Nanotechnology Perceptions
ISSN 1660-6795
www.nano-ntp.com

High Speed with Low Input Voltage based dc/dc Converter using Inductor for Energy Harvesting Application

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To operate portable devices in low input supply voltages dc-dc converter are very helpful and this type of devices are usefull in energy harvesting application. In this work to boost low voltage dc-dc converter with inductor is used to produce high voltage supply voltage. In this work input supply voltage is 550mV and it produce output voltage of 1.0 v. and by delivering a output current of 5.018µA and efficiency of about 35.66%. and inductor were sized in 60µH to boost input voltage. Output power is 7.2216µW.

Keywords: Converters, dc/dc power conversion, integrated circuit (IC) design.

1. Introduction

Energy scavenging is method in which energy is derived from outer source like solar power, thermal energy, salinity gradients, kinetic energy and wind energy are captured and stored for small wireless automous devices, these are used in wireless sensor networks and wearable electronics[1]. Energy harvesting have the low quality like low current and voltages or both and it is unsuitable for standard integrated devices for supplying. A energy harvesting takes the energy from environment and converts that energy into electrical energy and gives the output or an unregulated source voltage. Energy harvesting are used in application like handheld, portable and implementable electronics.

A dc/dc converter is a type of device like electronic circuit or electromechanical device, it converts from one voltage level to another voltage level of direct current (dc) and it is a type of power converter that converts level range of power from very low that is small batteries to very high that is high voltage power transmission.

The dc/dc converter Rises voltage of circuit without using more batteries of portable devices for to increase power. To increase the ultralow voltage dc/dc converter uses inductive based circuit, with the use of inductor it Rises the voltage level and these are widely used in power

electronics. An inductor is driven by almost lossless devices, ideal clock signals with large currents. In dc/dc converter it uses boost converter to step up voltage. The boost converter is used to increase the input voltage level from supply to high output voltage level to load. The boost converter is a class of switched mode power supply with containing two semiconductors that is diode and transistor and containing one storage element that is capacitor or inductor or both. In dc/dc converter output voltage is greater than source voltage. The boost converter is also called as step up converter and here p=vi, the output current is lower than source current.

2. Related Work

Some researches were proposed to differentiate between:

Richelli, Colalongo, Quarantelli, Carmina, Kovacs-Vajna, "A Fully Integrated Inductor using 1.8V to 6V step up converter," in this paper designed full integrated step up converter with using of inductive elements, it is fabricated in 180nm process with supply voltage of 1.8V and produce output voltage of 6V at 10kΩ resistive load with external clock frequency as 60MHz. Low voltage technologies are used in I/O circuits, memories, processor and many more applications. Usually flash memories like EEPROM and OTP memories takes high internal voltages in operations of hot electron injection in operation like writing and erasing operations and in order to activate tunnelling. In this paper to step up voltage charge pumps are used it is based on the model Dickson architecture. These results in power efficiency degradation and area is also more. In this paper dc/dc up converter is designed with inductor there is no external voltage taken. This paper is for understanding how input voltage is step up to high voltage that is dc/dc converter with inductor supply voltage of 1.8V and it is used for low voltage but not for high voltage.

Richelli, Colalongo, Tonoli, Kovacs Vajna, "A 0.2v/1.2v DC/DC Boost Converter in application Power Harvesting," In this paper DC-DC converter can boost up at 200mv input voltage and produce output voltage at 1.2V. The converter is based on hybrid inductive and capacitive these are for power harvesting. This paper is designed 180nm process technology at low threshold voltages. In this design as voltage is increases by charge pumping this leads to threshold voltage of MOS transistor increases because of body effect and overall efficiency is decreases. As number of charge pump stage is increases threshold voltage of MOS transistor also increases so instead of increasing the charge pump stage inductors are used to increase input voltage. So combining of these two charge pump stage and inductor both used to increase input voltage. This architecture produce output current 120µA and maximum efficiency of 36%. Two inductors are used for external component.

