On-Chip Current Sensing Approaches for DC-DC Converters

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***Abstract*—In this paper, methods suitable for sensing the output load current (or current consumption) of analog circuits were studied and analyzed. The main focus was paid on approaches that can be implemented on a chip. The proposed approach for sensing the output current of a DC-DC converter is based on measuring the slope of a voltage sensed by an output bypass capacitor. Such an indirect sensing approach shows better efficiency than a common shunt resistor sensing method. The presented approach was used in a flyback type DC-DC converter. The simulated results prove better voltage conversion efficiency using the proposed indirect measurement approach.**

***Keywords*—Indirect current sensing method, Flyback converter, shunt resistor, voltage drop, slope detector.**

I. Introduction

Nowadays, the low power consumption is one of the most important parameters to fulfill in integrated circuits (ICs) and complex systems on chip (SoC) design. Therefore, for the low-power analog IC design, it is rather essential to establish (or know) currents, which flow through particular circuit branches. This feature contributes to overall electronic system efficiency significantly. The current value often serves as a parameter that controls the other parts of the electrical circuit or system. One of the field, where the electric current can be used as the control signal, is a controller for DC-DC converters. A flyback DC-DC converter can be classified as a simple topology isolated converter that is widely used as the power supply circuit in cellphones, notebooks, personal computers, LCD TVs, and other portable devices [1]. A transformer is used in the flyback converter for energy storage, input-output isolation and output power transformation [2]. The schematic diagram of a flyback DC-DC converter is depicted in Fig.1. The orientation of primary and secondary winding is not same. Operation of the flyback converter is rather simple. When the switch (NMOS transistor) is turned-on, energy from the input DC source is stored in the primary winding of the transformer. When the switch is turned-off, the stored energy is transferred to the secondary winding.

II. Overview of existing approaches

Several different current measurement methods have been developed so far. Since lot of complex ICs are digitally controlled nowadays, it is necessary to convert the analog current value to a digital form. The solution to this task is the use of an analog-to-digital converter [3].

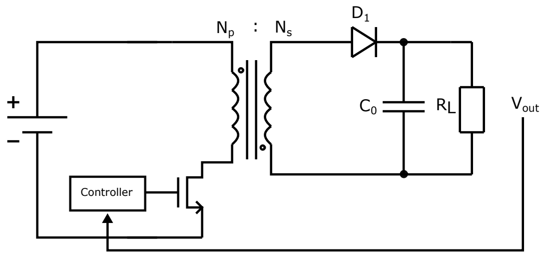

Fig. 1: Flyback DC-DC converter

One of the simplest methods of measuring electric current is using a shunt resistor. This method is based on the Ohmic law. Disadvantage of this measurement method is lays in the increase of power dissipation originating from the shunt resistor, which is connected to the circuit. The power dissipation value is given by:

$$P_{loss} = i^2 * R \quad (1)$$

The particular way to sense the voltage drop across the shunt resistor is to use an non-inverting amplifier. Such a setup is depicted in Fig.2.

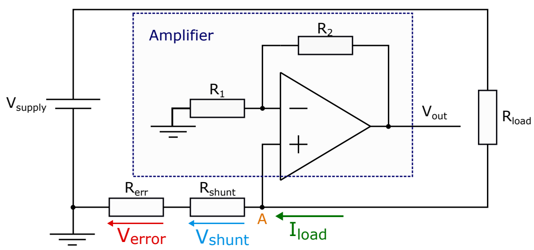

Fig. 2: Non-inverting amplifier measurement setup

However, using a non-inverting amplifier to sense a voltage across the shunt resistor can lead to measurement errors. The important source of error is a parasitic resistance R_{err} of connections that appears in series with R_{shunt}. Depending on the application, I_{load} current can change its value within hundreds of amperes. Therefore, already a small value of R_{err} might produce a significant error voltage V_{error} [4].

More efficient way of sensing the voltage drop across the shunt resistor is to use a differential amplifier instead of the non-inverting amplifier. Such a setup is depicted in Fig.3. This solution eliminates a voltage drop across R_{err}, because the differential amplifier senses a voltage between A and B points (a voltage drop across the R_{shunt}). The output voltage of the differential amplifier is then as follows:

$$V_{vout} = \frac{R_2}{R_1}(V_A - V_B) = \frac{R_2}{R_1}V_{shunt} \qquad (2)$$

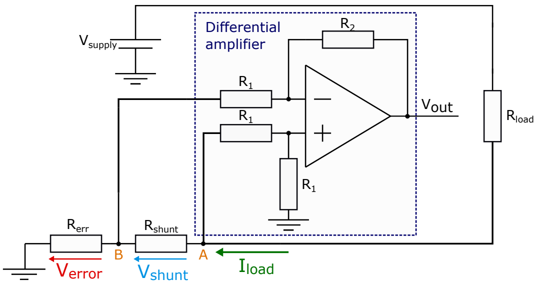

Fig. 3: Measurement of a current using the differential amplifier

Another measurement technique for current sensing is to use a MOSFET transistor acting like a resistor. Assuming the small drain-source voltage, the equivalent large signal resistance of the device is:

$$R_{DS} = \frac{L}{W\mu C_{ox}(V_{GS} - V_T)}, \qquad (3)$$

where μ is the mobility of charge carriers, C_{ox} is the oxide capacitance per unit area, V_T is the threshold voltage and V_{GS} is the voltage between MOSFET gate and source electrodes. The current flowing through a MOSFET is determined by the voltage between drain and source electrodes, supposing that R_{DS} of the MOSFET is known. The main disadvantage of this measurement technique is low accuracy, since C_{ox} and μ are parameters affected by the particular fabrication process. Moreover, V_T varies according to the temperature change [5].

Another measurement approach uses a sensing transistor in parallel with the power MOSFET, which represents a highly effective way of measuring the load current in power electronics [6]. In this approach called SENSEFET, the measured load current is split into two branches - the switching power MOSFET and sensing MOSFET transistor [7], [8], as shown in Fig.4. The topology is based on two parallel FET devices with a common gate and drain connections but separate sources, which forms a current mirror. Typically, the sensing circuit is designed in such a way that the ratio between the sensing (mirror) transistor and the switch (source) transistor is 1:1000. This settles also a ratio between I_{mirror} current and I_{source}) current [9]. The comparison of different measurement methods for the electric current sensing is depicted in Tab. 1.

III. Proposed current sensing approach

As part of our research, we decided to focus on indirect measurement methods. The great advantages of such a method is its lossless since there is no sensing component connected in series with the load, if compared to commonly used direct methods. This

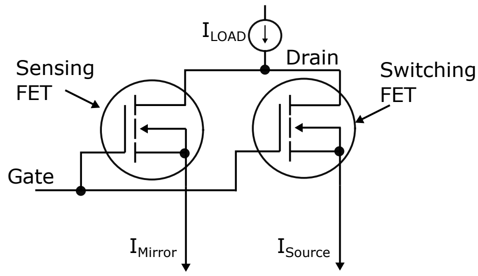

Fig. 4: SENSFET equivalent circuit

Technique	Advantages	Disadvantages
External sensing resistor	High accuracy	Low efficiency Known resistor value
On-resistance of Power MOSFET	Lossless	Low accuracy
SENSFET	Lossless Possible integration Practical Moderate accuracy	Matching issues Low bandwidth

Tab 1: Comparison of current measurement methods [10].

approach considers a high value of the output load capacitor, where linear dependence of the output voltage in time can be observed. In such a case, the output voltage change directly depends on the output load current variations. Our research was focused on comparison of the proposed approach to ordinary direct shunt-based measurement method in terms of the conversion efficiency of the DC-DC Flyback converter.

The block diagram of the whole indirect measurement system for the load current sending is depicted in Fig.5. It contains five circuit parts: a frequency divider, a 4-channel multiplexer, a driver, a 9-bit counter, and a slope detector.

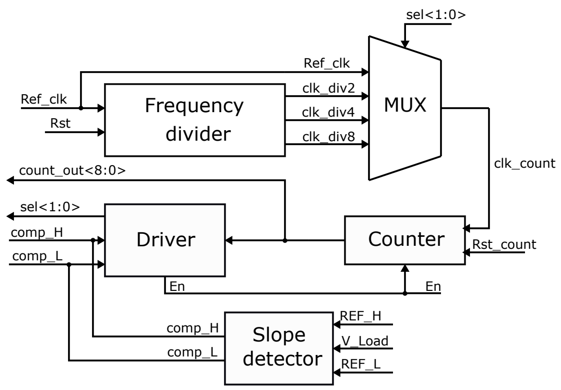

Fig. 5: The proposed current measurement method.

The output voltage representing the load current of the measured system (a flyback converter) is led to the slope detector input labeled as V_{Load}. The slope detector is realized by a window comparator. Two inputs REF_H and REF_L set the length of a time window for the measurement. By this window the counter is activated. The references are powered by an external power supply. Principle of the slope detector function is depicted in Fig.6. Then, the measured output load current is given by:

$$i = C\frac{dv}{dt}, \quad (4)$$

where C is value of the external capacitor, dv is a change of the output voltage that set to constant value of $50mV$, and dt is time during which the output voltage drops from REF_H to REF_L. If these comparators have significant input offset voltage, a measurement error will occur. For this reason, it is necessary to set wider intervals for counter counting (to be explained) that represent particular current values. In the first approximation, the input offset of comparators used in the slope detector have not been considered.

