Adaptive optocoupler degradation compensation in isolated feedback loops

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***Abstract*—An optocoupler is an optoelectronic device, based on a light emitter and detector pair. Any degradation in the emitted light causes a change in the output of the component. This gain change is also known as CTR (current transfer ration) degradation, – although in some cases, the emitted light output actually increased over time. This phenomenon is inherent of the p-n junction electroluminescence and it is unpredictable. Excessive amount of degradation may cause a deviation from optimal operation or a catastrophic system failure. This paper puts forward a robust, microcontroller based solution for this problem.**

I. Introduction

A. Optoelectronic components

Optoelectronic components are used to emit or detect light, generally in visible or in IR region. Optoelectronic devices are usually electrical-to-optical or optical-to-electrical transducers, if both functions are present in the device than it makes, an optocoupler (Fig. 1.). [1]

An optocoupler is an electronics component that transfers electrical signals between two galvanically isolated circuits by typically using IR light. Optocouplers are also called opto-isolators, photocouplers, or optical isolators.

Reliability of these devices is almost taken for granted, whereas in this paper the main emphasis is going to be on adaptive degradation compensation of LEDs and optocouplers.

A common type of optocoupler consists of a light source (LED), a dielectric barrier and a sensor (phototransistor) – it is shown in Fig. 2 – in the same package. Optocouplers are able to transfers both digital and analog signals.

B. LED degregation method

One favored material for red LEDs are GaAsP and GaP, du to their structure. Light emission is achieved via direct hole and electron recombination. To grow semiconductor compounds (eg. InGaAsP), at high quality epitaxial layers on a common semiconductor substrate – the most common method is liquid phase epitaxy (LPE) –, it is necessary to assure lattice matching. This prevents dislocations and other defects which could affect radiated emission efficiency and reliability. Radiated light emission is generated by a hole or electron injection across a p-n junction. The type of LED also depends of the geometry on the chip. [2]

The LED's p-n junction is heavily forward biased. The amount of emitted photons is linearly correlated with the injected current.

The main causes of degradation are the irreducible crystal dislocations and defects. At these defects, there are formed non radiative recombination hubs, and they depress the quantum efficiency of the LED. The above mentioned hubs use the energy they absorb in order to grow their sizes and to generate new non radiative recombination hubs.