Halvorsen, Lande, and Hjortland, "Power Harvesting Circuit using 90nm cmos," In this paper circuit is implemented in 90nm CMOS process technology. This architecture uses capacitors and rectifiers that is diodes and this rectifier element is challenging. Here four step cascaded charge pump is required. In 90nm process technology low threshold voltage exhibits that is about 0.18v. In this design there are two methods to improve output voltage one is increasing charge pump stage by doing this efficiency is decreases and also increases circuit size so minimize the voltage drop of transistor is efficient way to improve charge pump. Input frequency a 900MHz and 2.45GHz and input voltage as 300mv. This architecture requires two

cascaded charge pump for positive output and negative output voltage. This architecture are used in RF signals to boost input voltage power harvesting in devices like RFID. It produce output current of about 60µW with 90nm CMOS process.

3. DC/DC Converter Architecture

In dc/dc converter there are three stages they are Boosting stage, Timing circuit and Regulator part. In order to exchange ultralow voltage to high voltage that is 300m to 1.2v, boosting stage requires two cascaded step up converter that is stepup1 and 2. In this work the voltage is step up by using inductor. In our design input voltage is increased by inductor. In boosting stage transistor is used as a inverter. Boost stage performs in two operation that is when switch is open and switch is closed. The clock generator second stage is to generate 75% duty cycle, combining D-flip/flop these are used to generate 50% duty cycle.

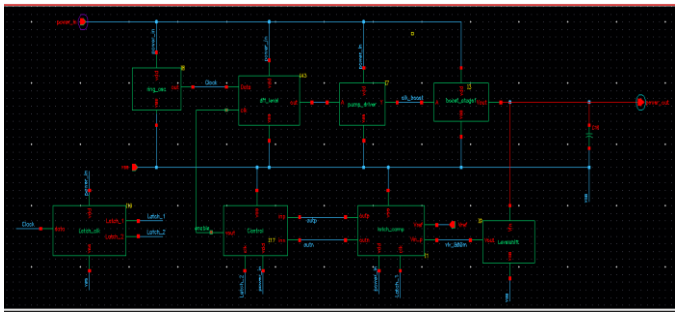

Fig 1: Top level for dc/dc converter

DC/DC converters are compatible with ultra low voltage for power harvesting application. In [4] DC/DC converter is driven by an internal low voltage clock generator this is directly connected to input of voltage source. DC/DC converter is formed by step up boosting stage and it is formed by step up boosting stage and it is formed by switch, diode (mosfet as a diode) and resistor and capacitor. The dc/dc converter operation is based on two methods. First method is when mosfet switch is ON, the current is flowing into the inductor from power supply and energy is stored in inductor, this energy is produced due to magnetic field in inductor. Energy produced by inductor is in form of voltage. If more current is flow in inductor more magnetic field is produce and more energy that is more voltage is produced. When mos switch is ON, diode is reverse biased and there is no current and voltage flow. Charge stored in load capacitor will cause output current. This means output current is produced by load capacitor.

Second method is when mos switch is fully turned off there is no current flow in inductor, no current means no magnetic field and no energy is produced. There is no sudden change in inductor current and this currents are appears as voltage spike, when mos switch is off then diode is acts as a forward biased and voltage spikes are produced by inductor are flow through the diode. In this condition inductor terminal negative to positive. In first method current flow from inductor to ground through mos switch in second method current is flow to load capacitor through diode.

A)Boosting Stage: In boosting stage to reach output voltage of 1.2v there is 2 boosting stage is required so that first stage produced of about 450m-700mv and from this output is given to input supply voltage of second stage from this overall circuit produces of 1.2v with help of [4]. Here mosfet M1 is act as a inverter and mosfet M2 act as a diode which is shown in below figure. First stage is drive second stage is with use of earlier buffer stage. So to achieve high voltage duty cycle was set to 50% with comparison between boosting of voltage and consumption of power. Size of inductors are depending on many factors like resistor, capacitor and conductivity of switch also load and so many factors are consider for sizing of inductor. Depending on this factor only inductors L1 is chosen with help of discontinuous conduction mode also. So inductor L1 is sized at 40µH. In boosting stage design mos switch M1 should be more in size, because more current flow in inductor cause more magnetic field and more voltage spikes are appeared. So that mos size is mm in width and length. Here inductor current and voltage is as shown by

$$VL = L\left(\frac{di}{dt}\right)$$

Ripple current in inductor is shown below

$$\Delta I = \left(\frac{Vs}{L}\right)T1$$

There are 2 modes of operation. In initial mode that is mode1 operation is given by, in this mode time completion is ($0 \leq t \leq DT$) so that t is ends with DT as current in inductor and switch is as shown by

