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Electroluminescence-based isolated high voltage bus DC current sensor

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ABSTRACT

Many high voltage sources, used in measurements, have mA order of maximum current. Implementing a miniature and isolated, high side output current monitoring is a challenge. Available isolated current sensing techniques either are aimed for high current, bulky, draw significant power from high voltage source or require isolated power source. Solution proposed draw just 0.04% of power delivered to the load. It is simple, small, provides high voltage isolation, does not require isolated power source, is immune to common mode transients and is suitable for direct microcomputer interfacing. Electroluminescence phenomenon is used: current to be measured is passed through the LED and produced light is registered using photodiode and transimpedance amplifier. Comparison between three optocouplers and readout topologies is given. Sensor is linear within 10% in 1 mA to 30 mA range. Nonlinear approximation was proposed, which extends the measurement range to three decades at 2% errors.

1. Introduction

High voltage (HV) direct current (DC) power sources are widely used in ultrasonic measurements [1,2], piezo driving, X-rays generation avalanche photodiodes, capacitor charging, electrophoresis, photomultiplier tubes, mass spectrometry, ion pumps etc. [3]. Majority of applications are concerned about output voltage, and the load current is required just for monitoring purposes (short-circuit prevention, approximate value of the consumed power, etc.). Monitoring of the output current gives the ability to judge the load behaviour and does not require high accuracy. One example could be cable isolation testing. It is the shape of the leakage current over time that is most important than the actual magnitude of the leakage current. In general, the leakage current starts relatively high and then drop, becoming constant. If the current does not drop or begins to rise, it is an indication of failure [20]. Another example could be ultrasonic equipment. High voltage is required for the transducer excitation. HV power source load current depends of transducer type, excitation signal and pulse repetition frequency (PRF). If rated current is exceeded, the output voltage will drop below the set level. Current monitoring is useful in photomultiplier tubes, microchannel plates, especially when multiple isolated power sources are used on last stages. Ground-referenced shunt [4] cannot be used when high side, isolated mA order current sensing is needed, when multiple HV sources are used, when isolation is required, when ground return current is not available. High-side shunt [5] or current mirror [6] solutions have drawbacks. Current mirror [6,7] will draw some bias current which will turn in high power dissipation in sensing circuit, can be beyond the allowed load current or induce output voltage-related current estimation error. It does not have isolation and is limited to few hundred volts [7]. Isolated shunt [8] will require isolated power source and output isolation. If isolated DC/DC converter is used as a power source, it will induce common mode interference. It also has limitations on isolation voltage. Battery solution has a limited life time. Both solutions are complex and occupy large printed circuit board (PCB) space or device volume. Many modern devices are portable. Therefore small size, low cost and low complexity are vital for current sensing circuit. Other solutions, like Hall effect [9], Neel effect [10], Faraday effect [4], Bragg effect [11] or magnetoresistive [12] sensors are suited for high, tens or hundreds of Amperes, currents due to poor immunity against external fields, zero offset and nonlinearity. There are reports on low current Hall [13] or tunnel magnetoresistive [14] sensing solutions, but these are complex, large and are not available commercially.

This short communication presents a simple idea for HV rail DC current sensing where electroluminescence phenomenon is exploited to provide the isolated low (mA order) current measurement.

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2. Proposed approach

Light emitting diode (LED) exploit electroluminescence phenomenon: device emits light in response to the passing electric current. Current sensor is obtained if this light can be tunneled using light guide or optical fiber and then converted to electrical signal by using photosensor. Essential, that distance to light-collecting photosensor can be arbitrary, ensuring the proper high voltage isolation. Similar devices (optocoupler) are already commercially available as integrated circuit and offer acceptable input-to-output isolation: 3750 Vrms [16,15], 1500 V [17] and even 50 kV electrical isolation [19] are offered. Optocoupler is intended to transfer the digital signals between two isolated circuits by using light coupling between light emitting diode (LED) and a photodiode or phototransistor. In our application it is used to directly measure the high voltage bus DC current. If HV power supply maximum current does not exceed 20 mA, this corresponds to maximum working current of optocoupler's transmitting LED. Though, some are rated for higher currents: 100 mA and 1 A in case of 10 ms pulse for LOC117 [15]. The idea is to place input LED in series with the HV output and use a resistor (Fig. 1) or transimpedance amplifier (Fig. 2) to convert the output current into voltage for further measurements (e.g. ADC).

Photodiode can be used in two modes: photoconductive (photodiode is reverse-biased) or photovoltaic. Photoconductive mode has better linearity but requires higher than output biasing voltage. Photovoltaic mode can use lover voltage, has no dark current and is more stable with temperature. Both modes can be used with resistor load (Fig. 1) or transimpedance amplifier (Fig. 2), but photovoltaic mode has better linearity with transimpedance amplifier. Majority of optocouplers are designed for logic level transmission and therefore have high current transfer rate. High current transfer rate is not suitable for current measurement task because relatively low, 10–20 mA current at the input will result in hundreds of mA at the output. Yet, there are plenty of devices where photodiode connection is available at the output so lower gain is attained and output current is low.

