A Wide Output Voltage Range Single-Input-Multi-Output Hybrid DC-DC Converter Achieving 87.5% Peak Efficiency With a Fast Response Time and Low Cross Regulation for DVFS Applications

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Abstract— **To improve the power delivery in System-on-Chips (SoCs), this paper proposes a single-input-multi-output (SIMO) hybrid converter to obtain fast response time, low cross regulation, and 87% peak efficiency by using a multi-output hybrid power stage and dual-switching-frequency technique. The multiple-output hybrid power stage improves the conversion efficiency without sacrificing the output voltage range, and the dual-switching-frequency technique enhances the response time and cross-regulation performance. The proposed SIMO hybrid converter achieves 87.5% peak efficiency with an output voltage range from 0.4V to 1.6V for all outputs and a total maximum load current of 450mAAdditionally, it achieves less than 0.01mA/mV cross-regulation and less than 20mV overshoot at full-load step transient response.**

Keywords—fast transient response; single-input-multi-output; hybrid buck converter; cross-regulation

I. Introduction

Advanced CMOS technology contributes smaller chip with higher performance for the portable devices. For the purpose of maximizing the performance of the modern system-on-chip (SoC)s, it has become indispensable for the power management system (PMS) in SoC to provide real-time scalable supply voltages for dynamic-voltage-frequency-scaling (DVFS) technique [2]. Inductor-capacitor hybrid method for PMS becomes popular due to the benefits of higher efficiency, less input noise, better packaging flexibility [1,2]. The hybrid converter has shown that by placing the inductor directly to the input power source, as shown in Fig.1, the converter offers better efficiency and higher power density due to reduction of the inductor current.

However, this hybrid topology reports only a limited output voltage range from 0.5x to 1x of the input voltage [1]. The hybrid power stage has also been extended for three outputs with large conversion ratio [2], but only one of outputs is tunable with the limited output voltage range of 1/3x to 1/2x of input voltages. The rest two outputs are regulated at 2x and 3x of the first output voltage, respectively. It is desired to implement multiple independently-scalable outputs for more efficient DVFS applications. Besides, cross-regulation between outputs has always been an issue for the multi-output converters. Existing works of cross-regulation reduction focus on conventional buck converters [3]. For the multi-output converters with hybrid power stage, the cross-regulation and large overshoot/undershoot due to the load/line transition are still unsolved yet.

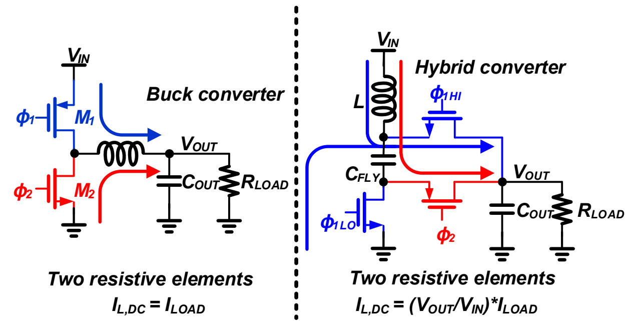

Fig. 1. Buck converter and hybrid converter.

To overcome these limitations, this paper presents a SIMO hybrid voltage regulator to achieve a wide output voltage range, higher efficiency, lower cross regulation and fast transient response for DVFS applications. The proposed hybrid SIMO

