THE FAULT TOLERANT LED POWER CONVERTER DESIGN FOR MORE EFFICIENT AND DURABLE LIGHTING

K. Gašparini[1] – A. Nasser[1] – S. Sladić[1*]

[1]University of Rijeka, Faculty of Engineering, Vukovarska 58, 51000 Rijeka, Croatia

ARTICLE INFO

***Article history*:**
Received: 11.11.2013.
Received in revised form: 04.01.2014.
Accepted: 21.01.2014.

Keywords:
Power electronics converter design
Current source converter
LED driver
LED lighting regulation
Reliability modeling
Fault tolerance
Graph theory

Abstract:

Optoelectronic coupler, characterized by long life and high reliability, is one typical kind of optoelectronic devices. Accelerated degradation testing is mostly utilized to assess optoelectronic coupler storage life. However, in engineering, integrated optoelectronic coupler may be nagged with the fusion of multi-channel degradation data. To solve the problem, the paper firstly conducts accelerated storage degradation testing on a certain type optoelectronic coupler, and analyzes the main degradation model and mechanism of optoelectronic coupler under storage environment. Meanwhile, the paper gives an access to processing multi-channel degradation data based on pseudo life, which can be also employed to assess other integrated devices, like memories, with their accelerated degradation data.

1 Introduction

There is a trend in modern production to increase the number of consumer products available on the market, which were designed for very limited life cycle [1]. After that relatively short period, maintenance of electronic equipment or cost effective electric motors is no longer acceptable from economic point of view, or it is not possible because of specific product design. In this paper an opposite design approach (discrete, long life design) has been used, leading to long term sustainability during use [2]. A fault tolerant power converter has been designed to enable repair, replacement of particular components and long term reliability using the advances in semiconductor and lighting technology, as well in reliability and graph theory. It has been reported that discrete design approach enables a higher efficiency than modular DC/DC converters, [3]. In this way LED (light emitting diode) power converter [4] which emulates current source, rather than voltage source could last as a durable LED lighting. This type of power electronic converters is sometimes referred also as LED drivers [5] which could be also a single resistor or a linear voltage regulator.

From the historical point of view, incandescent light bulbs have been used in wide variety of applications for more than a century. Main drawbacks of this solution are low efficiency (5%-10%) and relatively short lifetime of incandescent light bulbs (typically 1000 hours) [6-7]. Low efficiency is a consequence of spectral distribution of energy, since larger part of energy remains in infrared pass (heat). Recently, European Union starts to remove incandescent light bulbs from the market leaving the space for more efficient lighting [7]. Important alternative is LED lighting, which has been already used for wide variety of applications like traffic, vehicle and commercial lights. Their wide application causes

[*] Corresponding author. Tel: +385 51 651 582
e-mail: sasa.sladic@riteh.hr

that the LED type of electronic power converters got an additional importance [4-5]. In order to support LED lighting advances, such as long life-time (more than 50000 hours) and high efficiency (around 90%) [6], this type of power converters has to be designed with highly reliable components, such as ceramic capacitors [4, 8], and robust industrial integrated circuits [9]. In this paper, a discrete design has been accomplished for directed, efficient, powerful and reliable hand light. In order to achieve such performances, a push-pull converter [8, 10-12], with current regulation has been implemented. In order to increase output luminescence, a forced cooling has been added. The main idea of this design is to accomplish powerful lighting, which could continue operation after breakdown of some of its components in frame of robust design. Figure 1 shows the schematic of classic hand light, which consists of battery, mechanical switch *S* and incandescent light bulb. This system is very simple which means, that it has potential to be very reliable. Such approach can be used for both incandescent light bulbs and LED light except that the LED driver, demands additional resistor in order to limit the load current. It seems that replacement of incandescent light bulb with LED light (and series resistor) would result in a reliable system. Such approach has been used in cost effective solutions. Unfortunately such unregulated solution does not allow optimization of efficiency and LED light life cycle. So, a more sophisticated circuit has been proposed, Fig. 2. Proposed circuit has more complicated internal structure involving more components and it enables optimization of LED light life cycle. However, trivial structure has been added to a sophisticated

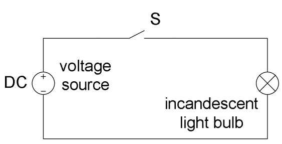

Figure 1. Classic cost effective hand light circuit.

