Single-Inductor Multiple-Output DC-DC Converter with Comparator-Based Feedback Circuit

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Abstract − **In this paper, a single-inductor multiple-output (SIMO) DC-DC converter with comparator based feedback circuit is proposed. The proposed SIMO converter does not need feedback loop which is composed of error amplifier or OTA and its compensation network. Therefore, tolerance of the feedback loop is improved since it does not suffer the variation of compensation resistor and capacitor. Also, variation of loop characteristic arises from external inductor value, capacitor value and load current can be removed. The measured peak power conversion efficiency is 81% when the output power is 140mW.**

I. INTRODUCTION

Recently, portable devices such as smart phone and smart watch are required to perform various functions while maintaining small device size. For example, in case of the mobile system like smart phone, various modules such as application processor, RF circuit, OLED display and audio codec are integrated in a system. Each system requires different supply voltage for its reliable performance or low power consumption. Thus, power management circuit is essential to provide optimal supply voltage to various systems.

Switching type DC-DC converter is widely used as power management circuit to generate supply voltage from battery. Although it has large size because of the external inductor, switching DC-DC converter is preferred because of its high power conversion efficiency. However, to provide several supply voltage, same numbers of the switching DC-DC converter are necessary as shown in Fig. 2 which results in large system size. Therefore, single inductor multiple output (SIMO) converter has been proposed and researched. Since the SIMO converter regulates several supply voltage with one external inductor as illustrated in Fig. 3, it can reduce system size and cost, and improve form factor of a system.

To regulate several output voltage simultaneously with SIMO converter, time multiplexing method is used conventionally [1]. The basic structure and operational waveforms of the time multiplexing method are shown in Fig. 4. In Fig. 4, it operates in non-overlapping phases, $\Phi_{1\text{-}3}$, rotationally. According to the distributed phase, each output voltage is charged independently. The charging duration of each output is T_S and the total output charging cycle is T_{CYCLE}. T_{CYCLE} is equal to three times of T_S since it regulates three output voltages simultaneously.

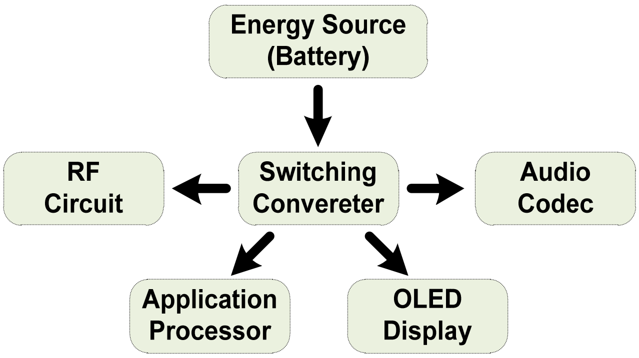

Fig. 1. Example of portable device with various functions.

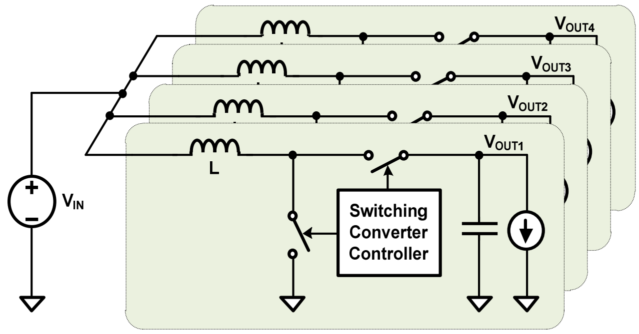

Fig. 2. Conventional method to generate multiple output voltages.

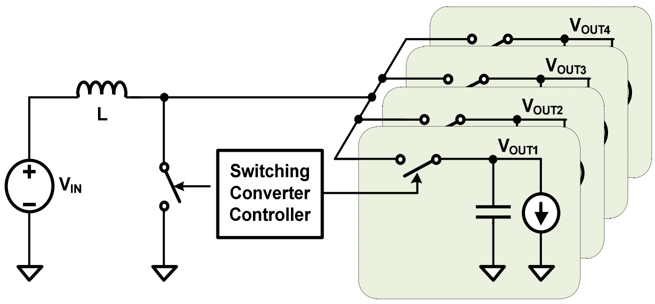

Fig. 3. Basic single inductor multiple output DC-DC converter.