$$Vs = L\left(\frac{di}{dt}\right)i1$$

Solution of above equation is

$$i1(t) = \left(\frac{Vs}{L}\right)t + I1$$

n above equation I1is initial current and this current is end at mode1 that is t=DT to I2 that is i1 (t=DT) = I2 for this above equation can be written as

$$I2 = \left(\frac{Vs}{L}\right)DT + I1$$

In mode 2 operation inductor current is to be

$$Vs = Ri2 + L\left(\frac{di2}{dt}\right) + E$$

Similarly I2 is initially current. So that above equation can be written as

$$i2(t) = ((Vs - E)/L)\,(1 - \left(e\hat{}\left(\frac{R}{L}\right)t\right) + I2\,e\hat{}\left(\frac{R}{L}\right)t$$

Here current end at mode 2 is similar to I1

$$i2(t = (1 - D)t) = I2 = \left(Vs - \frac{E}{L}\right)(1 - e\hat{} - (1 - D)z) + I2\,e\hat{} - (1 - D)z$$

Here $z = \frac{TR}{L}$

So ripple current is given by

$$\Delta I = I2 - I1 = \left(\frac{Vs}{L}\right) DT$$

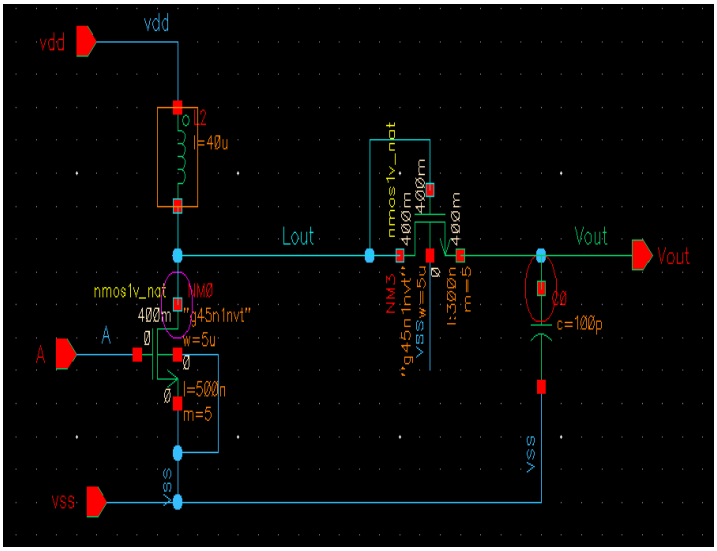

Fig 2: Single stage step up converter.

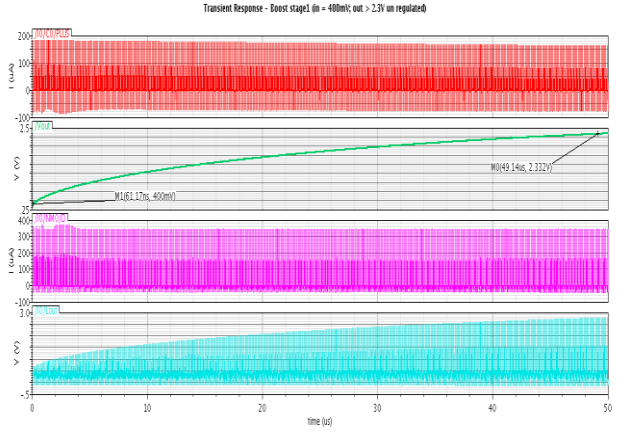

Fig 3: Output waveform for single stage step up converter.

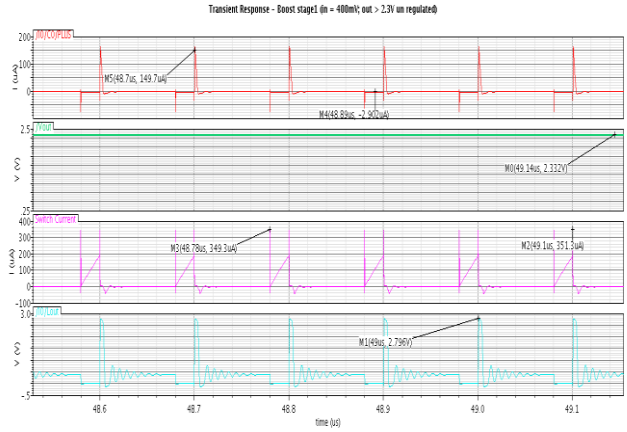

Fig 4: Un- regulated output for single step up converter.