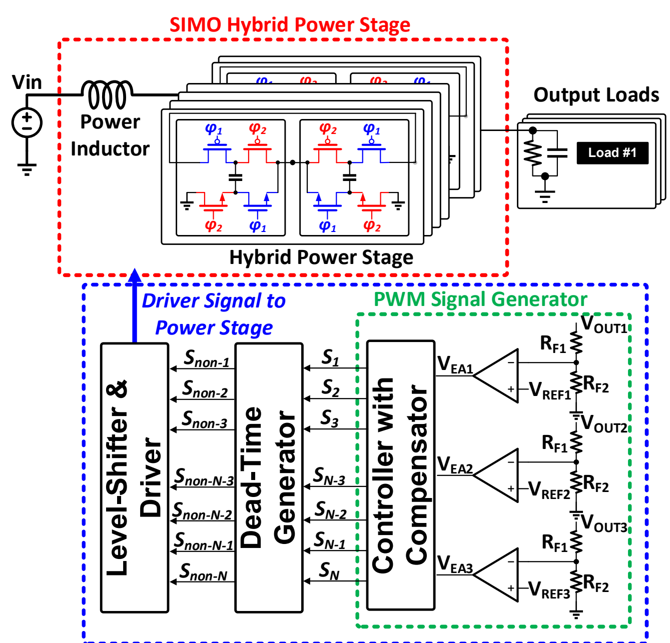

Fig. 2. System block disgram of the proposed hybrid SIMO converter

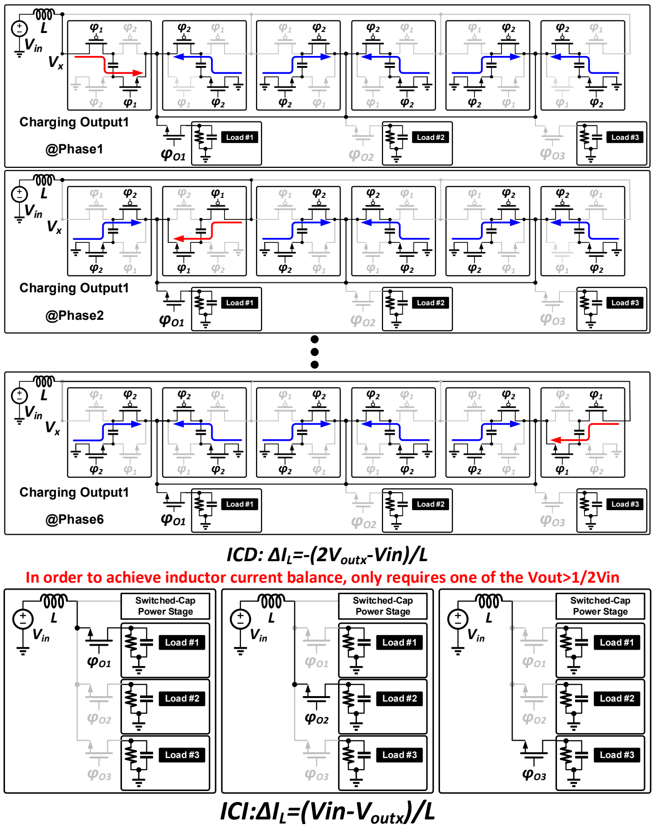

Fig. 3(a) Steady-state operation of the power stage at ICD mode; (b) Steady-state operation of the power stage at ICD mode

converter demonstrates three advantages: 1) extending the output voltage range from 0 to 1x of input voltage like buck converters; 2) enhancing the response performance for voltage/load transition; 3) reducing the cross regulation between different outputs due to the load variation.

In the section II, the hybrid power stage and the operation of the SIMO converter is explained with the circuit diagram. The regulation methodology is presented in section III. Measurement results from the fabricated chip are shown in the section IV. Finally, section V concludes the paper.

II. Multi-Output Hybrid Converter

A. System Diagram of the Proposed SIMO Hybrid Converter

Fig. 2 illustrates a block diagram of the proposed SIMO converter. In this converter, a power inductor connected between the input power source and the rest part of the SIMO converter. By connecting the inductor directly to the input power source, the proposed hybrid SIMO topology gains the benefits of hybrid power stage to improve the efficiency by reducing the inductor current [1]. The rest part of the SIMO hybrid converter includes a set of on-chip switched-capacitor power stages (SCPSs), voltage sensor, comparator, dead-time generator, level-shifter, power MOSFET with driver and the controller.

