Boost DC-DC Converter With Adaptive-Window-Based Mode Selector," in IEEE Transactions on Circuits and Systems II: Express Briefs, vol. 69, no. 4, pp. 2196-2200, April 2022, doi: 10.1109/TCSII.2021.3139100.

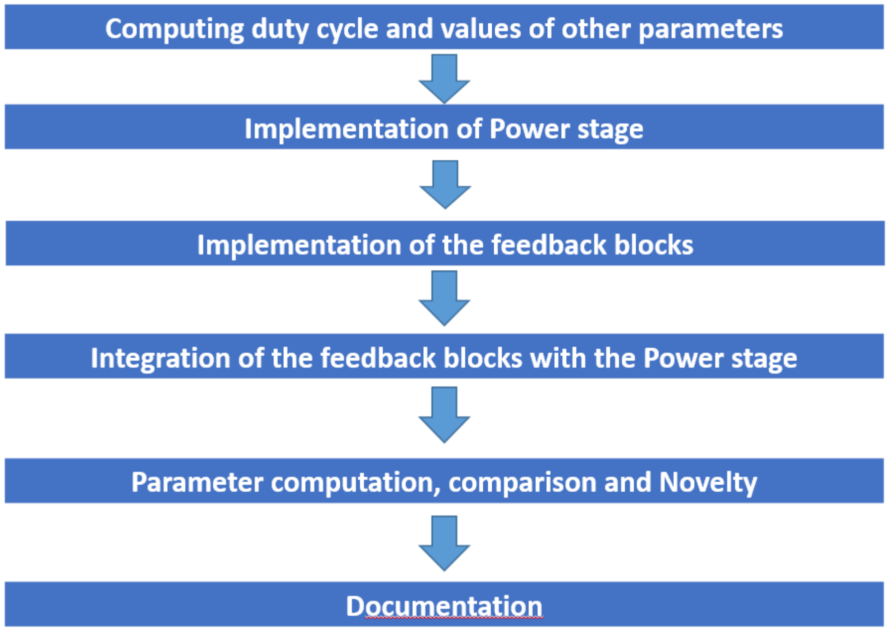
- This paper's buck-boost DC-DC converter is made to only run in the buck or boost modes, not the buck-boost mode, in order to maximize conversion efficiency.
- When the converter is set to run in the buck-boost mode, power loss results from all four switches turning on and off at the same time.
- This converter uses a MRAOT control approach, which helps to achieve improved efficiency across a wide range of input voltages and does not require slope adjustment.
- This paper proposes an Adaptive-Window-Based mode selector which generates V high, V low, and V Middle voltages, when the output voltage goes higher than V high or lower than V Low, the circuit generates a control signal indicating the converter to smoothly switch the mode of operation.
- This converter has a 2.5 V to 5 V input voltage range and a 3.3 V output that is controlled. 350 mA is the greatest load current that was achieved. The suggested converter uses a variable switching frequency mode of operation.
- The converter suggested in this paper has a 97.8% conversion efficiency.
- The proposed converter has been implemented using the tsmc350nm library.

[9] C. -H. Huang, H. -H. Wu and C. -L. Wei, "Compensator-Free Mixed-Ripple Adaptive On-Time Controlled Boost Converter," in IEEE Journal of Solid-State Circuits, vol. 53, no. 2, pp. 596-604, Feb. 2018, doi: 10.1109/JSSC.2017.2756871.

- A MRAOT controlled boost converter without a compensator has been proposed.
- The suggested control technique maintains load regulation while lowering chip space and cost by doing away with the requirement for a compensator network.
- Depending on the loading situation, the converter may seamlessly transition between CCM and discontinuous conduction mode.
- The suggested converter performs better than other cutting-edge designs in terms of wide load range, chip area efficiency, and load regulation.
- The converter has an output voltage of 1.8V and a maximum load current of 400mA. It operates in the input voltage range of 0.8V to 1.4V.
- In CCM, the switching frequency (750 KHz–860 KHz) is fixed. The switching frequency in DCM is inversely related to the load current.
- The converter that was used has a 92.4% efficiency.
- A 0.18-µm CMOS technology was used to implement the circuit.

CHAPTER 3

METHODOLOGY AND PROBLEM STATEMENT



PROBLEM STATEMENT:

Design and implementation of Mixed-Ripple Adaptive On-Time Controlled Non-Inverting Buck-Boost DC-DC Converter for biomedical sensor applications.

CHAPTER 4
BUCK-BOOST CONVERTER

4.1 WORKING OF BUCK-BOOST CONVERTER

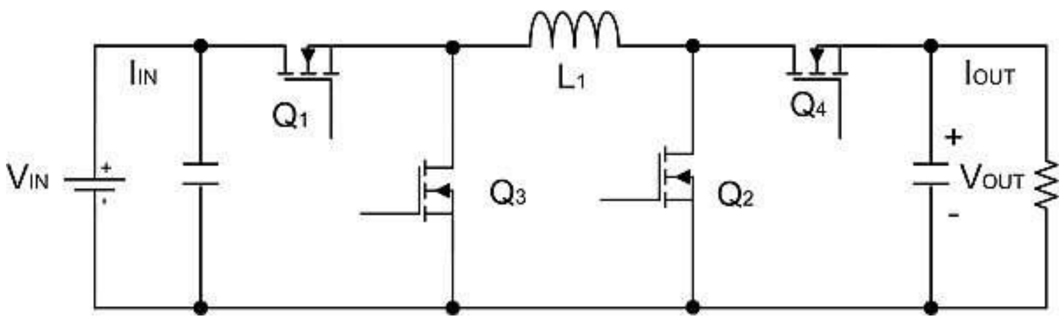


Fig 4.1 Basic Buck-Boost Converter

Fig 4.1 shows the circuit of basic buck-boost converter

Buck mode:

The converter functions in the buck mode when the needed output voltage is lower than the input voltage. In this mode, Q1 and Q3 are concurrently turned ON and OFF by applying a pulse of calculated duty cycle to their gates, while Q4 is turned ON and Q2 is turned OFF throughout this operation.

Boost mode:

The converter runs in boost mode when the needed output voltage is higher than the input voltage. In this mode, Q2 and Q4 are concurrently turned ON and OFF by applying a pulse of calculated duty cycle to their gates, while Q1 is turned ON and Q3 is turned OFF throughout this operation.

The suggested converter regularly alternates between the buck and boost modes to obtain the desired voltage when it is extremely near to the input voltage. The buck-boost mode of operation demands simultaneous switching of all four transistors in the circuit, which results in power loss, so this converter is not used in that mode.

4.2 OVERVIEW OF MIXED-RIPPLE ADAPTIVE ON-TIME CONTROLLED BUCK-BOOST CONVERTER:

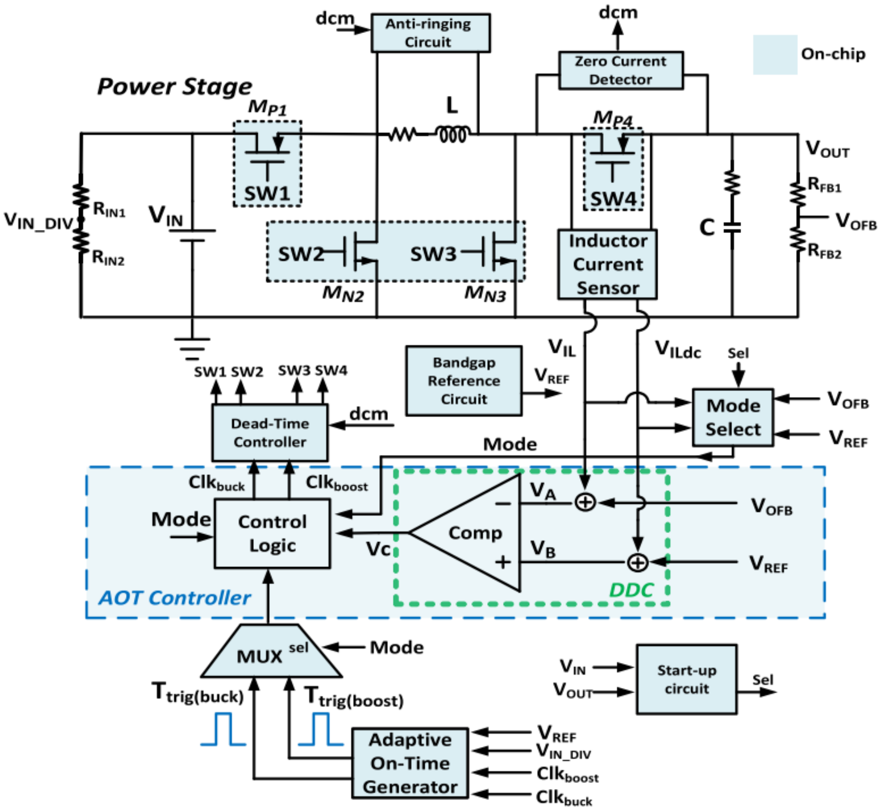


Fig 4.2 Block diagram of the MRAOT-controlled Buck-Boost Converter

Figure 4.2 shows an example of a mixed-ripple adaptive on-time controlled buck-boost converter. The output voltage, or VOUT, is split and then sent to the MRAOT controller. While this controller decides when the converter enters the inductor charging phase (i.e., on-time), the adaptive on-time generator establishes the duration of the on-time period. The adaptive window-based mode selector also chooses the operating mode of the converter, either buck or boost. Following that, the appropriate switching signals are generated to control the four power switches.

4.3 DESIGN SPECIFICATIONS OF BUCK-BOOST CONVERTER

Table 4.3 Design Specifications of Buck-Boost Converter

Parameter	Parameter Value	
	Base Paper	This Paper
Technology	350nm	45nm
Vin	2.5-5V	0.8-1.3V
Vout	3.3V	1V
Switching frequency	Varied	1MHz
Output Current	350mA	500mA
Output Voltage ripple	20mV	10mV

Table 4.3 shows the comparison of the base paper with the proposed paper. It shows the parameters such as technology used, V_{in}, V_{out}, switching frequency, output current and output voltage ripple.

CHAPTER 5

POWER STAGE AND FEEDBACK BLOCKS

5.1 IMPLEMENTATION OF BASIC BUCK-BOOST CONVERTER

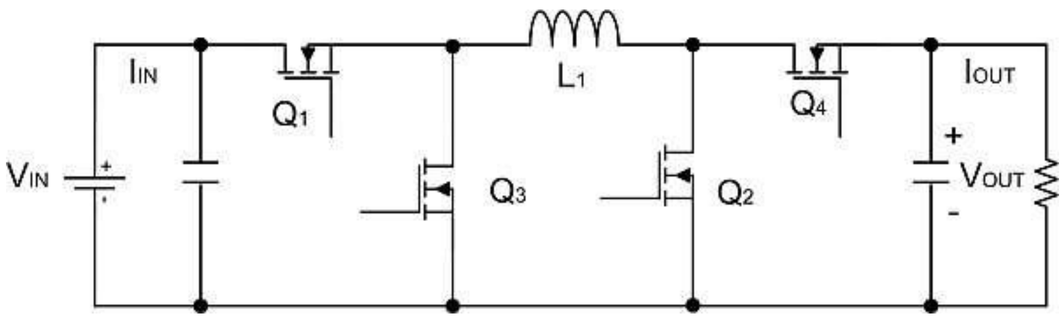


Fig 5.1 Basic Buck-Boost Converter

Fig 5.1 depicts the circuit of the basic Buck-Boost Converter using MOSFETs as switches. The design requirements to be considered are: Input voltage V_{in} in the range of 0.8-1.3V, output voltage V_{out} equals to 1V, switching frequency f of 1 MHz, and output load current of 500mA. In addition to these specifications, certain assumptions need to be made when designing the basic buck-boost converter: these are ΔI_L = 30% I_{out}, $\Delta V_{out} = 10mV$.

