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A 70mV Input Bulk Switching Inductive-Load Ring Oscillator Based Start up Circuit for Thermal Energy Harvested DC-DC Boost Converter with 69% Efficiency

Maliha Naaz[1*], Kaleem Fatima[2], B. Rajendra Naik[3]

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Abstract: An ultra low voltage startup for DC-DC boost converter for portable applications is presented in this work. This work makes use of proposed bulk switching Inductive-load ring oscillator (ILRO) to generate high amplitude signals at voltages as low as 70 mV without use of off chip inductor. The proposed circuit serves as part of auxiliary DC converter for the Thermo Electric Generator based DC-DC converter. The output of proposed ILRO drives the 6-Stages of charge pump. The output of charge pump is used as supply for the control circuits in the boost converter. The complete design is implemented in 180nm CMOS technology using Cadence Virtuoso. The proposed work shows better performance in terms of low operating input voltage, boosted output voltage and efficiency. The TEG input voltage is 70mV and the output boosted voltage achieved is 1V with a conversion efficiency of 69% and output power of 65µW. There are no external off-chip components used in the design of start-up circuit.

Keywords: *DC-DC Boost Converter, bulk switching ILRO-Inductive load ring oscillator, CP-Charge pump, duty cycle generator.*

1. Introduction

There is an emerging trend of battery-free power sources that use environmental energy to accomplish their power requirements. Solar, vibration, thermal, wind and other energy harvesting sources can be utilized to power low-power devices. All these energy sources can be successfully exploited with appropriate transducers which convert energy into an electrical signal [1]. Typically, the harvested energy has very low power and voltages. The boost converter is designed to convert harvested energy (which is very low) to sufficient amount to be used for ultra-low power circuits such as wearable electronics, implantable biomedical sensors and wireless sensor networks (WSNs), where the replacement of batteries poses challenges due to its complexity and high costs. Portable calculators, watches, smoke detector, medical implants such as pacemakers and retinal implants, and structural health monitoring are a few examples. Energy harvesting through Photovoltaic cells is also one of the most commonly used methods but it depends on availability of light. The most popular energy source for low voltage applications is thermal energy due to its continuous availability [2].

Boost converter consists of semiconductor devices. The converter's control circuit needs a sufficient voltage to function, in order to eliminate the threshold limitation of these devices. However the input voltage obtained from thermal energy harvesting is insufficient to power the control block. As a result, an external circuit known as auxiliary/start-up circuit is required to generate power supply for a period of time until the voltage at the output reaches a sufficient level which is the main motivation of this paper.

There are two ways for initiating the converter operation: First, external start-up assistance is used; second, a low voltage start-up circuit is used. External start-up assistance can be achieved in one of three ways: by using an external battery to power the control block, a capacitor precharged to a preset voltage, or a mechanical switch. Another approach is to use a charge pump as a low-power start-up circuit. A charge pump is essentially a voltage multiplier that can be used to boost voltage levels to a certain level in order to power the boost converter's control block. Oscillators are used to generate clock signals to stimulate a charge pump. Ring oscillators are an excellent choice for integrated design applications because they do not require any passive components. One disadvantage of Ring oscillators is the difficulty in operating the oscillator at low voltages. Ring oscillator fails to operate at ultra-low voltage input. The ring-type oscillators also require a large number of power-hungry buffer circuits to generate the necessary clock signals thereby decreasing the efficiency and increasing the dynamic power dissipation. Because of their high voltage gain, lack of a buffer circuit, and improved cold start-up low power efficiency, inductive converters with LC tank oscillators are an appealing

