<http://www.diva-portal.org>

Postprint

This is the accepted version of a paper presented at *IEEE International Conference NORCHIP, Tampere, Finland, Nov. 2014.*

Citation for the original published paper:

Katic, J., Rodriguez, S., Rusu, A. (2014)

Analysis of Dead Time Losses in Energy Harvesting Boost Converters for Implantable Biosensors.

In: (pp. 1-4). IEEE

<http://dx.doi.org/10.1109/NORCHIP.2014.7004714>

N.B. When citing this work, cite the original published paper.

Permanent link to this version:

<http://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-163558>

Analysis of Dead Time Losses in Energy Harvesting Boost Converters for Implantable Biosensors

Janko Katic, Saul Rodriguez and Ana Rusu
School of Information and Communication Technology (ICT)
KTH Royal Institute of Technology
SE-164 40 Kista, Sweden
Email: katic@kth.se

Abstract—Efficiency of an ultra-low power energy harvesting dc-dc converter depends on its losses and the power consumption of the control circuit. Unlike other loss mechanisms, losses related to dead times have not been thoroughly studied. Therefore, in most cases these losses are not adequately suppressed. This paper investigates dead time losses and their impact on the overall system efficiency. Simple expressions for fast estimation of dead time losses are derived. Analysis shows that in many applications where high voltage conversions are required, such as implantable biosensors, the efficiency reduction due to these losses can easily exceed 2%. The analysis is validated using an adaptive dead time circuit which minimizes the associated losses and improves the overall system efficiency according to the calculated values.

I. INTRODUCTION

Energy harvesting is becoming an increasingly popular solution for powering wireless sensor nodes, including body area sensor nodes, such as implantable biosensors [1]. In contrast to batteries, which have a limited lifetime and need to be changed periodically, the energy harvesting technology has potential to autonomously power the sensor nodes [2]. Unfortunately, the available energy sources are, by nature, variable and unpredictable and can not be used to directly power the sensor nodes. Therefore, a dedicated power management unit (PMU) is required, as it is shown in Fig. 1.

Biomedical applications demand scavenging energy from specific environments, where available power levels are extremely low. For instance, an implantable biosensor should be able to harvest energy while completely surrounded by human tissue. In such applications, the amount of available power and output voltage can be extremely low, dictating severe requirements for the input dc-dc converter [3]. Namely, the input converter should be able to start-up and operate with input voltages as low as tens of mV [4]. At the same time, it should facilitate maximum power extraction (MPE) at any time by presenting adequate loading to an energy harvesting device. Finally, it should process only several μW of input power with relatively high efficiency. Consequently, all losses within the converter have to be minimized, as well as the power consumption of the control circuitry.

Various techniques for improving the efficiency and minimizing losses of these converters have been investigated [4]–[6]. However, losses related to dead times have not been addressed. This paper investigates these losses in detail and derives expressions to quickly calculate their influence. The

Fig. 1. Traditional micropower energy harvesting system architecture.

investigation shows that in biomedical applications these losses are significant. Therefore, contrary to the general practice, they should not be neglected, but rather properly estimated and, if it is necessary, suppressed. For this purpose, a simple, but effective adaptive dead time circuit can be used [7]. This circuit improves the overall system efficiency according to estimated values and confirms the derived expressions.

The paper is organized as follows. Section II presents the micropower energy harvesting system architecture, discusses its main blocks, their topologies and requirements. Section III analyzes the dead time losses and estimates their impact on the overall system efficiency. Section IV validates the derived expressions using the adaptive dead time circuit. Finally, conclusions are made in Section V.

II. ENERGY HARVESTING SYSTEM ARCHITECTURE

The traditional micropower energy harvesting system architecture is illustrated in Fig. 1. A key component of this system is the input dc-dc converter. As it was already mentioned, the input converter has to carry out multiple tasks under strict requirements. The start-up circuit has to pre-charge the storage device so that the circuits controlling the switches can work properly. The storage device acts as an energy buffer. It stores energy during the sleep period of the sensor node operation and provides energy when the node is active. Finally, since the storage element voltage varies over time, another dc-dc converter is required to provide a stable voltage supply for the sensor node.

Fig. 2. Input dc-dc converter architecture.

A. Input Converter

The input converter topology, which can meet previously defined requirements, is a boost converter with an external inductor operating in discontinuous conduction mode (DCM) [3]. This topology, including its simplified control block, is illustrated in Fig. 2. Even though it is a relatively simple topology, there are various sources of losses within the converter, and all of them have to be carefully examined and addressed in order to obtain sufficient efficiency.