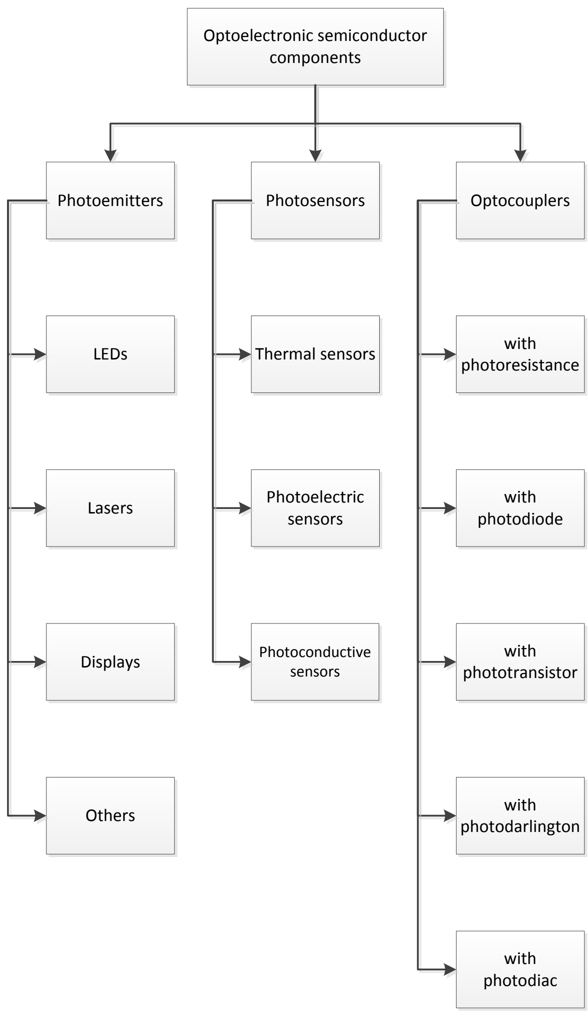

Figure 1. Classification of optoelectronic semiconductor components

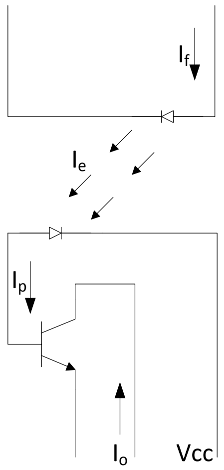

Figure 2. Schematic diagram of an optocoupler

The main reason of chip failure is caused by the packaging. The covering inside an optocoupler – between the LED and the photodetector device – must be transparent. If the transparent material and the IC encapsulant material do not have the same thermal coefficiency, then it can trigger several problems, such as bond lift-offs caused by bonding stress, separation of the transparent epoxy from the substrate caused by mechanical stress and epoxy cracking caused by bending stress. [3]

C. *LED reliability*

Based on experimental results [4], subtle differences in technological processes, concentrations of impurities and doping, cause a largely differences between LED batches. The degradation mechanism of LEDs are not fully understood yet, therefore it is hard to make a good prediction about failures without resource-intensive investigating at the actual batch.

The significant variability of LED aging test results shows that, early life test data is difficult to interpret due to the erratic manner of device parameters in different batches. The end of life parameter is the most favored when it comes to measuring LED reliability.

LED failure is a gradual process, and it also depends on, what criteria had been used to define the failure of the device. The end of life of an LED is often determined when the power of the emitted output has fallen to 70%, according to other , more permissive sources 50% or 1/e – of its original value. There is another parameter used to define the lifespan of these devices is reliability life which refers to the time when some percentage of the population falls – in telecommunication systems it is 2%, and in this area, pulsed operation testing is a realistic method [5].

II. Optocouplers reliability

An optocoupler also contains an LED, therefore optocouplers are likely to suffer from transmitted power degradation. It does not cause any problems when transferring digital signals, however it could be a crucial problem when transferring analog signals. When the gain of the optocoupler is changing over time, it is called CTR (current transfer ratio) degradation. The gain change is

$$\Delta CTR = CTR_i - CTR_f \,, \qquad (1)$$

where CTR_i is the initial current transfer ratio, and CTR_f is the final current transfer ratio. In a long lifetime system this degradation must be compensated.

A. *Optocouplers aeging*

The main cause of the CTR degradation is the reduction in quantum efficiency of the LED – in the optocoupler. Quantum efficiency is defined as the amount of photons emitted per electron of the LED constant forward input current. The LED constant forward current mainly contains a diffusion current – the radiative – component and a space-charge recombination – the non-radiative – current:

$$I_f(U_f) = Ae^{\frac{qU_f}{kT}} + Be^{\frac{qU_f}{2kT}} \,, \qquad (2)\ [5]$$

where I_f is the forward current, flowing through the LED; U_f is the forward voltage dropping in the LED; A and B are independent constants from U_f; q is the charge of the electron; k is Boltzmann's constant, T is temperature in degrees of Kelvin.

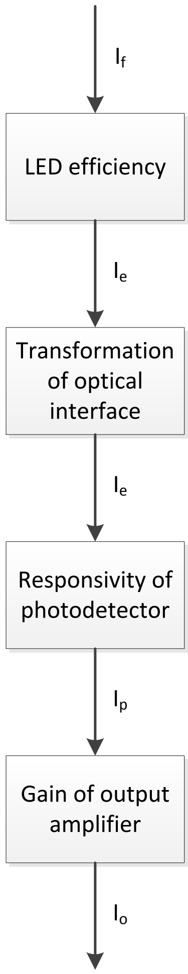

Figure 3. Block diagram of an optocoupler

Over time, at constant forward current, the radiative diffusion current will decrease – due to a decrease in value of A –, and the non-radiative space-charge recombination current – due to an increase in value of B –will increase. The reduction in radiated light output is proportional of the increase if the space-charge recombination current, due to the temperature of the pn junction - and also the density of current of the pn will increase. Higher junction temperature will accelerate the aging of the component. [6]