[1*]*Research Scholar, Department of Electronics and Communication Engineering, MuffakhamJah College of Engineering and Technology, Osmania University, Hyderabad, India.*
[2]*Professor, Department of Electronics and Communication Engineering, MuffakhamJah College of Engineering and Technology, Banjara Hills, Hyderabad, India.*
[3]*Professor, Department of Electronics and Communication Engineering, University College of Engineering, Osmania University, Osmania University, Hyderabad, India*.
** Corresponding Author Email: maliiha.naaz@gmail.com*

alternative for ultra-low voltage applications. One of the critical issues of boost converter operating at low input DC voltages lies in designing a startup circuit that can kickstart the control circuit [3]. The low voltage startup circuits has gained significant popularity and many researchers are investigating techniques that can be used to design a startup circuit that operates at low voltage and can kickstart the boost converter.[4] employs a 650mV pre-charged output capacitor which requires an external component and is an expensive solution. In [5], a mechanical switch was used to kick start the converter, but it was limited by the mechanical switch's requirement for vibration to activate. Furthermore, this method cannot be used where mechanical energy is not available. To self-start the converter, a transformer [6] is used, and the transformer's secondary coil is used to increase the oscillations. However, the bulkiness limits the achievable form factor. An 80 mV start-up converter is proposed by the authors in [7] which utilizes a oscillator whose threshold voltage can be tuned.

Chen et al [8] proposed a start-up circuit whose charge pump works on 180 mV supply voltage using forward body biasing technique. Further in [9], a capacitor pass on scheme which achieves 95 mV cold start was proposed. The drawback of this scheme is it requires post fabrication trimming. Goeppert and Manoli [10] used Schmitt trigger oscillators for kick starting the converter at 70 mV input voltage, but this required a large storage capacitor and the start-up time was more. Ring oscillator and charge pump is used to start up at 60 mV [11]. Using a 60 mV supply, it can deliver only 4.5μW. In the design of start-up circuits using conventional ring oscillators the start-up time is more and the supply voltage is limited.

The LC oscillators have the advantage over ring oscillators where it can operate at low voltages but at the expense of large size inductors. Researchers have extensively explored and studied methods to eliminate the necessity of employing bulky off-chip inductors within the start-up circuit design. In [12], [13], [14] and [15], an LC oscillator-based start-up was proposed rather than a Ring Oscillator-based start-up. The authors in [16] have proposed an ultralow voltage start-up circuit which utilizes enhanced swing ring oscillator (LC oscillator) that operates at 86 mV. The disadvantage with this technique is it utilizes 4 inductors which consumes lot of chip area. The authors in [17] proposed a startup circuit which utilizes an LC oscillator and a charge pump (CP). The conversion efficiency of the CP is significantly lower due to the fact that the power consumed by the oscillator exceeds the output power of the CP.

Hence, this paper proposes a new start-up circuit which utilizes bulk switching inductive load ring oscillator to drive the charge pump. The proposed oscillator works at low supply voltage of 70 mV without utilizing any off chip inductors. The proposed oscillator provides sustained oscillations and generates a high amplitude signal which can drive the charge pump (CP). The output of the CP further serves as supply for the control circuits in the boost converter. All the blocks are finally integrated to form a system level design of DC –DC boost converter with ultralow voltage start-up circuit for thermal energy harvesting applications.

To address the issue of converter's low efficiency, we propose the following:

1) Bulk Switching ILRO with only two inductors provides an effective solution for start-up oscillator; and 2) concept of synchronous conversion. When compared to conventional voltage converters, this produces more output power and have higher conversion efficiency at an input voltage of 70 mV.

This paper's structure is as follows: Section 2 presents the block diagram illustrating the converter. Section 3 covers the discussion of the proposed oscillator circuit employed in the start-up circuit design for the boost converter, along with explanations of all utilized circuits. The experimental analysis and results are discussed under Section 4. The conclusions of this paper are addressed in Section 5.

2. Architecture of the boost converter

The block diagram of the converter, which includes the start-up mechanism, is shown in Fig. 1. The boost converter's start-up phase starts before it enters steady-state operation. The energy harvested from the environment is insufficient to power the boost converter's control circuits. As a result, an external voltage supply is required to accomplish this. The Start-up mechanism, also known as the sub DC-DC converter, supplies enough voltage to power the control circuits in the Main DC-DC converter.

