# Specifics of Using Current Mirrors for High-side Current Measurements in Detector Power Supplies

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*Abstract* - **In this article are described novel, current mirror based, high-side current measurement circuits for ionizing radiation detector power supplies. The principles of operation are discussed. The circuits are analyzed and simulations are made to show their characteristics. The proposed circuits have the potential to simplify high-voltage power supply design, reduce costs and improve its power efficiency.**

*Keywords* – **current mirrors, high-side current measurement, high-voltage power supplies**

## I. INTRODUCTION

### A. *General information about current measurements in power supplies for ionizing radiation detectors*

The existing great variety of ionizing radiation detectors requires different power supplies with diverse characteristics. A lot of supplies share one common requirement – the ability to accurately measure the current consumed by the detector. This provides for easy monitoring and evaluation of the working conditions. Oftentimes it is only possible to measure this on the high side of the power supply, with a complex circuit.

### B. *Existing current monitoring solutions.*

There are a lot of current monitoring ICs by different companies. These are usually oriented to some low voltage industrial applications (mobile devices, motor control etc.) [1]. Some of these circuits can handle common-mode voltages as high as 80 V, or more, and by adding one or two high voltage transistors the sensing range can be extended up to 500 V for some of them. Obviously, such a modification increases the end price and, as a rule, increases the quiescent current consumed from the measured voltage, thus reducing power efficiency. These ICs themselves normally have low efficiency at low current measurements.

The schematics that are mostly used for current monitoring in current generation high-voltage power supplies, mostly rely on special low-consumption operational amplifiers, connected in a complex circuit in such a way that wouldn't exceed their maximal operating conditions [2]. That involves creating a zener stabilized supply off the high-voltage line for the operational amplifier, and usage of a high voltage transistor as an amplifiers' output buffer.

### C. *Goals and tasks*

The available current monitoring ICs aren't well suited for application in high-voltage power supplies and the solutions used are very sophisticated.

The goal of this study is to evaluate the specifics of using current mirrors for high-side current measurement in ionizing radiation detector power supplies and propose suitable schematic solutions. For that to be achieved, it's necessary to fulfill the following tasks:

1. Research and analyze suitable current mirror based schematics
2. Examine the behavior of the circuits with an electronic circuits simulator

## II. PRESENTATION

### A. *Principles of operation.*

In order to measure the output current of a power supply we can use a Wheatstone bridge.

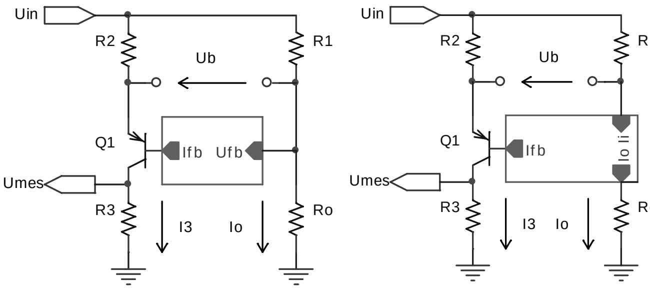

Fig. 1

When balanced ($U_b$=0, see fig. 1) the output current $i_o$ will be proportional to the current flowing through a standard resistance R3. If we measure the voltage drop across it, we can calculate the current as follows:

$$i_o = \frac{u_{mes}}{R3}\frac{R2}{R1} \qquad (1)$$

The current mirror should be connected in a way that will allow it to automatically balance the bridge. One (or more) of the mirror transistors is connected to act as a variable resistance in series with R3. The rest of the mirror circuit acts as a feedback to control it. The feedback can be connected in series with the load (current feedback) or in parallel (voltage feedback).

### B. *Types of mirrors*

There are three types of current mirrors that will be discussed throughout this article.