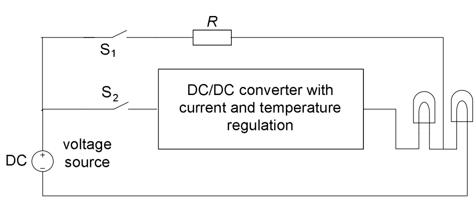

Figure 2. Proposed hand light circuit.

one maximizing the reliability of this approach. Disadvantage of this (unregulated) solution, which is represented in Fig. 3(a), is that output power has to be reduced (connection of reduced number of LEDs up to the input voltage level), insuring the high redundancy in the system.

2 Reliability model of LED power converter and its life-cycle management

LED power converter could be shown as a reliability network [13] where each component (or each function block) can be shown with appropriate reliability [14-17]. Figure 3 shows reliability networks for different types of hand lights. Figure 3(a) shows hand light with battery characterized by reliability r_0 (node *A*), single switch with optional resistor (node *B* – r_8) and LED light bulb (node *G*). Reliability of mechanical switch is high, but it could be destroyed because of chemical reactions (oxidation or battery leakage). Reliabilities of incandescent or halogen light bulbs are lower (frequent replacements) compared to LED light [6]. Other reliabilities in Fig. 3 are listed: DC/AC converter – r_1 (*C*) and its regulation circuit – r_2 (*D*), rectifier – r_3 (*E*) followed by the output of converter (*F*) with output filter – r_4 and LED light source (nodes *F* and *G*); there are two blocks with different reliabilities: LED light and brush ventilator (r_5 and r_6). Brushless ventilator has higher reliability r_7; generally, series system reliability R_S is given by:

$$R_S = \prod\nolimits_{i=1}^{n} R_i \,, \qquad (1)$$

where R_i represents particular subsystem reliabilities. Malfunction of any part leads to malfunction of whole system, Fig. 3(a). In this moment an important question arises in electronic circuit design: how reliable system could be designed with unreliable components [13]? According the numerous authors from field of network theory, it seems that certain amount of redundancy has to be added into the designed system [18 - 19], leading to adaptive and evolutionary systems used in space or military purposes [8,14,16,20]. Parallel system reliability R_P:

$$R_p = 1 - \prod\nolimits_{i=1}^{n} (1 - R_i) \,, \qquad (2)$$

R_i represents a particular subsystem reliabilities, again. It can be noted that by increasing of a component number in series system formed from particular reliabilities less than 1, reliability of series system tends to zero (nonoperating system). However, the reliability of parallel system is increasing by adding additional paths. Each functional block of power converter [10-12] is shown by its reliability, Fig. 3.

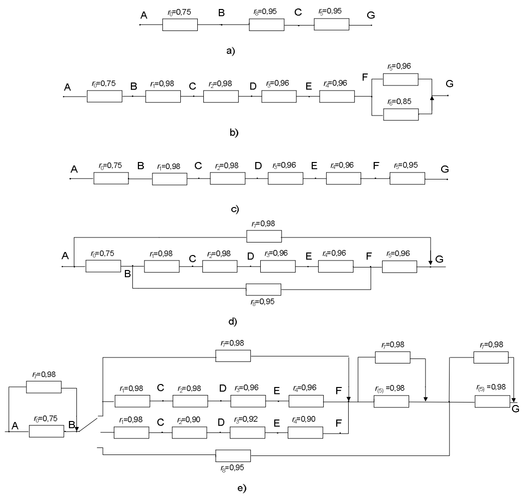

Figure 3. Reliability models for different types of hand lights.

This approach is common for electronics used for military applications [14, 16]. In order to improve reliability of system from Fig. 3(a), the first clue is to add a ventilator, Fig. 3(b). In case of LED driver composed of several power converters and brush DC machine used for cooling of the LED light, there is some redundancy which involves the fault tolerance related to DC brush machine, however operation of ventilator without LED cannot be considered as an operating system.

