Better-Than-Worst-Case Design Methodology for a Compact Integrated Switched-Capacitor DC-DC Converter

Dongkwun Kim

Electrical Engineering
Columbia University, New York, NY, USA
dk2990@columbia.edu

Mingoo Seok

Electrical Engineering
Columbia University, New York, NY, USA
ms4415@columbia.edu

Abstract

We suggest a new methodology in co-designing an integrated switched-capacitor converter and a digital load. Conventionally, a load has been specified to the minimum supply voltage and the maximum power dissipation, each found at her own worst-case process, workload, and environment condition. Furthermore, in designing an SC DC-DC converter toward *this* worst-case load specification, designers often have been adding another separate pessimistic assumption on power-switch's resistance and flying-capacitor's density of an SC converter. Such worst-case design methodology can lead to a significantly over-sized flying capacitor and thereby limit on-chip integration of a converter. Our proposed methodology instead adopts the better than worst-case (BTWC) perspective to avoid over-design and thus optimizes the area of an SC converter. Specifically, we propose BTWC load modeling where we specify non-pessimistic sets of supply voltage requirement and load power dissipation across variations. In addition, by considering *coupled* variations between the SC converter and the load *integrated* in the same die, our methodology can further reduce the pessimism in power-switch's resistance and capacitor density. The proposed co-design methodology is verified with a 2:1 SC converter and a digital load in a 65 nm. The resulted converter achieves more than one order of magnitude reduction in the flying capacitor size as compared to the conventional worst-case design while maintaining the target conversion efficiency and target throughput. We also verified our methodology with a wide range of load characteristics in terms of their supply voltages and current draw and confirmed the similar benefits.

CCS Concepts

Hardware → Integrated circuits

Keywords

Fully integrated power converter, Switched-capacitor (SC) DC-DC converter, 2:1 DC-DC converter

1. Introduction

<https://doi.org/10.1145/3218603.3218610>In today's multicore processors, the per-core dynamic voltage frequency scaling (DVFS) is highly desirable to optimize energy-efficiency and

Permission to make digital or hard copies of all or part of this work for personal or classroom use is granted without fee provided that copies are not made or distributed for profit or commercial advantage and that copies bear this notice and the full citation on the first page. Copyrights for components of this work owned by others than ACM must be honored. Abstracting with credit is permitted. To copy otherwise, or republish, to post on servers or to redistribute to lists, requires prior specific permission and/or a fee.

Request permissions from Permissions@acm.org.
ISLPED '18, July 23–25, 2018, Seattle, WA, USA
© 2018 Association for Computing Machinery.
ACM ISBN 978-1-4503-5704-3/18/07 \$15.00
<https://doi.org/10.1145/3218603.3218610>

performance under the thermal and reliability envelop [1, 2]. To implement the per-core DVFS, a key challenge is to enable compact and thus fully-integrated DC-DC converters. Board-level power conversion is increasingly less attractive as the number of cores in a processor rapidly increases. A switched-capacitor (SC) based converter is often more favorable than an inductor-based converter due to their higher power density and CMOS process compatibility [3]. Recent works show the promise to implement fully-integrated SC converters for a low-power digital load that operate at deeply-scaled supply voltage [2].

Conventionally, an SC converter and a load circuit are designed based on the worst-case design paradigm, i.e., design them such that they can achieve the promised performance in the worst-case process, voltage, temperature, and workload condition. In addition, even though they are integrated in the same chip, they are often designed rather separately without much consideration on the coupling between them.

Such conventional methodology starts typically by pessimistically specifying a load. The key parameters to specify for a load are: (i) the maximum current draw, and (ii) the minimum supply voltage (V_{DD}). First, the V_{DD} is specified such that it can achieve a target clock frequency even in the worst-case corner. In our exemplary case with a digital circuit whose critical path is 40 Fan-Out-of-4 (FO4) delays in a 65 nm, we need at least 0.45V V_{DD} to meet the target clock frequency (80MHz) at the SS and -20°C corner. Then next, we specify the worst-case current draw across process and temperature corners. As shown in Fig 1, at the 0.45V V_{DD} that is just specified, the maximum current draw is estimated ~ 3.1 mA at the FF and 80°C corner. This is about $24.8\times$ larger than the current draw of 0.13mA at the SS and -20°C corner.