B. Hybrid Power Stage Operation with Extended Output Voltage Range

The converter operates in two modes – the inductor current increasing mode (ICI) and the inductor current decreasing mode (ICD), as illustrated in Fig. 3. Six SCPSs are connected between the power inductor and the three outputs. Fig. 3(a) shows the operation principle of the SCPS in the ICD mode, when it charges the first output load 1. In the top part of Fig. 3(a), schematic of ICD in phase 1 is presented. In phase 1 of this mode, the flying capacitor in the first SCPS is in series with the output capacitor of load #1 while the flying capacitors in other SCPSs are in parallel with the output capacitor of load 1. Thus, the inductor current is charging the flying capacitor of the first SCPS and the output capacitor together while the other flying capacitors work as on-chip output capacitor. The red curves show the current flow paths from the inductor to the output and the blue curves show the current flow paths from the on-chip flying capacitors to the output. In phase 2, 3, 4, 5 and 6, the flying capacitor in the second, third, fourth, fifth and sixth SCPS, respectively, is connected in series with the output capacitor of load 1, and the other flying capacitors are in parallel with the output capacitor of load 1,. In ICD mode, the inductor is connected between Vin and 2*Vout1, andthus the inductor current is decreasing with the slew rate of (Vin-2*Vout1)/L.

Fig. 3 (b) illustrates the operation principle of the ICI mode. The inductor is connected directly to all three outputs. Thus, the inductor current is increasing with the slew rate of (Vin-Vout)/L. In the steady-state, the converter will be switching between the ICI mode and ICD mode. Furthermore, unlike the previous hybrid converters [1, 5], this proposed SIMO topology allows a full-range conversion from 0 to 1x because output voltages are not regulated by the duty cycle but by the time period of signals of φ_{O1}, φ_{O2} and φ_{O3} as shown in Fig. 3. These signals can determine the power splitting for each output that can be regulated to any voltage between 0 and 1x [3]. Moreover, in order to regulate the inductor current in the steady-state, only one of the output is required to be higher than 1/2x of the input voltage. For example, the topology in the ICI mode will always force the inductor current to increase since the output voltage is always lower than input voltage. During phase 1 of ICD mode, if Vout1 is > 1/2Vin, then Vin-2*Vout1 is negative to ensure the inductor current is decreasing. Hence, the proposed SIMO hybrid converter can extend the output voltage range from 0 to 1x of the input voltage with both output voltages and inductor current regulated.

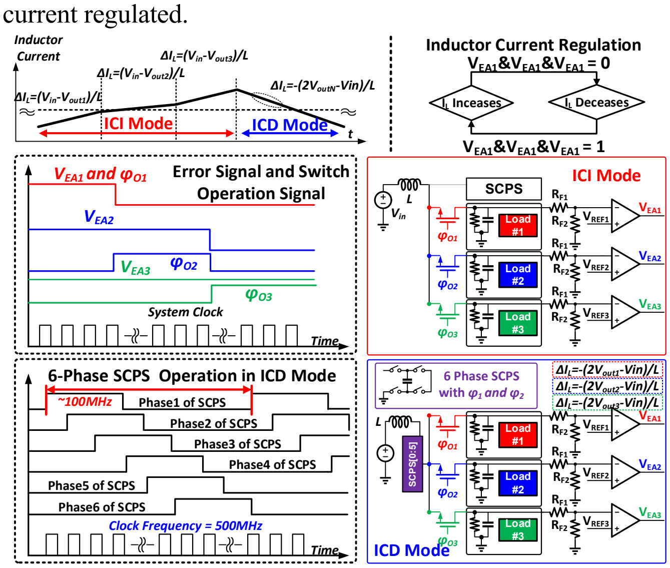

Fig. 4. Steady-state operation with control signal of the hybrid converter.