B. Sources of Losses

The sources of losses inside a boost converter can be roughly divided into three categories: conduction losses (related to parasitic resistances within the converter), switching losses (linked to undesired capacitances) and synchronization losses (related to errors in the pFET switch, M_P , turning ON and OFF timings). Generally, conduction losses are proportional to the power levels, while switch driving losses are scaled down with the reduction of the operating frequency. On the other hand, synchronization losses mainly depend on the control circuitry and its performance.

C. Control

The associated control of the micropower energy harvesting dc-dc converter is mainly digital. An oscillator generates a clock signal, with a particular frequency and duty cycle, which drives the nFET switch, M_N , for proper input matching. The same signal is then delayed and used to generate pulses that drive M_P . The pulse width is controlled by a counter value. A similar control is used in almost all related state-of-the-art solutions [4]–[6]. This type of control is simple, consumes very low power, easily achieves zero current switching (ZCS) and, consequently, high efficiency. Synchronization losses related to M_P turn-OFF timing are minimized. On the contrary, synchronization losses related to M_P turn-ON timing (dead time losses) remain, unless the adaptive dead time block is added.

Fig. 3. Waveform of the voltage V_X during the dead time, illustrating long dead time.

III. DEAD TIMES ANALYSIS

In order to prevent a situation in which both switches are conducting at the same time, it is necessary to introduce the dead time during their transition. Otherwise, a low resistance path between output and ground will be created. This path would discharge the output capacitance and severely degrade the efficiency. In DCM operating boost converters, the dead time starts after M_N turns OFF and lasts until M_P turns ON, as illustrated in Fig. 3. Unfortunately, even when the dead time is introduced, significant losses might remain. Three different cases may be distinguished:

- Dead time is accurate, $t_{dead} = t_{acc}$. After M_N turns OFF, the inductor current starts charging the parasitic capacitance at inverter node X , building up the voltage V_X . If M_P is turned ON at the same moment when this voltage is equal to the output voltage, then almost lossless zero voltage switching (ZVS) is achieved.
- Dead time is short, $t_{dead} < t_{acc}$. In other words, M_P is turned ON early. In this situation, the voltage V_X is still lower than the output voltage and due to charge distribution it gets instantly charged from the output capacitor. The reversed current flow results in significant losses.
- Dead time is long, $t_{dead} > t_{acc}$. In fact, this means that M_P is turned ON late, as it is shown in Fig. 3. In this situation, voltage V_X becomes higher than the output voltage. Eventually, the body diode of M_P starts conducting, and due to its voltage drop unnecessary power is dissipated.

The accurate dead time depends on the conversion ratio of the converter. Therefore, any selected fixed dead time will lead to unminimized losses. To demonstrate this statement, a detailed analysis of appropriate dead time duration and related losses is required. In order to do that, the equivalent converter circuit during the dead time and the parasitic capacitance at node X need to be extracted.

During the dead time, by definition, both switches are OFF. Therefore, they can be represented as their body diodes, as it

Fig. 4. Equivalent circuit of the input converter during dead time.

is shown in Fig. 4. At the same time, the inductor is acting as a current source of approximately constant current (this is valid if the dead time is much lower than M_P ON time). The capacitance C_X is given by:

$$C_X = C_{jN} + C_{ovN} + C_{jP} + C_{ovP} + C_{par}, \quad (1)$$

where C_{jN} and C_{jP} are depletion capacitances of reverse biased nFET and pFET body diodes respectively, C_{ovN} and C_{ovP} represent the overlap and fringing capacitance of turned-off transistors and C_{par} is the sum of parasitic capacitances at the node X , such as board capacitance, pad capacitance, etc. The depletion capacitance is given by:

$$C_j = \frac{C_{j0}A}{\sqrt{1 + \frac{V_R}{\Phi_0}}}, \quad (2)$$

where C_{j0} is a depletion capacitance per unit area when $V_R = 0$, A is a depletion region area, V_R is a reverse-bias voltage of the diode and Φ_0 is a built-in junction potential. It can be concluded from equations (1) and (2) that both C_{jN} and C_{jP} , as well as C_X depend on the voltage V_X . However, because C_{jN} decreases with V_X and C_{jP} increases with V_X , their total influence on C_X remains almost constant. In addition, other terms in (1) do not depend on V_X . Therefore, in most cases, the variation of capacitance C_X due to the voltage V_X will be very low. Consequently, and for the sake of simplicity, this capacitance will be considered constant in the following analysis.