Fig. 1. The current draw of a near-threshold voltage digital circuit across process and temperature corners

With this overly pessimistic load specification, the design of SC converters also becomes highly pessimistic. Furthermore, designers can add another separate pessimistic assumption on the resistance of power-switches and the capacitor density. Due to all of these overly pessimistic assumptions, the resulting flying capacitor, which typically dominates the size of an SC converter, can be significantly larger than necessary.

In this paper, to tackle this problem, we propose a methodology based on the better than worst case (BTWC) perspective [4]. First, we propose BTWC load specification where we aim to find non-pessimistic supply voltage requirements and load power dissipations. Next, we propose to consider coupled variations between a converter and a load in the design process. Since they are integrated in the same die, they share the similar variations. As a result, the proposed BTWC methodology can reduce the pessimism in sizing a flying capacitor and power transistors while maintaining target power conversion efficiency (PCE).

We experimented the proposed methodology with a 2:1 converter and a digital load circuit in a 65 nm CMOS. Our methodology can successfully reduce flying capacitor size by 4.1 to 42.9 $\times$ over the conventional worst-case methodology while achieving the target computing throughput of the load as well as the target PCE of the converter. We also verified the proposed methodology across multiple load current levels, V_{DD} regimes, and capacitor types, confirming the similar or better benefits.

The remaining paper is organized as follows. In Sec. 2, we will discuss the conventional worst-case design methodology for an integrated SC converter. In Sec. 3, we will outline our BTWC load specification. We will also discuss the BTWC converter design by considering the coupled variations between a load and a converter, together with our simulation results on the scaling of a flying capacitor. In Sec. 4, we will investigate the impact of load current,

load V_{DD} , and on-chip capacitor type on the efficacy of our proposed methodology. Finally, we will conclude in Sec. 5.

2. Conventional Worst-Case Methodology

In this section, we describe the steps of the conventional worst-case design approach of an SC converter. For the integrated converter design, it is ideal to *co-design* a converter and a load. However, this quickly increases design complexity and simulation/verification time. Therefore, in many cases, a load is abstracted to a current source and a converter is designed toward satisfying the specifications of a load.

Fig. 2. Schematic of the benchmark circuits consisting of a 2:1 single-phase SC converter and an inverter-based load circuit

Fig. 2 shows a system of a converter and a load, which we use to benchmark the design methodologies in this paper. It is comprised

Fig. 3. (a) Conventional WC design methodology, (b) the minimum V_{DD} for the target throughput, (c) the maximum I_{LD} at the fixed minimum V_{DD} , (d) the minimum C_{FLY} for the target PCE, (e) the minimum A_{FLY} for the target C_{FLY}

of a single-phase 2:1 SC converter, an inverter-chain based load circuit, a non-overlapping clock generator, level shifters, buffers, and a decoupling capacitor (C_{DC}). The load is 150 of 40 FO4 inverter chains with nodal switching activity of 0.2 [5]. The area of the load circuits is estimated at 0.104 mm² considering 80% cell utilization and the overhead of power rings and grids. The non-overlapping clock generator is used to minimize crowbar current [6, 7]. Level shifters can reduce the swing of the converter clock by half, improving PCE [7]. All the capacitors are implemented in a MOS capacitor while other types of capacitors will be considered in Sec. 4.3. The power consumption of all the peripheral blocks is accounted for PCE calculation. The input voltage (V_{IN}) is 1.0V.

As shown in Fig. 3(a), the first step of the worst-case methodology is to specify the load, namely finding the minimum V_{DD} and the maximum current draw (I_{LD}). We simulated the load across process and temperature corners and found V_{DD} that achieves the target throughput of 80MHz across all the corners considered. As shown in Fig. 3(b), the worst-case V_{DD} is found 0.45V at the SS and -20°C corner for the target throughput. We then set V_{DD} to 0.45V ($V_{DD,WC}$) and simulate the I_{LD} of the load across process and temperature corners. As shown in Fig. 3(c), the worst-case I_{LD} is found to be 3.1 mA at the FF and 80°C corner. Note that this is significantly larger than the I_{LD} found at TT and 25°C. Also, the minimum V_{DD} and the maximum I_{LD} are specified to two different corners, incurring overly pessimistic load specifications.

