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Reliability Evaluation of a Buck Converter Based on Thermal Analysis

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Abstract: *The design, which is based on the concept of reliability, is impressive. In power electronic circuits, the reliability design has been shown to be useful over time. Moreover, power loss in switches and diodes plays a permanent role in reliability assessment. This paper presents a reliability evaluation for a buck converter based on thermal analysis of an insulated-gate bipolar transistor (IGBT) and a diode. The provided thermal analysis is used to determine the switch and diode junction temperature. In this study, the effects of switching frequency and duty cycle are considered as criteria for reliability. A limit of 150°C has been set for over-temperature issues. The simulation of a 12kW buck converter (duty cycle = 42% and switching frequency = 10 kHz) illustrates that the switch and diode junction temperature are 117.29°C and 122.27°C, respectively. The results show that mean time to failure for the buck converter is 46,432 hours.*

Keywords: *Reliability, Mean Time to Failure, Buck Converter, Junction Temperature.*

INTRODUCTION

In recent years, the use of renewable energy has become more popular because of the negative impacts of fossil fuels and the environmental pollution they cause. Nowadays, various methods and topologies for extracting energy from different renewable sources are being introduced. Solar energy, which can be harnessed using photovoltaic panels, is one of the alternative sources of energy and offers many advantages (such as less negative environmental effects and affordability) in comparison with other sources. As renewable energy sources continue to be used more often, more attention is now being paid to power electronics. A converter frequently used for photovoltaic panels in power electronics, as well as in several wind turbine energy conversion systems, is the dc–dc converter. In the last few decades, there have been many dc-dc converter topologies introduced, which have been generally classified based on the ratio of voltage output to input (also known as gain) into three fundamental groups: buck, boost, and buck-boost. This paper focuses on the buck converter type, often used in small or low power systems as a simple, remarkably efficient way to reduce the input voltage to a regulated dc voltage (Huangfu t al., 2015).

More efficient use of any device has always been a goal of manufacturers. In power electronics, the proper functioning of converters encompasses high output quality, a long lifespan, and less energy consumption. Due to the increase of power electronic converters in different devices, an especially important factor for optimizing converters is power quality, which can be described in terms of its thermal characteristics. Indeed, previous researches have clarified the relationship of converter performance and quality in terms of heat loss (Stupar et al., 2010; Zhang et al., 1997; Bašić et al., 2014). Furthermore, Usui and Ishiko presented a simple approach for the thermal design of an IGBT module practised only in steady state operation (Usui & Ishikomm, 2005).

In recent decades, different approaches for thermal analysis have also been introduced, including the highly accurate method of computational fluid dynamics (CFD), based upon how airflow conditions determine heat transfer coefficients (Lee & Mahalingam, 1994).

Converter lifespan is another significant factor with a direct relationship to reliability, which represents the probability of failure in a system at a specific time (Lee & Hwang, 2008). The reliability of a system depends on various parameters; for this reason, identifying the indicators and calculation of the reliability parameters of the system's parts is required. Usually, two parameters are used to assess the reliability of the system. The first parameter is failure rate explained by failure distribution, and the next parameter is mean time to failure (MTTF) which presents the average operation time before the first failure of a component (Stapelberg, 2001).

There are different researches related to the reliability assessment of various circuits and power converters. These circuits include multilevel inverters (Ding et al., 2010; Alavi et al., 2016), DC-DC converters (Dhople et al., 2012), and AC-AC converters (Arifujjaman & Chang, 2012).

Khosroshahi et al. (2015) evaluated the reliability of two conventional and interleaved DC-DC boost converters based on the MIL-HDBK-217 procedure. They found that the interleaved boost converter performs better in terms of reliability in comparison with the conventional boost converter. Perhaps, the most crucial weakness of this article is using approximate relations for calculating power dissipation in the switch and diode, which are based on their internal resistances.