3. Experimental results

Three optocoupler candidates have been chosen for the validation experiments: 6N136 [16], LOC117 [15] and TLP3914 [17]. 6N136, is a classical optocoupler, but with photodiode output available. LOC117, has only photodiode at the output and is intended for linear applications, like servo voltage transfer [8]. TLP3914, is intended for MOSFET gate drive and has multiple serially connected photodiodes at the output. All three candidates have been measured in photoconductive (Fig. 1) and photovoltaic (Fig. 2) configurations. Measurement setup is presented in Fig. 3.

Programmable high voltage source PPS3E004 was used as a high voltage source. DM3068 digital voltmeters were used for the voltage measurement. HV power source load R_{Load} was a 0.1% 10 kΩ resistor. Every configuration (Figs. 1, 2) has different current transfer ratio, therefore resistor R_{Ref} was selected to have the output voltage approximately 5 V at 20 mA current at sensor input. Input current was calculated using grounded shunt R_{Load} (refer Fig. 3). Input current and output voltages were registered while input current was varied by changing the HV source output voltage. HV source output voltage was varied in such fashion that input current varied from 1 μA to 40 mA (200 steps) in logarithmic law. Obtained output voltages were normalized to voltage obtained at 10 mA sensor input current. Results for sensor output voltage relation to input current are presented in Fig. 4. Resistor-based (Fig. 1) current sensor measurements are labelled "R" and transimpedance amplifier (Fig. 2) results are labelled "TIA". More details on sensor linearity can be obtained from current transfer ratio (CTR) curves, presented in Fig. 5. CTR was obtained by dividing output current (output voltage V_{out} divided by R_{Ref}, see Figs. 1, 2) by input current I_{in} (load voltage V_L divided by R_L, see Fig. 2).

Fig. 4 demonstrate that sensor is linear in mA range and current I_{measL} can be estimated using a linear approximation of the transfer function:

$$I_{measL} = a + b \cdot V_{out} \tag{1}$$

where V_{out} is the voltage at sensor output, a and b are approximation parameters. Linear approximation, using (1) errors can be analysed using Fig. 6.

Comparison of actual and approximated transimpedance gain for 6 N136 is presented in Fig. 7. Inverse function (1) is compared against actual transimpedance gain, obtained from Fig. 4 results.

It can be seen that approximation error for optocouplers analysed is less than 10% for 1 mA to 30 mA range. However, transimpedance gain becomes nonlinear at low currents, as can be

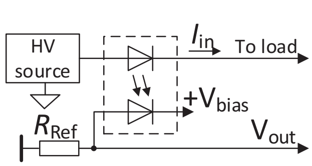

Fig. 1. Current sensor circuitry using photoconductive mode output to resistor.

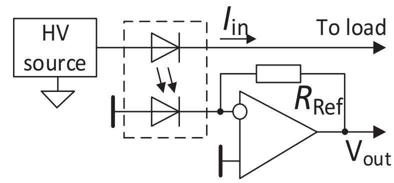

Fig. 2. Current sensor circuitry using photovoltaic output into transimpedance amplifier.

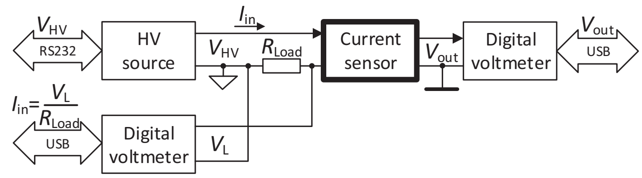

Fig. 3. Current to voltage transfer ratio measurement setup.

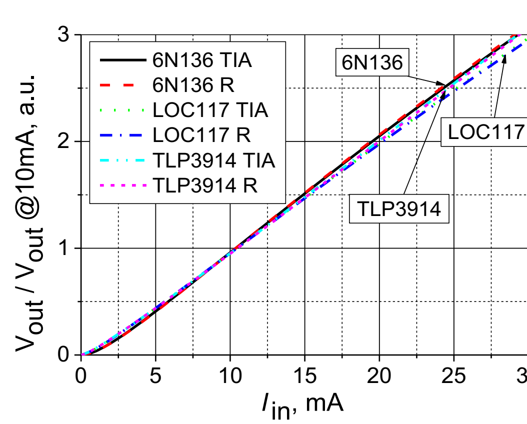

Fig. 4. Optocoupler as a current sensor: output voltage vs. input current (linear scale) normalised at 10 mA.

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