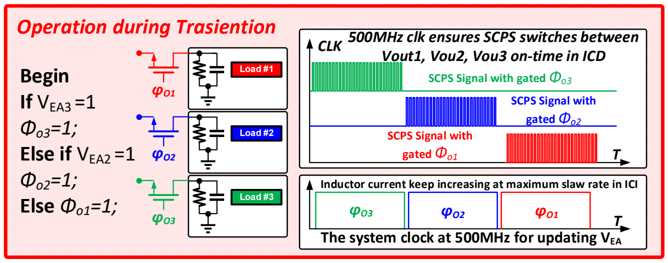

Fig. 5.Control signals of switches for splitting power to different outputs

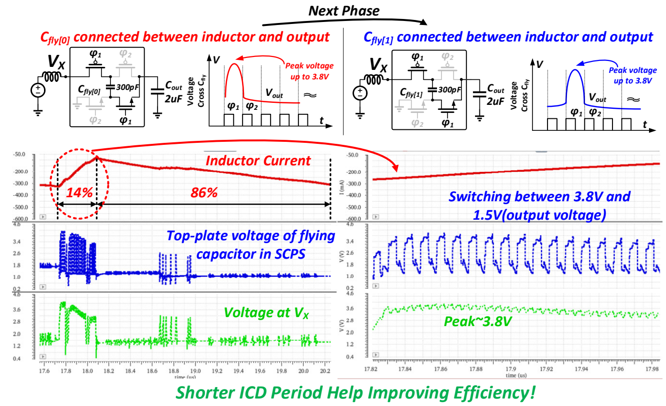

Fig.6. Transient and efficiency enhancement during ICD

III. Regulation Method of the SIMO Hybrid Converter

A. Control Method of SIMO Hybrid Converter

Fig. 4 illustrates the control method of the proposed converter. The controller uses PWM control to regulate the inductor current. The output voltages are compared with the reference voltages to generate the error signal. The converter is controlled to switch between the ICI and ICD modes depending on the state of the error signal. When all of the output voltages are higher than the reference voltage, the converter will operate in the ICD mode. During the ICD mode, the SCPSs are switching in six interleaved phases driven by a system clock of 500MHz. For each single phase of the SCPS, it is switching around 100MHz. This frequency is determined in order to handle the high inductor current and deliver power to the output efficiently.

In Fig. 5, the converter delivers power with the sequence of output1, output2, and output3, and the charging period of each output is adjusted automatically by the control signal generated from the error signals (VEAs). In both ICD and ICI modes, the controller is operating with a 500MHz system clock; thus, it can immediately respond to the load/line variation. In the ICI mode, control signals for φ_{O1}, φ_{O2} and φ_{O3} are generated by slowly changing error signals due to large output capacitors. Thus, the switching frequency in the ICI mode is around 500KHz, which saves switching loss. This dual-switching frequency between 500KHz and 100MHz can enhance the efficiency while improving transient response and cross regulation as described in the following sub-sections.

B. Transient Respose Enhancement

Another benefit of the proposed converter is illustrated in Fig. 6. During the ICD mode, the flying capacitor $C_{fly[0]}$ in SCPS will first be charged up to higher than 2V when it is connected to the inductor in a certain phase, because the size of the flying capacitor is much smaller than output capacitor. In the next phase, it will deliver the energy to the output capacitor and be discharged to the output voltage, while the flying-capacitor $Cf_{ly[1]}$ in the next SCPC cell will be charged up to higher than 2V. Thus the voltage of the node Vx that connects the SCPSs and inductor will be close to 3.8V. It will work same as for the flying capacitors from $C_{fly[2]}$ to $C_{fly[5]}$. Thus, during the whole period of ICD mode, Vx will be held around 3.8V. This leads to a larger voltage across the inductor so that the slew rate of inductor current decreasing will be much higher. It causes the duty-cycle of ICD mode to be much less than that of the ICI mode because the slew rates of inductor current change are high and low in ICD and ICI modes, respectively. Since the SCPC is switching at a very high frequency in the ICD mode while the main power splitting switches are switching at a low frequency in the ICI mode. The small duty cycle in ICD mode significantly reduces the switching loss of the proposed hybrid converter, without compromising output voltage regulation.

Furthermore, it helps to minimize the response time when the converter changes from high load condition to low load condition. During load variation from low to high, unlike the conventional SIMO buck converter, the inductor current in the proposed converter keeps increasing during transient period till all of the outputs achieve the reference voltages.