Rashidi-Rad et al. (2012) performed a reliability analysis of modular multilevel converters (MMCs) with the presence of half and full-bridge cells. Their examination illustrated that the modular converters that used half-bridge cells have more reliable performance than other state.

Arifujjaman and Chang (2012) compared the reliability of three ac-ac converter namely intermediate boost converter (IBC), intermediate buck-boost converter (IBBC), and back-to-back converter (BBC) with the well-known matrix converter. They concluded that the intermediate boost converter exhibits more reliable than other ones.

In (Javadian & Kaboli, 2013), the reliability of a buck converter was assessed in the presence of N-channel and P-channel MOSFET drivers. They showed that the considered buck converter has more reliability when an N-channel MOSFET is used as switch. However, they ignored some portions of the power losses in switch and diode, thus the obtained results may not be referred.

Ranjbar et al. (2009) carried out a reliability assessment of single/two stage power factor correction (PFC) converters. The MIL-HDBL-217 was considered as reliability estimation procedure in this analysis. The outcomes demonstrated that the single-stage shows the reliability of 1.6 higher than two-stage converter. In this study, for simplicity of calculations, the case temperature was intended to be a fix value of 35°C. This leads to an inaccuracy in the results.

The main purpose of this paper is to estimate the reliability of a buck converter based on the MIL-HDBK-217 standard. To investigate the reliability of semiconductor devices, there is a need for determining the junction temperature in these types of components, and in this study, the selected approach is based on information from manufacturer's datasheet. A one-cell Cauer thermal model was utilized in order to provide a precise relationship between the power losses and the junction temperatures in the presence of a heatsink. This approach has an acceptable result as well as suitable speed in calculations. Additionally, this is the first time that the simultaneous impact of switching frequency and duty cycle on the power losses and the junction temperature has been analyzed.

The rest of this paper is structured as follows: Section 2 describes the buck converter as a case study. The reliability principals employed for the analysis are discussed in Section 3. In Section 4, the accurate thermal analysis for the buck converter is discussed. In Section 5, the results and reliability evaluation are presented. Finally, conclusions are drawn in Section 6.

The buck converter

The buck converter circuit shown in Figure 1 is a highly efficient step-down dc-dc converter which is commonly used in switched-mode power supply circuits (SMPS). Generally, the dc input voltage of the buck converter is derived from the output of a rectifier through a dc-link. In this paper, an IGBT is used as a switch for the converter. Also, the thermal analysis has been performed, neglecting the voltage drop across the diode and the transistor.

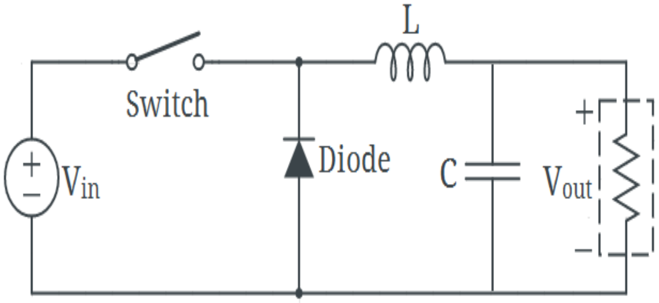


Figure 1: Topology of a buck DC-DC converter.

When the buck converter operates in continuous conduction mode (CCM), its current will never fall to zero during the cycle. Assuming the steady state operation for this converter, it can concluded that the energy stored in each of circuit components at the end of a cycle is equal to energy stored at the beginning of the cycle. Therefore, the input and output voltages in the buck converter have a direct relationship with the duty cycle of the pulses, which can be shown as follows:

$$V_{out} = DV_{in} \qquad (1)$$

where V_{out}, V_{in}, and D are the output voltage, the input voltage, and the converter duty cycle, respectively. With regard to the value of $0<D<1$, as a consequence, the output voltage is always lower than the input voltage. The basic characteristics of the converter are summarized in Table 1.