Duty cycle calculations:

1) **Buck mode:**

$$V_{out} = D * V_{in}$$

$$D_{Buck} = \frac{1}{1.3} = 0.769$$

2) **Boost Mode:**

$$V_{out} = \frac{V_{in}}{(1 - D)}$$

$$D_{Boost} = 1 - \frac{0.8}{1} = 0.2$$

Calculations for inductor and capacitor values:

1) **Inductor:**

$$L > \frac{V_{out} \times (V_{inmax} - V_{out})}{K_{ind} \times f_{sw} \times V_{inmax} \times V_{out}}$$

$$L > \frac{1 \times (1.3 - 1)}{0.3 \times 1 \times 10^6 \times 1.3 \times 1}$$

$$L > 1.538\ \mu\text{H}$$

2) **Capacitor:**

$$C_{OUT\,min} = \frac{I_{out} \times D_{boost}}{f_{sw} \times \Delta V_{out}}$$

$$C_{OUT\,min} = \frac{0.5 \times 0.2}{1 \times 10^6 \times 10 \times 10^{-3}}$$

$$C_{OUT\,min} = 8\ \mu F$$

The basic buck-boost converter is implemented as illustrated in Fig 5.1 using the calculated values. Each MOSFET in gpdk045nm library has a very low drive current, therefore to get the required output current, we need to place many MOSFETs in parallel.

5.2 IMPLEMENTATION OF DEAD TIME CONTROLLER:

The DTC helps to avoid the simultaneous switching of the MOSFET switches. Every switching cycle in discontinuous conduction mode (DCM) results in zero inductor current. The inductor current in Continuous Conduction Mode (CCM) is never zero. Without the dead time in the control signals, there is a possibility of flowing a reverse current in the circuit that leads to DCM mode of operation. The converter can make sure that the inductor current has time to drop to zero before the next switch is turned on by adding a delay between turning off one switch and turning on the next. The adaptive dead time controller is therefore used.

The moment the signal ZCD becomes high, the power PMOS should be turned off. Because the V_{LX} is connected to a lower voltage rather than the higher voltage V_{OUT}, malfunctions may occur when the AND gate is used to create the necessary signal to switch OFF the power PMOS using V_{LX} and ZCD. As a result, a two-to-one multiplexer based on transmission gates is utilized instead of AND gates.

Dead time controller circuit is depicted in Fig 5.2. The outputs of the DTC are P_drive and N_drive which are used to control power MOSFETs in the power stage.

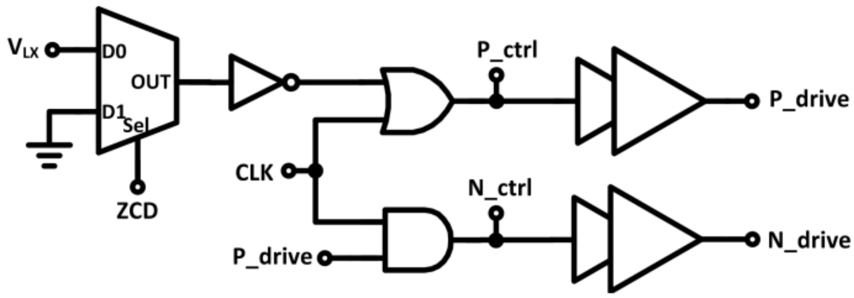


Fig 5.2 Dead time Controller circuit

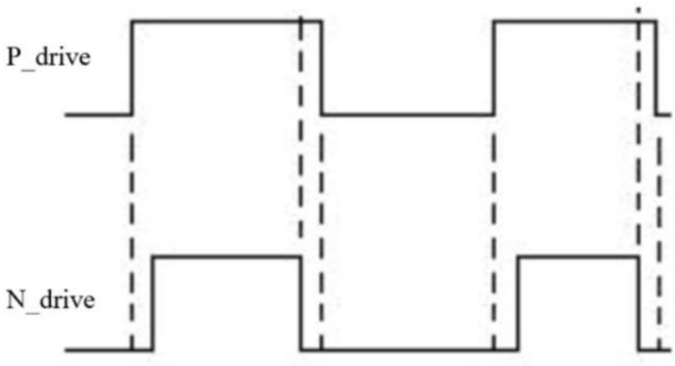


Fig 5.3 Dead time between P_drive and N_drive

As illustrated in Fig 5.3, the dead time between switching of PMOS to NMOS and NMOS to PMOS is 5ns. During this period of time, both the switching transistors are turned OFF.

5.3 DIFFERENTIAL DIFFERENCE COMPARATOR:

The comparator in a buck-boost converter manages the converter's switching. The converter's operation in both continuous and discontinuous conduction modes (CCM and DCM) is managed by the differential difference comparator (DDC). The DDC determines whether to turn the switch ON or OFF by comparing the output voltage to the reference value.

The two input signals to DDC are represented by V_A and V_B,

Where $V_A = V_{OFB} + V_{IL}$ and

$V_B = V_{REF} + V_{ILdc}$

In this case, the output feedback voltage is denoted by V_{OFB}, the reference voltage is V_{REF}, the average inductor current is represented by V_{ILDC}, and the sensed inductor current is represented by V_{IL}.

The power transistor MP4 is used to sense the inductor's current. In the boost mode's inductor charging phase, this transistor is not turned on, which means that V_{IL}, which represents the current in the inductor, is zero during this phase. However, MP4 is always active in the buck mode, which means that the V_{IL} waveform is continuous in the buck mode. DDC is shown in the Fig 5.4.

When the V_A exceeds the V_B, the DDC output is 1. When the signal V_A falls below the signal V_B, then the DDC output is 0.

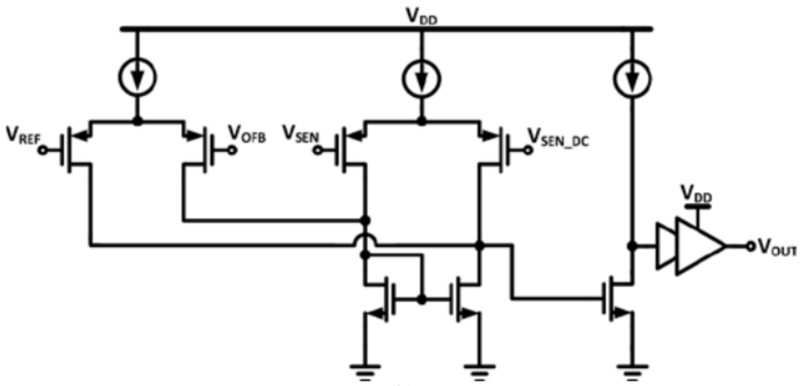


Fig 5.4 Differential Difference Comparator (DDC)

5.4 VOLTAGE COMPARATOR:

When two voltages or currents are compared, a voltage comparator determines which is larger by producing a digital signal at the output. The open-loop operational amplifier (op-amp) comparator is the most common type of comparator. It utilizes an op-amp to compare two voltage signals and determine which one is larger.

There are two primary types of voltage comparators: inverting and non-inverting. The type that is used depends on where the input signal is applied. An inverting comparator has an inverting terminal where the input signal is applied, and a non-inverting terminal where the reference voltage is located. A positive output voltage is produced by this comparator if the input voltage is lower than the reference voltage. In a non-inverting comparator, the input signal is applied to the non-inverting terminal, and the reference voltage is located at the inverting terminal. A positive output voltage is produced by this comparator if the input voltage is greater than the reference voltage.

Voltage comparator circuit is shown in Fig 5.5. It provides an output signal which is either high or low by comparing the values of its inputs Vp and Vn.

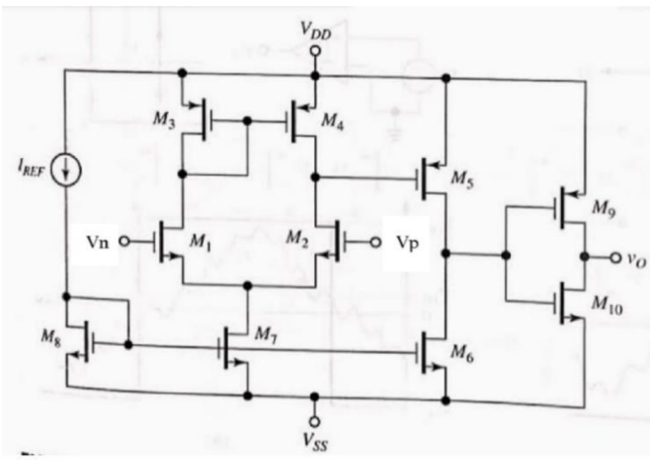


Fig 5.5 Voltage Comparator Circuit

Fig 5.6 illustrates the output of voltage comparator, which explains the working of the voltage comparator i.e., it generates high output when Vp is greater than Vn and low output when Vp is less than Vn

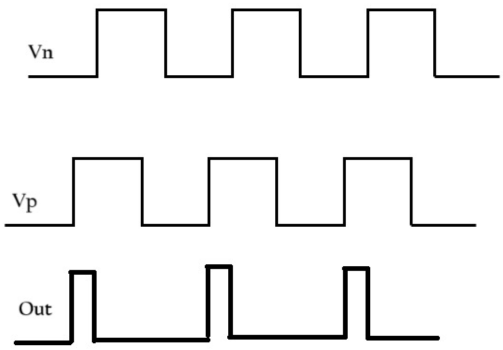


Fig 5.6 Voltage Comparator Waveforms

5.5 ADAPTIVE ON-TIME GENERATOR:

An on-time generator acts as a crucial part in the buck-boost converter and helps in determining the time period during which the switch should be in the ON state in each cycle of the converter. One of the key elements influencing the converter's output voltage is the on-time. As a result, the on-time generator controls the length of time the switch is active.
An integral component of the converter's feedback loop, the on-time generator enables the converter to dynamically modify its output voltage in response to variations in the input voltage and load current. This feature of the on-time generator increases flexibility and efficiency. In spite of variations in the load current, this aids in maintaining a steady output voltage.
Based on the input and reference voltages, the on-time generator modifies the on-time duration it generates. Consequently, the most important factor in deciding the converter's output voltage is an on-time generator.

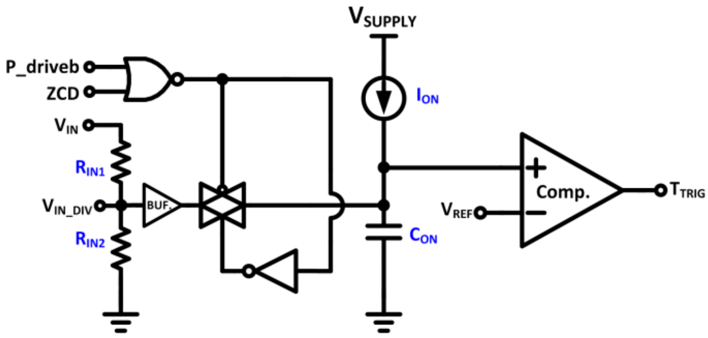


Fig 5.7 Adaptive On-time Generator (AOT) circuit

When the converter functions in the off phase, the capacitor Con starts discharging as soon as the capacitor voltage drops below V_{IN_DIV}, the comparator switches off the NMOS in the discharge path and the capacitor charges to V_{IN_DIV}.The capacitor is charged to the supply voltage during the on phase. Charging of the capacitor continues until the capacitor voltage crosses the reference voltage. At this point, the output of the comparator T_{trig} goes high, which signals end of the on phase. AOT generator is shown in Fig 5.7.

5.6 ZERO CURRENT DETECTOR:

Zero current detector is one of the prominent feedback blocks used in buck-boost converters. It is used mainly to detect zero current in the circuit. This function is important for preventing reverse inductor current, dealing with which is important for the safe and efficient operation of the converter.

In discontinuous conduction mode (DCM) at light loads, a zero current detector (ZCD) is primarily used to detect zero inductor current and turn off the power transistor Mp. By doing this, reverse inductor current is avoided.

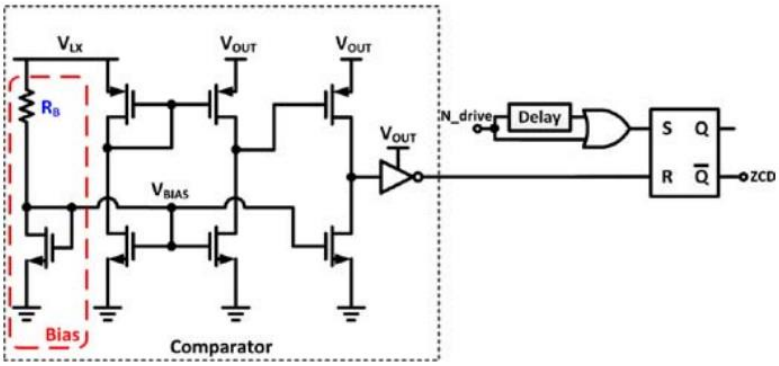


Fig 5.8 Zero Current Detector (ZCD) circuit

The ZCD circuit is illustrated in Fig 5.8. The process involves comparing the voltages at the two terminals of the power transistor MP, V_{LX} and V_{OUT}. The circuit consists of a comparator which is used to detect if V_{LX} and V_{OUT} exceeds the control circuit's supply voltage.
The circuit is enabled only during off-time phase as reverse current can only occur during off-time phase, thereby reducing power consumption.