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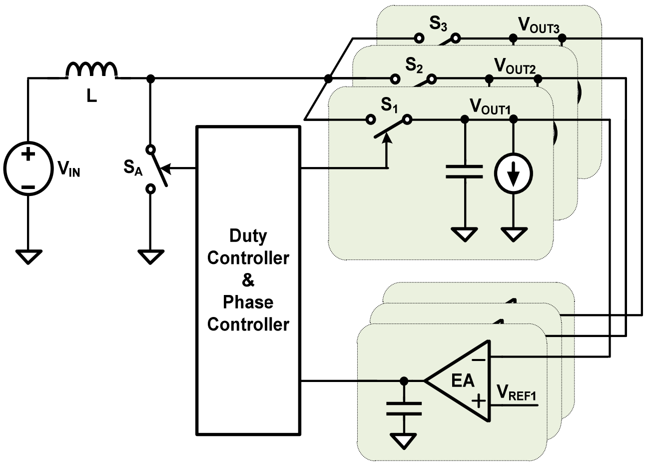


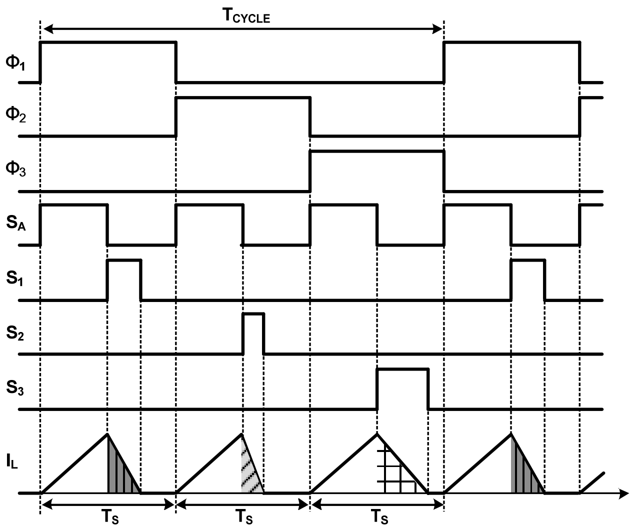
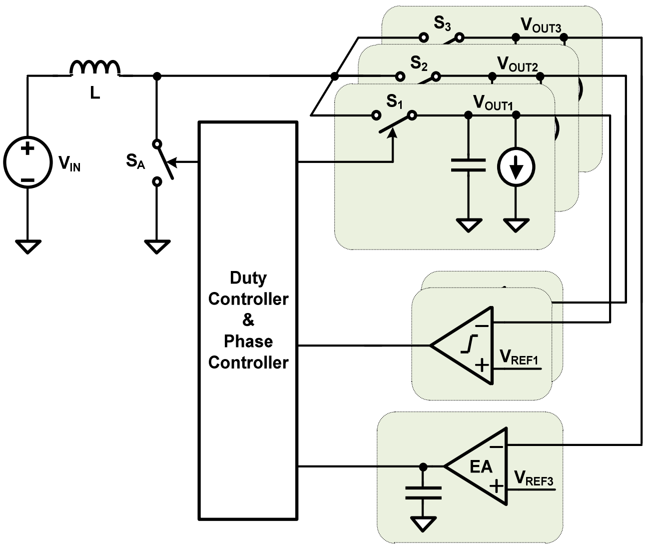


Fig. 4. SIMO converter with time multiplexing method.



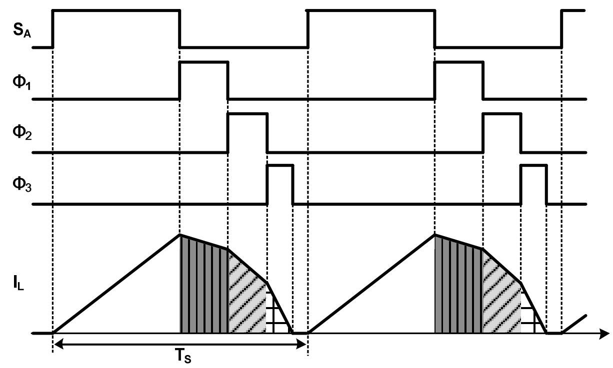


Fig. 5. SIMO converter with integral charging method.

As shown in Fig. 4, each output needs its own feedback loop in time multiplexing method. It means that same numbers of error amplifier and R-C compensation network is essential to make stable output voltages. It results in large silicon area and chip size for constructing compensation network. Also, because loop stability is influenced by the value of external inductor, capacitor and load current, complexity of designing compensation network increases. In addition, increasing the number of output stage can be limited in time multiplexing method. Since T_{CYCLE} is determined as $N \times T_S$ where N is the number of output stage, T_S/T_{CYCLCE} is reduced when N is large. Therefore, the ripple of the output voltage may increase as the number of output stage increases.