B) Clock Generator: Clock generators are used to give the signal value for input voltage to dc/dc converter. Clock generator consist of oscillator and d flip flop. Oscillator give oscillation signals to circuit. D flip flop completes duty cycle to circuit. Clock generator is first stage of converter and it is self generated input input signal without using any external voltage it give self input to circuit. Clock generator is has no work but oscillator it give timing signal to converter in order to stabilize synchronization operation of the circuit. Clock signals may be analog or discrete signal it provide both analog signal and digital signal.
C) Oscillator: In this paper oscillator is a simple ring chain oscillator. The inverter back to back connection is formed by oscillator, number of inverter stages are connected back to back and number should be odd number. From supply voltage it will work on its own input supply voltage this means without need of external input supply voltage it will work with supply voltage. Oscillator amplify noise signal and produce output signal. In this paper after 10µs only oscillator get oscillate input signal before that 10µs there is no oscillation work process after 10µs only oscillator give signal. As the number of oscillator stages reach frequency high also increases and delay decreases. Delay & frequency are inversely proportional to each other and formulae for delay is given by t=1/(2nF) or F=1/(2nt).

To achieve higher frequency one number of stages should be more or delay should be less and in this work operating frequency be 1MHz to 5MHz and 1MHz is sufficient to operate circuit. In this work circuit is operating in low input voltage so inverter stage of PMOS and NMOS must have low threshold voltages. This low threshold voltage cause leakage current. In inverter NMOS and PMOS is taken as low threshold voltages in order to reach low input power supply. Oscillator has no work but electronic device it produces electric signal in a periodic event manner so signals like square dac wave or sine dac wave and it is used to switch over direct current to alternating current with use of supply voltage. Oscillator in form of inverter and it produce AC of high signal.

D) D Flip Flop: In our project D flip flop are used to produce 50% of duty cycle. D flip flop architecture are based on pass transistor. D flip flop produce Q and $\bar{Q}$ as output these produce 50% duty cycle. Output of oscillator gives input of this D flip flop so overall clock signal produce with 50% duty cycle. D flip flop architecture with use of pass transistor is mainly

because of low power supply voltage, with use of low input voltage it must work. Another advantage of pass transistors are used to design D flip flop because it requires less count and area of transistor and also to reduce power consumption.
E) Regulator: Regulator is a device which is used to control circuit like temperature and speed of circuit. Regulator give enable signal to clock generator to first stage of step up converter. It consist of mainly voltage reference and level shifter these two output are connected to input of comparator, it compares two input signals that is Vref and level shifter and give output zero and ones. In regulator it maintains output voltage means it fixed at a certain voltage. In our project regulator output is fixed at 1.2V. Current is appear at load it changes dramatically so regulator is used. Power supply of regulator has output of regulator and converter takes power consumption.
F) Voltage Reference: In voltage reference there are three stages those are first stage is start up stage, second stage is current generator and last stage is acts as a active load in [10] so from current generator stage it fixes constant output voltage. Voltage reference can operate minimum voltage that is 0.9v to 4v. In active load stage all transistor should be saturation region and it is given by equation as
$Vref=Vth+(\sqrt{2}I/k)$
Where I is current at active load stage. In output of voltage reference temperature is varies on various factor those are mobility, threshold voltage and bias current. So above this equation states that output of voltage reference is varies on mobility that is k and threshold voltage Vth and I is bias current. So in voltage reference bias current should be fixed so current generator are used to produce fixed output voltage. The generator current consist of simply NMOS and PMOS back to back connection totally current in all mosfets should be same so that generator current can achieve. In current generator M1 & M3 transistors are in sub threshold region and M2 & M4 transistors are in saturation region. In active load stage 3 transistors are used and those are diode connected & these transistors were mainly used to compensate temperature of voltage reference. In band gap there is a resistors are used for voltage reference so area is more for resistor but in this architecture there is use of resistance only mosfets are used so area is also less.