Table 1: Rated parameters for the desired buck converter

Characteristic	Value
Rated output active power P_o	12 kW
Input voltage V_{in}	300 V DC
Output voltage V_{out}	125 V DC ± 1.2%
Switching frequency f_s	10 kHz
Inductor L	3 mH
Capacitor C	1 µF

A buck converter with parameters based upon Table 1 is simulated in Matlab/Simulink. An open-loop controller is used for the simulation. Furthermore, a value of 42% is considered the duty cycle in this state. The results of the simulation are shown in Figure 2:

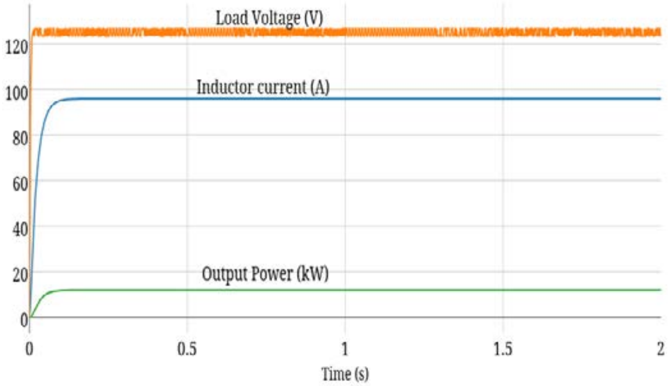


Figure 2: The simulation results of basic characteristics of the converter.

The reliability principle

Reliability means the ability of an item to perform a specific function under given conditions over a specific time period, which is expressed as a probability or failure frequency (Wang et al., 2012). The importance of reliability in space and in the arms industry is more prominent than that of other industries because in these significant instruments, detecting or replacing a failed part is very difficult. Different methods have been introduced to improve the reliability of a system. One of these methods involves adding redundancy to parts of the converters, thereby increasing the global reliability of a system. Reliability is improved by adding more parts for redundancy, but cost is a deterrent to increasing the number of redundancy circuits (Richardeau & Pham, 2013).

One of the factors influencing reliability is failure rate. Failure rate can be expressed as the probability of failure per unit time occurring in the interval [t, t+Δt], and there is no failure before time *t*. Usually, Δt is a very small value, and it is close to zero (Lyu, 1996).

If we present a failure rate with λ, the probability distribution function for failure can be expressed as a relationship in terms of failure rate, and can be obtained using the exponential distribution. Equation (2) presents the distribution function:

$$f(t,\lambda) = \lambda e^{-\lambda t} \qquad (2)$$

Also, the reliability function can be expressed as follows (Stapelberg, 2001):

$$R(t,\lambda) = e^{-\lambda t} \qquad (3)$$

where in the above equations, λ is the component's failure rate. Another influential factor of reliability is mean time to failure (MTTF). MTTF is the average length of time before the first failure of a component or device occurs after it starts to work, after which the device is no longer able to continue with its normal operation. MTTF is expressed by the integral of reliability as follows:

$$MTTF = \int_0^{+\infty} R(t)dt \qquad (4)$$

A simple equation for the expression of MTTF is derived by substituting Equation (3) with Equation (4):

$$MTTF = \frac{1}{\lambda} \qquad (5)$$

In the last decades, various procedures have been introduced to estimate the reliability of different organizations. Some of the most popular procedures, such as RAC's PRISM (Denson, 1999), Telcordia SR-332 (2001), SAE's

PREL (1998), CNET's reliability prediction method (Union Technique de L'Electricité, 2000), Siemens SN29500 standard (1999) and British Telecom's HRD-4 (1987), are described and discussed according to the organization's strategies. A comprehensive comparison has been made among these procedures in (Pecht & Nash, 1994). Today, the MIL-HDBK-217F handbook is used as a suitable reference for estimating reliability. This paper also used a calculation based on the MIL-HDBK-217F procedure (1995).

Two methods that include parts stress and parts count are discussed in the handbook. In the parts count method, less information is required, such as number of parts, quality level and environmental situation (Abdi et al., 2009).