2.1 Start-up mechanism

The Start-up circuit is intended to supply power to the boost converter's control circuits. The Oscillator drives a Charge Pump in the Start-up circuit. To improve voltage swing, an inductive load ring oscillator is used instead of a conventional ring oscillator.

The oscillator output is routed to six stages of the charge pump. The harvester's output voltage, which can be as low as 70mV, is used as the input supply to the oscillator and the first stage of the CP. The output of the first stage of the CP circuit serves as the input supply for the next stage, and so on. The charge pump's six stages produce an increased output voltage of around 700mV, which is sufficient to power the Control circuitry. The control block drives the gates of the MOSFETS from the main converter which performs the boosting operation. For the operation of the boost converter, off chip inductor and capacitor are used.

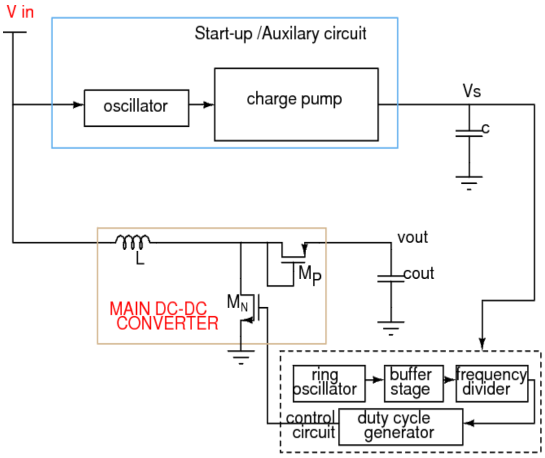

Fig. 1: DC-DC Boost Converter block diagram

As shown in the Fig. 1, the block diagram of the converter is an integration of start-up circuit, control circuit and main boost converter whose working is explained below in detail with respective circuitry.

3. Proposed Circuit

3.1 Proposed oscillator

To operate the conventional ring oscillator at low V_{dd} was reported in [18]. As the supply V_{dd} reduces, the voltage swing also reduces which makes it difficult for the MOSFETS in the charge pump to operate properly. The LC oscillators provide better swing as compared to other oscillators.

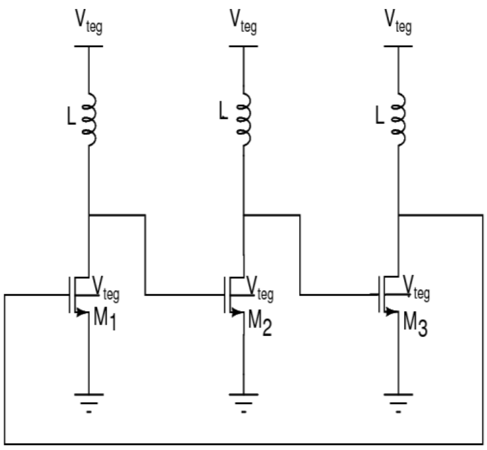

Fig. 2: Schematic of the proposed oscillator

The conventional ring oscillator is inverter based which makes use of PMOS and NMOS transistors. A series of cascaded odd stages of inverters connected in feedback loop forms the conventional ring oscillator.

The conventional ring oscillator is modified by replacing the PMOS transistor with an inductor resulting in Inductive load ring oscillator. The NMOS transistor makes use of bulk switching technique where the bulk of the NMOS is connected to power supply V_{dd} (here V_{teg} is the supply) instead of ground. Using this technique, the oscillator is able to boost the voltage swing above the supply.

Frequency of Oscillations is given by Eq.

$$F_{osc} = \frac{1}{2\pi\sqrt{LC}} \quad (1)$$

where C includes the parasitic capacitances.

The Schematic of the proposed bulk switching inductive load ring oscillator is shown in Fig. 2. The above circuit is implemented using cadence virtuoso UMC 180 nm technology.

The circuit works at ultra-low voltages and is capable of generating non–overlapping clock signals with good voltage swing. Further, the non over lapping clock signals are provided as input clock to the charge pump circuit.