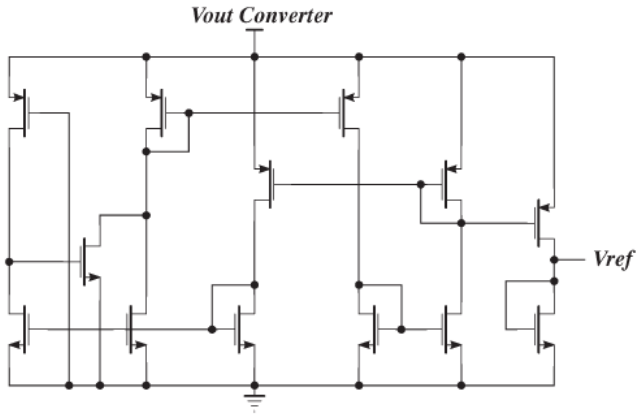

Fig 5: Schematic diagram for Voltage Reference.

G) Level Shifter: Level shifter is a digital device and it is used to produce one voltage to another domain so it also convert one logic level to another logic level. It produce output voltage below supply voltage. If there is no level shifter voltage levels are cross signals then correctly it will not sampled. It completely converts one voltage level to a different voltage level. In level shifter there is a diode connected so Vds is equal to Vgs & supply voltage is distributed to both Vds1 and Vds2.

So that Vds1=Vdd – Vds2.

In M2 Vds < Vth1 so, Vgs2 ≤ Vth1 ≥ Vds2 so Vds ≤ Vth1.

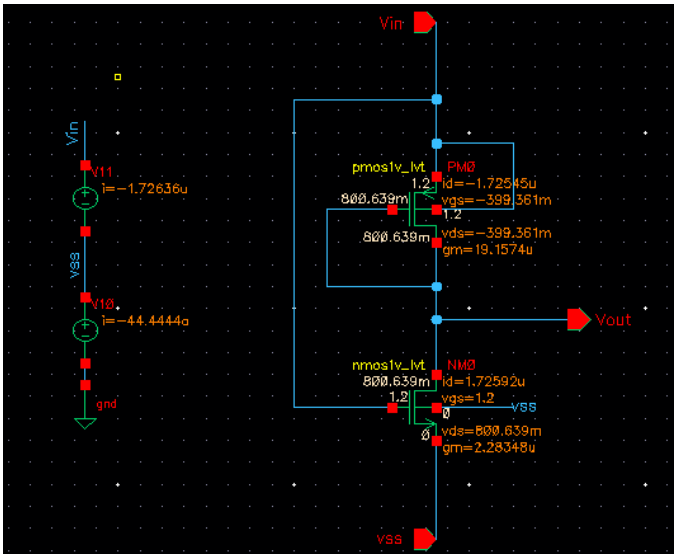

Fig 6: Schematic diagram for level shifter.

H) Comparator: In this work comparator is used as a regulator to fix output voltage in comparator it compares two input voltage and produce output signal in high or low voltages or one and zero signal. Output of comparator is one means it produce whatever in supply voltage it will produce and zero means it produce zero voltage. In comparator output is digital form because it produce one or zero. Output voltage works on condition like v+ and v- there are two input signal if v+ is greater than v- it will produce high supply voltage that is 1 and one more condition if v+ is less than v- it will produce zero voltage or 0. Here v- is reference voltage is used as v- and level shifter is used as a v+ and it produce output in 1 or 0. Comparator is an operational amplifier comparator voltage and op-amp have differential input it contains three stages one is differential amplifier and second stage is common source amplifier if one more inverter is added to that common source amplifier that it becomes comparator so both differential and common source amplifier should be in active region.

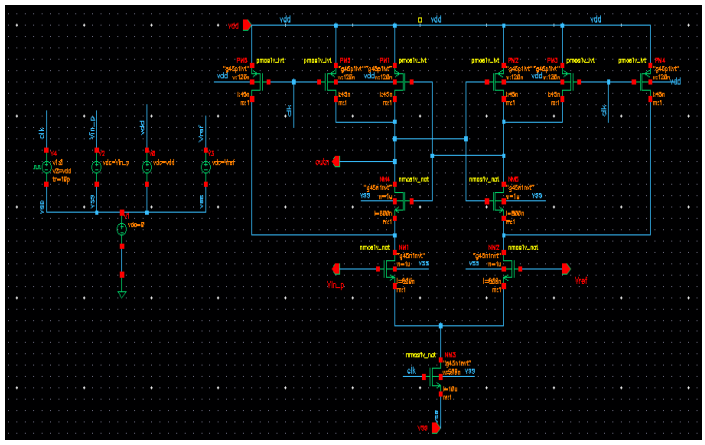

Fig 7: Schematic diagram for latched

Above figure 7 shows schematic diagram for latched comparator, there are two differential input in circuit and produce output in form of zero and one these output is shown in below output waveform.