In order to compare different lighting systems an arbitrary reliability of each subsystem could be chosen [14] in order to compare systems architecture. Otherwise, an empirical data [16-17] brings more realistic results. In this case an empirical data was taken. Reliabilities R_{3A} to R_{3E} for systems in Fig. 3(a)-(e) are compared:

$$R_{3A} = r_0 \cdot r_8 \cdot r_5 = 0.75 \cdot 0.95 \cdot 0.95 = 0.68\,, \quad (3)$$

$$\begin{aligned} R_{3B} &= r_0 \cdot r_1 \cdot r_2 \cdot r_3 \cdot r_4 \cdot r_5 \\ &= 0.75 \cdot 0.98 \cdot 0.98 \cdot 0.96 \cdot 0.96 \cdot 0.96\,, \quad (4) \\ &= 0.64 \end{aligned}$$

It seems, however that commercial LED drivers [9] do not prefer this approach. There are several related reasons for that:

1. Cooling device reduce efficiency of the system (because of mechanical losses)
2. Cooling device increase the mass of the system
3. Brush DC motor has a low reliability and ventilator operation does not count as operating system (only series connections).

Commercial approach [9], could reach very high efficiency, low mass and consequently low price. Its reliability, Fig. 3(c), could be determined as:

$$\begin{aligned} R_{3B} &= r_0 \cdot r_1 \cdot r_2 \cdot r_3 \cdot r_4 \cdot r_5 \\ &= 0.75 \cdot 0.98 \cdot 0.98 \cdot 0.96 \cdot 0.96 \cdot 0.95\,, \quad (5) \\ &= 0.63 \end{aligned}$$

It seems, however, that low reliability DC brush machine is not appropriate for such approach. In other hand AC machine cooling could bring additional reliability to whole system, since, temperature increase decreases the lifetime of electronic components, especially capacitors [9]:

$$l_c = k l_0 2^{\frac{\tau - \tau_0}{10}}\,, \quad (6)$$

l_c – life cycle at operating temperature
l_0 – life cycle at referent temperature
T – operating temperature
T_0 – referent temperature
k – constant which depends on ripple current flowing through the capacitor;

Equation (6) is valid for modeling a capacitor lifetime. It can be seen that capacitor lifetime l_c increases for factor 2 each time when the temperature drops for 10°C. Similar dependences could be found also for other electronic components [16]. That means, light source efficiency as well as converter efficiency has to be high. It also means that cooling is the main issue in converter design where the high reliability is tried to achieve. In these circumstances an approach shown in Fig. 3(d) has been analyzed. In this case cooling is applied to whole system. Instead of brush DC motor a more reliable brushless DC motor is applied maximizing the reliability of whole system. Furthermore, a direct connection between DC source and LED light was introduced enabling the additional short-term operation of system in case of complete malfunction of power converter. R_{D1} represents the DC/DC converter reliability and r_8 reliability of additional path, as shown in Fig. 2:

$$R_{D1} = r_1 \cdot r_2 \cdot r_3 \cdot r_4 = 0.98 \cdot 0.98 \cdot 0.96 \cdot 0.96 = 0.89, \quad (7)$$

$$R_{D8} = (1-(1-R_{D1}) \cdot (1-r_8)) = 1 - 0.11 \cdot 0.05 = 0.99. \quad (8)$$

Reliability of system from Fig. 3(d) is given by:

$$R_{3D} = r_0 \cdot R_{D8} \cdot r_5 = 0.75 \cdot 0.99 \cdot 0.96 = 0{,}71, \quad (9)$$

Parallelism introduced by additional independent reliability path in Fig. 3(d) (R_{D1} and r_8) increase the reliability of the system. In the same time its lifetime is increased also. Compared to first, single-switch system, reliability is increased for 3% and for the third case 8%, Fig. 3(c).