According to the equivalent circuit of the converter during the dead time shown in Fig. 4., the constant current $I_{L,max}$ charges the capacitor C_X to $V_X = V_{out}$:

$$\frac{I_{L,max}}{C_X} t_{acc} = V_{out}. \quad (3)$$

From (3), the accurate dead time t_{acc} can be easily estimated:

$$t_{acc} = \frac{C_X L}{\tau_N} \frac{V_{out}}{V_{in}} = \frac{C_X L}{\tau_N} K, \quad (4)$$

where τ_N is ON time of M_N and $K = \frac{V_{out}}{V_{in}}$ is the conversion ratio of the converter. For $V_{out} \gg V_{in}$, the accurate dead time is approximately:

$$t_{acc} \approx \frac{C_X L}{\tau_P}, \quad (5)$$

where τ_P is ON time of M_P . Indeed, the accurate dead time depends on both the input and the output voltages.

In order to avoid a situation in which the dead time is short for some conversion ratios (significant losses), usually a fixed

dead time is used, t_{fix} . The fixed dead time corresponds to the maximum possible conversion ratio. This results in a long dead time and the pFET body diode conduction. Taking this into account, the losses related to a dead time error can be estimated as:

$$P_{loss,dead} = V_{diode} I_{L,max} t_{err} f_s, \quad (6)$$

where V_{diode} is a voltage drop of the pFET body diode, $t_{err} = t_{fix} - t_{acc}$ is the dead time error shown in Fig. 3., and f_s is the switching frequency. Further, after inserting (4) into (6):

$$\begin{aligned} P_{loss,dead} &= V_{diode} \frac{V_{in}}{L} \tau_N \frac{C_X L}{\tau_N} (K_{max} - K) f_s \\ &= V_{diode} V_{out} C_X f_s \left(\frac{K_{max}}{K} - 1 \right). \end{aligned} \quad (7)$$

If the output voltage is considered constant, equation (7) may be rewritten as:

$$P_{loss,dead} = V_{diode} V_{out} C_X f_s \left(\frac{V_{in}}{V_{in,min}} - 1 \right). \quad (8)$$

According to (8), maximum losses related to the dead time will be dissipated when $V_{in} = V_{in,max}$. Unfortunately, in many applications, the ratio between $V_{in,max}$ and $V_{in,min}$ can easily reach values higher than 10, resulting in considerable losses. The expressions (7) and (8) can be used to quickly estimate the losses related to dead times. Furthermore, the efficiency reduction due to dead time losses can be derived as:

$$\begin{aligned} \Delta EFF &= \frac{P_{loss,dead}}{P_{in}} \\ &= \frac{V_{diode} V_{out} C_X f_s \left(\frac{K_{max}}{K} - 1 \right)}{\frac{V_{in}^2}{R_{in}}} \\ &= \frac{V_{diode} R_{in} C_X f_s \left(\frac{K_{max}}{K} - 1 \right) K^2}{V_{out}}, \end{aligned} \quad (9)$$

where R_{in} is the input resistance of the converter, defined by the MPE. The reduction reaches its maximum for $K = \frac{K_{max}}{2}$ and it is equal to:

$$\Delta EFF_{max} = \frac{V_{diode} R_{in} C_X f_s K_{max}^2}{4 V_{out}}. \quad (10)$$

This expression provides a fast insight into the maximum overall efficiency reduction related to the dead time losses. Most of the parameters in (10) are usually known or simple to extract, only C_X needs to be estimated from the design. As it will be shown in the next section, this degradation of the efficiency can easily exceed 2% in most biomedical applications.

IV. VALIDATION OF DERIVED EXPRESSIONS

To suppress the dead time losses an additional block, dead time block shown in Fig. 2., can be employed. By comparing the efficiency of the converter with and without this block the efficiency reduction due to the dead time losses can be obtained. Note that the power consumption of this block has to be negligible compared to the dead time losses given by (7) in order to obtain accurate results.

Fig. 5. Adaptive dead time circuit.

As it can be noticed from the equation (5), the accurate dead time depends on M_P ON time τ_P . This time is specified by the counter value in order to achieve ZCS. Therefore, if C_X is previously estimated, the same counter can be used to define an adaptive dead time. Following this idea, a single delay element controlled by the counter value can be used to obtain the accurate dead time at any conversion ratio.