Next, a converter designer receives the load specifications found above (i.e., $V_{DD} > 0.45V$, $I_{LD} = 3.1mA$) and based on those starts to design a converter (the lower part of Fig. 3(a)). Specifically, we need to find the optimal sets of flying capacitor capacitance (C_{FLY}), power transistor width (W_P), and switching frequency (F_S). To do this, we swept those parameters across process and temperature corners and collected the key performance metrics of an SC converter, namely the minimum output voltage ($V_{OUT,MIN}$) and PCE.

Based on the collected metrics, the designers now choose the configuration that meets system-level needs. In this benchmark, we choose the configuration that leads to the smallest C_{FLY} while making PCE greater than 85% and $V_{OUT,MIN}$ greater than $V_{DD,WC}$. We assume we can dynamically change W_P and F_S optimally to environmental changes. But we do not consider to modulate C_{FLY} since the area of the flying capacitor is already committed to support the largest C_{FLY} and the modulation cannot save its area. Fig. 3(d) shows the impact of C_{FLY} on PCE across process and temperature corners. To achieve the target PCE at the worst-case corner (SS and -20°C), we need $C_{FLY} > 2.15$ nF. Finally, we consider the worst-case capacitor density across process and temperature corners and determine the area of a flying capacitor (A_{FLY}). As shown in Fig. 3(e), this another worst-case consideration leads to A_{FLY} of 0.45 mm². This A_{FLY} is $\sim 4.3\times$ larger than the size of the load (0.104 mm²).

3. Proposed BTWC Methodology

3.1 Overview

The worst-case methodology that we outlined in Sec. 2 has considered multiple pessimistic assumptions, e.g., the worst-case condition for the minimum V_{DD} , that for the maximum I_{LD} , that for the largest power-transistor resistance, and that for the smallest capacitor density. However, it is highly unlikely if not impossible that all the worst-case assumptions happen simultaneously. For example, an integrated converter would experience the similar process and temperature corner with the load. Therefore, it is not necessary to assume that they would be in two opposite corners.

To mitigate those pessimisms, therefore, we propose the BTWC design methodology for an integrated converter design. As shown in Fig. 4, our proposed methodology uses the BTWC specification instead of the worst-case specification for a load. Here we specify pairs of the minimum V_{DD} and the maximum I_{LD} in the same process and temperature corners. In addition, we consider that the converter and the load would experience the same process and temperature variations. With these less pessimistic assumptions, designers can determine C_{FLY} , W_P , and F_S for the target PCE and the minimum A_{FLY} .

3.2 BTWC Load Specification

We propose the BTWC load specification that reduces the pessimism in specifying the minimum V_{DD} and the maximum I_{LD} . As shown in Fig. 5(a), each process and temperature corner requires the different minimum V_{DD} . In near and sub-threshold voltage regime, the load becomes faster at the FF and 80°C corner. This is because the threshold voltage of a transistor (V_{TH}) reduces at that corner, which exponentially increases weak-inversion drain current [8]. In our benchmark circuits (Fig. 2), the minimum V_{DD} s are 0.45V at SS and -20°C, 0.35V at TT and 25°C, and 0.24V at FF and 80°C.

Fig. 4. Proposed BTWC methodology for an integrated SC converter

Fig. 5. (a) Minimum V_{DD} for across different throughputs, (b) maximum I_{LD} across V_{DD} s

In specifying the maximum I_{LD} , we can consider this minimum V_{DD} specification of each process and temperature corner, instead of considering a fixed V_{DD} across all corners. For example, we can achieve the target throughput at lower V_{DD} in the FF and 80°C corner. Therefore, the I_{LD} at that corner, which used to be very high ($24.8\times$ greater than the smallest I_{LD}) in the experiment using the fixed V_{DD} , can be reduced. As shown in Fig. 6, our experiment with the benchmark circuit (Fig. 2), the largest I_{LD} is reduced to 1.32mA, which is $2.4\times$ smaller than the previous worst-case specification of I_{LD} , 3.1 mA (Fig. 3).