5.7 CURRENT SENSOR:

A current sensor is a block which is used to keep track of the current flowing through the inductor. The work of this sensor is to convert the output current (V_{sen_dc}) and the inductor current (V_{sen}) into voltages.

Determining the ripple in the inductor current is a crucial task for the inductor current sensor. The inductor current increases during the switch-on phase of the cycle and decreases during the switch-off phase, which defines this ripple.
This sensor plays an important role in maintaining the converter's efficiency and reliability.

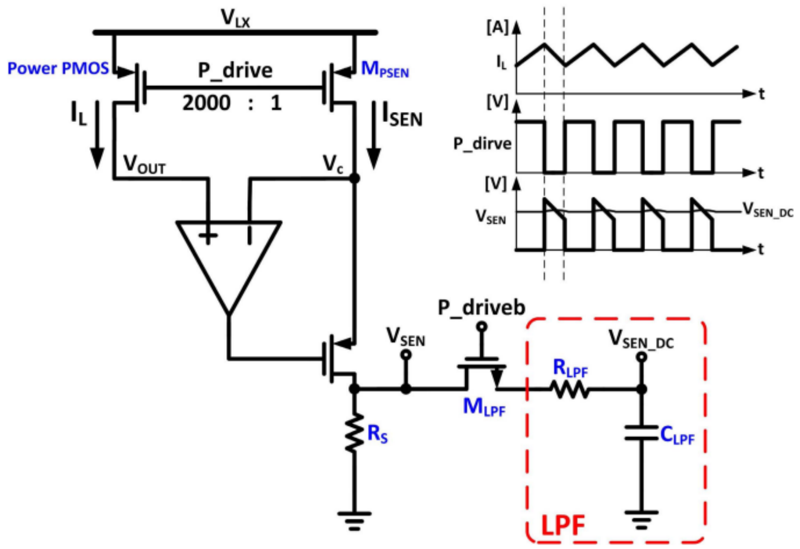


Fig 5.9 Current sensing circuit

The current sensing circuit is depicted in Fig. 5.9. With a ratio of 1/2000, the inductor current (I_L) and the current produced by the p-type sensing transistor (MP_{sen}) are closely followed by each other. I_{SEN} is converted to a voltage signal (V_{SEN}) after passing through the resistor (R_S). Furthermore, the dc voltage of V_{SEN} is extracted using the current sensing circuit. An analog low-pass filter is used to accomplish this.

To ensure the accuracy of the DC value extracted, this low-pass filter's corner frequency is meticulously designed to be far below the converter's switching frequency. The off-time phase is the only time the current sensing circuit operates. During the on-time phase, VSEN is isolated from the LPF using a transistor (M_{LPF}). Consequently, even in the event that V_{SEN} drops to zero during the on-time phase, the LPF's output (V_{SEN_DC}) keeps its previous value.

5.8 MRAOT CONTROLLER:

The MRAOT controller is a control strategy utilized in DC-DC converters, including buck-boost converters. This controller has been developed to control the inductor's ripple current and modify the switches' on-time in response to the state of the load at that moment. In Fig 5.10, the MRAOT controller is displayed.

The MRAOT controller works by monitoring the ripple in the current flowing through the inductor. The inductor current rises during the switch-on phase and falls during the switch-off phase. The controller modifies the on-time of the switches based on the current load condition. This allows the converter to operate in CCM when the load is light, and in DCM when the load is heavy. This can help to reduce the chip area and cost.

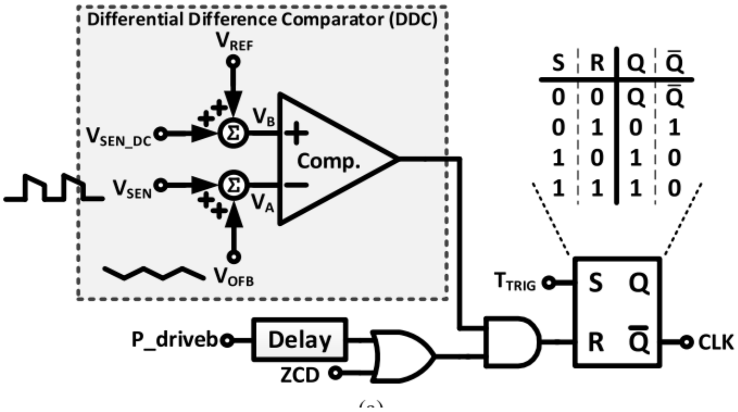


Fig 5.10 MRAOT Controller circuit

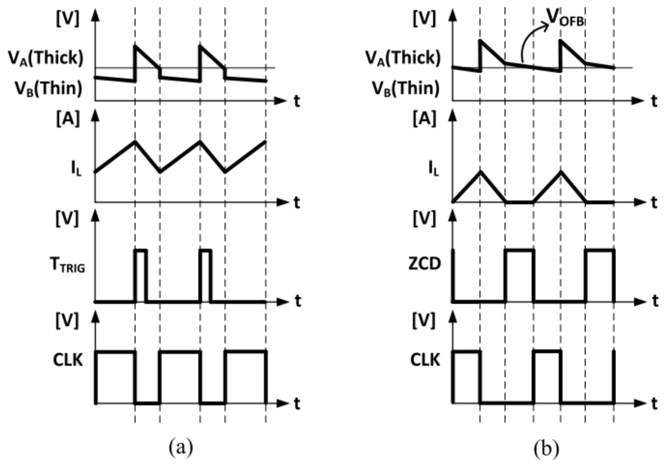


Fig 5.11 Waveforms of MRAOT controller operating in (a) CCM (b) DCM

The MRAOT controller's significant waveforms in both CCM and DCM modes are displayed in Fig 5.11. T_{trig}, the output of the on-time generator, is in charge of managing the on-time duration. Rather than the output voltage ripple (from V_{OFB}), the primary factor affecting the length of the off-time in CCM is the ripple in the inductor current (from V_{SEN}). In contrast, the output voltage ripple plays a significant role in determining the duration of the off-time in DCM.

CHAPTER 6

IMPLEMENTATION

1) Power stage:

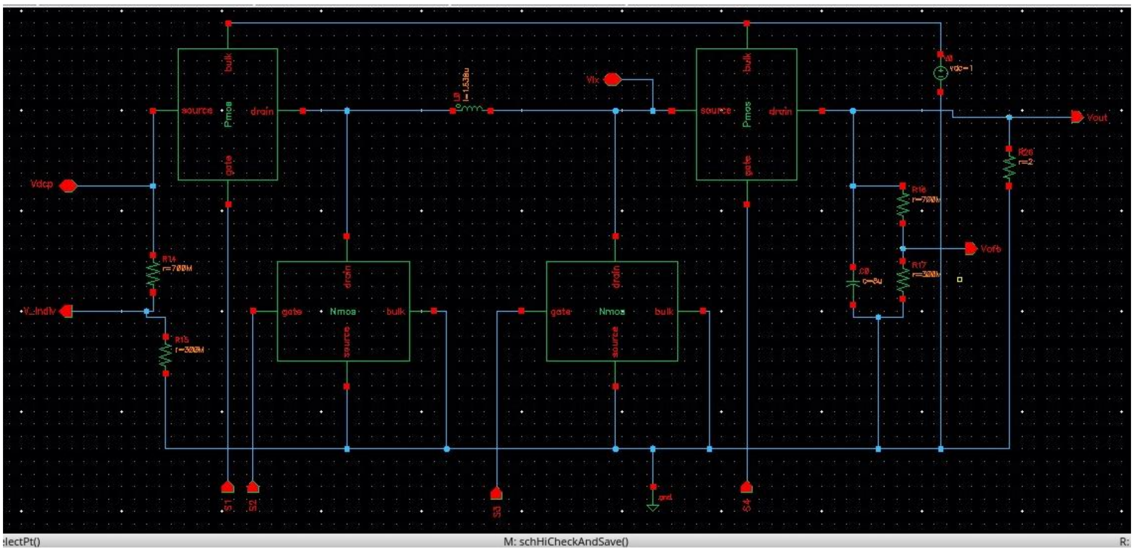


Fig 6.1 Implemented circuit of power stage

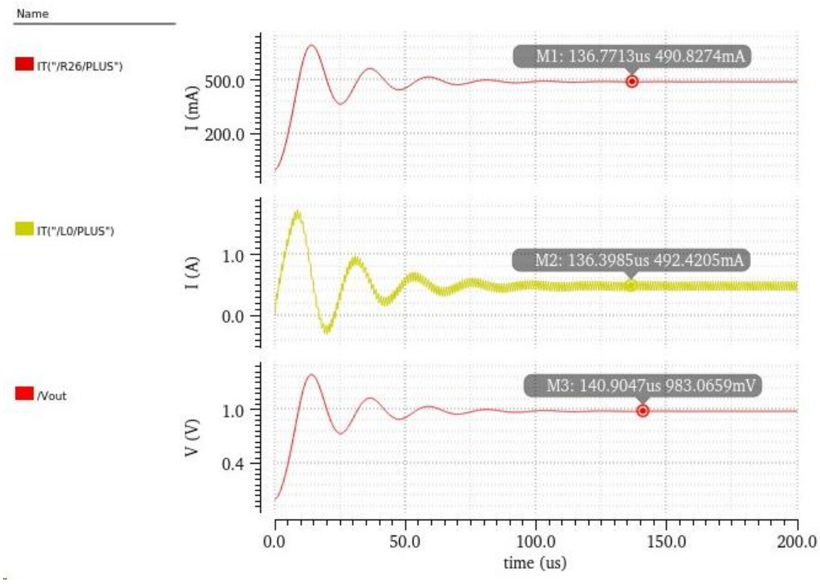


Fig 6.2 Simulation outputs of voltage and current in buck mode

Fig 6.1 illustrates the design of the buck-boost converter's power stage.

Fig 6.2 displays the plotted results of the voltage and current in the buck mode of operation.

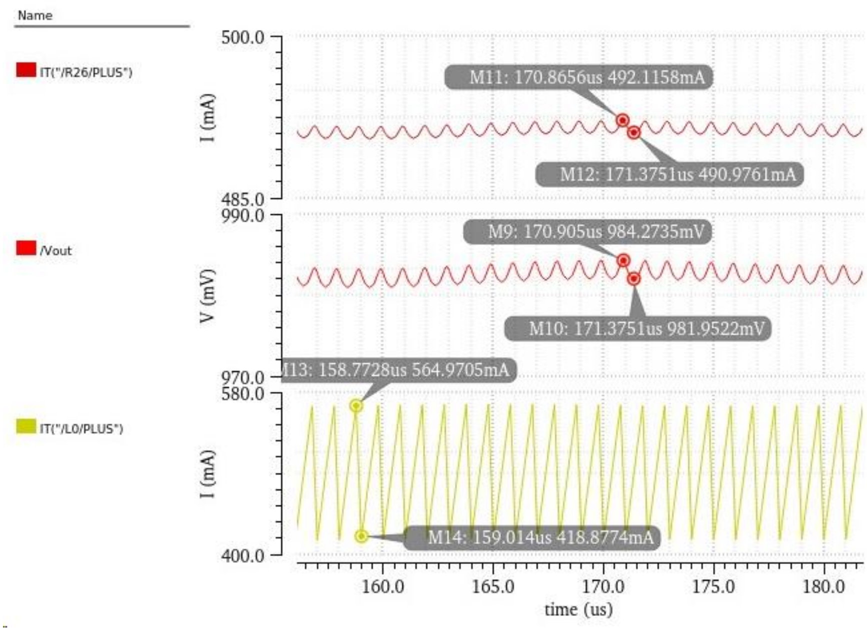


Fig 6.3 Voltage and current ripples in buck mode

Fig 6.2 displays the plotted results of the voltage and current in the buck mode of operation, while Fig 6.3 shows the voltage and current ripples.