The most basic current mirror (fig. 2a) consists of two transistors (Widlar current mirror). For its operation it relies heavily on the parity of parameters and regimes between the two. Considering that the base-emitter voltages are equal and assuming the βs are identical and with very high value, the collector currents should be identical too. Due to the finite β the base currents are not null so:

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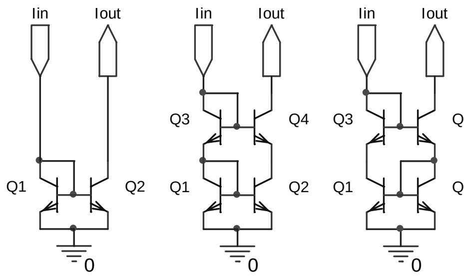


a) b) c)

Fig. 2

$$i_{in} = i_{c1} + i_{b1} + i_{b2} \neq i_{out} = i_{c2} \qquad (2)$$

Even if we choose to ignore the base currents, as they are usually a lot smaller than collector currents, the real transistors are not ideal and the collector currents are never equal:

$$i_c = I_s e^{\frac{V_{be}}{V_t}}\left(1+\frac{V_{bc}}{V_A}\right) \qquad (3)$$

where:

- $i_c$ is the collector current
- Is is the reverse saturation current
- $V_{be}$ is the base-emitter voltage
- $V_t$=kT/q is the thermal voltage
- $V_{bc}$ is the base-collector voltage
- $V_A$ is the Early voltage

The main reason for the difference in the two collector currents is the Early effect because the transistors are working at different collector voltages.

The structure on Fig. 2b consists of two cascaded Widlar current mirrors. It is designed to resolve the Early effect problem. The upper mirror (Q3, Q4) acts as a voltage regulator for the lower mirror (Q1,Q2):

$$V_{c1} = V_{b34} + v_{be3} \approx V_{b34} + v_{be4} = V_{c2} \qquad (4)$$

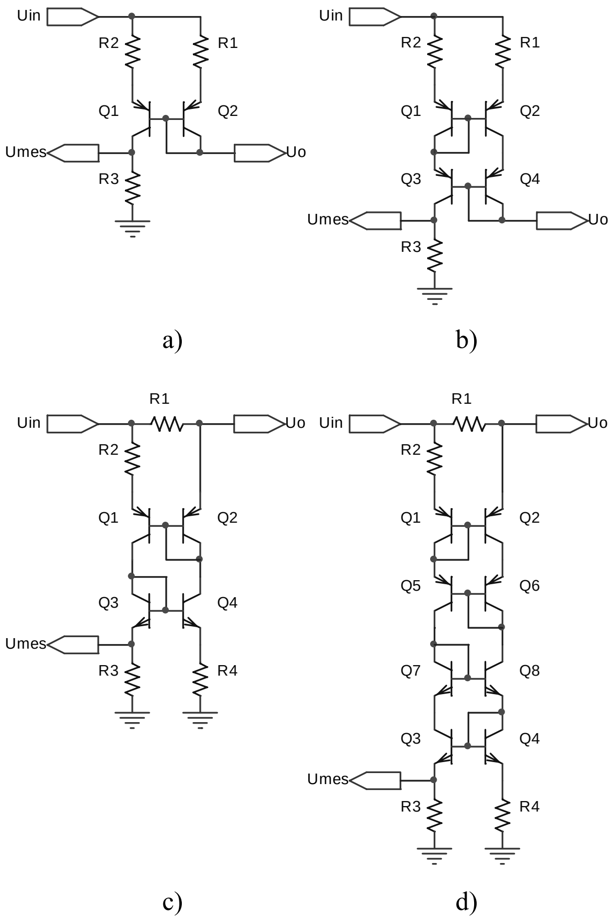
where:

- $V_{c1}$,$V_{c2}$ are respectively the collector voltages of Q1 and Q2
- $V_{b34}$ is the base voltage of Q3 and Q4
- $v_{be3}$, $v_{be4}$ are the base-emitter voltages of Q3 and Q4

As $V_{c1} \approx V_{c2}$, the difference due to the Early effect in $i_{c1}$ and $i_{c2}$ is minimized. Still this schematic shares the problem of transferring the base currents of Q2 and Q4 from the input to the output. This is avoided in the Wilson current mirror (Fig. 2c). The Q4 transistor transfers $i_{b4}$ from the input to the output circuit. The Q1 transistor transfers $i_{b1}$ from the output to the input circuit. As the base currents of all four transistors are nearly identical and the net current transfer between the input and the output circuit is minimized.

The advantage of the basic mirror is that it has a simpler schematic and a lower number of parts. Its application is limited to low-voltage circuits where the influence of the Early effect would be insignificant. Because of its simplicity it is used to illustrate the principles of operation.