Above figure 8 shows output waveform for comparator, input is level shifter and voltage reference so output in zero and one.

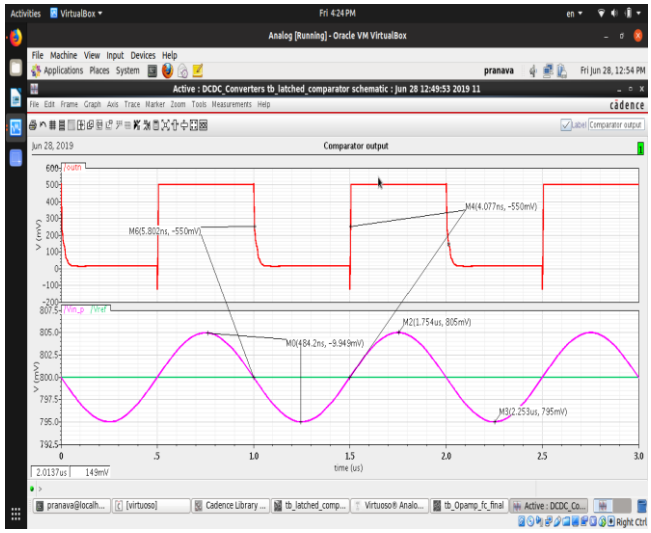

Fig 8: Output waveform for Comparator.

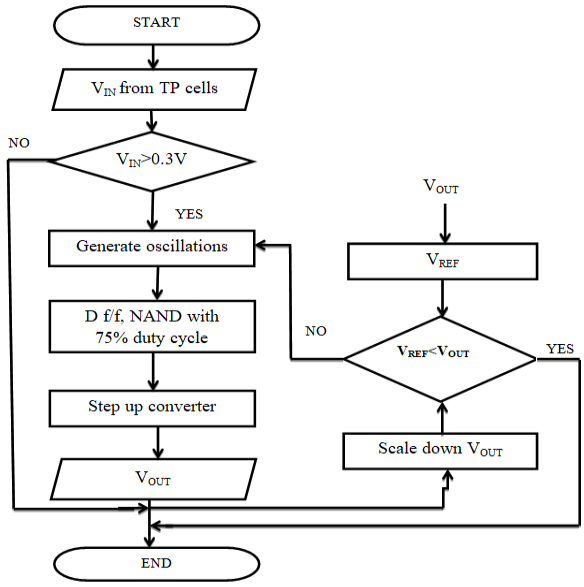

Fig 9: Flow chat for Block Diagram.

4. Experimental Results

Output waveform for complete dc/dc converter produces 1.2v. For regulated output it produces 1.2v but in unregulated output it can produce more than 2.5v, for these two waveform is given below.

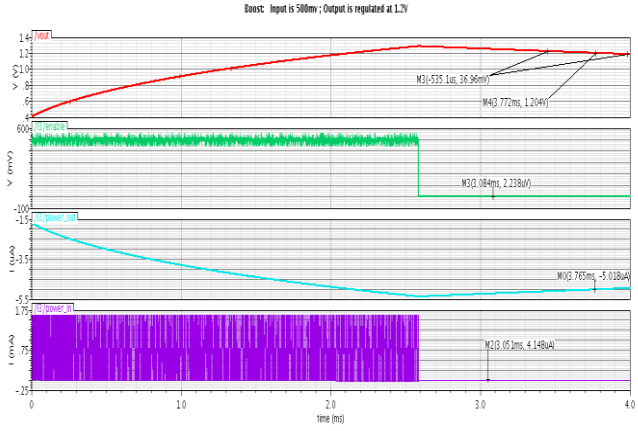

Fig 10: Output waveform for regulated output voltage.