In Fig. 3., a system model can be seen, to show a basic parameters of an optocoupler – if it is working its linear region. The relationship between the input current and the output current is:

$$CTR = \frac{I_o}{I_f} 100[\%] = KR\eta\left(I_f, t\right)\beta\left(I_p, t\right), \quad (3)$$

where I_o is the output current; K is the transmission factor of the optical path; R is also a constant, that represents the resistivity of the photodetector, defined as a number of electrons per the incoming photons; η is the quantum efficiency of the LED, and it depends the amount of the forward input current and time; β is the gain of the output amplifier, and it depends the amount of the photo current and time; I_p is the photodetectors current, and it depends the amount of the input current.

At constant input current – K and R are also constants – , and based on equation 3., a normalized change in CTR is shown below:

$$\frac{\Delta CTR}{CTR} = \frac{\Delta\eta}{\eta} + \frac{\Delta\eta}{\eta}\frac{\delta \ln\beta}{\delta \ln I_p} + \frac{\Delta\beta}{\beta}. \quad (4)$$

The first factor, represents the major cause of the change in CTR, due to the degradation of the emitted output of the LED – it is strongly related to the level of the input current. The second factor, represents a secondary cause of the change in CTR, due to the change in the photodetectors current and the change in the gain of the output amplifier. The third factor, represents a negligible change in the gain of the output transistor. [7]

B. CTR degradation

Barring catastrophic failures – like open circuits or short circuits – over time, the change of the emitted photon flux of an LED – driven by constant forward current – is unpredictable, therefore CTR degradation is also unpredictable.

There are several different factors which may influence the degree of CTR degradation. In general, the degradation is a result of electrical and thermal stressing of the p-n junction. [8] On an experimental basis it possible to establish an expected statistical value of degradation for a specific type of device, however this curve is totally different at another type of component, and also different for the same type of component from another batch.

III. REALIZATION

This realization presents a compensation of an isolated power supply, for a component that requires high-stability and precision supply voltage. In such circuit, there is a

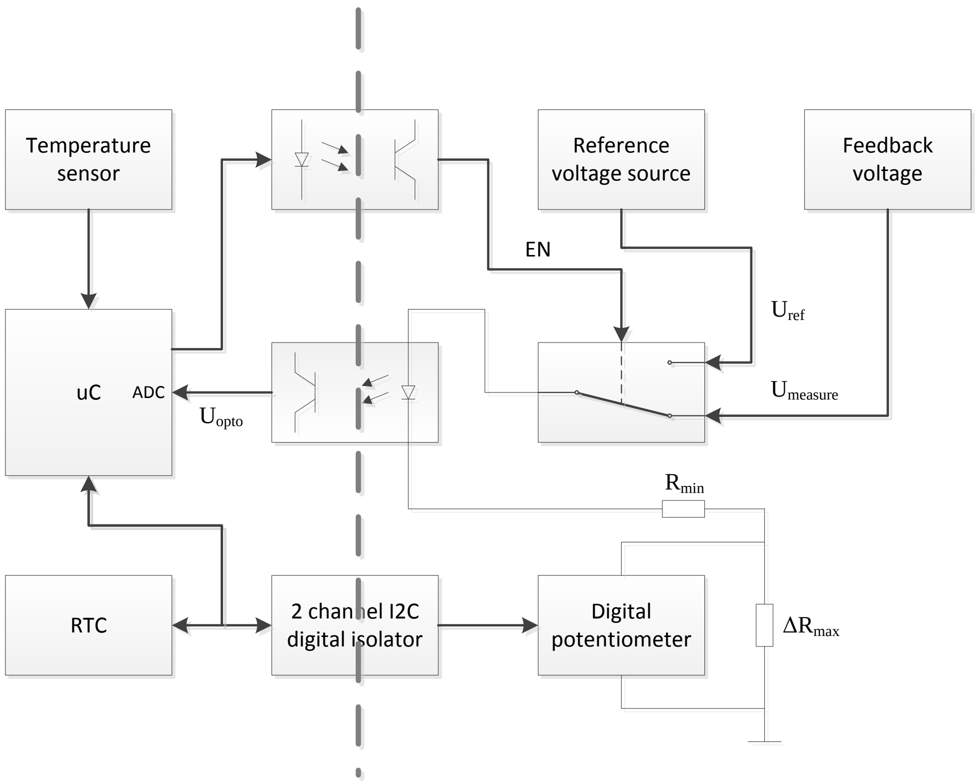

Figure 4. System architecture of the adaptive optocoupler degradation compensation feedback loop in a galvanically isolated design