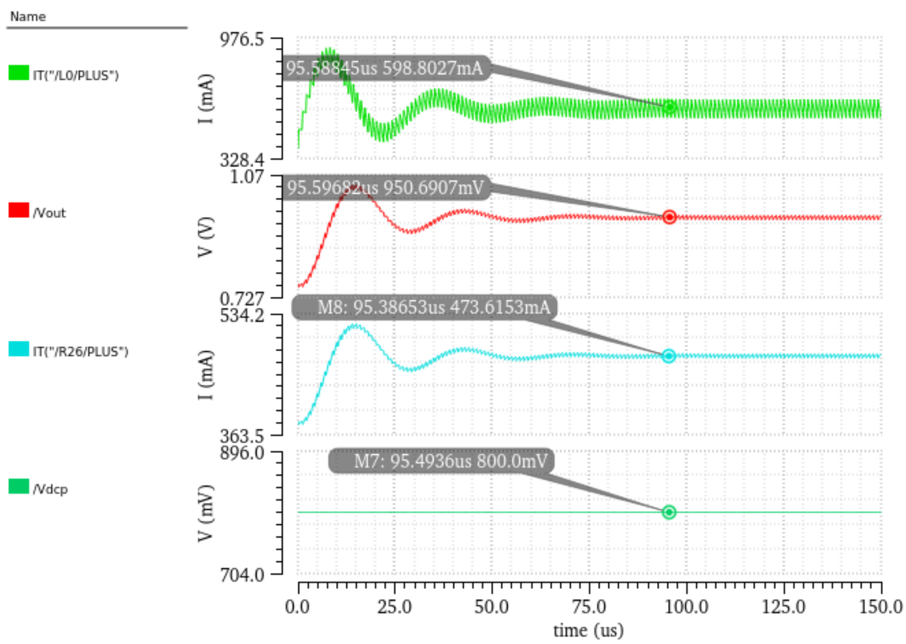


Fig 6.4 Simulation outputs of voltage and current in boost mode

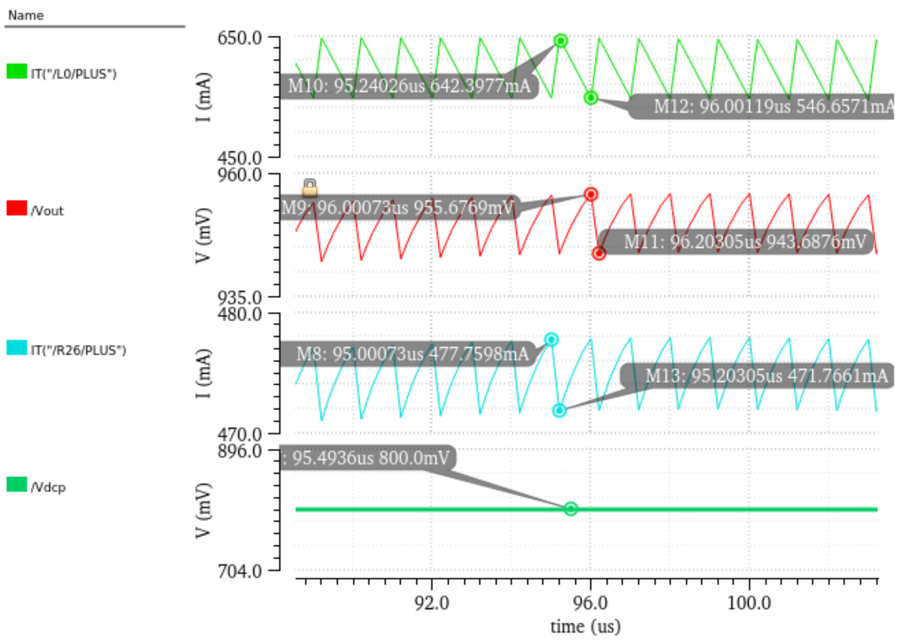


Fig 6.5 Voltage and current ripples in boost mode

Fig 6.4 displays the plotted results of the voltage and current in the boost mode of operation, while Fig 6.5 shows the voltage and current ripples.

2) Implementation of Dead Time Controller (DTC):

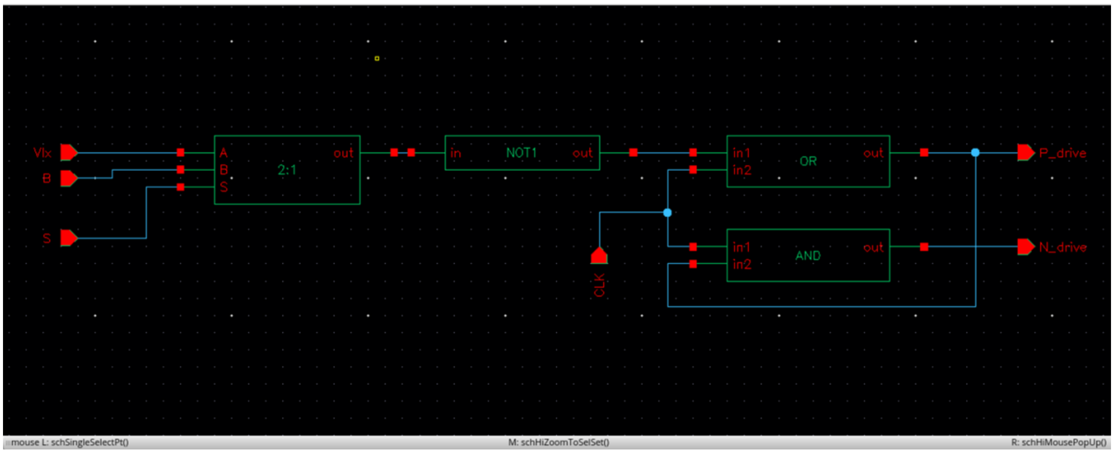


Fig 6.6 Implemented circuit of dead time controller

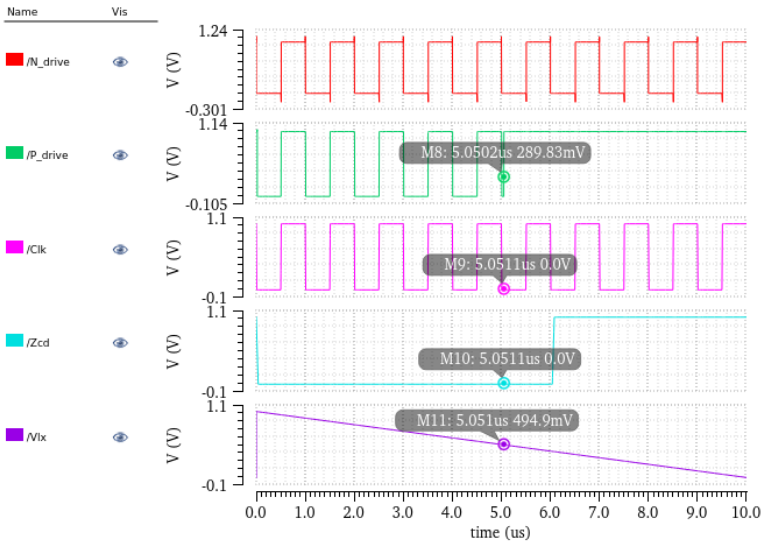


Fig 6.7 Output waveform of DTC when ZCD is low

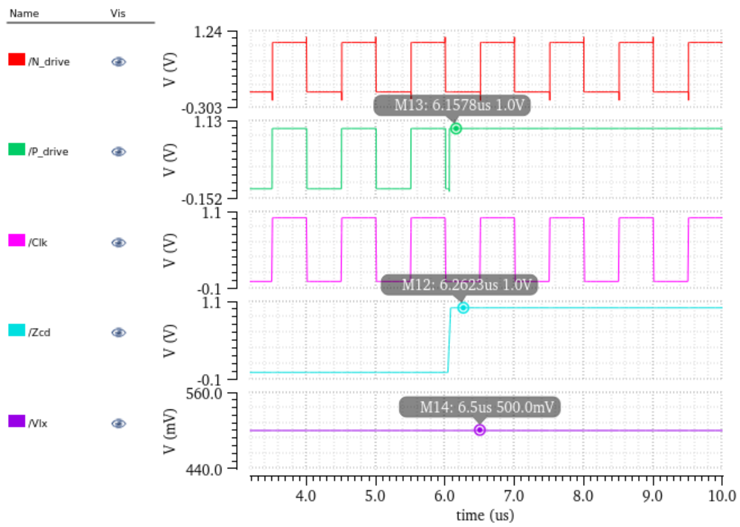


Fig 6.8 Output waveform of DTC when ZCD is high

The Fig 6.7 and Fig 6.8 show the output waveforms of the DTC. When clk is high it indicates the ON phase and when clk is low it indicates the Off phase and both P_drive and N_drive follow the clock, when zero current in detected zcd goes high and the P_drive signal goes high thereby turning Off the PMOS to avoid reverse current flow.

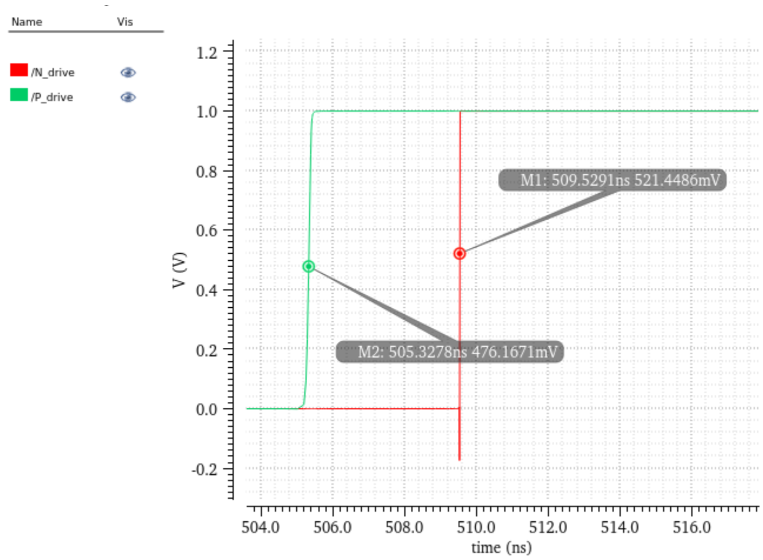


Fig 6.9 Dead time during rising edge of a signal

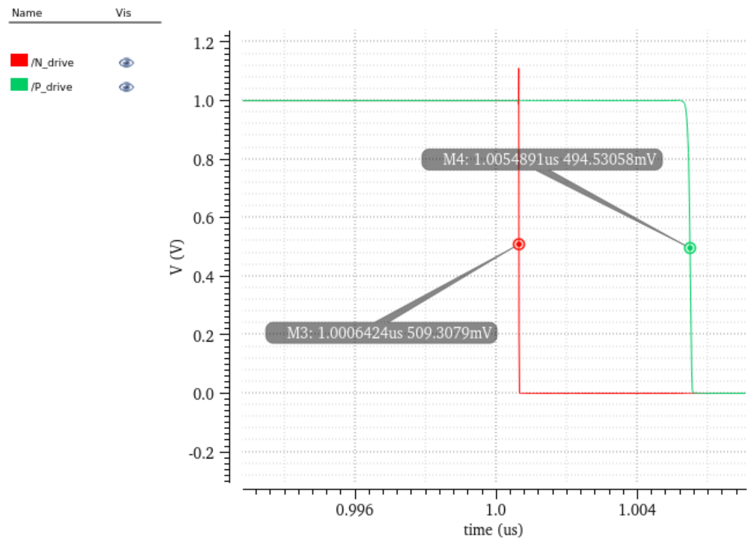


Fig 6.10 Dead time during falling edge of a signal

The introduction of a dead time of roughly 5 ns prevents the simultaneous activation of PMOS and NMOS, which could result in a short circuit, as seen in Fig 6.9 and Fig 6.10.