During the reliability modeling of power converter it was attempted to maintain functionality in presentation, from the electronic point of view. With that main idea, Fig. 3(e) has been drawn. In that case reliability elements are shown twice; once with operating ventilator and without it. Such approach enables more precise modeling and more accurate analysis of system reliability, taking into account temperature difference in case of ventilator failure. The circuit represents inactive (cold) standby redundancy where switch has two modes during the failure, one when switch is off, and another when it is commanded to be on. For example, it is possible for DC/DC converter to stop operation while its ventilator cools additional resistor with LED light. Besides, it is noticeable that only half of LEDs are active (reduced heating) which is meant as way for further LED driver life cycle prolongation even if the ventilator stops cooling the system. According to manufacturer data [21], this is the key issue since LED life time is function of its operating temperature, Fig. 4. It can be noticed that life-time of LED light can be even longer than 50000 hours in optimal conditions [6].

3 Power electronic converter design

Intention is to design high power electric hand lamp according to reliability scheme in Fig. 3(f). For development of tolerant circuits a feedback is used

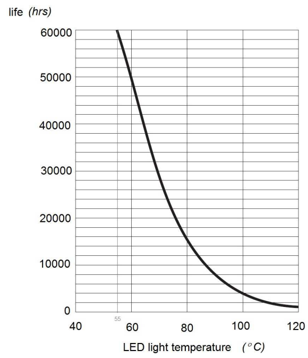

Figure 4. Durability of LED lighting versus operating temperature [21].

to electrically compensate variations and thereby provide stable performance. LED lights demands current source which means that current feedback loop has to be applied. High quality product, demands DC/DC power converter in range of few hundred watts which means a half-bridge, bridge or push-pull converter [5, 10, 12] has to be used. In order to achieve highest powers a bridge converter has to be used. However, in this case a push-pull converter, which has two power transistors instead of four, has been used.

3.1 Power circuit design

In order to design reliable long-life electric hand light it is necessary to determine optimal operating point [11] in sense of load current and operating temperature. Among other light sources a LED light has been explored in many ways [4]. In order to achieve output power larger than 100 W, converters without transformer are less suitable than topologies with galvanic isolation. In this paper a push-pull topology has been chosen. This topology involves only two transistors making it to be the first choice in situations when the power comes out of “the range” of DC/DC converters without transformer (boost, buck and buck-boost topology). Its operation principle is based on Forward converter operation. However, a demagnetization winding is not needed since magnetic core has been magnetized in both directions repeatedly. Disadvantage of this topology is that magnetic core saturation can arise in case when the different duty cycles arise in two symmetrical primary windings of the same transformer. So, the reliable industrial solution has been applied (TL594) in order to avoid possible transformer saturation. Operating

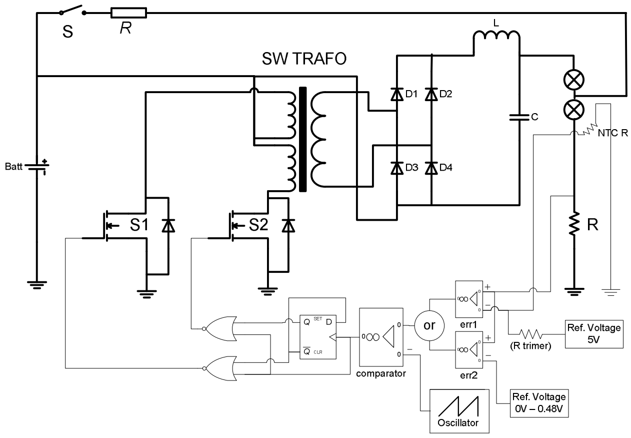

Figure 5. Push-Pull DC/DC power converter with current and temperature regulation.

frequency of PWM generator has been set to 60 kHz, which means that switching frequency of each transistor is 30 kHz. This topology has been used in PC supplies and in emerging field of renewable energy sources [12]. Realized circuit has been shown in Fig. 5. Constant output current is ensured with output *LC* filter (100 µH, 4700 µF). In order to reduce switching losses on high switching frequency, MOSFET transistors have been used. In order to increase efficiency and reliability of DC/DC converter, an additional driver for transistor switches were used. Output inductance tends to filter AC component from output current and to enable constant light source. Ventilator automatically increases the spinning speed (3000-6000 rpm) if the temperature of output airflow exceeds 50°C. Figure 6 shows ideal waveforms for transistor control signals and Fig. 7 shows measured transistor control signals at 60 kHz.