feedback loop that contains an optocoupler. In this feedback path, an analogue voltage is coupled, that is proportional with the output voltage [9]. The optocoupler's ΔCTR is changing with over, and also depends on the junction temperature and the current density of the LED.

It is not possible to correctly predict CTR degradation, therefore it needs zeroing out of the offset error of the optocoupler. Reliability is something that must be "built in", not "tested in" [10].

A. Hardware architecture

For compensating the optocoupler, it is needed to use a precise reference voltage, and from time to time swap the input of the optocoupler with this reference voltage and the measured voltage [11]. The switchover between the voltage sources can be done by an analogue multiplexer – it needs to be calculated with an n·10 Ohm switch on resistance –, or a golden plated relay. In this realization a Hamlin reed relay had been used – maximal contact resistance is 0.200 Ohm.

The output of the optocoupler is measured by an ADC (Analog to Digital Converter), to digitalize the measured values. [9] The higher resolution of the ADC will provide better resolution. The conversion time of the converter is not critical, since there is no need to chop with high frequency between the two voltage sources. A microcontroller can also be used.

The precision voltage reference in this realization is an AD584. It provides flexibility with the Four programmable output voltages 10V, 7.5V, 5V, and 2.5V,

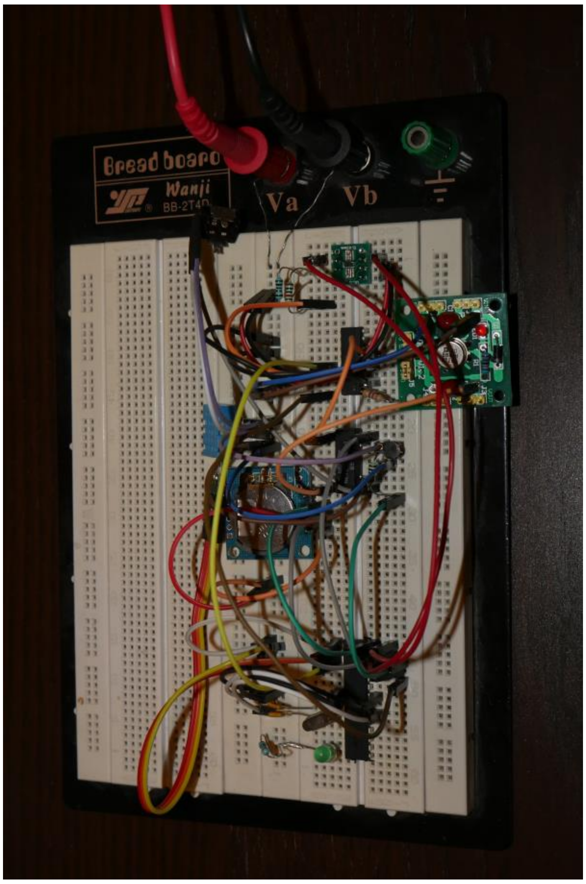

Figure 5. The model of the circuit

and it is easy to use since no external components are required. The most accurate result is in the 10V output, with at 11V-12V supply voltage.

With help of the digital potentiometer, the adjustment of the current limiting resistor is solvable. The MCP40D1x with the parallel ΔR_{max} can precisely compensate the optocoupler.

$$\Delta R_{max} = R_{max} - R_{min}, \qquad (5)$$

where ΔR_{max} is the designed value of the resistance change, R_{max} and R_{min} are the maximal and minimal value of the optocouplers current limiting resistance.