Fig. 6. Maximum load current draw at the V_{DD} that is set for the target throughput at each corner

3.3 BTWC Converter Design

Using the BTWC load specification, we can design an integrated SC converter. Here, it is also desirable to mitigate the pessimistic assumptions on power switch resistance and capacitor density, which together determines the output impedance of an SC converter. Specifically, power transistor resistance creates the fast switching limit impedance (R_{FSL}) i.e., the resistance impedes the current flow to and from a flying capacitor. The capacitor forms the other limit, called slow switching limit impedance (R_{SSL}), i.e., the capacitor size (together with other factors) affects the amount of charge transfer via charge sharing. These two form the asymptotic limits in the output impedance of an SC converter [3, 9].

In the BTWC converter design, we consider that a converter and a load are integrated in the same die and thus share the similar process and temperature variations. This provides an important opportunity. In Sec. 3.2, we found that the maximum I_{LD} is 1.32 mA at the FF and 80°C corner. This large I_{LD} could require large C_{FLY} . However, the converter is also in the same corner (FF and 80°C). Thus, its R_{FSL} is substantially reduced, allowing the converter to use faster F_s while using smaller C_{FLY} to support the large I_{LD} without PCE degradation.

Fig. 7. Normalized MOS capacitor density across process, voltage, and temperature variations

Another opportunity is the capacitor density. In the FF and 80°C corner, where the converter needs the largest C_{FLY} , the MOS capacitor density is also larger than the other corner. This is because the V_{TH} of MOS capacitor reduces, which inverts the channel more

Fig. 8. The minimum C_{FLY} for the converter in the (a) SS and -20°C, (b) TT and 25°C, and (c) FF and 80°C corner. And, the MOS capacitor density and the minimum A_{FLY} in the (d) SS and -20°C, (e) TT and 25°C, and (f) FF and 80°C corner.

strongly [10]. The other factor that needs to be considered in capacitor density is that it is also a function of voltage. The MOS capacitor density reduces at lower V_{DD} due to the less strong channel formation. The FF and 80°C corner have the smallest V_{DD} requirement, reducing the density. Fig. 7 shows the variation of MOS capacitor density as a function of process, voltage, and temperature. Overall, we find a moderate amount of scaling in A_{FLY} for the same C_{FLY} requirement by considering the capacitor density variations.

Fig. 8 shows the simulation results of our experiment, i.e., designing the converter using the proposed BTWC methodology. Our experiment is based on the circuits shown in Fig. 2 in a 65 nm, same as that in Sec. 2. First, we find required C_{FLY} , W_P , and F_S that can support the BTWC load specification at each corner and achieve the target PCE. Fig. 8(a) shows the C_{FLY} requirement if the converter is at the SS and -20°C corner. For the integrated converter design, only the leftmost data-point is valid because the load should be in the same SS and -20°C corner. Similarly, we also find the C_{FLY} requirement if the converter is at the TT and 25°C corner in Fig. 8(b) and at the FF and 80°C corner in Fig. 8(c). The largest C_{FLY} across the three corners is 0.14 nF. This is $15\times$ smaller than the C_{FLY} requirement (2.15 nF, Fig. 3(d)) found by the conventional worst-case methodology. Note that although the V_{DD} needed for target throughput is very low for some cases (e.g., FF, 80°C), the output voltage of the SC converter turns out to be higher than that to achieve the target PCE.

Fig. 9. Optimal F_S and W_P found by the proposed BTWC design methodology across process and temperature corners

Fig. 10. PCEs of SC converters designed by the BTWC and the conventional WC design methodology

Finally, we consider the capacitor density variation together with other variations to set A_{FLY} . Fig. 8(d) shows the MOS capacitor density at the SS and -20°C corner considering the V_{DD} requirement. Since the load is in the same corner for the integrated scenario, the data points other than the leftmost are unrealistic. Similarly, in Figs. 8(e, f), we simulated A_{FLY} for the two other corners. The largest A_{FLY} across the three corners, which we need to commit, is 0.027 mm^2 . The A_{FLY} determined by the worst-case methodology is 0.45 mm^2 (Fig. 3(e)), confirming our proposed BTWC design methodology can scale the A_{FLY} by $16.7\times$.