3.2 Control circuit design

In order to regulate light intensity of LED lighting, load current has to be constant, adjustable and regulated from 0 A to 3.2 A. Designed converter could reach 36 V of output voltage. Input voltage is available from batteries and nominally is 14 V (or minimally 7 V). It can be calculated, that output power could reach more than 100 W. There is a current regulation path, so the different LED lights could be used. Such approach optimizes the life-cycle of the LED lights of different powers (20 W, 30 W, 50 W, 100 W) and enables light control for each option. It is possible, also to connect multiple LED lights. Further improvement of low cost hand

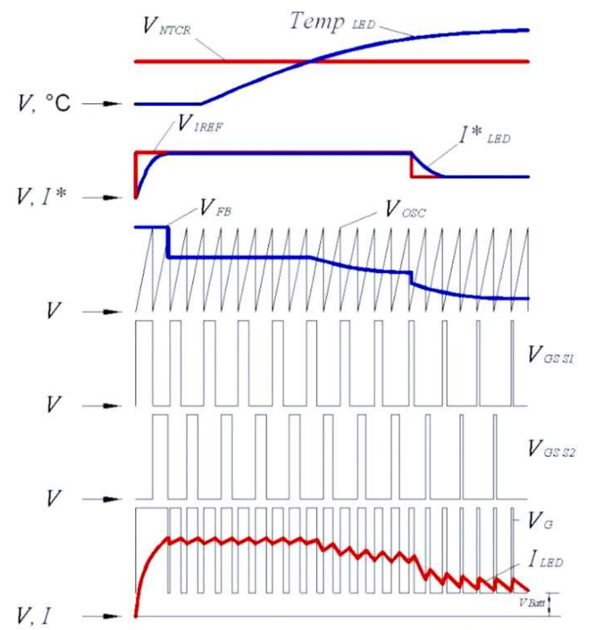

Figure 6. Principal LED driver waveforms for a step LED light temperature increase.

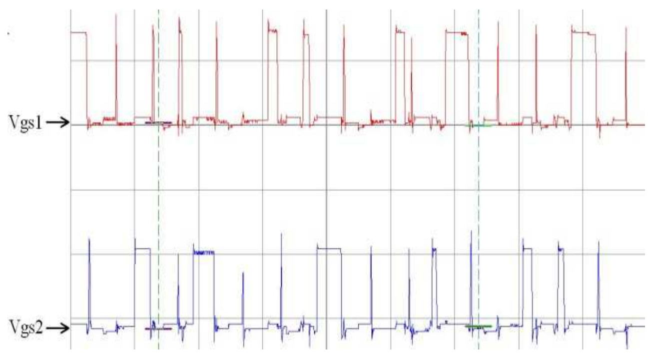

Figure 7. LED driver waveforms during LED light temperature change with current and temperature regulation (control signals of transistors S_1, S_2, 10 V/div., 50µs/div).

lights [9] is achieved with cost effective brushless ventilator which tends to decrease cooler temperature. However, that is not only way of temperature regulation. Temperature regulation is achieved by NTC resistor connected to current regulation path. So, the emitted light is proportional to dissipated power. LED lightning, as well as its temperature could be adjusted in order to achieve increased life-cycle, Fig. 4. Regulation is designed in such a way that LED diode emits strongest light after the switching on, when the components are on ambient temperature. After the intense of light emission and dissipation of heat, the temperature arises and light intensity automatically decreases.

That means current reference decreases by temperature increase, Fig. 6. Light intensity is regulated; however maximum light intensity is limited by temperature of the LED lights and depends on output temperature, Fig. 8.