The architecture [12] of the device is shown in Fig. 4. As can be seen, – because of the galvanic isolation – the control signals are also needed to be coupled. One digital signal for the relay, which is possible with a regular optocoupler, and two digital signals for the programmable resistance. This component also needed to handle the I2C bus speed properly – which can be 400 kbit/s in full speed grade. The circuit model is shown in Fig. 5.

Key advantages of CMOS digital communication bus interface isolation have over optocouplers are: no aging or performance degradation over time; increase system reliability due to a ten times lower failure (FIT) rate; better noise immunity; wider temperature range; it also allows designers to create lower cost, smaller size, higher performance, lower power.

For example ADUM125x is a magnetic isolation technology to support a complete isolated I2C interface up to 1MHz. Or Si86xx family is also a possible solution, it is based on RF isolation technology, and supports I2C clocks up to 1.7 MHz. Both enable robust operation in harsh industrial applications.

B. Software solution

The optocoupler compensation subroutine is called time to time from the main program. As shown in Fig. 4., a temperature sensor and an RTC (Real Time Clock) can also be found in the system. The software monitors and logs the environmental and internal data [13]. If the temperature change is higher than a predefined value, the optocoupler compensation subroutine (Fig. 6.) is also called.

In the compensation process firstly, the measured value is disconnected form the input of the optocoupler, than the reference voltage source is connected to its place – by the relay, controlled by the microcontroller. Then the optocoupler's compensation is started by adjusting the digital potentiometer. The sub process is finished, when the output of the optocoupler reaches the minimal difference from the reference voltage source. The measurement is done by the ADC of the microcontroller. Finally, the reference voltage is disconnected form the input of the optocoupler, than the measurable value is connected to its place, and the feedback loop can continue doing its original task.

This routine can be run in a microcontroller, which is embedded beyond the system [14], or it can be implemented within the power supply managing microcontroller, by calling a library and using some extra pins of the controller [15]. With the duplication or triplication of the above mentioned architectural elements, the robustness of the system could also be increased [16]. This architectural solution is usable for line-in power supply systems [17] and also for off-grid or mobile power supply systems [18].

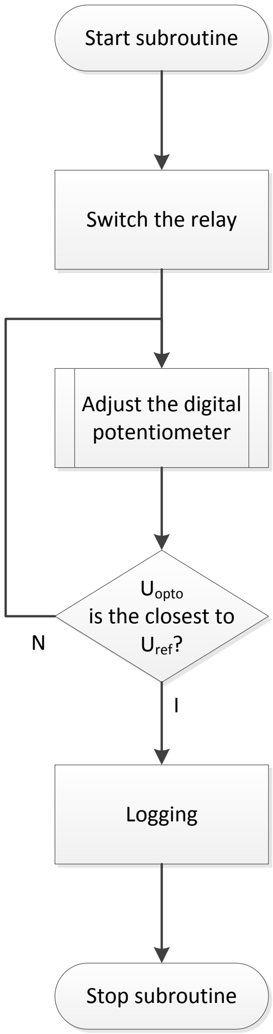

Figure 6. Flowchart of the optocoupler degradation compensation subroutine

CONCLUSION

The main reason for CTR degradation of optocouplers is the decrease in quantum efficiency of the built-in LED. Secondary causes of CTR degradation are the aging of the transparent epoxy, the decrease in sensitivity of the photodetector, and the change in the gain of the output amplifier. The rate of CTR degradation depends on manufacturing materials and parameters and using conditions, therefore it is unpredictable. It still needs to compensate these changes at a highly reliable, highly accurate circuitry, where proper analogue signal coupling is crucial. For such purpose, an adaptive and robust solution, which has been presented in this paper could be used. Proposed solution needs some extra hardware and software redundancy, yet it is still feasible at low cost. We believe that this technique can be useful for civilian and industrial applications, where reliability is highly required.

REFERENCES

[1] Biijenescu, T. I. Degradation and reliability problems of optocouplers. Proc. of Annual Semiconductor Conference - CAS '93, Sinaia, Romania. 1993.