3) Differential Difference Comparator (DDC):

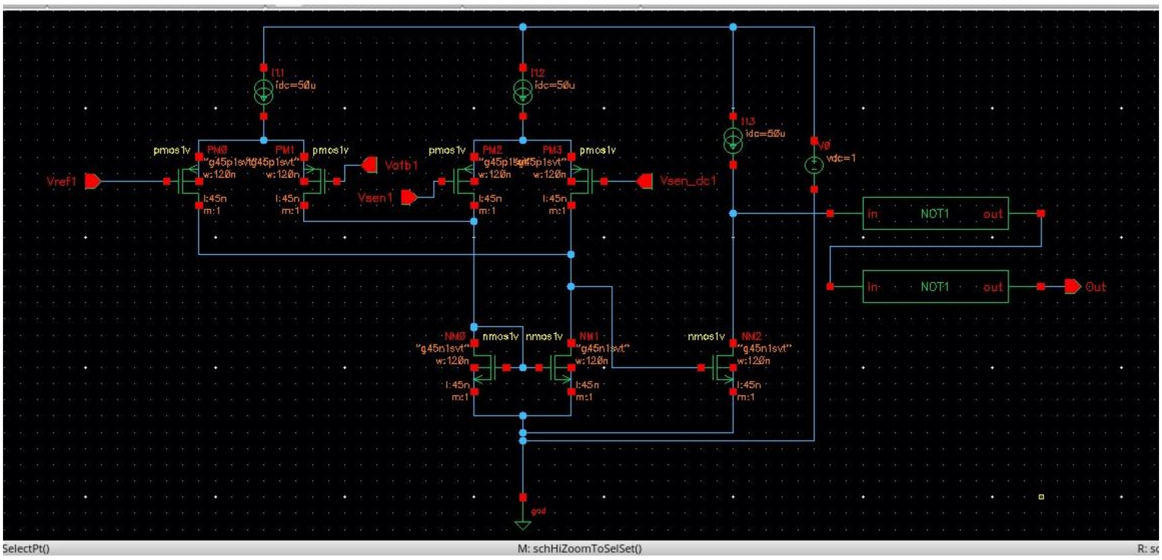


Fig 6.11 Implemented circuit of Differential Difference Comparator

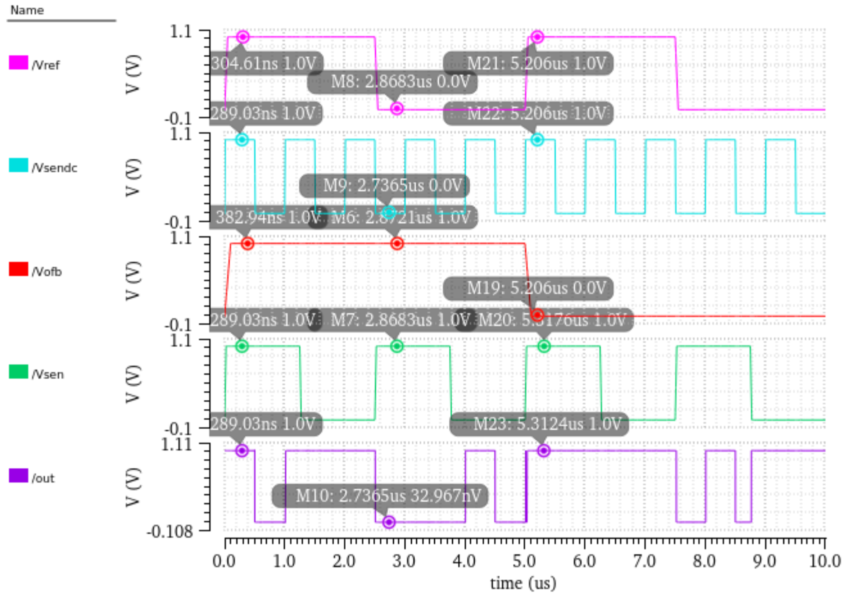


Fig 6.12 Obtained waveforms of DDC

The Fig 6.11 and Fig 6.12 show the waveforms of the DDC. From the waveforms we can infer that when:

$V_{ref} + V_{sendc} > V_{ofb} + V_{sen} \qquad V_{out} = 1$

$V_{ref} + V_{sendc} < V_{ofb} + V_{sen} \qquad V_{out} = 0$

$V_{ref} + V_{sendc} = V_{ofb} + V_{sen} \qquad V_{out} = 1$

4) Voltage Comparator:

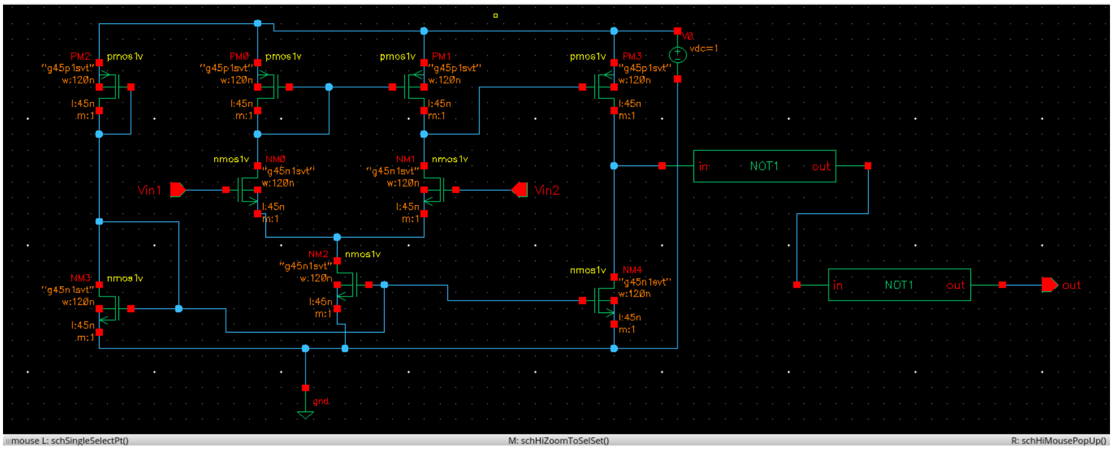


Fig 6.13 Implemented circuit of voltage comparator

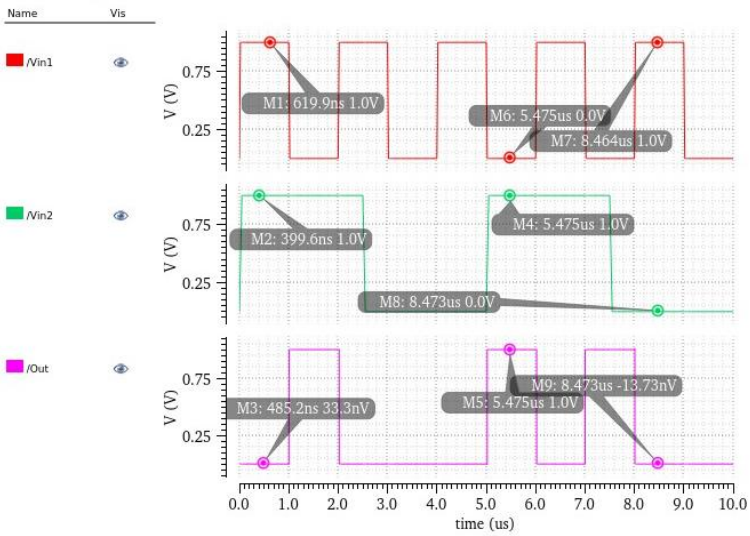


Fig 6.14 Obtained waveforms of voltage comparator

The voltage comparator's implemented circuit is depicted in Fig 6.13, and its waveform is shown in Fig 6.14. The waveform shows the behaviour of a basic CMOS voltage comparator for different input voltage combinations.

When,

$V_{in2} > V_{in1} \qquad out = 1$

$V_{in2} < V_{in1} \qquad out = 0$

$V_{in2} = V_{in1} \qquad out = 0$

5) Adaptive On-time (AOT) Generator:

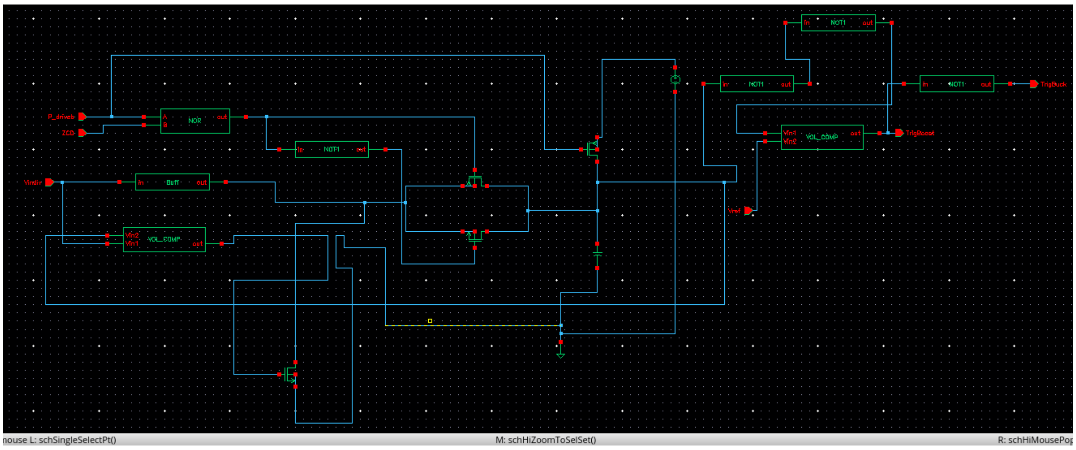


Fig 6.15 Implemented circuit of AOT generator

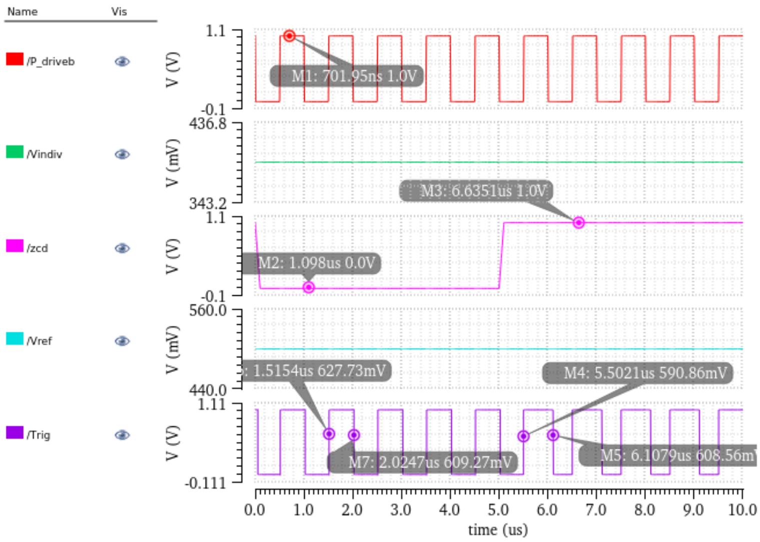


Fig 6.16 Obtained waveforms of AOT generator

Fig 6.15 shows the implemented circuit of AOT generator and Fig 6.16 shows the output waveform of the AOT Generator. When circuit is in the ON phase, ZCD is low and P_drive is high which means that the P_driveb is low which would make the output of NOR gate go high thereby turning the transmission gate OFF and this is when the capacitor starts charging. When the capacitor voltage crosses the reference voltage T_{trig} goes high. During the OFF-phase P_drive goes low thereby turning the transmission gate ON and this causes the capacitor to discharge through the discharge path and during discharging when the capacitor voltage crosses and drops lower than the reference voltage T_{trig} goes low.