3.2 Cross coupled charge pump

Charge pump (CP) circuits are frequently utilized in voltage multiplication applications, where the input voltage can be increased to achieve the desired high voltage [19]. To accomplish this, the charge pump circuit is made up of transistors that act as switches and capacitors that transfer charge from input to output. Furthermore, the switches help to generate the desired voltage.

There are different topologies existing in the literature for charge pumps. Due to less number of MOSFETs in a single stage, the cross-coupled charge pump provides higher efficiency in ultra-low voltage operation and maintains DC output throughout the entire clock cycle.

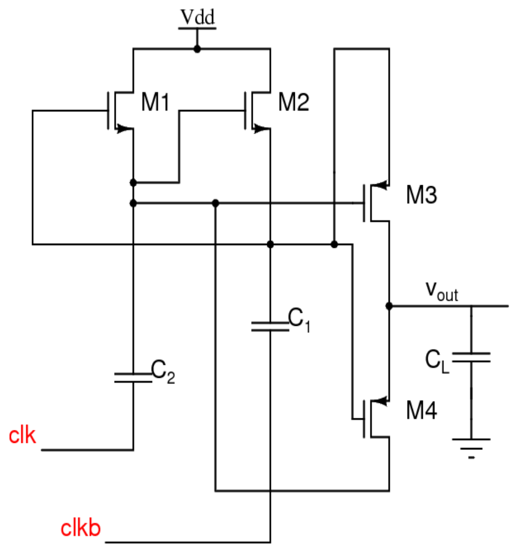

Fig. 3: Schematic of cross coupled CP

A Cross Coupled CP consists of two nmos which are cross connected and two pmos transistor series-connected a single output is obtained. The clock signals clk, clkb govern the charge transfer. The clock signals are complementary. When clk is low, the capacitor charges, and when clk is high, the node voltage is increased and the charge held is transferred from the capacitor to the next step.

The output voltage is given by

$$\boldsymbol{V_{out}} = (\boldsymbol{M} + \boldsymbol{1}) * \boldsymbol{V_{in}} \quad \text{Eq.} \qquad (2)$$

Where M=no of stages, Vin is the input voltage

A circuit schematic of a one-stage CP is shown in Fig 3.

3.3. Control block

Ring oscillator, buffer circuit, frequency divider, and duty cycle circuit are components of the control circuit stage. The required timing signals will be produced by the ring oscillator. The clock generator circuit's timing output is a square wave having MHz frequency. This high frequency is reduced by using a frequency divider. The frequency divider is composed of D-Flip flops. To get duty cycled output, the frequency dividers output is given to a duty cycle circuit which will help the boost converter to increase the output voltage.

3.4. Ring oscillator

A ring oscillator circuit has odd number of inverter stages connected in such a way that the output from each stage serves as the input for the subsequent stage, while the final stage's output is looped back to its own input. The basic component of a ring oscillator is an inverter circuit as shown in Fig. 4.

The equation of the frequency oscillation is defined by

$$f_{osc} = \frac{1}{2KT_d} \qquad (3)$$

where K= odd no of inverter, Td= delay

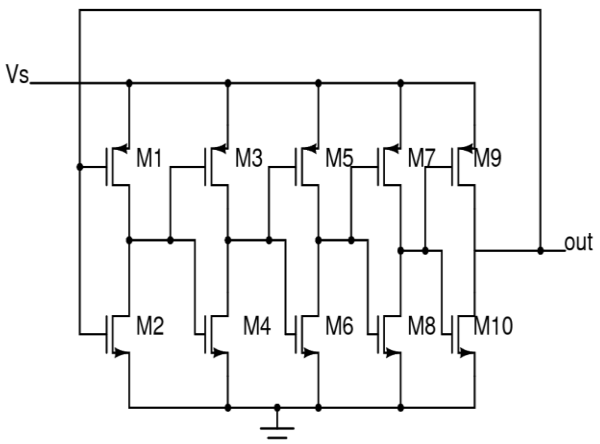

Fig. 4: Schematic of ring oscillator

3.5 Frequency divider

A frequency divider circuit scales the output frequency.