Instead of time multiplexing method, integral charging method is also used to regulate several output voltage simultaneously [2,3]. The structure and operational waveforms are illustrated in Fig. 5. Integral charging method charges inductor current initially, and distributes charged energy to each output in a sequence. Unlike aforementioned time multiplexing method, all of the output voltages are regulated using comparator except for last output voltage which is regulated with OTA. If V_{OUT3} is lower than V_{REF3}, OTA based feedback loop will control inductor current charging time to increase total energy delivered to output. Therefore, only one compensation network needs to generate stable output voltages regardless of the number of output stage.

Advantages like chip size reduction and simplified design of the compensation network can be achieved via integral charging method. Also, all of the output stages are charged once in a switching period regardless of the number of output stage. Thus, the limitation is increasing the number of output stage because of the output voltage ripple is solved. However, because of the OTA based feedback loop, loop stability may be affected by the value of external inductor, capacitor and load current.

In this paper, the new SIMO converter is introduced which feedback loop is tolerant to the external inductor and capacitor value and load current. In Section II, the structure of the SIMO converter with comparator based feedback circuit is introduced and explains its operation principle. Circuit implementation details are introduced in Section III and experimental results are shown in Section IV. Section V concludes this paper.

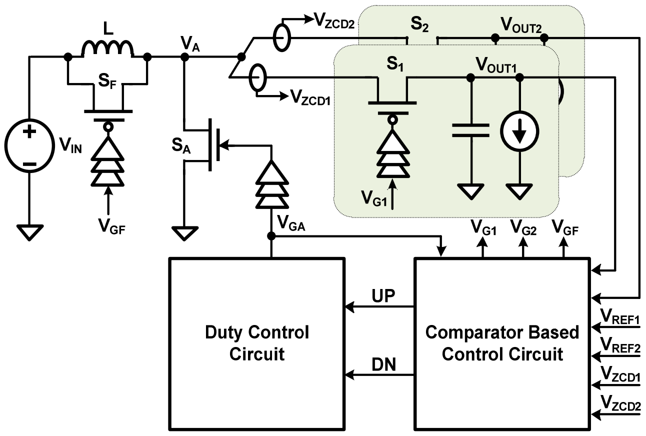


Fig. 6. Proposed SIMO converter structure with comparator based feedback circuit.

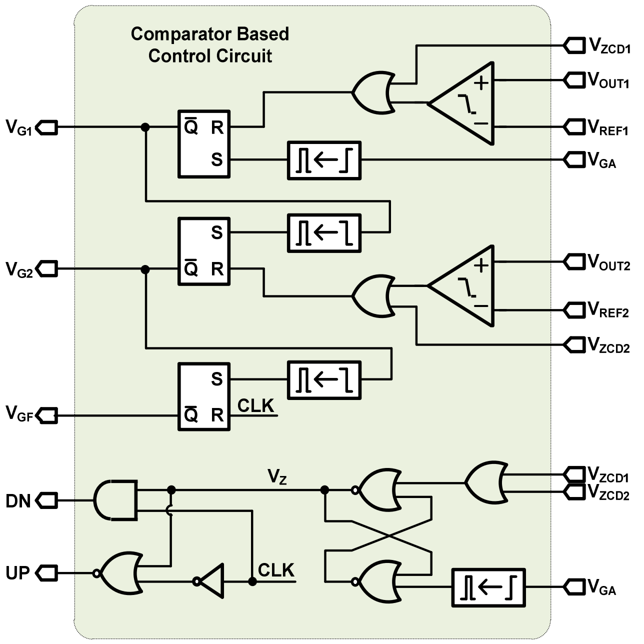


Fig. 7. Schematic of the comparator based control circuit.

II. THE PROPOSED SIMO CONVERTER WITH COMPARATOR BASED FEEDBACK CIRCUIT

The new SIMO converter structure is proposed to simplify the conventional feedback loop which is constructed with at least one error amplifier or OTA and its compensation network. The proposed SIMO converter structure regulates all the output voltage with comparator. Therefore, the proposed structure improves sensitivity of loop characteristic resulted from the variation of compensation resistor and capacitor. Also, loop characteristic variation arises from external inductor value, capacitor value and load current can be removed.