6) Zero Current Detector (ZCD):

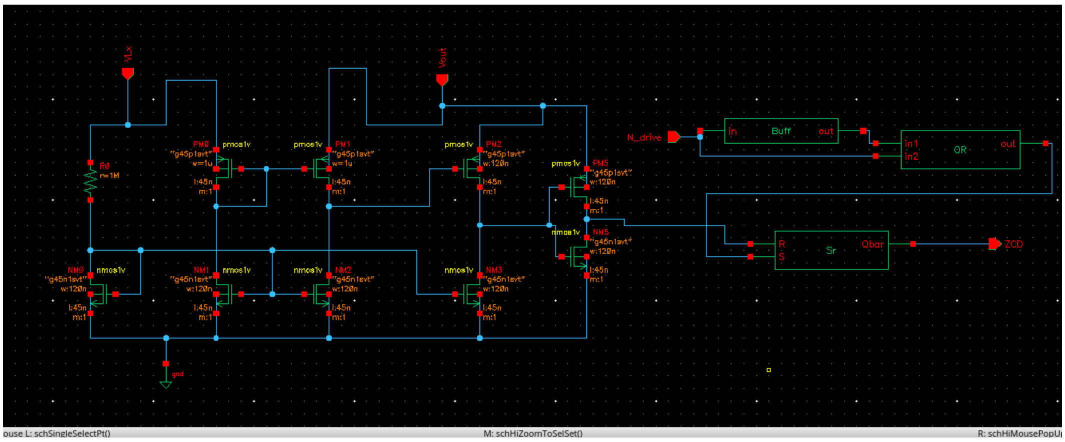


Fig 6.17 Implemented circuit of ZCD

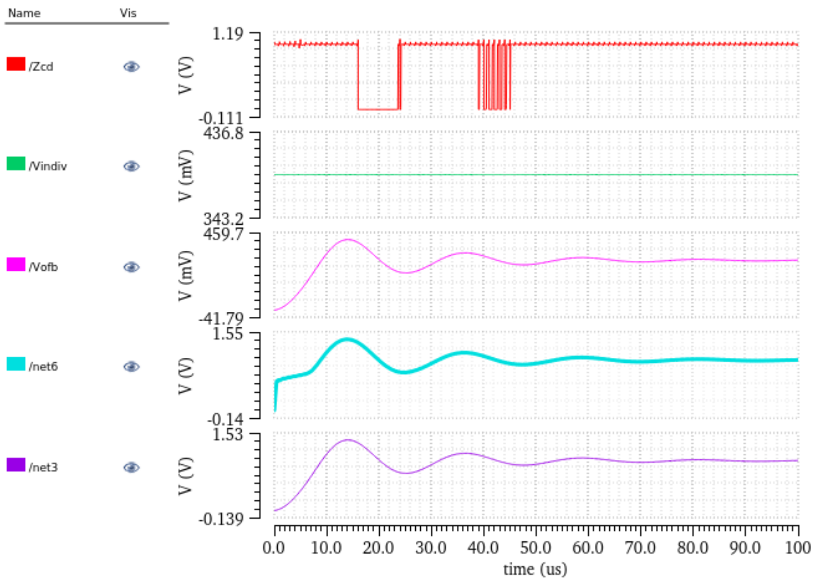


Fig 6.18 Obtained waveforms of ZCD

As seen in Fig 6.18, the reducing inductor current is emulated by presenting reducing voltages across the power PMOS terminals, namely V_{LX} (named in the figure as v_min) and V_{OUT}. When the inductor current reaches zero, the voltage V_{LX} is lower than the threshold value of the NMOS used in the comparator turning them OFF and thus triggering the ZCD signal to go high.

7) Current Sensing Circuit:

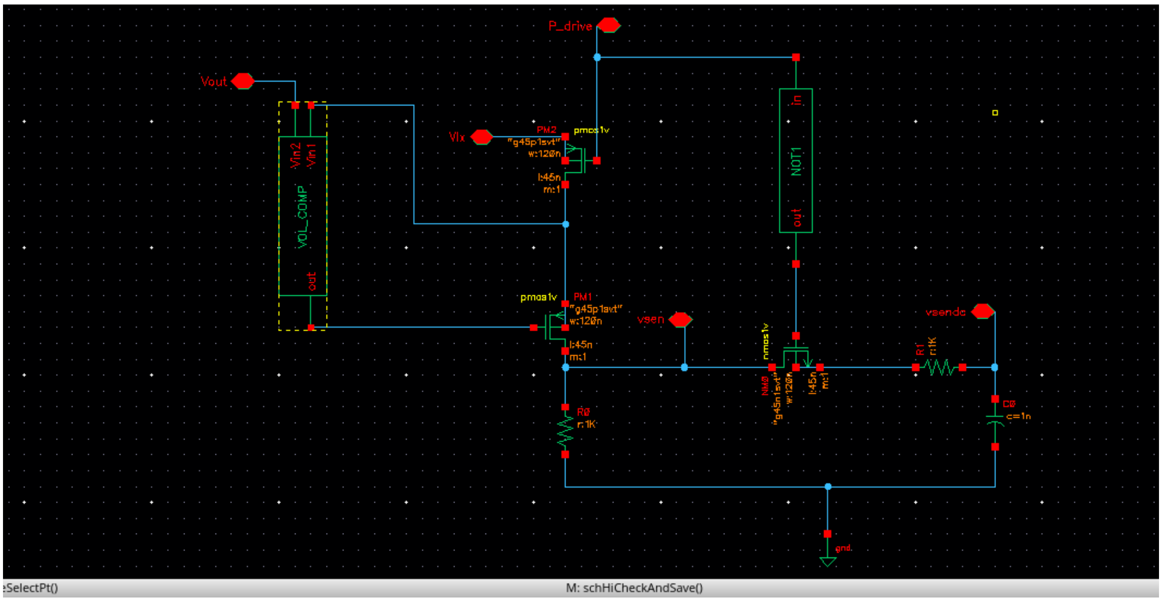


Fig 6.19 Implemented circuit of current sensor

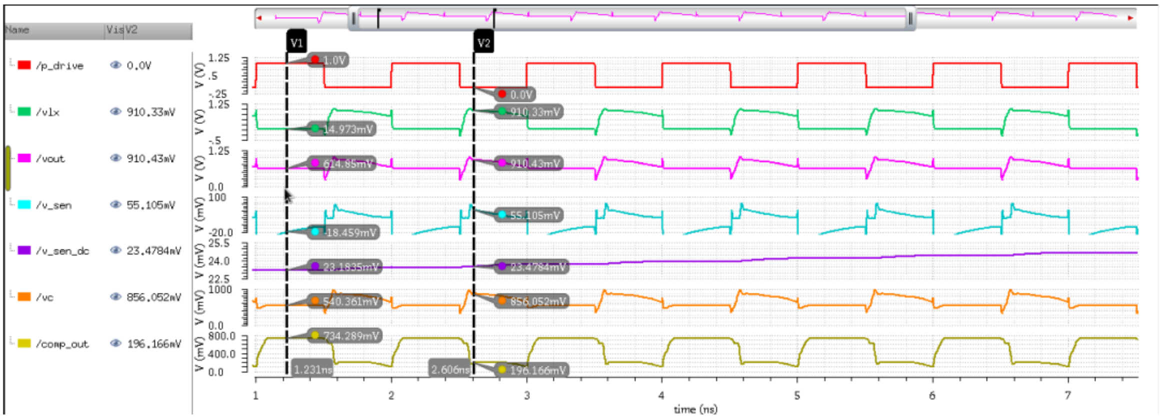


Fig 6.20 Obtained waveforms of the current sensor

As seen in Fig 6.20, the V_{SEN} signal is only sensed during the OFF phase (when P_drive is low) and gradual decrease in the V_{SEN} high corresponds to gradually decreasing inductor current. The V_{SEN_DC} remains almost constant throughout. Output voltage is regulated at approximately 1V

8) Mixed-Ripple Adaptive On-time (MRAOT) Controller:

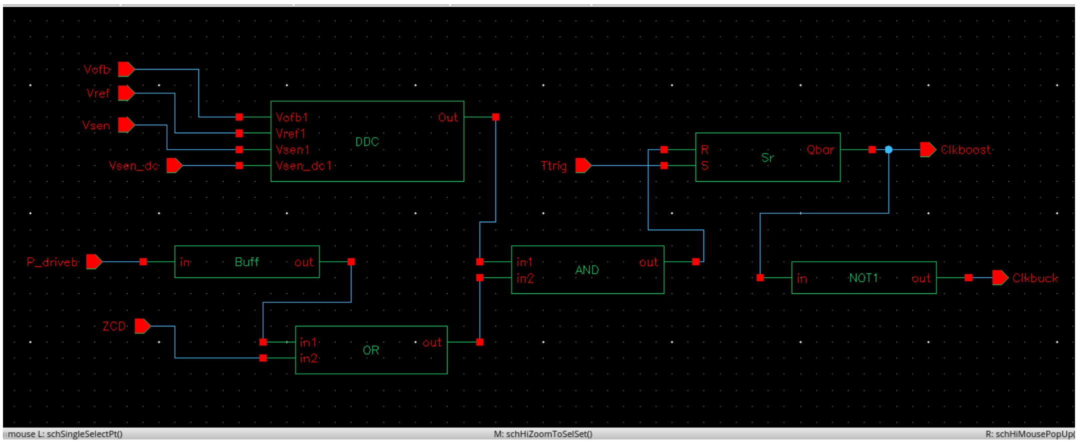


Fig. 6.21 Implemented circuit of MRAOT controller

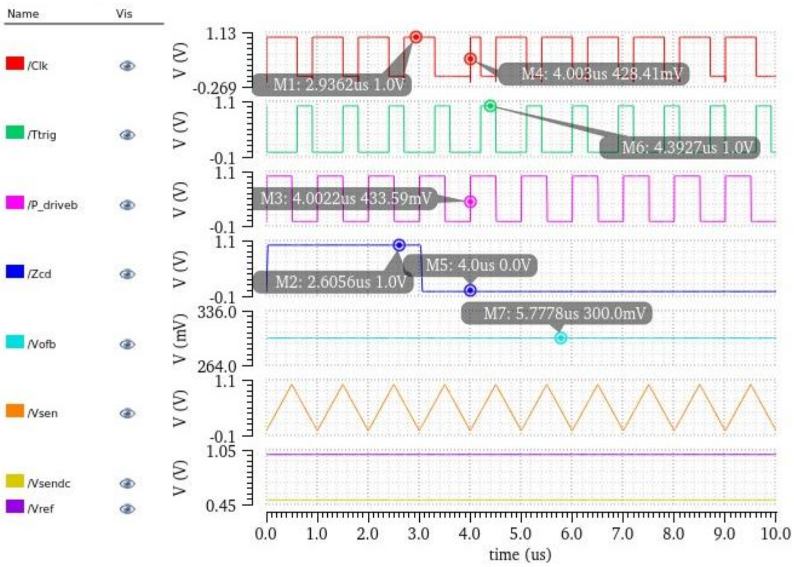


Fig 6.22 Obtained waveforms of MRAOT controller

Fig 6.21 shows the implemented circuit of MRAOT controller and Fig 6.22 shows the output waveform of the MRAOT controller. When T_{trig} goes high clk goes low indicating the end of the on phase. During the Off-phase P_driveb goes high thereby making the OR output to go high, V_{sen} goes higher than V_{sen_dc} making the output of the comparator go low and therefore the output of the AND gate goes low. At this instance S=1 and R=0 thereby making Q=1 and Qbar=0 where Qbar is taken as the Clk.

9) FINAL INTEGRATED CIRCUIT OF NON-INVERTING BUCK-BOOST CONVERTER

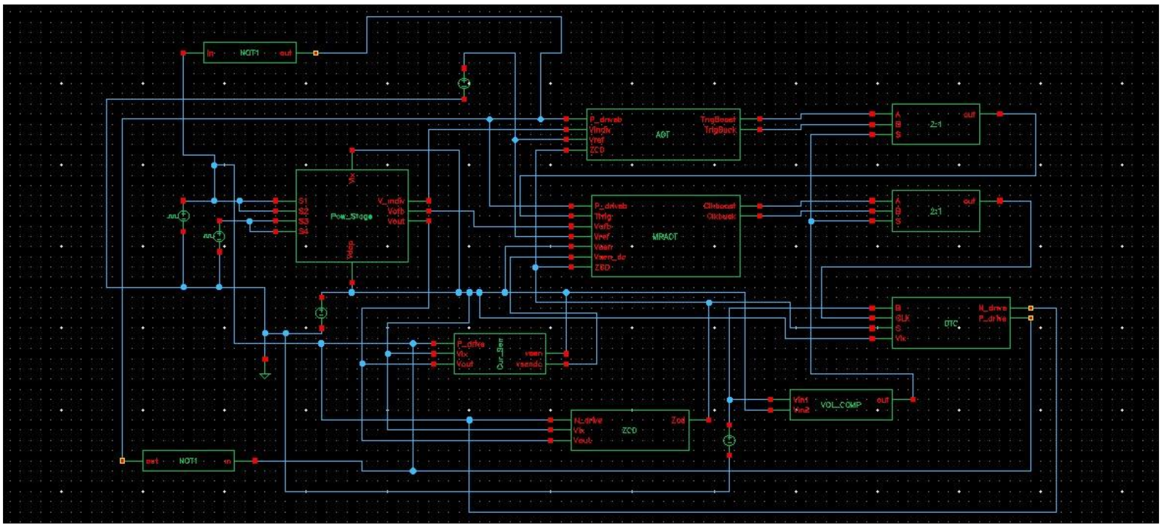


Fig 6.23 Implemented circuit of MRAOT-controlled Buck-Boost Converter

Fig 6.23 shows the implemented block of the mixed-ripple adaptive on-time controlled buck-boost converter. When operating in the buck mode, when $V_{in} = 1.3\,V$ the output parameters were observed to be as follows: V_{out} = 0.982 V, Output ripple = 3 mV, and $I_{Load} = 491\ mA$

When operating in the boost mode, when $V_{in} = 0.8\,V$ the output parameters were observed to be as follows: V_{out} = 0.950 V, Output ripple = 11 mV, and $I_{Load} = 474\ mA$.