Fig. 9 shows the W_P and F_S configurations that are found/used by the proposed BTWC methodology, with A_{FLY} being optimized to 0.027 mm^2 . Frequency and conductance modulation techniques have been available and widely used [11, 12]. With the configurations, the converter can achieve $> 85\%$ PCE across process and temperature corners. In general, as I_{LD} increases, so do the optimal W_P . In addition, Fig. 10 shows the PCEs across the corners, achieved by the proposed BTWC design methodology. Again, the BTWC methodology yields $A_{FLY} = 0.027 \text{ mm}^2$. The lowest PCE is achieved at the FF and 80°C corner. Fig. 10 also shows the PCEs of the converter designed by the conventional worst-case methodology. It shows similar PCEs across corners, but the smallest PCE appears at the SS and -20°C corner. This is because the power switch resistance increases at this corner and degrades PCE.

4. Impact of Load Current, Load V_{DD} , and On-chip Capacitor Type

4.1 Load Current Draw

In this subsection, we experiment the scalability of the proposed design methodology. Particularly, the experiment in Sec. 3 uses a single arbitrary-chosen load current level (0.18 mA at TT and 25°C). Here we will verify the efficacy of the proposed methodology for a $125\times$ range of load current from $0.04 \mu\text{A}$ to 4.56 mA .

Fig. 11(a) summarizes the A_{FLY} results achieved by the proposed and the conventional design methodology. It shows that the A_{FLY} increases roughly linearly with the load current in both methodologies. Fig. 11(b) summarizes the optimal W_P and F_S across the I_{LD} levels. In general, the optimal W_P increase linearly with I_{LD} while the optimal F_S appear around 30 MHz across the load current range considered. This experiment confirms that the proposed methodology maintains the benefits over a wide range of I_{LD} levels.

Fig. 11. (a) Capacitor area achieved by the BTWC and the conventional WC design methodology and (b) optimal F_S and W_P found via the BTWC design methodology

4.2 Load V_{DD}

In this section, we investigate the impact of load V_{DD} on the efficacy of the proposed BTWC methodology. The V_{DD} of the load circuit considered in Sec. 3 is 0.24V to 0.45V across the process and temperature corners. In such near- and sub-threshold voltage regime, leakage takes a considerable amount of total current draw even in the TT and 25°C corner [13]. At the FF and 80°C corner, this leakage current increases exponentially, which is the root cause of the large variation of current draw across corners that we observed in Fig. 1.

At the load V_{DD} that is higher than the threshold voltage, called super-threshold regime hereafter, leakage (static) current makes less impact on the total current draw. This makes the conventional worst-case design methodology less pessimistic for a super-threshold voltage load, as compared to near- and sub-threshold loads.

The aforementioned changes affect the savings from the BTWC methodology. Fig. 12 shows the results of our experiment, where we modulate the V_{IN} of the converter (Fig. 2) from 0.8 to 1.8V. The nominal output of the converter is 0.4V to 0.9V. At 0.8V V_{IN} , we find that the proposed BTWC methodology can provide greater benefit, reducing A_{FLY} by 42.9× over the worst-case methodology. On the other hand, at the higher V_{IN} of 1.8V, the BTWC methodology achieves a still considerable but less amount of improvement: 4.1× A_{FLY} scaling as compared to the worst-case methodology. This is mainly because the I_{LD} variability is smaller and thus the worst-case methodology becomes less pessimistic.

Fig. 12. Capacitor area scaling of SC converters designed by the BTWC and the conventional WC design methodology

4.3 Capacitor Type

In Sec. 3, we have considered the MOS capacitor to implement flying capacitors. In this subsection, we will consider the other popular type of the capacitor, metal-insulator-metal (MIM) capacitor, and investigate its impact on the proposed BTWC methodology. As compared to the MOS capacitor, the MIM capacitor typically has a better linearity over temperature and voltage variation. Also, it is implemented in the back end of CMOS technology, making it would not share process variation with transistors. Therefore, we have to consider the worst-case capacitance density to ensure the proper amount of charge transfer. We did the same benchmark converter design using MIM capacitors. The resulting A_{FLY} savings over the worst-case methodology is 15×, which is slightly lower than the savings achieved with MOS capacitors.