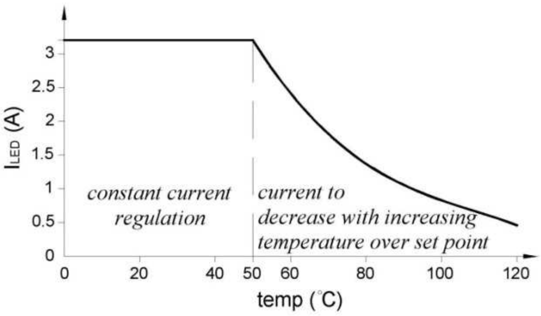

Figure 8. LED current versus its temperature.

Choosing the lower light intensity of LED diodes their life cycle will be increased. LED power can be adjusted for all temperatures which are assuring 50000 h of LED lifetime, otherwise (according to Fig. 8; 50 °C), output current is automatically decreased.

4 System performances

During the operation it can be noticed that LED diode emits light of constant adjustable intensity which means that output converter current has smooth DC regulated value, but during the heating up of the LED light intensity gradually decreases. Comparing designed system with other hand lights available at the market, it shows up that, such hand lights, generally, are not available, since LED hand lights are available on lower power. However, unregulated 55 W halogen lights can be found. During the long term operation, it could happen that ventilator will be destroyed leaving the LED light and the LED driver to operate alone. Such malfunction causes current regulation to operate alone without temperature setting of operation point leading to decreased reliability of whole system. Since the hand light was designed to operate at relatively large power, approaching to strong lights on the personal car, ventilator malfunction can influence reliability of all electronic components positioned nearby. LED light, however could operate in classic hand light approach which is shown in Fig. 3(a). However, such approach decreases efficiency and eliminates many LED light advantages over the incandescent light (or electric) bulb. In order to achieve reliable hand light, a current regulation with temperature regulation is necessary. Dynamic performance of such system is not the key issue as in electric drives or in power supplies because load changes are much slower than in mentioned applications. In sense of efficiency of hand light the power converter has the key role since its proper design could bring efficiency up to 98% [22]. However, efficiency is rather an output current function [3] than a constant. An efficiency of 84.86% was measured for designed converter, which means that overall LED system efficiency of 75% was obtained, compared to 10% achieved with classic electric bulbs. LED light could continue operation after the failure of converter, however, without regulation, life time and efficiency decreases. Comparing the reliabilities it can be founded in literature that life-cycle of electric bulb is around 1000 h. Expected life-cycle of LED light is approximately the same at the temperature of 120ºC. If the temperature is reduced by cooler and ventilator application, involving the current regulation LED light life cycle could extend for 60 times. That means if classic light last for about one year, LED life could last for life time (60 years or more).

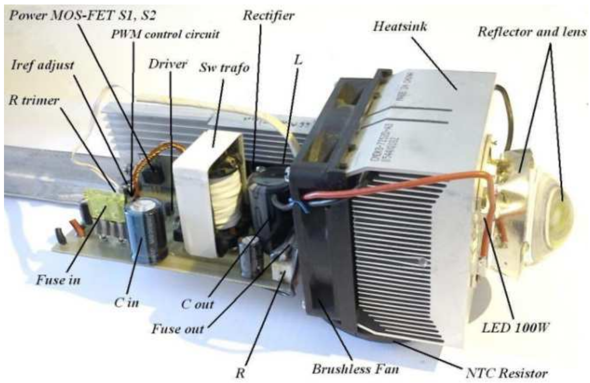

Figure 9. 100W hand light with DC/DC converter.

5 Conclusion

In this paper a design of robust, current source, fault tolerant LED power converter has been presented. A power converter design has been performed in order to maximize converter output power and LED light intensity for different operating conditions. Uncommon possibilities of connecting LED lights have been used to ensure a fault tolerance, making a redundant mehatronic solution of two mutually supported systems (electronic and heat) involving the current and temperature regulation. Graph theory was used in order to explore possibilities for reliability improvement and light intensity regulation. Possibility of uniform modeling of mechatronic system in sense of reliability, efficiency, electronic and heat functionality were efficiency and even the life cycle of the equipment has been gradually reduced. It is an author's opinion that such design could be applied as a light both in electric and conventional cars. Excluding the battery from the analysis, an even higher difference in reliability can be obtained.

