TIME MODULATION – THE EXPONENTIAL WAY

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Abstract*–A solution for obtaining an exponential variation of time versus input voltage of a time-modulating circuit is investigated, implemented and its performances are measured. Most time-modulating circuits produce a delay that is linearly dependent on the input voltage. This paper proposes a new method of controlling the time delay output by making it vary exponentially with the input voltage. This solution is especially useful in aplications where the time-delay is constantly modulated by a prior error amplifier.*

Keywords: *time-modulation, high threshold MOS switch, exponential dependency, CMOS technology, charge capacitor.*

1. INTRODUCTION

Time-modulating circuits are commonly used in switching applications. Switch-Mode Power Supplies (SMPS) such as buck or boost converters rely mainly on the dynamic variation of the "on" and "off" time, depending on external components, as well as loop architecture.

An exponential function of output versus input delivers an important advantage over its linear alternative. In an exponential variation, any Ä variation at any input value would generate the same percentage difference in output. This consideration is important when designing complex control loops, due to ease of calculations.

This paper presents a time modulator architecture that offers a quasi-exponential relation between input voltage and output time delay.

2. PROPOSED ARCHITECTURE

The block schematic of a linear time-modulating architecture is depicted in Fig. 1a. When the RST signal is active, the capacitor (C) voltage is set to ground. As soon as RST is disabled, current source I starts charging the capacitor. When its voltage reaches V_{CTRL}, the comparator's output switches from zero to V_{DD}. The time (T_{OUT1}) required to switch is:

$$T_{OUT1} = \frac{V_{CTRL} \cdot C}{I} \tag{1}$$

This time is linearly dependent on the value of input V_{CTRL}.

By modifying the architecture as depicted in Fig. 1b, we can obtain a dependency that is close to an exponential curve. Capacitor C is now charged by current sources I_1 and I_2. When input voltage V_{CTRL} is high enough to open transistor M_1, the charge current is significantly decreased. This increases switching time (T_{OUT2}) to the value calculated below [1], [2]:

$$T_{OUT2} = \frac{V_{CTRL} \cdot C}{I_2 + (I_1 - I_{M1})} \tag{2}$$

where, from [3]

$$I_{M1} = \frac{W}{L} \cdot \frac{k_n}{2} (V_{CTRL} - V_T)^2 \tag{3}$$

Replacing eq. (3) in (2) gives:

$$T_{OUT2} = \frac{V_{CTRL} \cdot C}{I_2 + \left[I_1 - \frac{W}{L} \cdot \frac{k_n}{2} (V_{CTRL} - V_T)^2 \right]} \tag{4}$$

The expression for I_{M1} is valid once V_{CTRL} is above the threshold voltage of M1. This solution offers a quadratic dependency of output time delay versus input voltage. M1 has been designed with a high value length, in order to ensure near exponential behavior only at the high-end of input voltage values.

The proposed architecture uses two current sources to charge capacitor C because it is desired to have a minimum charge current when M1's drain current exceeds the value of I_1. In such a case, should the input voltage

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range exceed expected values for any reason, the circuit's response becomes linear again.

The suggested solution is meant for applications where the time-modulating architecture is controlled by an error amplifier, as presented in [4] and illustrated in Fig. 2.

The setup ensures desired precision even when functioning on the steep slope of the exponential curve.

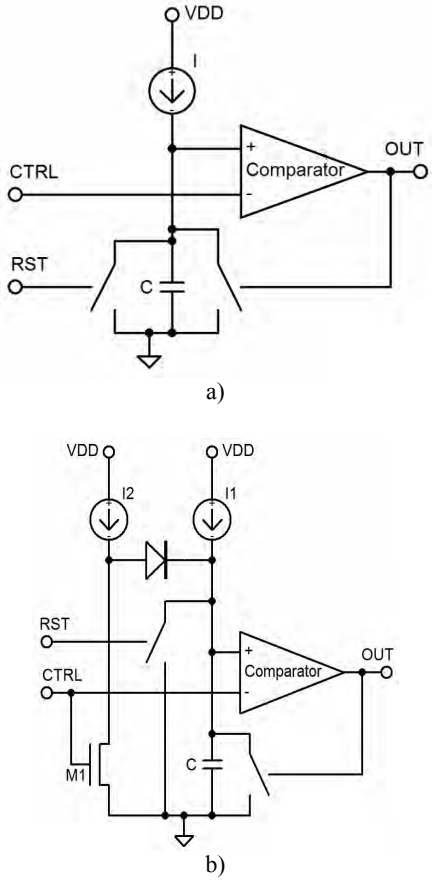

Fig. 1. Linear (a) and exponential (b) time-modulating architectures.

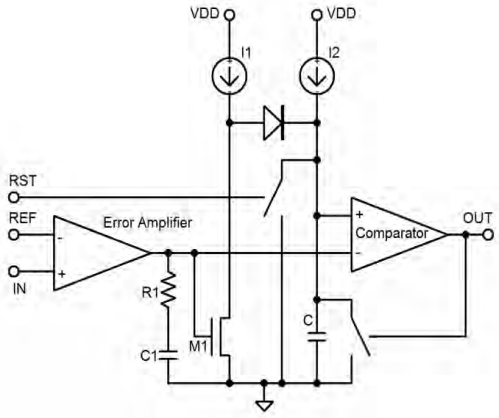

Fig. 2. Block diagram of suggested design.