According to the series structure of the buck converter, the failure rate can be calculated using the summation of all failure rates of the circuit components, as shown in Equation (6) (Rausand & Hoyland, 2004):

$$\lambda_{System} = \sum \lambda_{Components} \qquad (6)$$

where $\lambda_{Components}$ is the failure rate of each circuit component.

With the increasing complexity of the studied system, the overall system should be divided into subsystems so that the reliability evaluation becomes simpler and more concise (Rausand & Hoyland, 2004).

The Reliability of Components

The buck converter consists of various components, including switch, diode, inductor and controller. In related studies on the reliability of electronic components (switches, diodes, capacitors and inductors), specific relationships for determining the failure rate for each component are expressed as follows (Richardeau & Pham, 2013; MIL-HDBK-217F, 1995; Abdi et al., 2009):

$$\lambda_p(Capacitor) = \lambda_b \pi_{CV} \pi_Q \pi_E \qquad (7)$$

$$\lambda_p(Inductor - Transformer) = \lambda_b \pi_C \pi_Q \pi_E \qquad (8)$$

$$\lambda_p(Switch) = \lambda_b \pi_T \pi_A \pi_Q \pi_E \qquad (9)$$

$$\lambda_p(Diode) = \lambda_b \pi_T \pi_C \pi_S \pi_Q \pi_E \qquad (10)$$

In Equations (7)– (10), λ_b is the base failure rate, which is different for each component. The base failure rates for the switch and the diode are 0.012 and 0.064 *failure/10⁶h*, respectively. Additionally, π_i is pi factor related to each component, and should be determined accurately.

The inductor base failure rate can be expressed as follows:

$$\lambda_b = 0.000335 \times \exp\left(\frac{T_{HS}+273}{329}\right)^{15.6} \qquad (11)$$

where T_{HS} is the hot spot temperature in degree Celsius, which can be determined using Equation (12):

$$T_{HS} = T_A + 1.1 \times \Delta T \qquad (12)$$

In Equation (12), T_A expresses the device ambient operating temperature in degree Celsius. Also, ΔT is the average temperature rise above the ambient (MIL-HDBK-217F, 1995; Abdi et al., 2009). The inductor failure rate is much lower than other circuit components, so it can be omitted from the analysis.

The capacitor failure rate can be described by following equation:

$$\lambda_b = 0.00254\left[\left(\frac{S}{0.5}\right)^3 + 1\right]\exp\left(5.09 \times \left(\frac{T_A+273}{378}\right)^5\right) \qquad (13)$$

where S is the ratio of operating voltage to nominal voltage.

The factors π_Q and π_E, represent quality and environmental, respectively. The quality and environmental factor values can be assumed to be equal to one, although the effects of these two factors were eliminated (Richardeau & Pham, 2013). The controller failure rate can be considered 0.88 (*failure/10⁶h*) (Abdi et al., 2009). Another factor is the application factor, π_A, and is based on different rated powers. π_T is the temperature factor that, for the switch and diode, can be expressed as follows (Abdi et al., 2009):

$$\pi_{T(S)} = \exp\left(-1925 \times \left(\frac{1}{T_j+273} - \frac{1}{298}\right)\right) \qquad (14)$$

$$\pi_{T(D)} = \exp\left(-1925 \times \left(\frac{1}{T_j+273} - \frac{1}{293}\right)\right) \qquad (15)$$

where T_j is the junction temperature.

One of the major concerns regarding reliable power electronics is the operating temperature. Thus, it seems that the precise determination of the junction temperature results in a more accurate analysis of the reliability. There are five different approaches introduced by Reliability Analysis Center (RAC) to predict the junction temperature for semiconductor devices. In this study, Method IV was used. This method is utilized when a heatsink is mounted on the device, and the exact value of the case temperature is also available (Chan & Calleja, 2011). According to the used approach, the junction temperature can be calculated from Equation (16):

$$T_j = T_C + \theta_{jc} \times P_{loss} \qquad (16)$$

In Equation (16), T_C is the heat sink temperature, θ_{jc} is the thermal resistance of the diode or switch, and P_{loss} is the total power losses of switch or diode.