The output frequency is given as

fout=fin/k (4)

A divide by 2 counter is used for frequency division which makes use of D flip-flops to serve the purpose. D flip-flops are employed in a chain as a divide by two counter for frequency division as it has the advantage that the output gives an exact 50% duty cycle.

3.6. Duty cycle control

The duty cycle T_{on}/T_{off} of the switches is a crucial parameter for achieving high output voltages. The high output voltage is a result of high duty cycle. A large current flows through the inductor as the duty cycle increases. On the other side, higher current across the switches results in higher power consumption. A duty cycle of 75% is chosen in our design.

3.7. Boost Converter

A boost converter is a step-up converter which increases or boosts the output voltage. In asynchronous rectification, at least two semi-conductor switches (a transistor and a diode) and an inductor are used, whereas in synchronous rectification, two transistors and an inductor are used. To reduce the output voltage ripple, capacitors are included at the output.

The converter is modelled based on PWM switch design. The PWM switch equivalent for the CCM and DCM is derived from [20].

The conventional boost converter conversion ratio in CCM mode is expressed as

$$\frac{V_{out}}{V_{in}} = \frac{1}{1-D} \qquad (5)$$

The conversion ratio in DCM mode is expressed as

$$\frac{V_{out}}{V_{in}} = \frac{1+\sqrt{1+\frac{2*D^2*R}{L*f_{sw}}}}{2} \qquad (6)$$

where D represents the duty cycle, R is the output resistance, L is the inductor, fsw is the switching frequency.

All the blocks are integrated together to form the final boost converter structure.

Efficiency of the converter is calculated from

$$\eta = \frac{P_o}{P_i} (7)$$

where P_o is the output power.

4. Experimental Analysis

In this section, we discuss the complete details of simulation experiments carried out over the proposed design. For simulation purpose, we have used cadence virtuoso tool and the simulations are carried out on circuit level design followed by system level integration.

The simulation setup and simulation results of each circuit is explained followed by the result of system level design . Finally, a comparative analysis is presented between proposed work and state of the art work.

4.1 Simulation setup

For experimental validation of our method, we used cadence virtuoso SPICE tool and simulated the circuits. The following specifications/parameters were used for simulation. Table 1 shows the specifications used for simulation.

Table 1: Simulation Parameters

Specifications	Value
Input Voltage	70 mV
No. of charge pump stages	6
Output voltage	1 V
Duty cycle	75%
Switching frequency	100 kHz
Maximum Efficiency	>65%
Load capacitance	1 pF
Ripple voltage	<10 mV

4.2 Simulation Results and Discussion

In the past few years, efforts have been made by researchers to propose different topologies and techniques that can be used to kick start the boost converters with DC voltages < 100 mV. Most of the solutions proposed in the literature make use of external components like pre-charged capacitor [4], MEMS switch [5], transformer [6]. Some techniques make use of integrated approach as in [9] but external trimming after the fabrication is required.

One of the integrated approach without use of external trimming was presented in [16] but it requires 4 inductors that consume lot of chip area. In [17] the boosted output voltage achieved is less.

To evaluate the effectiveness of our work, the proposed work is compared with existing work related to the proposed work. The parameters or specifications used in this comparison are the start-up mechanism, input and output voltage, off-chip components and the efficiency. A comparison between existing techniques and proposed work in terms of the above parameters is shown in Table 2. Table 2 validates that the proposed work achieves better efficiency at low input voltage without using any off chip components in the startup design as compared to the reported works.

It can be seen that the proposed work presents a solution to the problems reported in the literature. The proposed design works at a DC input voltage of 70 mV without using any external components like MEMS switch, capacitor and transformer and provides better efficiency and output voltage.

All the circuits are simulated using cadence software. All these blocks are integrated together to form final circuit of boost converter. Fig 5-11 show the results that are obtained from simulations.