The proposed structure of the SIMO converter with comparator based feedback circuit is shown in Fig. 6. The switch S_A charges energy to the inductor, and the switch $S_{1\text{-}2}$ controls which output is to be charged and the switch S_F is a freewheeling switch. Feedback loop is composed of comparator based control circuit and duty control circuit. The comparator based control circuit contributes to the distribution of the charged energy to each output stage by controlling output charging sequence. The duty control circuit manages total charged energy in the inductor by monitoring whether delivered energy is enough or not.

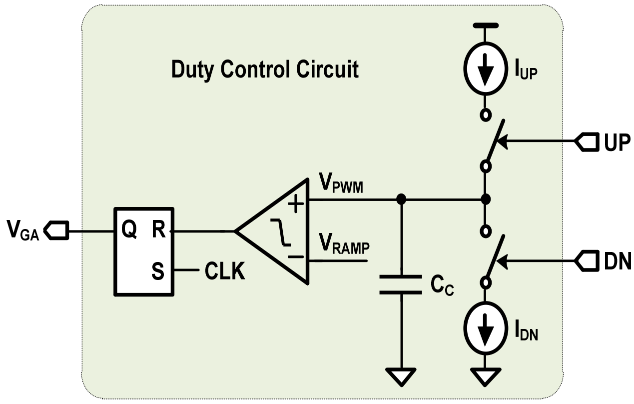


Fig. 8. Schematic of the duty control circuit.

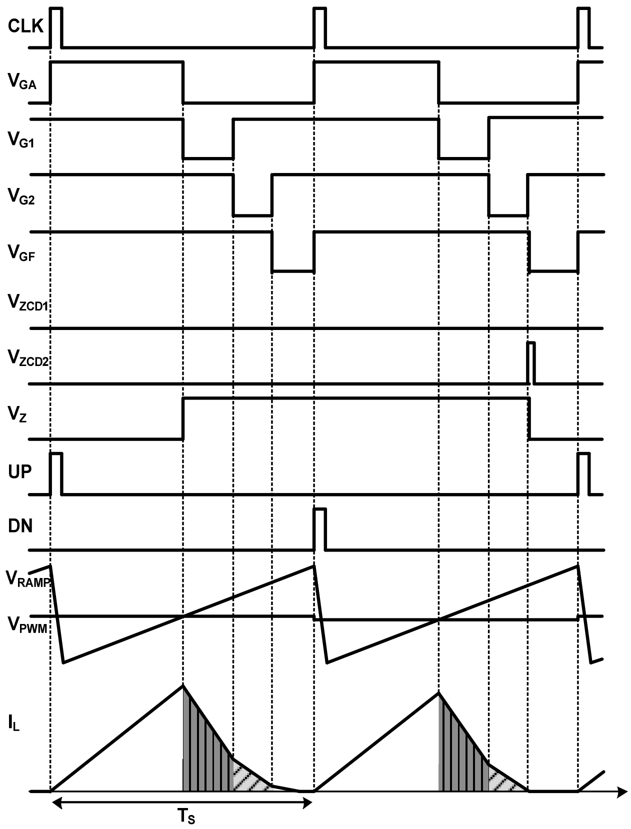


Fig. 9. Operational waveforms of the proposed SIMO converter.

The details of the comparator based control circuit are illustrated in Fig. 7. At the start of a period, switch S_A is turned on and inductor current is charged with the slope of V_{IN}/L. After the charging time, S_A is turned off and S_1 is turned on by detecting falling edge of V_{GA}. Then the inductor current flows to the first output stage and charges V_{OUT1}. At this time, the inductor current decreases with the slope of $(V_{IN}\text{-}V_{OUT1})/L$. When V_{OUT1} reaches V_{REF1}, S_1 is turned off and S_2 is turned on by detecting rising edge of V_{G2}. Then the inductor current flows to the second output stage and charges V_{OUT2}. At this time, the inductor current decreases with the slope of $(V_{IN}\text{-}V_{OUT2})/L$. When V_{OUT2}

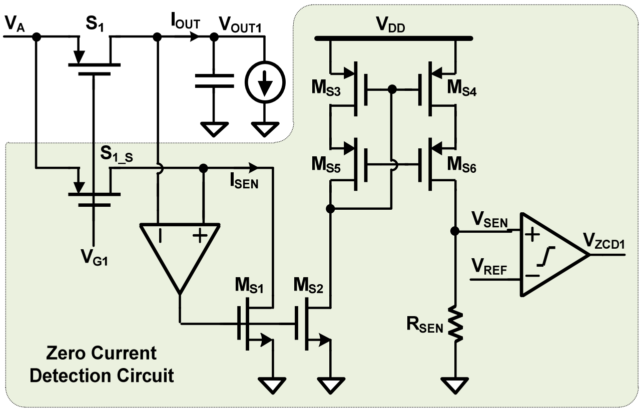


Fig. 10. Schematic of zero current detection circuit.