3. SIMULATION RESULTS

The purpose of the paper is the design of a time modulator capable of an output time range in the 0.5 - 15µs interval, for input voltages of 0.2V to 1.4V. Also, the two current sources I_1 and I_2 are designed to offer 1µA and 0.2µA, respectively.

Simulations were performed in a PSpice environment, using EKV models for both N-type and P-type MOSFETS. The design kit belongs to a 0.5µm CMOS technology.

Fig. 3 shows a comparison between calculated –eq (4) – and simulated results, in order to validate design performances. As expected, the proposed schematic delivers the calculated variation, achieving desired results.

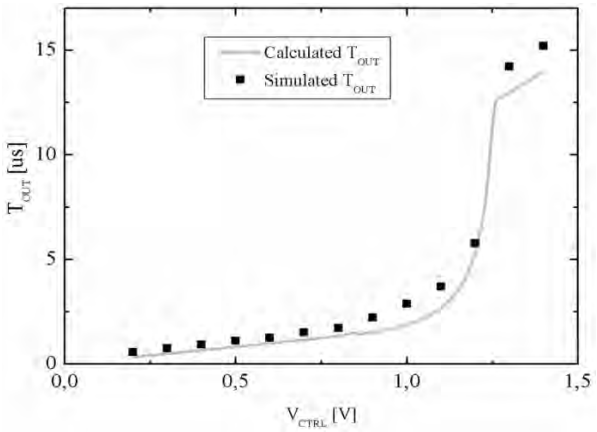

Fig. 3. Comparison of (a) calculated and (b) simulated results.

In order to illustrate the near exponential behavior of the design, simulation results were compared to their best fitting exponential function (5). Results are depicted in Fig. 4.

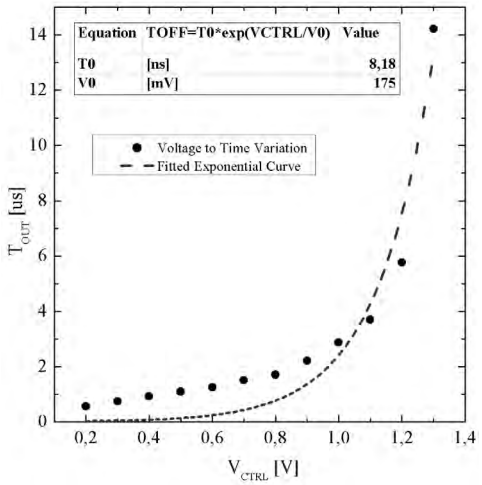

Fig. 4. Exponential fitting of simulated results.

$$T_{OUT} = T_0 e^{\frac{V_{CTRL}}{V_0}} \quad (5)$$

where T_0 =8.18 ns and V_0 =175 mV.

Comparative simulations of the proposed schematic versus linear time modulators were performed in order to outline the exponential characteristic of the former (Fig. 5c). The two slopes of the linear time variations correspond constant charge currents of I_2 (Fig. 5a) and $I_1 + I_2$ (Fig. 5b). It is noted that the exponential modulator has both high precision for low input voltages and a high dynamic output range. These advantages are mutually exclusive in the case of the linear modulators.

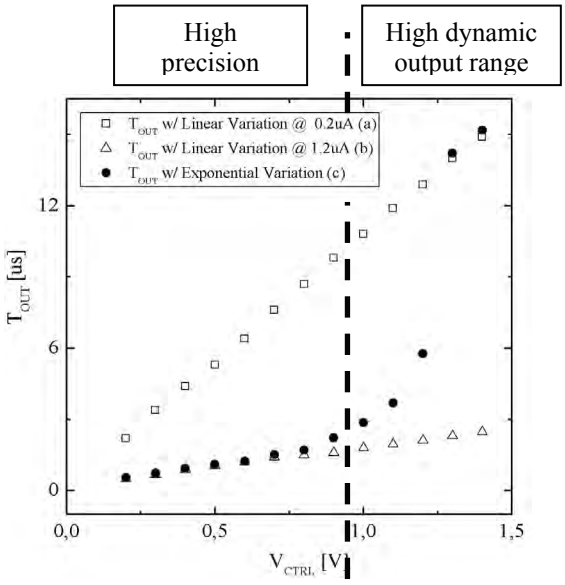

Fig. 5. Time range comparison of linear (a,b) and exponential (c) time-modulators.

Current switches and M1 dimensions were designed to produce exponential behaviour only at the high-end of input voltages, and have been tuned so that the response becomes linear should the input exceed a preset value, for safety concerns.

Capacitor charge current for an input range of 0V – 1.5V is depicted in Fig. 6. It is observed that the circuit modifications are effective for input voltages between 750mV and 1.3V. Outside of these limits the total current charging the capacitor is either 1.2µA or 0.2µA. These situations correspond to M1 draining none or all of I_1's current, respectively.