The simulation results of the conventional and proposed inductive load ring oscillator are presented in Fig 5. The simulation results show an improved amplitude swing in the proposed circui

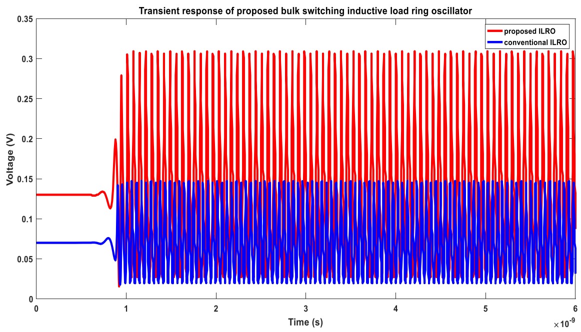

Fig 5: Simulation result of conventional and proposed inductive-load ring oscillator

Fig 6 shows the output for six stages of charge pump without load capacitance for an input of 70mV. The output has ripple voltage of around 100mV.

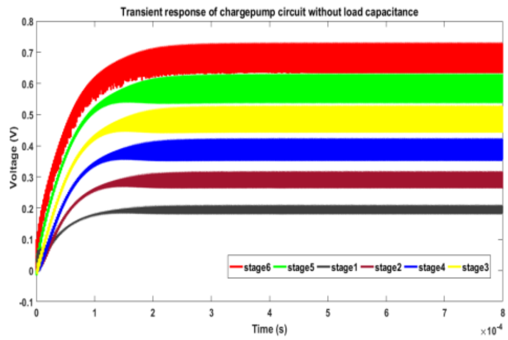

Fig 6: Simulation result of 6stages of charge pump without load capacitance

Fig 7 shows the output for six stages of charge pump after adding capacitor 1pF at the load. The ripples got reduced to 2mV.

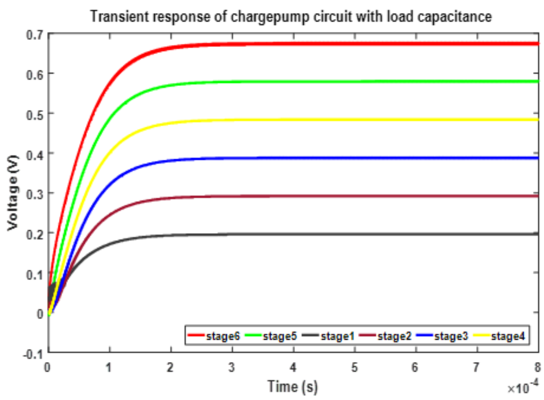

Fig 7: Simulation result of 6stages of charge pump with load capacitance

The output of 5 stages ring oscillator is shown in Fig.8. It produces square wave signal which acts as pulse generator for the control block of the converter.