5. Conclusion

In this paper, we propose the BTWC design methodology for compact integrated SC DC-DC converters. The methodology aims to replace multiple worst-case assumptions with realistic and practical ones. Across ranges of load current and load V_{DD} , the proposed methodology successfully scales the size of a flying capacitor, an area-dominant component of an SC converter, by 4 to 43×, while achieving the target PCE and the target throughput.

Acknowledgement

This work is supported by Semiconductor Research Corporation (SRC, Task 2712.012), NSF (CCF-1453142), and Catalyst Foundation. We appreciate Drs. Minki Cho, Ram Krishnamurthy, Seongjong Kim, Suhan Kim and Suyoung Bang from Intel Circuit Research Lab (CRL) for valuable feedback and discussions.

References

- [1] H.-P. Le, S. Sanders and E. Alon, "Design Techniques for Fully Integrated Switched-Capacitor DC-DC Converters," *IEEE J. Solid-State Circuits*, vol. 46, no. 9, pp. 2120–2131, Sep. 2011.
- [2] S. T. Kim et al., "Enabling Wide Autonomous DVFS in a 22 nm Graphics Execution Core Using a Digitally Controlled Fully Integrated Voltage Regulator," *IEEE J. Solid-State Circuits*, vol. 51, no.1, pp. 18–30, Jan. 2016.
- [3] S. Bang, D. Blaauw and D. Sylvester, "A Successive-Approximation Switched-Capacitor DC-DC Converter With Resolution of $V_{IN}/2^N$ for a Wide Range of Input and Output Voltages," *IEEE J. Solid-State Circuits*, vol. 51, no. 2, pp. 543–556, Feb. 2016.
- [4] T. Austin et al., "Opportunities and challenges for better than worst-case design," in *Proc. Asia and South Pacific Design Automation Conference (ASP-DAC)*, pp. 12–17, Jan. 2005.
- [5] M. Seok, D. Sylvester and D. Blaauw, "Optimal Technology Selection for Minimizing Energy and Variability in Low Voltage Applications," *ACM/IEEE International Symposium on Low Power Electronics and Design (ISLPED)*, pp. 9–14, Aug. 2008.
- [6] A. Saiz-Vela et al., "Low-Power High-Voltage Non-overlapping Clock Generators for Switched-Capacitor step-up DC-DC Converters," *IEEE International Midwest Symposium on Circuits and Systems (MWSCAS)*, pp. 61–64, Aug. 2006.
- [7] L. Chang et al., "A Fully-Integrated Switched-Capacitor 2:1 Voltage Converter with Regulation Capability and 90% Efficiency at 2.3A/mm²," *IEEE Symposium on VLSI Circuits (VLSI)*, pp. 55–56, Jun. 2010.
- [8] M. Wirmshofer, "Sources of Variation. In: Variation-Aware Adaptive Voltage Scaling for Digital CMOS Circuits," *Springer Series in Advanced Microelectronics*, vol. 41, Springer, Dordrecht.
- [9] M. D. Seeman and S. R. Sanders, "Analysis and Optimization of Switched Capacitor DC-DC Converters," *IEEE Trans. Power Electron.*, vol. 23, no. 2, pp. 841–851, Mar. 2008.
- [10] M. Seok, "Decoupling capacitor design strategy for minimizing supply noise of ultra low voltage circuits," *ACM/IEEE/EDAC Design Automation Conference (DAC)*, pp. 968–973, Jun. 2012.
- [11] R. Jain et al., "Conductance Modulation Techniques in Switched-Capacitor DC-DC Converter for Maximum-Efficiency Tracking and Ripple Mitigation in 22 nm Tri-Gate CMOS," *IEEE J. Solid-State Circuits*, vol. 50, no. 8, pp. 1809–1819, Aug. 2015.
- [12] X. Mi et al., "Fully-Integrated Switched-Capacitor Voltage Regulator with On-Chip Current-Sensing and Workload Optimization in 32nm SOI CMOS," *ACM/IEEE International Symposium on Low Power Electronics and Design (ISLPED)*, pp. 140–145, Jul. 2015.
- [13] Joao Pedro Cerqueira and Mingoo Seok, "Temporarily Fine-Grained Sleep Technique for Near- and Subthreshold Parallel Architectures," *IEEE Trans. Very Large Scale Integration (VLSI) Systems*, vol. 25, no. 1, pp. 189–197, Jan. 2017.