In fact, Equation (16) exhibits a scheme of the one-cell Cauer thermal network. Figure 3 shows this modeling.

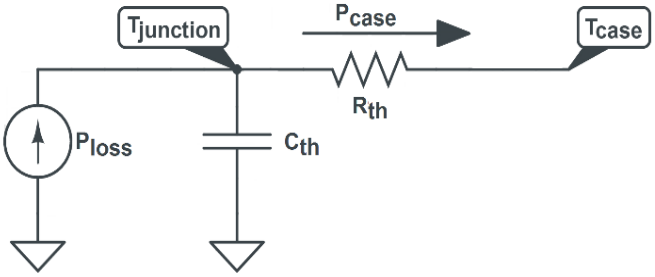


Figure 3: One-cell Cauer thermal network model.

In Figure 3, R_{th} and C_{th} are the thermal resistance and capacitance from junction-to-case, respectively, and these indicators should be selected from the datasheet of the used IGBT module. Also, by similarity of thermal modeling and electrical modeling, the junction temperature can be found easily from the total power losses.

As mentioned earlier, the determination of semiconductors' failure rate depends on their power losses. The utilized approach in this paper is based on calculating both conduction and switching losses for the diode and switch using lookup tables. Detailed explanation of this process is given in (Graovac & Purschel, 2009).

In the following equation, π_S is the stress factor for diodes:

$$\pi_S = V_S^{2.43} \tag{17}$$

where V_S is the ratio of operating voltage to nominal voltage.

π_C explains the contact construction. Considering it is metallurgically bonded, the contact construction leads to the value of 1 for π_C (Abdi et al., 2009).

In the capacitor failure rate, π_{CV} is the capacitor factor which can be calculated as follows:

$$\pi_{CV} = 0.34 \times C^{0.12} \tag{18}$$

where C is the capacitance in microfarad.

Thermal analysis of buck converter

In order to determine the thermal analysis of the converter, a Fuji 2MBI150U2A-060 600V/150A IGBT module is selected as the switch. The features of this module include high speed switching, voltage drive, and low inductance (Fuji Electric Device Technol, 2004).

From the datasheet, the values of the thermal resistance and capacitance for the Cauer network are 0.25 K/W and 0.18 J/K, respectively.

Figure 4 shows the IGBT on-state characteristics in 25°C and 125°C, based on Collector current versus Collector-Emitter voltage.

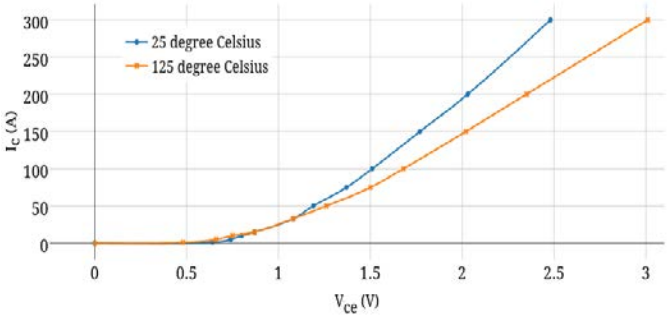


Figure 4: IGBT's Collector current in terms of Collector-Emitter voltage (Fuji Electric Device Technol, 2004).

The rated current distributions for the switch and diode are shown is Figure 5, which this figure clearly demonstrates the summation of switch and diode currents can produce the inductor current (when the switch is on, the diode is off). Conversely, when the diode is on, the switch is off. The inductor current will be a triangular waveform when its voltage analogue is pulsating in a rectangular form.