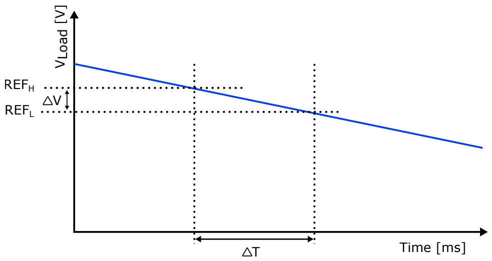

Fig. 6: Principle of the slope detection

The role of a frequency divider is to divide the input reference frequency Ref_{clk} by two, four and eight. All outputs from the frequency divider are fed to a 4-channel multiplexer. The reference clock signal is connected to one of the multiplexer inputs as well. Its function is to link one of the inputs clock signals to the output. The multiplexer is controlled by 2-bit signal $sel < 1 : 0 >$, which selects the desired switching frequency, as given in Tab. 2.

sel<1:0>	Frequency [kHz]
00	Ref_clk
01	clk_div2
10	clk_div4
11	clk_div8

Tab 2: The frequency selection by a multiplexer

The heart of whole indirect measurement system is a 9-bit counter, which measures time. The counter linearly increments its output by each rising edge of the clock signal clk_{count}. The counter input signal labeled as EN tuns on the counting process, and the input signal RST_{count} resets the counter. Another very important block for the proper functioning of the whole system is the driver. This block checks the actual state of counter and sets its output to the respective value of $sel < 1 : 0 >$ in order to properly adjust the switching frequency for the counter. The relation between the selected switching frequency, the output current value, and the counter state is depicted in Tab 3.

frequency [kHz]	I_out [mA]	count
50	10	461
	20	336
	30	294
100	40	272
	50	247
	60	231
	70	218
200	80	209
	90	195
	100	184
	110	175
400	120	167
	130	154
	140	143
	150	133

Tab 3: Conversion table between counted value, output current and switching frequency.

IV. SIMULATION RESULTS

The schematic diagram of the top level functional demonstration of the proposed indirect measurement method of the output current, which was applied to the flyback DC-DC converter, is depicted in Fig.7.

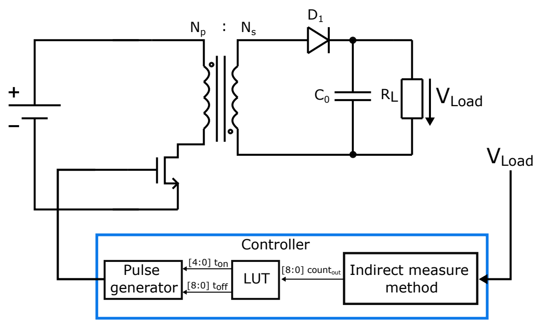

Fig. 7: The load output current measurement method applied to the DC-DC converter.

The basic parameter of transformer include: $Lprim = 500\mu H$, L_{sec} = 14μH, R_{prim} = 0.5Ω and R_{sec} = 50mΩ. The controller consists of three main blocks: the proposed indirect measurement of the output current, a lookup table (LUT), and a pulse generator. The pulse generator is a sequential circuit that was described at RTL (Register Transfer Level) using Verilog language. It generates the control signal $pulse_{out}$, which drives the high power NMOS transistor at the primary side of the flyback transformer. The control signal is determined by a 5-bit input t_{on} and a 9-bit input t_{off}. One could classify this type of control as pulse width modulation (PWM) and pulse frequency modulation (PFM). The input signals for the pulse generator are led from a LUT block, which is controlled by a 9-bit signal $count_{out}$ generated by the indirect measurement method system. The LUT translates data obtained from the measurement method into a signal that is fed to a pulse generator. Thus, the control switching signal for the high power NMOS transistor is constructed from t_{on} and t_{off} values obtained from the LUT.

The proposed measurement circuit together with the flyback converter were simulated in Cadence design environment under different conditions. Parameters t_{on} and t_{off} were swept, and the overall conversion efficiency of the converter was verified. The best efficiency was achieved for the load output current values (measured by the proposed current sensing method) and respective parameter t_{on} and t_{off} values given in Tab. 4.

I_{out} [mA]	t_{on} [μs]	t_{off} [μs]
150	0.8	160
125	0.8	160
100	1.7	255
75	1.2	240
50	1.7	170
25	1.7	170

Tab 4: Method parameters obtained by simulation.

In order to compare the proposed indirect current sensing method to the shunt-based measurement method. The schematic diagram of the direct shunt measurement method, used in simulations, is depicted in Fig. The shunt resistor was connected in series with the output DC-DC converters. 8. The simulation conditionals were the same for both investigated methods.