[2] Bergh, A. A., Dean, P. J. Light-emitting diodes. Clarendon Press. 1976

[3] Amerasekera. E. A., Campbell, D. S. Failure mechanisms in semiconductor devices. J. Wiley & Sons. Chichester. 1987

[4] Zippel, C. L. et al. Competing processes in long-ternl accelerated ageing of double heterostructure GaAIAs light emitting diodes. 1982. 1. Appl. Phys., vol. 53, pp. 1781-1786.

[5] Biijenescu, T. I. CTR degradation and ageing problem of optocouplers. Proc. of the fourth international conference on solid-state and integrated-circuit technology. Beijing, China. October 24-28, 1995. pp. 173-175

[6] Gage. Stan I. Hewlett-Packard. Optoelectronics applications manual 1977

[7] Ladislav Fozo, Rudolf Andoga, Radovan Kovacs. Thermo-dynamic cycle computation of a micro turbojet engine. In: CINTI 2016. - Danvers : IEEE, 2016 P. 000075-000079. - ISBN 978-1-5090-3909-8

[8] Ueda, O. Reliability and degradation of III-V optical devices. Artech House. Inc. Norwood, MA. 1996.

[9] Maroš Komjáty, Ladislav Főző, Rudolf Andoga. Experimental identification of a small turbojet engine with variable exhaust nozzle. In: CINTI 2015. - Danvers : IEEE, 2015 P. 65-69. - ISBN 978-1-4673-8519-0

[10] T. I. Băjenescu, M. I. Bâzu. Reliability of Electronic Components. Berlin. Springer-Verlag Berlin Heidelberg GmbH. 1999. 311.-328. pp. ISBN 978-3-642-58505-0

[11] Rudolf Andoga, Ladislav Főző, Ladislav Madarász, Tomáš Karoľ. A Digital Diagnostic System for a Small Turbojet Engine. In: Acta Polytechnica Hungarica. Vol. 10, no. 4 (2013), p. 45-58. - ISSN 1785-8860

[12] Györök György. Programozható analóg áramkörök mikrovezérlő környezetben. Óbudai Egyetem, ISBN 978 615 5018 97 8, Budapest, 2013.

[13] Rudolf Andoga, Ladislav Madarász, Ladislav Főző, Tobiáš Lazar, Vladimír Gašpa. Innovative approaches in modeling, control and diagnostics of small turbojet engines. In: Acta Polytechnica Hungarica. Vol. 10, no. 5 (2013), p. 81-99. - ISSN 1785-8860

[14] Györök György, Beszédes Bertalan. Duplicated Control Unit Based Embedded Fault-masking Systems. In: Szakál Anikó. IEEE 15th International Symposium on Intelligent Systems and Informatics: SISY 2017. Szabadka, Szerbia, 2017.09.14-2017.09.16. New York: IEEE, 2017. pp. 283-288. ISBN:978-1-5386-3855-2

[15] Gy. Györök. A-class amplifier with FPAA as a predictive supply voltage control. Proc. 9th International Symposium of Hungarian Researchers on Computational Intelligence and Informatics (CINTI2008), pages 361–368, November 2008.

[16] György Györök, Bertalan Beszédes. Fault-tolerant Software Solutions in Microcontroller Based Systems. In: Orosz Gábor Tamás. AIS 2017 - 12th International Symposium on Applied Informatics and Related Areas: Proceedings. Székesfehérvár, Magyarország, 2017.11.09. Székesfehérvár: Óbudai Egyetem. 2017. pp. 7-12. ISBN:978-963-449-032-6

[17] Györök György, Bertalan Beszedes. Fault tolerant power supply systems. In: Orosz Gábor Tamás, 11th International Symposium on Applied Informatics and Related Areas (AIS 2016). Székesfehérvár, Magyarország, 2016.11.17. Budapest: Óbudai Egyetem, 2016. pp. 68-73.

[18] Györök György, Tihomir Trifonov, Alexander E. Baklanov, Bertalan Beszédes, Svetlana V. Grigoryeva, Aizhan Zhaparova. A Special Robust Solution for Battery Based Power Supply. In: Orosz Gábor Tamás. 11th International Symposium on Applied Informatics and Related Areas (AIS 2016). Székesfehérvár, Magyarország, 2016.11.17. Budapest: Óbudai Egyetem, 2016. pp. 32-35.