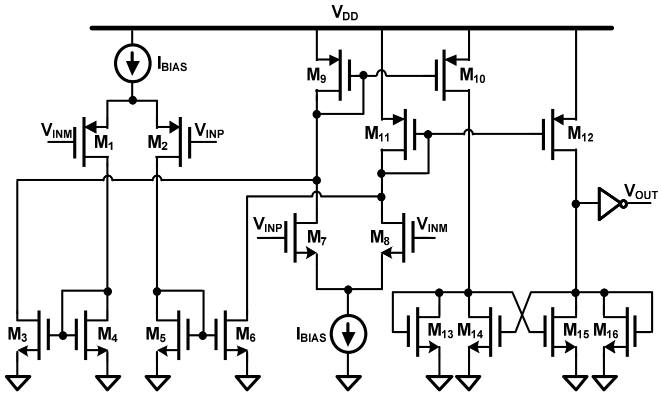


Fig. 11. Rail-to-rail comparator structure.

reaches V_{REF2}, S_2 is turned off. Then freewheeling switch S_F is turned until the next switching period is initiated.

The comparator based control circuit investigates whether the inductor current becomes zero or not via the signal V_{ZCD1} and V_{ZCD2}. If V_{ZCD1} or V_{ZCD2} is triggered in a period, the controller recognizes that supplied energy from the input is smaller than the total amount of energy that output needs. Then the controller generates UP signal to increase supplied energy. Conversely, if neither V_{ZCD1} nor V_{ZCD2} is triggered in a period, the controller recognizes that supplied energy from the input is larger than the total amount of energy that output needs. In this case, the controller generates DN signal to decrease supplied energy from the input.

Along with the obtained UP/DN information from the comparator based control circuit, the duty control circuit manages the amount of supplied energy from the input. The details of the duty control circuit are shown in Fig. 8. According to the UP/DN signal, charge pump circuit charges V_{PWM} up or down. For example, when the UP signal which means more energy is necessary to regulate all outputs is triggered from the comparator based control circuit, charge pump circuit charges V_{PWM}. Then, increased V_{PWM} is compared with V_{RAMP} which increases turn on time of the switch S_A. Since the switch S_A charges energy to the inductor, increased turn on time ensures more energy to be charged to the inductor. Conversely, the DN signal decreases V_{PWM} with charge pump circuit. Because of the decreased V_{PWM} which reduces turn on time of the switch S_A, the charged energy in the inductor decreases also. The operational waveforms which explain all the aforementioned

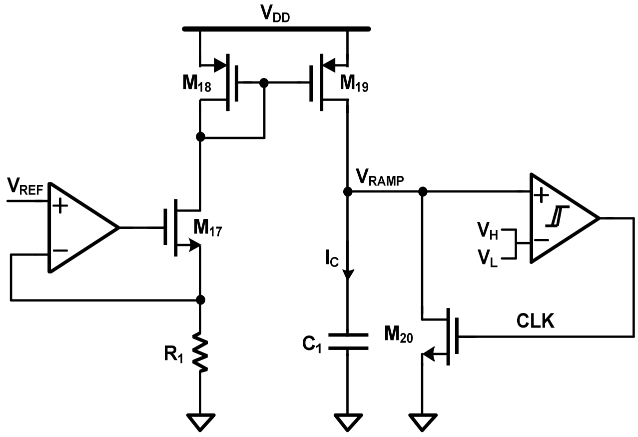


Fig. 12. Clock and ramp generator.

operational principle are illustrated in Fig. 9. In this way, the proposed SIMO converter structure can manage amount of supplied energy to be equal to the total energy that all outputs need.

III. CIRCUIT IMPLEMENTATION

A. Zero current detection circuit

To detect zero inductor current instant, the zero current detection circuit is implemented in the proposed SIMO converter structure as shown in Fig. 10. It employs current sensing transistor which is connected parallel switch S_1[4]. The size of the sensing transistor is scaled down to 1/1000 comparing with the switch S_1. Therefore, sensed current, I_{SEN}, is also scaled down to 1/1000 of I_{OUT} which enables quasi-lossless current sensing circuit. The sensed current is mirrored via $M_{S2\text{-}6}$ and flows through R_{SEN}. Therefore, the obtained V_{SEN} reflects current information flowing through the output and can be used to detect zero current instant. To reduce current mirror mismatch arise from the channel length modulation and improve accuracy of the zero current detection circuit, operational amplifier is utilized to make drain voltage of sensing transistor equal to V_{OUT}.