CHAPTER 7
SOFTWARE DETAILS

- Cadence is a leading EDA and Intelligent System Design provider delivering hardware, software, and IP for electronic design.

- The company is known for its electronic design automation (EDA) software, in addition to software, hardware and silicon structures for integrated circuits, printed circuit boards and systems on chips.

CADENCE VIRTUOSO:

- Virtuoso is majorly used for custom design and analysis of circuits based on MOS technologies, especially in the CMOS VLSI course.

- The Cadence Virtuoso ADE Suite is the industry's leading solution for design exploration, analysis, and verification of analog, mixed-signal, and RF designs.

- Cadence Virtuoso is a comprehensive tool for integrated circuit design, providing a wide range of features for schematic capture, layout design, simulation, verification, and more.

CHAPTER 8
RESULTS AND CONCLUSION

8.1 Results

8.1.1 Power Efficiency

Power efficiency = (Output power) / (Input power)

1) Buck mode:

Output voltage (Vout): 0.984V

Output current (Iout): 0.492A

Input voltage (Vin): 1.3V

Input current (Iin): 0.4941A

Power efficiency = 75.37%

2) Boost mode:

Output voltage (Vout): 0.95V

Output current (Iout): 0.474A

Input voltage (Vin): 0.8V

Input current (Iin): 0.598A

Power efficiency = 94.13%

The power efficiency for buck and boost mode of operation are found to be 75.37% and 94.13% respectively.

8.1.2 Load Regulation

Table 8.1 Output voltage for different load resistance values

Resistance value (in Ohms)	Output Voltage (in V)
0.5	0.920
1	0.962
1.5	0.975
2	0.98
2.5	0.988
3	0.99
3.5	0.992

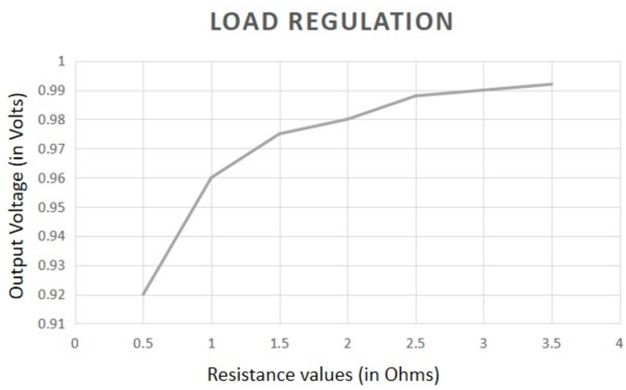


Fig 8.2 Load Regulation

8.1.3 Line Regulation:

Table 8.3 Output voltage for different input voltage values

Input voltage (in V)	Output Voltage (in V)
0.7	0.942
0.8	0.95
0.9	0.958
1	0.967
1.1	0.973
1.2	0.979
1.3	0.984

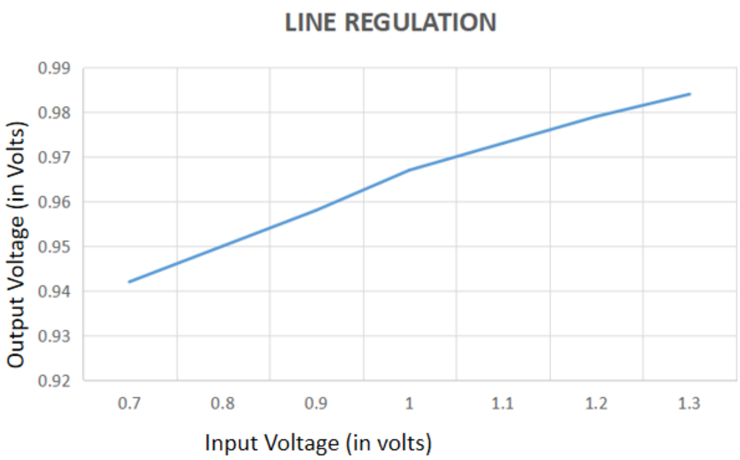


Fig 8.4 Line Regulation

8.1.4 Stability Analysis (AC Response)

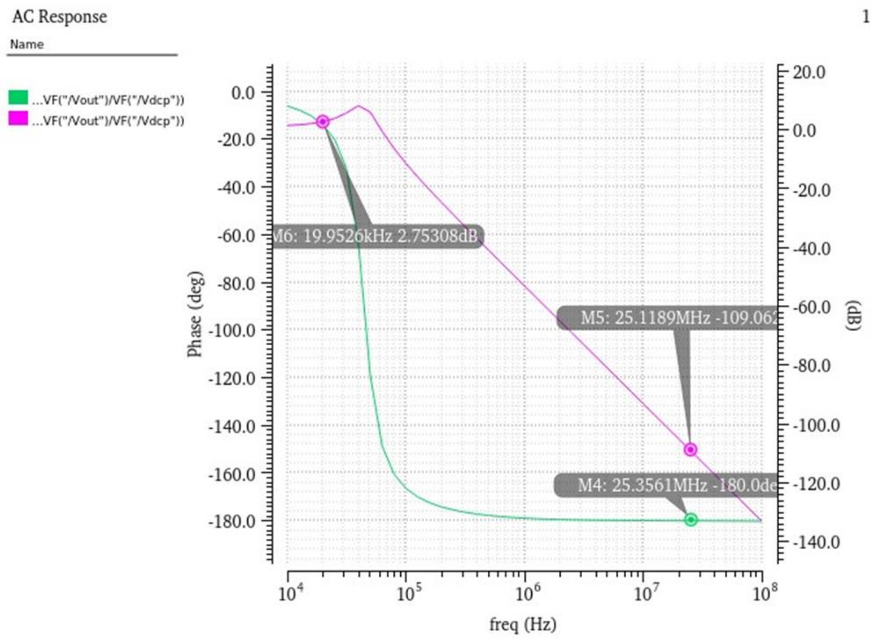


Fig 8.5 Phase-Gain plot

When phase is -180^0, gain is negative which indicates that the system is stable.

8.2 Conclusion

- Power efficiency of 95% has been obtained for boost operation.
- Power efficiency of 75% has been obtained for worst corner case of 1.3 V during buck mode.
- Stable output voltage with minute ripple of 10 mV has been obtained with a small amount of settling time.
- Load and Line regulation analysis performed and the output remains stable across the wide range of load values.

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Mixed Ripple Adaptive ON-Time Controlled Non-Inverting Buck-Boost For Biomedical Sensor Applications

Keshavadithya S. Akhilesh. Vishwanath Vijay Tirakapadi. Amogh Mudakavi.

Project Guide: Prof. Sunita M S

Project ID: N-16 B.Tech 2020-24

Motivation:

Any electronic device is composed of different modules and each module functions at a particular fixed DC voltage.But the power which we get from the power line is not usually the required level for the device to function.

Therefore a vital role is played by the power management integrated circuit(PMIC) for voltage regulation.The component of PMIC which does this job is the voltage regulator and our project is one such voltage regulator.

Working principle:

- A non-Inverting buck-boost converter is used to either step down or step up the input voltage to get the required output voltage.
- This is done by using an inductor to store energy and dissipate across the output accordingly.
- MOSFETs are used like switches to control the charging and discharging of the inductor and the output capacitor.
- Adaptive ON-Time(AOT) generator produces a trigger signal which indicates the on time for the clock which is given as input to the gates of the switches.
- The duty cycles for each mode of operation that is, the buck and the boost modes is produced by the AOT generator.
- In buck mode switch SW3 is OFF,SW4 is ON and SW1,SW2 are switched ON and OFF simultaneously to get the required output.
- In boost mode switch SW2 is OFF,SW1 is ON and SW3,SW4 are switched ON and OFF simultaneously.In this,the inductor and input voltage behave like 2 sources in series to obtain the required output voltage.

Feedback Blocks:

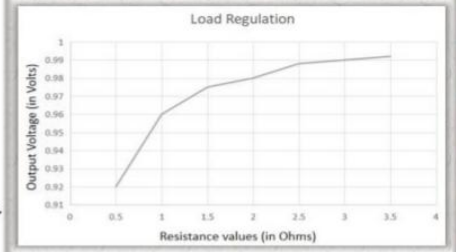
- Differential Difference Comparator (DDC)
- Zero Current Detector (ZCD)
- Inductor Current Sensor
- Adaptive ON-Time Generator (AOT)
- Dead-Time Controller (DTC)
- MRAOT Controller

Software Used:

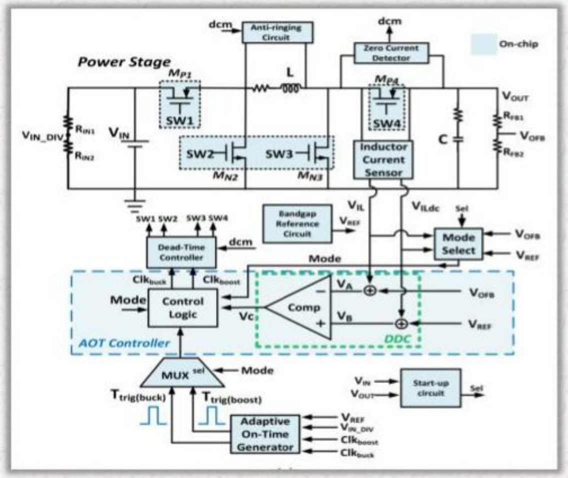
This project has been implemented on Cadence Virtuoso.

Technology node:

Implemented using the gpdk045nm CMOS library.



BLOCK DIAGRAM

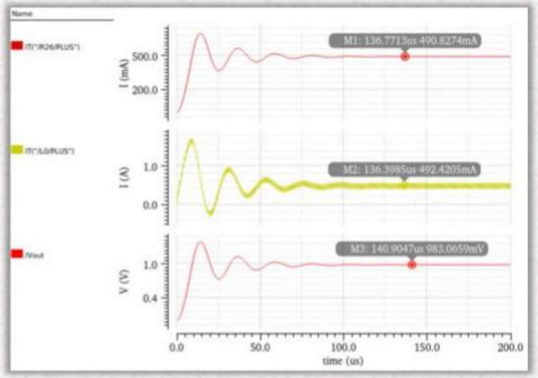


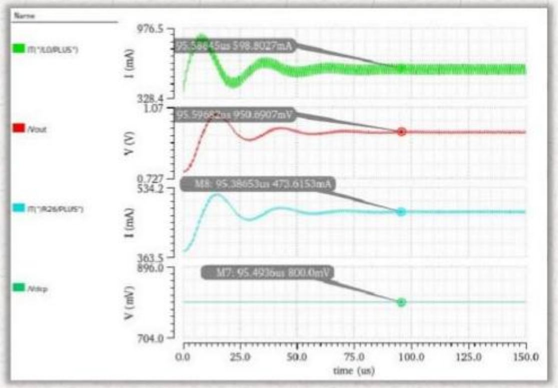
Design Parameters

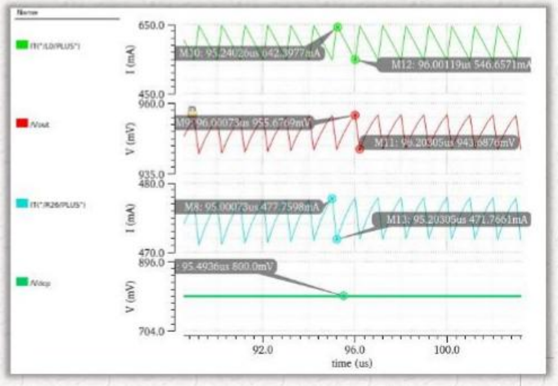
Parameter Name	Value
Technology (nm)	45 CMOS
Inductor (µH)	1.538
Capacitor (µF)	8
V_{In} (V)	0.8-1.3
V_{Out} (V)	1
Switching Frequency (MHz)	1
D_{Buck}	0.769
D_{Boost}	0.2
Load Current (A)	0.5
Max Voltage Ripple (mV)	10

Parameter	Parameter Value	
	Base Paper	This Paper
Technology	350nm	45nm
Vin	2.5-5V	0.8-1.3V
Vout	3.3V	1V
Switching frequency	Varied	1MHz
Output Current	350mA	500mA
Output Voltage ripple	20mV	10mV