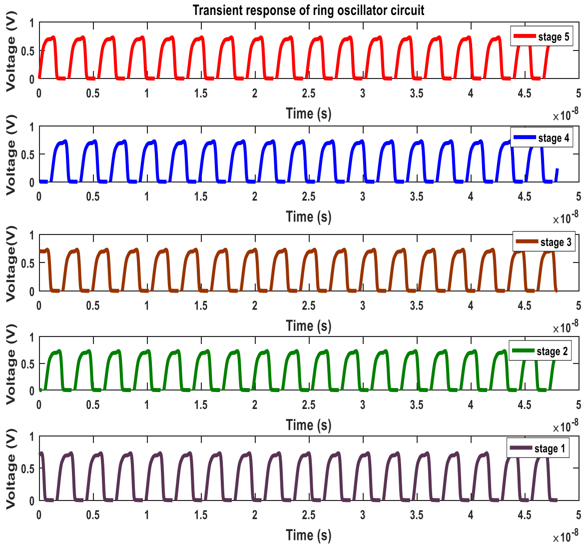

Fig 8: Simulation result of ring oscillator

Table 2: Comparison of proposed work with reported work

REF	[4]	[5]	[6]	[7]	[9]	[10]	[16]	[17]	This work
CMOS technology	130nm	350nm	130nm	65nm	65nm	130 nm	130nm	65nm	180nm
Startup mechanism	External voltage 650mv	Mechanical switch	Transformer	Charge Pump	Capacitor pass on	Storage Charge pump	Charge Pump and Enhanced swing ring oscillator	Charge pump and LC oscillator	Charge Pump and Bulk switching Inductive load ring oscillator
components in startup	Precharged capacitor	MEMS switch	1 transformer	Not specified	Trimming is required	No auxiliary power source	4 inductors	2 inductors 2 capacitors	No external components used. Only 2 on chip inductors are used.
Vin/startup voltage	20 m V	25 mV 35 mV for start up	40 mV	180 mV	95 mV	70 mV	86 mV	100 mV	70 mV
Vout	1V	1.8V	2V	650mV	930 mV	1.25 V	1 V	760 mV	1V
Output power / current	175μW	10uW at 25mV	2.7mW at 300mV	45uA at 300mV	Not specified	17 μW	1uW 1uA	6.6uW 8.6uA	65uW at 70mV
Efficiency	75%	58%	61% at 300mV	n/a	n/a	58%	n/a	33%	69% at 70mV

The output of frequency divider is shown in Fig.9 in which the waveforms for input clock frequency divided by 2, 4 and 8 is shown.

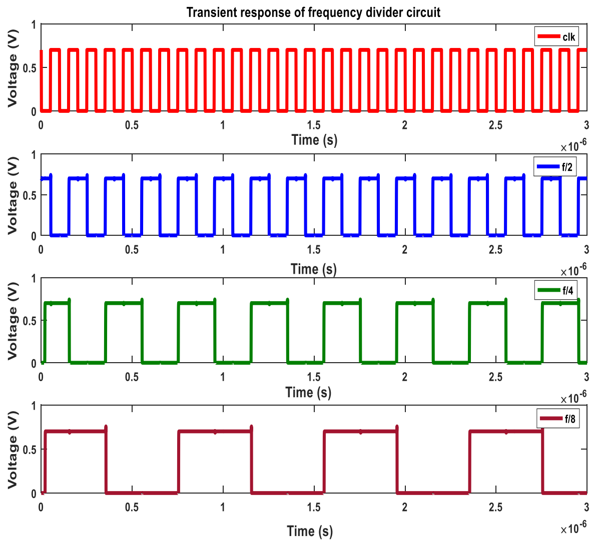

Fig 9: Simulation result of frequency divider

Fig.10 shows the output of the duty cycle circuit. It generates the waveforms with 25% and 75% duty cycle.

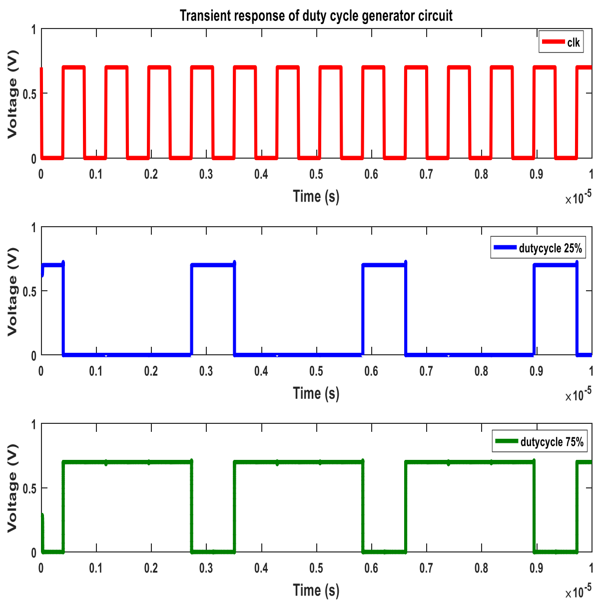

Fig 10: Simulation result of duty cycle generator

The final output is shown in Fig.11 which depicts the boosting of input voltage from 70mV to 1V. Fig.11 shows the transient response of the DC-DC boost converter simulated with the proposed start-up circuit.