References

[1] Berrin A., Wu, S.D.: *Characterization of demand for short life-cycle technology products*, Ann Oper Res, Springer Science + Business Media, LLC, 2010.

[2] Sibaud, P., Woodrow, A.: *SHORT CIRCUIT: The Lifecycle of our Electronic Gadgets and the True Cost to Earth*, The Gaia Foundation, UK, 2013.

[3] Kugelstadt, K.: *Discrete design of low-cost isolated 3.3-to 5-V DC/DC converter*, Power Management, Texas Instruments, 2010.

[4] Zhang, B., Yang, X., Ming, X., Qiaoliang, C.: *Design of Boost-Flyback Single-Stage PFC converter for LED power supply without electrolytic capacitor for energy storage*, Power Electronics and Motion Control Conference, IPEMC 09, Wuhan, China, 2009, 1668-1671.

[5] Arias, M., Vázquez, A., Sebastián, J.: *An Overview of the AC-DC and DC-DC converters for LED Lighting Applications*, Automatika, 53 (2012), 2, 156-172.

[6] Lingard, R.: *LED Luminare Reliability*, U.S. Department of Energy, 2009.

[7] Oettinger, G., Lowe, P.: *European lamps become more energy efficient*, Directorate - General for Energy and Transport, European commission, 2009.

[8] Xia, Y. et al.: *Novel push-pull forward converter for high reliability and high input voltage applications*, Energy Conversion Congress and Exposition, IEEE, 11.-22.9., Phoenix, USA, 2011, 2506-2511.

[9] Kleisterlee, G.: *Led driver lifetime and reliability*, Koninklijke Philips Electronics N.V., 2011.

[10] Ruiz-Caballero, D.A., Barbi, I.: *A New Flyback-Current-Fed Push-Pull DC-DC Converter*, Transactions on Power Electronics, 14 (1999), 6.

[11] Kuyula, C. K., Janse van Rensburg, J. F.: *Development of a Push-pull Converter for Fuel Cell Applications*, Southern Africa Telecommunication Networks and Applications Conference (SATNAC), George, Western Cape, 2012.

[12] Maiti, D., Mondal, N., Biswas, S. K.: *Design Procedure of a Push Pull Current-Fed DC-DC Converter*, Indian Institute of Technology Roorke, NPEC, 2010.

[13] Ferrer, R., Janssen, C., Solé, R.V.: *Topology of Technology Graphs: Small world Patterns in Electronic Circuits*, Phys. Rev., 64 (2001).

[14] Turner, S.D.: *Reliability Advantages of Modular Solid State Power Amplifiers compared to Traveling Wave Tube Amplifiers*, Reprint: Armed Forces Int., 2003.

[15] Solé, R.V., Valverde S.: *Information Theory of Complex Networks*: *On Evolution and Architectural Constrains*, *Complex Networks*, Lecture Notes Physics, 650, 189-207, 2004.

[16] Military handbook, *Electronic reliability design handbook*, MIL-HDBK-0300-0499 Department of defense, USA, 1998.

[17] David D.D., Gossin P.M.: *A comprehensive Reliability Assessment Tool for Electronic Systems*, Reliability and Maintainability Symposium, Philadelphia, 308-313., 2001.

[18] Von Neuman J.: *In Automata Studies*, C. E., Princeton University Press, Princeton, 1956.

[19] McCulloch W.S.: *In Self-Organizing Systems*, M. C. Yovits and S. Cameron, Pergamon Press, New York, 264-281, 1960.

[20] Ren, A. et al.: *Implement of evolable hardware based improved genetic algorithm*, 7th International conference on Natural Computation (ICNC), 26.-28. July, 2011.

[21] Shieh, K. J., Lee, J.: *Visible light product specification*, *High power LED*, *HPR40E-19K100xWG*, Huey Jann electronics industry CO., LTD. 2011.

[22] Colonel Wm. T. McLyman: *Designing a 100kHz 32 watt Push-Pull Converter*, Kg Magnetics, Inc., Sierra Madre, Ca. 2002.