The accuracy of the zero current detection circuit is also affected by the matching characteristic between S_1 and S_{1_S}, sensing resistor variation and input offset of the operational amplifier. To improve the matching characteristic, common centroid layout technique is adapted to S_1 and S_{1_S}. Also, R_{SEN} is selected as an off-chip component to reduce variation of resistance. With precise zero current detection circuit, peak inductor current can be regulated to the value which guarantees all output voltages to be fully charged and stable.

B. Comparator

Since the proposed SIMO converter structure regulates output voltage with comparator, performance of the comparator is important. The schematic of comparator is illustrated in Fig. 11. For wide input range, rail-to-rail input stage is applied in comparator design. Therefore, comparator can operate regardless of output voltage level. Also, a cross coupled NMOS pair ($M_{14\text{-}15}$) is used to boost response speed of the comparator. With rail-to-rail comparator introduced above, output voltage regulation and zero current detection can be achieved.

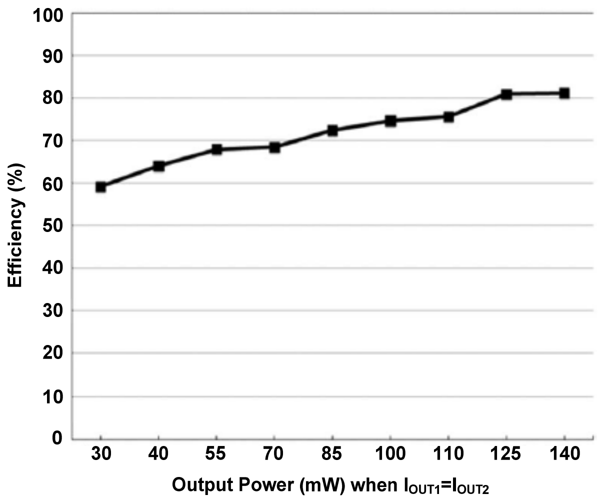


Fig. 13. Measured power efficiency versus the output power.

C. Clock and ramp generator

The clock and ramp generator circuit is shown in Fig. 12 which structure is similar with conventional one [5]. The clock and ramp signal are synchronized each other since it is made from same circuit. It is composed of voltage-to-current converter and hysteretic comparator. Initially, V_{RAMP} increases because I_C charges capacitor C_1. When the V_{RAMP} touches upper boundary V_H, CLK signal becomes high and M_{20} pulls down V_{RAMP}. The size of M_{20} is designed to be large enough to fully discharge V_{RAMP}. If V_{RAMP} decreases and touches lower boundary V_L, M_{20} is turned off and V_{RAMP} starts to be charged again. The frequency of clock and ramp signal can be calculated as follows:

$$f_{CLK} = \frac{I_C}{C_1(V_H - V_L)} = \frac{V_{REF} W_{M19}}{R_1 C_1 (V_H - V_L) W_{M18}} \qquad (1)$$

The frequency can be controlled by changing I_C which is determined by V_{REF}, R_1 and the width ratio between M_{18} and M_{19} or changing capacitor C_1. In this way, clock and ramp signal are generated.

IV. EXPERIMENTAL RESULTS

The proposed single inductor multiple output (SIMO) DC-DC converter which builds its feedback loop only with comparators is introduced. The input voltage ranges from 1.2V to 2.2V, and it regulates two output voltages which level is 3V and 2.5V, respectively. The switching frequency of the proposed SIMO converter is 500-kHz and external inductor and capacitor value is 1-μH and 10-μF, respectively.

Fig. 13 shows power conversion efficiency in terms of output power level. The output power of both output stage are adjusted to be equal while measuring power efficiency. The measured peak efficiency is 81% when the output power is 140mW.

V. CONCLUSIONS

In this paper, a single-inductor multiple-output (SIMO) DC-DC converter which is controlled only with comparators is proposed. The proposed SIMO converter does not need feedback loop which is composed of error amplifier or OTA and its compensation network. Therefore, tolerance of the feedback loop is improved since it does not suffer the variation of compensation resistor and capacitor. Also, loop characteristic variation arises from external inductor value, capacitor value and load current can be removed. The experimental results prove that the proposed SIMO converter regulates two stable output voltages.

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