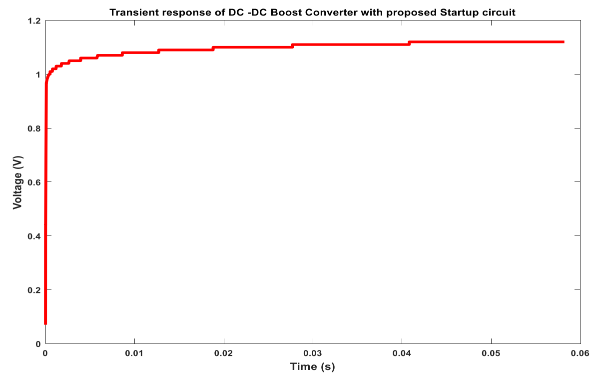

Fig 11: Simulation result of DC-DC boost converter

Fig. 12 shows the comparison of proposed work with conventional design and state of the art work. In comparison with [10], [16] and [17] , the proposed work shows better performance in terms of output power.

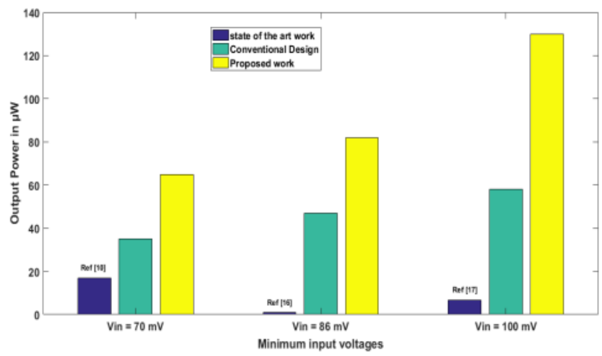

Fig 12: Comparison of proposed work with existing work

Fig.13 shows the efficiency obtained by the proposed work along with state of the art work. It is evident that the suggested design gives better efficiency as compared to other reported works. The efficiency is high in [4] as compared to our work but the design in [4] makes use of pre charged capacitor which is an external component. The proposed work achieved decent efficiency of 69% with no external components in the startup circuit.

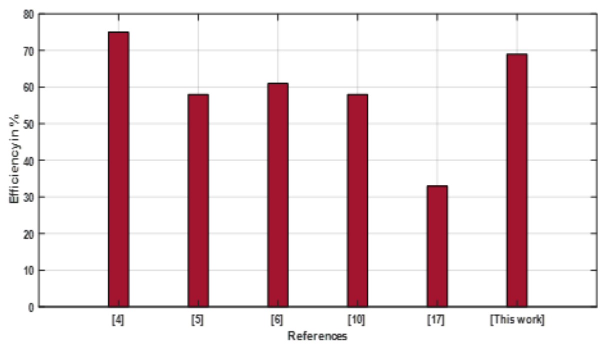

Fig 13: Efficiency Comparison of proposed work with state of the art work

5. Conclusion

In this paper we proposed a ultralow voltage start-up circuit for DC-DC boost converter which uses a a bulk switching inductive-load ring oscillator that drives the charge pump. The proposed oscillator is used for startup mechanism which produces 303mV signal for an input of 70 mV. The oscillator circuit used in the design of the start-up circuit doesn't make use of any external off –chip components. Also, as compared to reported work in the literature it performs better at low voltages. The output of the oscillator goes as input to the charge pump which generates a steady output of 700 mV. The output of charge pump works as supply for the control circuits in the boost converter. Finally all the blocks are integrated to form the boost converter suitable for Thermal energy harvesting applications. The final boost converter circuit produces output voltage of 1V with a conversion efficiency of 69% at 70 mV input DC voltage. The simulation results show performance improvement over reported works. Table 2 compares this work to current state-of-the-art work.

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