A. Circuit Description

For validation, the adaptive dead time circuit shown in Fig. 5. is used. An n -bit digital signal (from the counter) is used to produce the adequate control signals for m parallel switches $sw_1 - sw_m$. The transistor M_0 is always ON and it defines the maximum dead time. The remaining switches control the circuit delay and, consequently, the dead time. One particular state of switches represents one desired delay value. As τ_P in (5) is linearly dependent on the counter value, to generate the best dead time approximation, a nonlinear decoding (n to m bits) is required. A very simple implementation of such delay element, with $n = 4$ and $m = 3$ is described and utilized in [7]. Depending on the required level of approximation, increasing m improves the dead time precision at the cost of somewhat increased complexity. Finally, for $m = n^2 - 1$, if the switches are properly sized, the accurate dead time can be achieved. However, relatively good approximations can be obtained with lower values of m .

B. Simulation Results

For the proof of concept, an input dc-dc converter, similar to the one presented in Fig. 2., is tested with fixed dead time (equal to the maximum possible) and the adaptive dead time circuit (with $n = 4$ and $m = 7$). Efficiency improvement depending on the conversion ratio is illustrated in Fig. 6. The simulated efficiency improvement follows the previous estimation in the equation (9), which proves the accuracy of the derived expression. The following parameters were used for simulation, V_{in} ranges from 20 to 150mV, $V_{out} = 1.8V$, $L = 10\mu H$, $R_{in} = 100\Omega$, $f_s = 50kHz$ and $C_X = 5pF$. With those parameters, the simulated power consumption of the adaptive dead time circuits is only 10nW and the maximum efficiency improvement is 2.2%. The calculated maximum losses according to (8) are 500nW and the estimated efficiency

Fig. 6. Efficiency improvement.

reduction due to dead time losses is 2.1%, almost the same as the simulated value.

V. CONCLUSION

A brief analysis of losses related to dead times within energy harvesting converters for implantable biosensors is presented. Related loss sources and mechanisms are discussed in detail, and expressions for fast estimation of these losses and their influence on the overall efficiency are derived. The analysis demonstrated that the effect of these losses can be significant and should be carefully addressed. In order to reduce the dead time losses, an adaptive dead time circuit can be used. This circuit is very simple to implement, occupies a negligible area, consumes only dynamic power, and it can potentially completely suppress the losses related to the dead time. When this circuit is utilized within the classical micropower energy harvesting systems, the simulation results confirm the accuracy of derived expressions.

ACKNOWLEDGMENT

The authors would like to thank the Swedish Research Council (VR) for funding this work.

REFERENCES

- [1] P. P. Mercier, A. C. Lysagh, S. Bandyopadhyay, A. Chandrakasan, and K. M. Stankovic, "Energy extraction from the biologic battery in the inner ear," *Nature Biotechnol.*, vol. 50, no. 12, pp. 1240-1243, 2012.
- [2] R. J. M. Vullers, R. van Schaijk, I. Doms, C. van Hoof, and R. Mertens, "Micropower energy harvesting," *Solid-State Electron.*, vol. 53, no. 7, pp. 684-693, 2009.
- [3] G. Villar-Piqué, H. Bergveld, and E. Alarcón, "Survey and benchmark of fully integrated switching power converters: switched-capacitor vs inductive approach," *IEEE Trans. Power Electron.*, vol. 28, no. 9, pp. 4156-4167, 2013.
- [4] Y. K. Ramadass, and A. P. Chandrakasan, "A battery-less thermoelectric energy harvesting interface circuit with 35 mV startup voltage," *IEEE J. Solid-State Circuits*, vol. 46, no. 1, pp. 333-341, 2011.
- [5] E. J. Carlson, K. Strunz, and B. P. Otis, "A 20 mV input boost converter with efficient digital control for thermoelectric energy harvesting," *IEEE J. Solid-State Circuits*, vol. 45, no. 4, pp. 741-750, 2010.
- [6] P.-S. Weng, H.-Y. Tang, P.-C. Ku, and L.-H. Lu, "50 mV-input batteryless boost converter for thermal energy harvesting," *IEEE J. Solid-State Circuits*, vol. 48, no. 4, pp. 1031-1041, 2013.
- [7] J. Katic, S. Rodriguez, and A. Rusu, "An Efficient Boost Converter Control for Thermoelectric Energy Harvesting," in *IEEE International Conference on Electronics, Circuits and Systems*, Dec 2013, pp. 385-388.