The cascaded mirrors and Wilson current mirror share the same number of elements and almost identical topology. Since the Wilson mirror has better characteristics, it is best suited for real life applications with wide voltage and current ranges.



a) b)

c) d)

Fig. 3

*C. Schematics and analyses*

In the current feedback circuits the feedback transistor is connected in series with the load. The load current creates a voltage drop across Q2 and R1 which is used to drive the Q1 transistor (fig. 3a).

The schematic on Fig. 3b uses the same principle of operation, but the Widlar current mirror is replaced with a Wilson mirror. For both current feedback circuits $u_{be1} \approx u_{be2}$:

$$i_{e1}R_2 + u_{be1} = i_{e2}R_1 + u_{be2} \qquad (5)$$

$$i_{e1} \approx i_{e2}\frac{R_1}{R_2} \qquad (6)$$

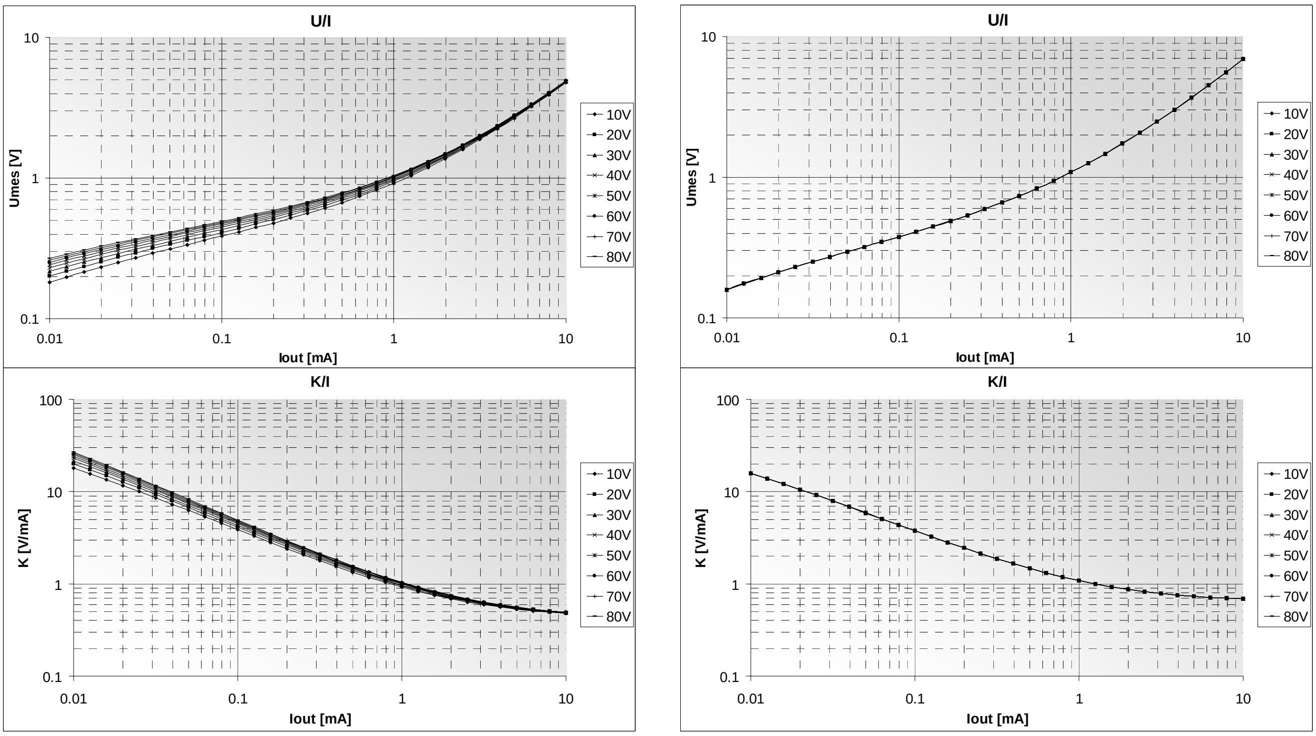
Since $i_c \approx i_e$ for all transistors:

$$\frac{u_{mes}}{R_3} = i_{c1} \approx i_{e1} \approx i_{e2}\frac{R_1}{R_2} \approx i_o\frac{R_1}{R_2} \qquad (7)$$

Then for the transfer function K of the schematic we have:

$$K = \frac{u_{mes}}{i_0} \approx R_3\frac{R_1}{R_2} \qquad (8)$$

In the voltage feedback circuits the feedback transistor is connected in parallel with the load (Fig. 3c). The load current creates a voltage drop across R1 which causes a proportional current flow through the measurement circuit. For the circuit $u_{be1} \approx u_{be2}$:



a)

b)