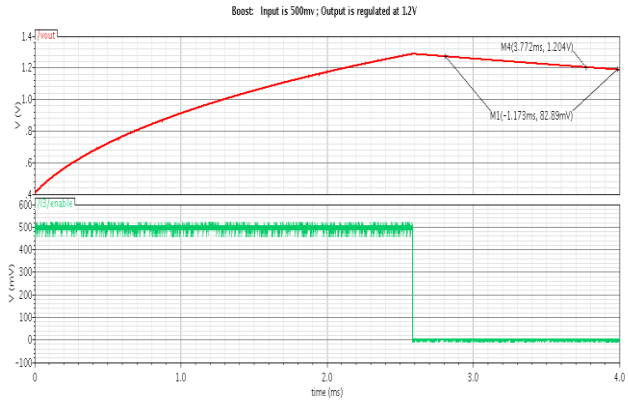

Fig 11: Outputs for vout and vin.

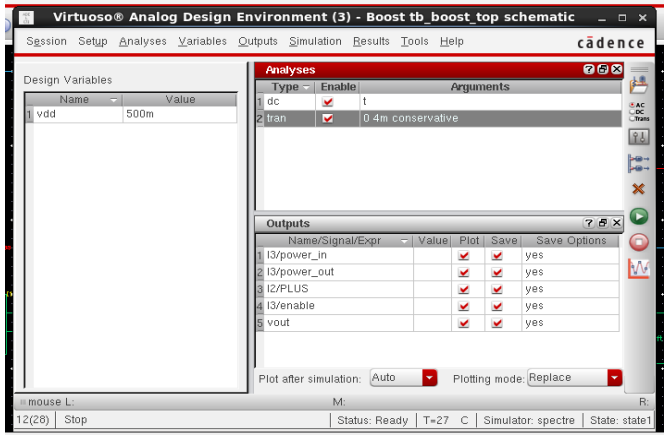

Fig 12: Transient time for converter.

The above Figure 12 shows transient execution window in cadence virtuoso software, so it's time is set as 4m conservative and it is checked for both dc and transient response. All will enable, input voltage output voltage and power in, outputs are shown in above window.

Discussion:

Comparison between previous work and with this work is given below comparison table 1.1. And working of block diagram is shown in flow chat Figure 9. In this work. It uses 550mv supply voltage and produce 1.0v output voltage. With efficiency of about 35.66%.

Comparison:

Parameter	[5]	[6]	[7]	[8]	[9]	[11]	Our Project
CMOS technology	180-nm	90-nm	35-nm	130-nm	350-nm	180-nm	45-nm
Extra masks	Low threshold	With tripple well	Not mentioned	Not mentioned	Not mentioned	Low threshold	Vth
Input supply Voltage	200mv	300mv	600mv	20mv	35mv	120mv	500mv
Output supply Voltage	1.2v	1v	2v	1v	1.8 v	1.2 v	1.2v
External supply voltage	no	no	2v	0.65v	no	no	no
External required Component	2 inductor	none	2v buffer capacitor	1 inductor 1capacitor	1 inductor 1 switch	2 inductors	1 inductor
Efficiency obtained	36%	Not provided	70%(just boost converter)	52%	58%	30%	34.44%

Table 1.1: Performance summary and comparison table between designed converter and previous work.

The above table 1.1 shows comparison between different work papers. In those paper they used different technology like 180nm, 90nm, 350nm, 35nm and 130nm but in this work, it consists of 45nm. Output voltage of those work are 1.2v, 1v, 2v, 1v, 1.8v, 1.2v and this work output is 1.2v. Input voltage of those work are 200mv, 300mv, 600mv, 20mv, 35mv and 120mv but in this work, It will be using 300mv. And it can ne seen that additional component are required in those work, so in this work also 2 inductors are used. In order to increase input voltage in paper [7] & [9] there is a use of external voltage supply. In this work, It will be using low threshold voltage in order to achieve low input voltage to step up and efficiency of each work is given above.

5. Conclusion

In this work dc/dc converter is operated with input voltage supply of 550mv. This converter will produce an output voltage of 1.0v, by delivering output current of 5.018µA and overall efficiency will produce 35.66%. And this circuit is used for energy harvesting application.

Future Scope: In this work. It consists of 65-Nm technology with 600mv initial input supply voltage and it will produces 1.2v output voltage. In future it can be designed to operate less than 500mv that is it can be 100m-300mv input supply voltage with operating in low threshold voltage. With low Vth, This work can be implemented in 100m-400mv with higher efficiency and can be achieve higher output voltage.

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