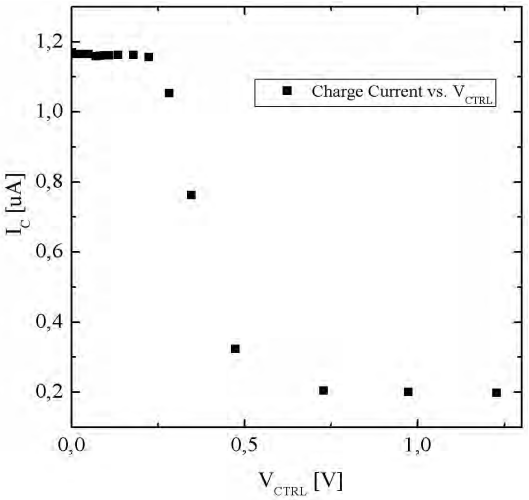

Fig. 6. Capacitor charge current versus input voltage.

4. MEASURED RESULTS

The proposed design from Fig. 2 is used as part of the control loop of a current mode buck controller application, also presented in [5] and [6]. The principle schematic is depicted in Fig. 7. The purpose of this application is to give a constant inductor current for a wide range of components (L, C, R_L, etc). The off time (T_{OUT}) is controlled by the design in Fig. 2, while the on time is controlled by another block which is not presented in this paper.

A constant 16V voltage supply – VHV – is used to power the buck loop. The time-modulator driver is powered from a constant 5V voltage supply.

The inductor current, measured via voltage drop on R_{FB}, controls the input of the time-modulator based driver. Based on the off time outputted, the inductor current is readjusted to the desired constant value. The modulator's input voltage is proportional to inductor value. Fig. 8 shows the off time (T_{OUT}) of the switch versus inductor values, ranging from 100µH to 2200µH.

Beyond the 1000µH inductance, M1 is completely closed and capacitor C from Fig. 2 is charged only by I_2. I_1 is no longer relevant from the standpoint of charging C and T_{OUT} is beyond the exponential variation. Although there is functionality in the system outside of the exponential range, the control loop does not respond as intended.

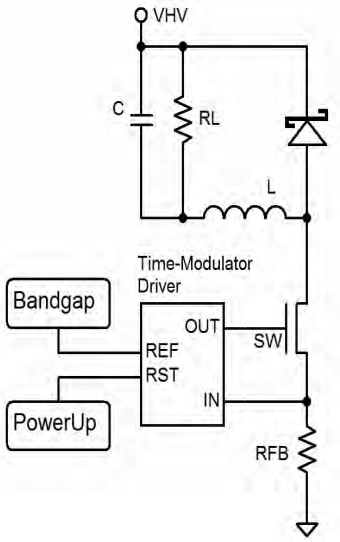

Fig. 7. Principle schematic of time-modulator based driver in a current mode buck controller application.

The switch gate voltage is also inspected on the oscilloscope using 470µH, 680µH and 1000µH inductances in the application. The results are presented in Fig. 9. Note that the off time (T_{OUT}) varies as an exponential function of the loop inductance. Although the on time is also variable, it is controlled by another circuit block.

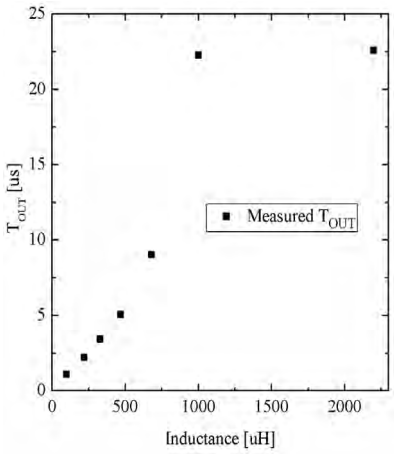

Fig. 8. T_{OUT} measurements for various inductor values.

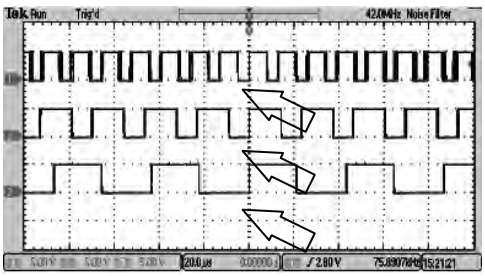

Fig. 9. T_{OUT} delays for inductors with 470µH (1), 680µH (2) and 1000µH (3) inductances.

5. CONCLUSIONS

An architecture for implementing exponential variation in a time-modulating architecture was analyzed and simulated. The solution was incorporated into a current mode buck controller, in a 0.5µm CMOS technology and its performances were measured. The measured results are in agreement with both mathematical formulas and simulations.

An exponential dependency, in comparison with a linear one, has the advantage that the same difference at any input value will cause the same percentage variation at the output. It has both increased precision at low input voltages, as well as a high dynamic output range.

Considering solution simplicity and ease of implementation, we recommend using this architecture in all applications that require time modulation and for which output percentage variation is required.

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