Fig. 4

$$i_{e1}R_2 + u_{be1} = i_o R_1 + i_{e2} R_1 + u_{be2} \tag{9}$$

$$i_{e1} \approx i_o \frac{R_1}{R_2} + i_{e2} \frac{R_1}{R_2} \tag{10}$$

Since current mirrors have best performance when the work regimes of the two transistors are well matched, a good solution would be to force through Q1 and Q2 equal currents. This could be done by adding another current mirror Q3-Q4 and an extra resistor R4. The ratio between R3 and R4 sets the ratio of the currents through Q1 and Q2. Since $i_{e3} \approx i_{e1}$ and $i_{e4} \approx i_{e2}$ and $u_{be3} \approx u_{be4}$ the following can be written:

$$i_{e3}R_3 \approx i_{e4}R_4 \tag{11}$$

$$i_{e2} \approx i_{e1}\frac{R_3}{R_4} \tag{12}$$

$$i_{e1}\left(1 - \frac{R_1 R_3}{R_2 R_4}\right) \approx i_o \frac{R_1}{R_2} \tag{13}$$

$$i_{e1} \approx i_o \frac{R_1}{R_2} \frac{R_2}{R_2 - R_1\frac{R_3}{R_4}} = i_o \frac{R_1}{R_2 - R_1\frac{R_3}{R_4}} \tag{14}$$

Since $i_c \approx i_e$ for all transistors:

$$\frac{u_{mes}}{R_3} = i_{e3} \approx i_{e1} \approx i_o \frac{R_1}{R_2 - R_1\frac{R_3}{R_4}} \tag{15}$$

Then for the transfer function K of the schematic we have:

$$K = \frac{u_{mes}}{i_0} \approx R_3 \frac{R_1}{R_2 - R_1\frac{R_3}{R_4}} \tag{16}$$

The schematic on Fig. 3d uses the same principle of operation, but the Widlar current mirrors are substituted by Wilson mirrors.

Due to the specific application there are some special requirements. Some of the transistors must be able to bear the high output voltage of the power supply. The transistors must have very low leakage currents in order to be able to accurately measure the low load currents. The board must be designed with a high level of isolation between the high-voltage and low-voltage areas in order to prevent surface leakages and break-downs.

### *D. Experimental setup*

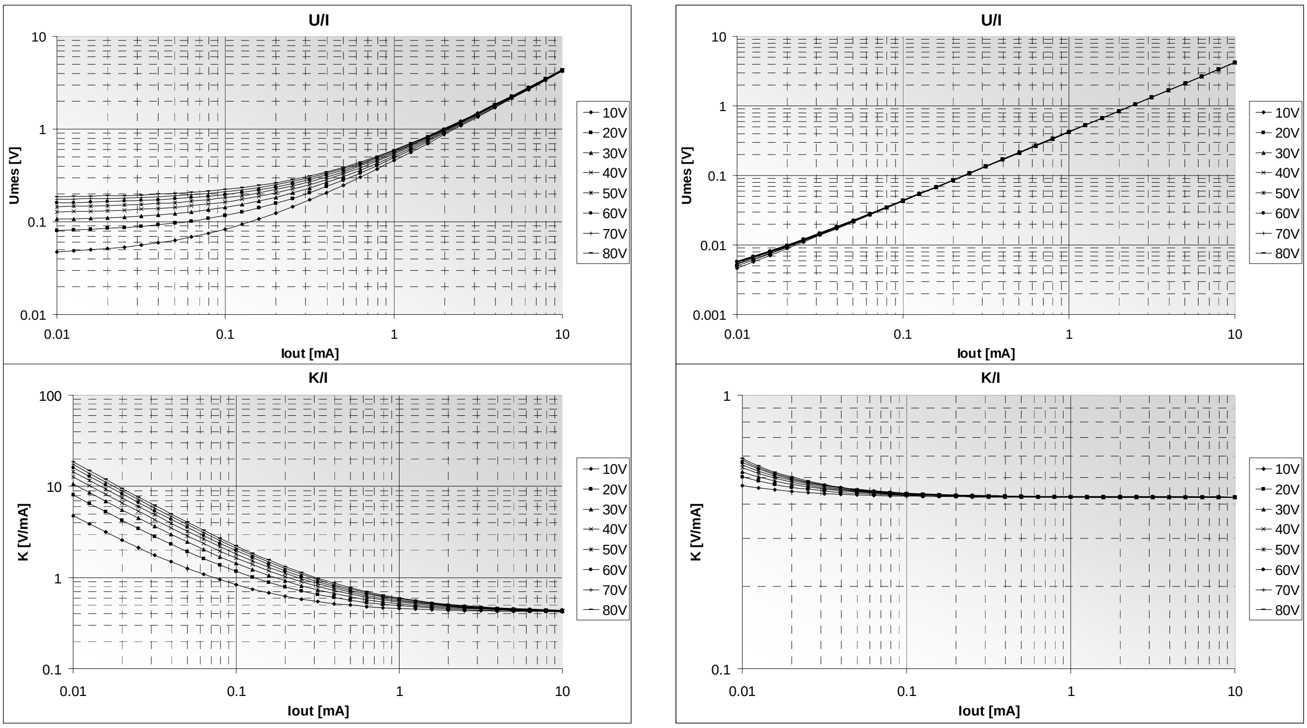
For the purposes of this paper, as a proof of the concept, are presented only PSPICE simulations of the proposed circuits and no real test bench results.