TABLE I. Pefromance comparison of SIMO Converters

	[2]	[3]	[4]	[5]	***This Work***
Process (nm)	28nm	180nm	28nm	130nm	***180nm***
Topology	3-Level	Conventional Buck	Conventional Buck/Boost	Hybrid	***Hybrid***
Supply Voltage (V)	3.0-4.5	3.3-4	0.2-1.8	9	***1.8***
Output Voltage Range(V)	0.8, 1.2, 1.45	NA	0.4-1.4	3-4.2, 2x, 3x,	***0.4– 1.6, 0.4– 1.6, 0.4– 1.6,***
Switching Frequency (MHz)	3	1	NA	2.3	***500KHz/100MHz***
Load Regulation Methods	SRC+AFC	OVACC	PFM+PWM+SSM	PWM	***PWM***
Number of Outputs	3	5	4	3	***3***
Total Off-chip Ind. (uH)	2.2	4.7	10	1, 0.522	***4.7***
Output Off-chip Cap. (uF)	2	10	1	NA	***1.5, 1.5, 3***
Max Load Current (mA)	1000	1000	100	3000	***450***
Max Output Power (mW)	1138	2.28	60	10900	***720***
Cross regulation (mV/mA)	0.032	0.016-0.035	NA	NA	***<0.01***
Area (mm²)	2.5	5.52	0.5	7.37	***1.95***
Eff. @ Max Power (%)	72	84	N/A	90	***83.5***
Peak Eff. (%)	89.6	86	68	93.4	***87.5***

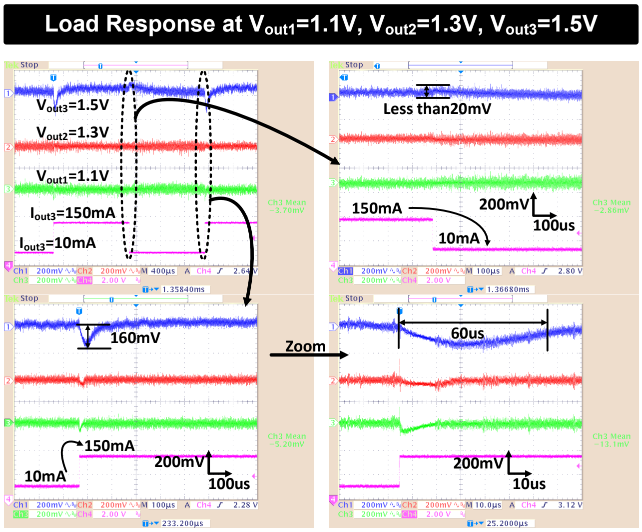

Fig. 8. Measured load response

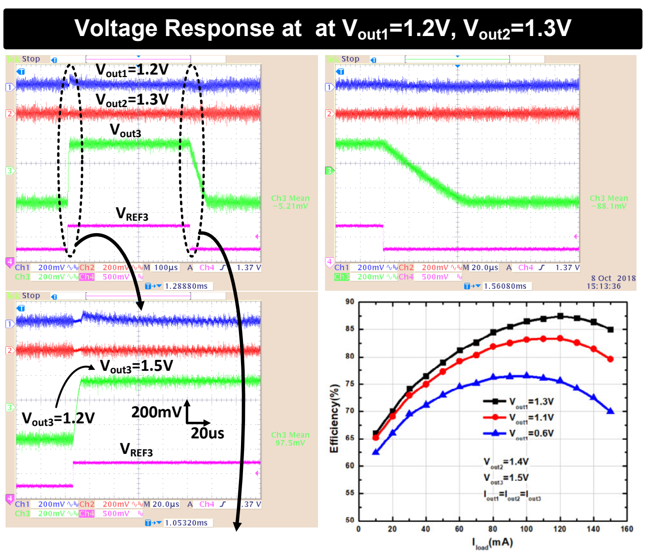

Fig. 9. Measured voltage response and efficiency

C. Cross-Regulation Reduction

As stated above, the regulation consists of inductor current regulation and output voltage regulation. The output voltage regulation is implemented by high-speed high precision clock comparator with 500MHz clock. The output voltage is precisely regulated at the reference voltage by using the hysteresis control method. The cross-regulation is reduced because the output voltage regulation and the inductor current regulation are separated while the output voltage is regulated regardless of the amount of inductor current. Low overshoot and undershoot are appearing at the beginning of the response period, but the output voltages will return to the reference voltages after the inductor current settles down.