SIMULATION RESULTS







Conclusion :

- ***Power efficiency of 95% has been obtained for boost operation.***
- ***Power efficiency of 75% has been obtained for worst corner case of 1.3 V during buck mode.***
- ***Stable output voltage with minute ripple of 10 mV has been obtained with a small amount of settling time.***
- ***Load and Line regulation analysis performed and the output remains stable across the wide range of load values.***

Mixed-Ripple Adaptive On-Time Controlled Non-Inverting Buck-Boost DC-DC Converter for Biomedical Applications

Keshavadithya S, Vishwanath Tirakapadi, Akhilesh, Amogh Mudakavi, and M S Sunita, PES University Bengaluru

***Abstract*-A mixed ripple adaptive ON-Time controlled non-Inverting buck-boost dc-dc converter is proposed. The proposed converter operates only in buck or boost modes and not in the buck-boost mode to avoid power loss that is incurred while operating in the buck-boost mode. Maximum efficiency is achieved at the lowest input while operating in the boost mode. The design was implemented on Cadence using the gpdk045nm CMOS (45nm CMOS) library. The input voltage ranges from 0.8 V - 1.3 V and the output is regulated to 1 V. The maximum power efficiency came out to be 94.13 % and at the highest voltage when operating in the buck mode the power efficiency achieved was equal to 75%.**

***Keywords:* Mixed Ripple Adaptive ON-Time control (MRAOT), ON-Time generator, Zero current detector (ZCD), Differential Difference comparator (DDC)**

I. INTRODUCTION

The power/voltage we get in the power line is not the level that a particular electronic device may require to function. Almost all electronic devices have multiple modules and each of these modules functions at a different voltage level. To deal with this, all electronic devices have a module called the Power Management Integrated Circuit or PMIC which delivers the required voltage to each of the modules in an electronic device.

One of the major components in a PMIC is a voltage regulator which can either step up or step down the voltage. The DC-DC non-inverting buck-boost converter is one such voltage regulator that can help solve this problem. This can operate in both buck and the boost modes and also in the buck-boost mode but in the proposed converter we refrain from operating in the buck-boost mode since operating in that mode would require simultaneous switching of all the switches/transistors which would lead to high switching losses. Hence to avoid the switching losses and to obtain a high conversion efficiency we operate the converter only in the buck or boost modes.

The proposed converter uses the Mixed ripple adaptive On-Time control which has a significant advantage as compared to the conventional PWM (pulse width modulation) based control, in this it doesn't require a compensation circuit which contributes to the total power required by the circuit. Therefore, by not using a compensator circuit we are reducing the chip area and are also cutting down on the total power utilized by the converter. It has the additional advantages of good load and line regulation, high conversion efficiency, and a smooth transition between the buck and boost modes. This design has been proposed for biomedical sensors which function on low voltages (1 V).

II. BLOCK DIAGRAM AND CIRCUIT IMPLEMENTATION

A. Block Diagram and Different Feedback Blocks

Fig. 1 shows the block diagram of the mixed-ripple adaptive on-time controlled buck-boost converter. Different blocks in the block diagram are implemented in this circuit. And no compensator is used in the implemented block diagram. The output voltage, or VOUT, is split and sent to the MRAOT controller. While this controller decides when the converter enters the inductor charging phase (i.e., on-time), the adaptive on-time generator establishes the duration of the on-time period.

The differential difference comparator (DDC) in the feedback circuit is used to control the operation of the converter in continuous and discontinuous conduction modes (CCM and DCM). The DDC compares the output voltage with the reference voltage and the switch will be turned ON or OFF based on the comparison result. The two input signals to DDC are represented by V_A and V_B.

Where $V_A = V_{OFB} + V_{IL}$ and

$$V_B = V_{REF} + V_{ILdc}$$

Here, V_{IL} is the voltage that represents the sensed inductor current, V_{REF} is the reference voltage, V_{OFB} is the output feedback voltage, and V_{ILdc} is the voltage that represents the average inductor current. When V_A is greater than the V_B, the output of the DDC V_{out} is 1. When the signal V_A gets lower than V_B, the output of the DDC V_{out} is 0.

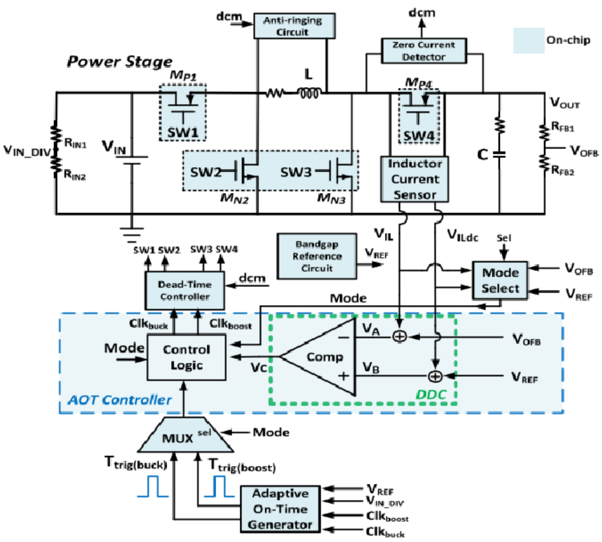


Fig. 1. Block Diagram of Mixed-Ripple Adaptive On-time controlled Buck-Boost converter

In a buck-boost converter, the on-time generator's role is to adjust the on-time duration based on the input and reference voltages. This adjustment is crucial in determining the output voltage of the converter. This adaptability enhances the converter's efficiency and flexibility, as it can sustain a stable output voltage even when the load current fluctuates.

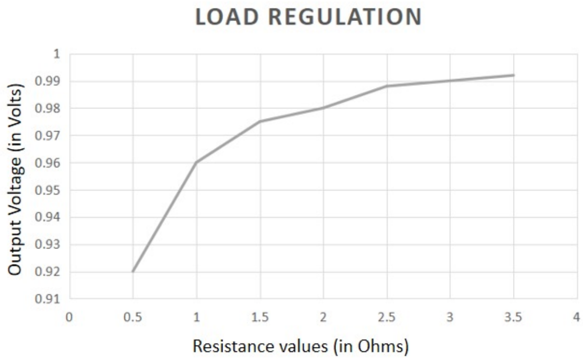
The Zero Current Detector (ZCD) in the feedback block is vital in a buck-boost converter operating in Discontinuous Conduction Mode (DCM) at light loads. It is used to identify the moment of zero inductor current and subsequently switches off the power transistor MP. This action prevents the occurrence of reverse inductor current. The circuit is designed to be enabled only during the off-time phase to minimize power consumption. This is because reverse current can only occur during the off-time phase.

In a buck-boost converter, an inductor current sensor is used to keep track of the current passing through the inductor in the circuit. This sensor plays a vital role in managing the converter's operation, maintaining its efficiency, and ensuring its reliability. It consists of a low-pass filter (LPF). The corner frequency of this low-pass filter is carefully designed to be far below the switching frequency of the converter, to ensure the accuracy of the DC value that is extracted.

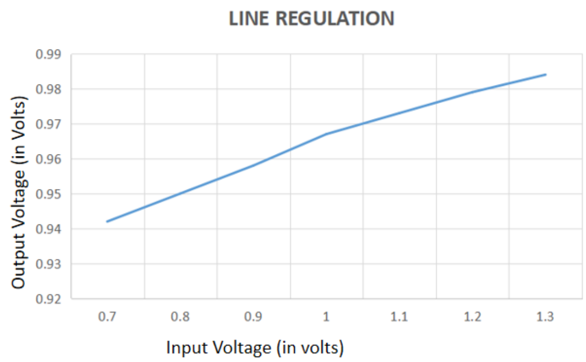
The Mixed Ripple Adaptive On-Time (MRAOT) controller is a control strategy utilized in DC-DC converters, including buck-boost converters. The MRAOT controller works by monitoring the ripple in the inductor current. The inductor current rises during the switch-on phase and falls during the switch-off phase. The controller modifies the on-time of the switches based on the current load condition. This allows the converter to operate in CCM when the load is light, and in DCM when the load is heavy. This can help to reduce the chip area and cost.

III. Measured Results

The proposed converter was implemented on Cadence Virtuoso using the GPDK 45nm CMOS library. The input voltage ranges from 0.8 V to 1.3 V and the output voltage is regulated to 1 V. The inductor and output capacitor values were computed and found to be equal to 1.538 µH and 8 µF respectively. The maximal load current is 500mA. When operating in the buck mode, that is when $V_{in} = 1.3\,V$ the output parameters were observed to be as follows $V_{out} =$ 0.982 V , Output ripple = 3 mV and $I_{Load} = 491\,mA$. When operating in the boost mode, that is when $V_{in} = 0.8\,V$ the output parameters were observed to be as follows: $V_{out} =$ 0.950 V, Output ripple = 11 mV and $I_{Load} = 474\,mA$. Also, load and line regulation graphs are plotted to verify the variation in the output voltage.



(a)



(b)

Fig. 2. (a) Load Regulation (b) Line Regulation

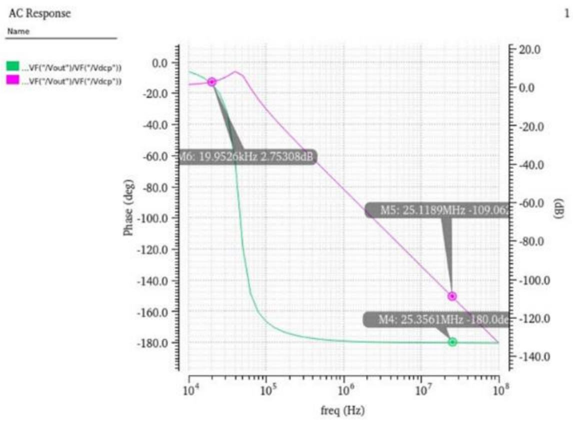
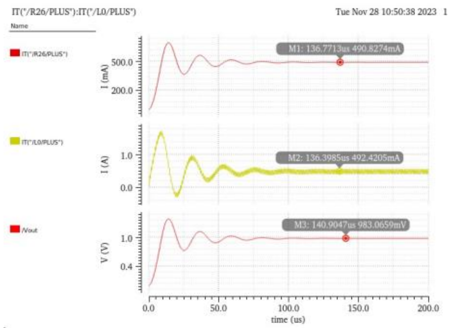


Fig. 3. Phase-Gain Plot



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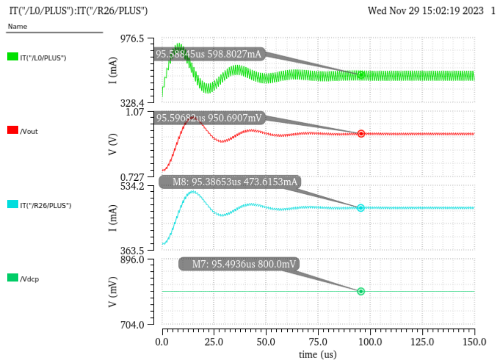

(b)
Fig. 4. Output waveforms in (a) Buck mode (b) Boost mode

TABLE 1
PERFORMANCE COMPARISON

Parameter	Parameter Value	
	Base Paper	**This Paper**
Technology	350nm	**45nm**
Vin	2.5-5V	**0.8-1.3V**
Vout	3.3V	**0.95V**
Switching frequency	Varied	**1MHz**
Output Current	350mA	**491mA**
Output Voltage ripple	20mV	**11mV**
Peak Efficiency	97.8%	**94.13%**

According to the measured results, the efficiency of 94.13% has been achieved in the boost mode for $V_{in} = 0.8\ V$ and an efficiency of 75% in the buck mode for $V_{in} = 1.3\ V$. he switching frequency was fixed to 1 MHz. A stability analysis was also conducted and can be seen from the phase-gain plot in Fig 3. The negative gain of -109 dB at -180^0 indicates that the system is stable. Line and load regulation was also observed from the figures. The proposed converter does not need any compensator.

IV. CONCLUSION

The proposed MRAOT-controlled non-inverting buck-boost converter does not require a compensation circuit, has a peak efficiency of 94.13 %, and a very low output voltage ripple ranging from 3 - 11 mV and MRAOT control allows for the smooth transitioning between buck and boost modes. Load and Line regulation analysis has been performed and the output remains stable across the wide range of load values.

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