In order for the results of all simulations to be comparable, the Wheatstone bridge will be configured in the same way for all of them. The used values will be R1=100 Ω and R2=15 kΩ, so that for R2/R1 the ratio is 150. Thus the current consumed by the measurement branch will be less than 1% of the load current, resulting in good power efficiency. The value of R1 is chosen to allow measurement of currents up to 10mA with a voltage drop across it of up to 1V. The value of R3=63 kΩ is chosen in order to achieve output voltage of about 4.2V under maximum load conditions. The R4 resistor is chosen equal to R3 in order to facilitate good mirror symmetry and better measurement characteristics. The transistors of choice are the complementary pair BC546/BC556.

For the current feedback schematics:

$$K \approx R_3 \frac{R_1}{R_2} = \frac{63.10^3.100}{15.10^3} = 420\left[\frac{V}{A}\right] \tag{17}$$

For the voltage feedback schematics (R4=R3):



a) b)

fig. 5

$$K \approx R_3 \frac{R_1}{R_2 - R_1} = \frac{63.10^3.100}{15.10^3 - 100} = 422\left[\frac{V}{A}\right] \quad (18)$$

### E. Simulation results.

Figures 4a and 4b show the simulation results of the first and the second current feedback schematics, respectively. One of the first things to notice is the relation between the output voltage and the supply voltage in the Widlar mirror. This is due to the Early effect and the different base-collector voltages of Q1 and Q2. As can be seen on Fig. 4b the Wilson mirror eliminates the problem almost completely. Both schematics can be used for measurements in the whole range of 3 decades (10µA-10mA), but the measured value should be recalculated in order to compensate for the nonlinear transfer function. Additionally, the values measured by the Widlar mirror schematic should be compensated for the influence of the supply voltage.

Figures 5a and 5b show the simulation results of the first and the second voltage feedback schematics, respectively. A relation is observed between the output voltage and the supply voltage in the Widlar mirrors schematic, due to the Early effect. The Wilson mirrors schematic displays a constant transfer function over two decades of operation (0.1-10mA), consistent with the theoretical value. In that range the schematic may be used for measurements without any further value corrections. On a larger scale, value correction should be applied due to the observed non-linearity.

## III. DISCUSSION

The obtained results show that current mirror based schematics are suitable for use as simple, cheap high-side current measurement circuits with possible application in some high-voltage ionizing detector power supplies. The main development effort should focus on the Wilson current mirror circuits, as they show better parameters, suitable for the outlined task. Nevertheless, the Widlar current feedback mirror is well suited for low-precision current monitoring and has a very simple structure. A real test board is feasible, using some high-voltage transistors like the FMMT458/FMMT558 complementary pair.

## IV. CONCLUSION

The schematics that are proposed show great potential as current measurement circuits in radiation detector power supplies. They allow for possible cut-down on component count, board space and manufacturing costs, as well as for power savings, with little or no sacrifice of measurement accuracy. These are especially important in multi-channel power supplies where the savings are multiplied by the number of power supply units.

## V. ACKNOWLEDGEMENTS

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