IV. Measurement Results

The proposed SIMO hybrid converter is fabricated in TSMC 180nm CMOS process and has an area of 0.85 mm x 2.3 mm excluding pads, shown in Fig. 7. The measurement result shows a peak efficiency of 87.5%, as shown in Fig. 9. With the input voltage of 1.8V, regulated output voltage levels from 0.4V to

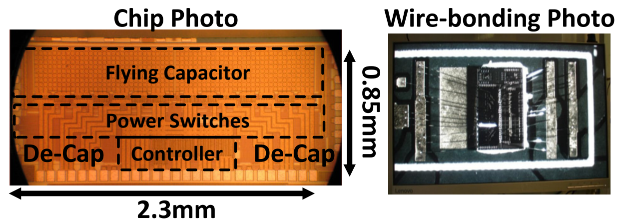

Fig. 7. Chip die photo and wire-bonding photo

1.6V are produced. The fabricated SIMO hybrid converter can also generate load current from 10mA to 150mA for each output (450mA total load current). Fig. 8 and 9 show the measured load transient response and voltage transient response. The load response is measured when Vout3 is switching between no-load condition and full-load condition. It shows a less than 2us of settling time with 20mV overshoot while the cross regulation has not been observed at the falling edge of load current. At rising edge, a 60us of settling time with 160mV undershoot is measured with no observable cross regulation. The voltage response is measured when one of the outputs is switching between 1.2V and 1.5V. It shows that a less than 60us of settling time with no overshoot and cross regulation is observed at falling edge, and an 8us of settling time with no overshoot and cross regulation is observed at rising edge.

V. Conclusion

This paper presents a fast response, low cross-regulation SIMO hybrid converter including two key components: a SIMO hybrid power stage to achieve higher efficiency without compromising the output voltage range and a controller with dual switching frequency to enhance the response speed and reduce the cross-regulation. To fully validate the speed of the dynamic response, the measurement is done to illustrate the 2us response with 20mV overshoot. In addition, this hybrid SIMO converter demonstrates a high peak efficiency of 87% and an efficiency of 83.5% at full load of 450mA. This proposed structure overcomes the conventional design trade-off among the dynamic speed, power consumption, and integration flexibility.

Acknowledgment

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References

[1] N. Tang, et al., "8.4 Fully Integrated Buck Converter with 78% Efficiency at 365mW Output Power Enabled by Switched-Inductor Capacitor Topology and Inductor Current Reduction Technique," *ISSCC*, pp. 152-154, 2019.

[2] L. Chu, et al., "10.5 A three-level single-inductor triple-output converter with an adjustable flying-capacitor technique for low output ripple and fast transient response," *ISSCC*, pp. 186-187, 2017.

[3] N. Pham, et al., "A 0.016 mV/mA Cross-Regulation 5-Output SIMO DC–DC Buck Converter Using Output-Voltage-Aware Charge Control Scheme," *IEEE Transactions on Power Electronics*, vol. 33, no. 11, pp. 9619-9630, Nov. 2018.

[4] S. S. Amin, et al., "MISIMO: A multi-input single-inductor multi-output energy harvester employing event-driven MPPT control to achieve 89% peak efficiency and a 60,000x dynamic range in 28nm FDSOI," *ISSCC*, pp. 144-146, 2018.

[5] C. Hardy, et al., "8.3 A 10.9W 93.4%-Efficient (27W 97%-Efficient) Flying-Inductor Hybrid DC-DC Converter Suitable for 1-Cell (2-Cell) Battery Charging Applications," *ISSCC*, pp. 150-152, 2019.