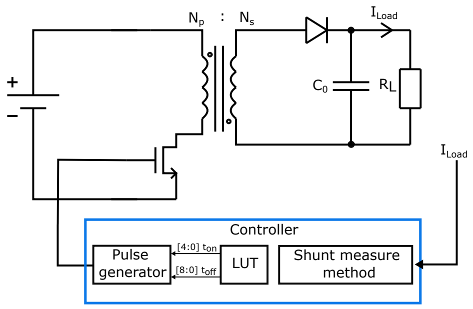

Fig. 8: Flyback converter with shunt measurement method.

The obtained simulation results are depicted in Fig.9. The shunt resistor value was changed to find out the effect on converter efficiency. It can be observed that by the direct current sensing method, the efficiency of DC-DC converter can be reduced. On the other hand, the converted efficiency is not influenced by the implemented current sensing approach based on the converter output voltage slope analysis. The appropriateness of the proposed approach is more pronounced for higher values of the output current (above 100 mA).

V. Conclusion

An indirect approach based on the voltage slope measurement for sensing the output load current of a

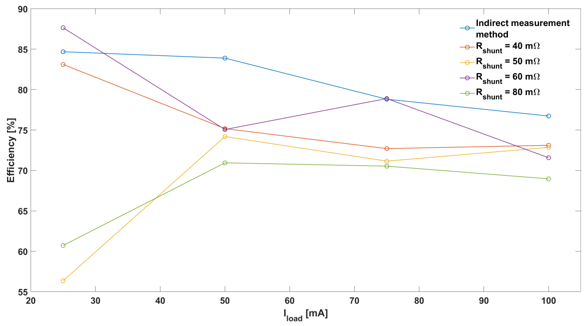

Fig. 9: Convertor efficiency for different measurement methods.

voltage converter is presented. Selected measurement methods were applied in the flyback DC-DC converter and analyzed. A comparison of these measurement methods has been done in terms of the converter efficiency. The obtained results shows that the proposed approach is a proper method for estimation the output load current. Additionally, no sensing element connected in series with the load is needed, and therefore, the power efficiency of a converter is not influenced. On the other hand, the presence of voltage comparators in the slope detector circuit may cause an inaccuracy in the slope measurement. Therefore, our future work will be focused on the robustness analysis of the proposed measurement system.

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References

[1] N. Coruh, S. Urgun, and T. Erfidan, "Design and implementation of flyback converters," in *2010 5th IEEE conference on industrial electronics and applications*, pp. 1189–1193, IEEE, 2010.

[2] M. C. Taneri, N. Genc, and A. Mamizadeh, "Analyzing and comparing of variable and constant switching frequency flyback dc-dc converter," in *2019 4th International Conference on Power Electronics and their Applications (ICPEA)*, pp. 1–5, IEEE, 2019.

[3] S. Ziegler and R. Woodward, "Hh-ching. iu, lj borle, current sensing techniques: A review," *IEEE Sensors Journal*, vol. 9, no. 4, 2009.

[4] S. Arar, "Using single-ended amplifiers in low-side current sensing: Error sources and layout tips - technical articles," Aug 2021.

[5] H. P. Forghani-Zadeh and G. A. Rincon-Mora, "Current-sensing techniques for dc-dc converters," in *The 2002 45th Midwest Symposium on Circuits and Systems, 2002. MWSCAS-2002.*, vol. 2, pp. II–II, IEEE, 2002.

[6] O. Aiello and F. Fiori, "A new mirroring circuit for power mos current sensing highly immune to emi," *Sensors*, vol. 13, no. 2, pp. 1856–1871, 2013.

[7] R. P. Singh and A. M. Khambadkone, "Giant magneto resistive (gmr) effect based current sensing technique for low voltage/high current voltage regulator modules," *IEEE transactions on power electronics*, vol. 23, no. 2, pp. 915–925, 2008.

[8] H. Takaya, K. Miyagi, and K. Hamada, "Current-sensing power mosfets with excellent temperature characteristics," in *2009 21st International Symposium on Power Semiconductor Devices & IC's*, pp. 73–76, IEEE, 2009.

[9] Y. Xiao, J. Cao, J. Chen, and K. Spring, "Current sensing trench power mosfet for automotive applications," in *Twentieth Annual IEEE Applied Power Electronics Conference and Exposition, 2005. APEC 2005.*, vol. 2, pp. 766–770, IEEE, 2005.

[10] C. F. Lee and P. K. Mok, "A monolithic current-mode cmos dc-dc converter with on-chip current-sensing technique," *IEEE journal of solid-state circuits*, vol. 39, no. 1, pp. 3–14, 2004.