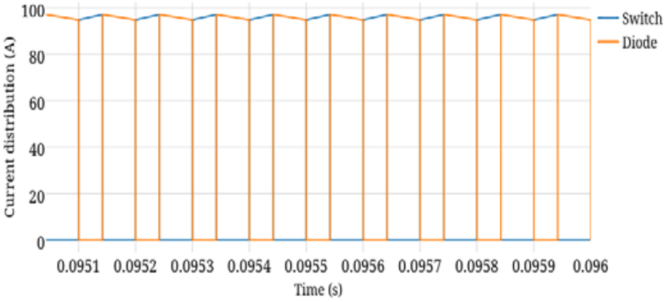
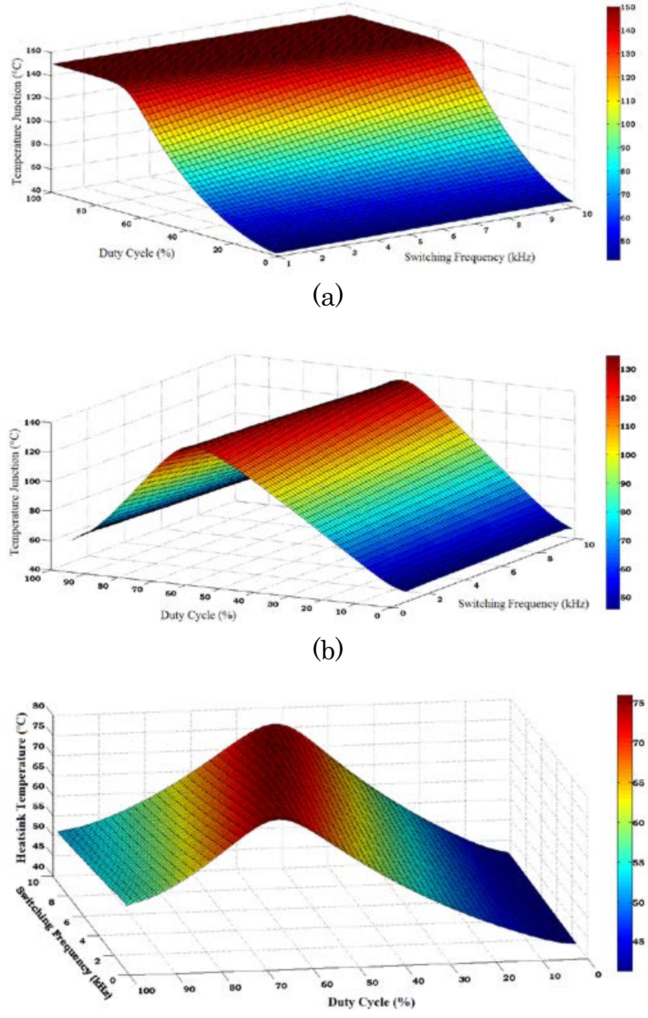


Figure 5: Current distributions of the switch and diode.

The most important factor in the evaluating converter reliability is temperature, which is directly related to power losses of the switch and diode. Thus, the calculation of the junction temperature is a sure way to assess reliability. Various elements can influence the junction temperature and its value will change with variations in component's power losses; increasing the switching frequency can lead to more power losses in the switch and diode. Another important factor for power losses in the buck converter is the modulation index or duty cycle. By setting a different duty cycle for the converter, the gain of the output voltage will change. An analysis is undertaken to show the effects of the switching frequency and the duty cycle on the junction temperature and the heat sink temperature. Figure 6 represents the items that can affect temperatures.

It is evident from Figure 6 that a lower duty cycle corresponds to a better performance in terms of temperature because of the decrease in the output voltage level. Therefore, it is possible to change the duty cycle to its desired value by changing the basic characteristics of the converter. Increasing switching frequency from 1 to 10 kHz has a negligible impact on the temperature, but switching frequencies higher than 10-kHz will increase the temperature.



(a)

(b)

(c)

Figure 6: Effects of duty cycle and switching frequency on a) the switch junction temperature, b) the diode junction temperature, c) the heat sink temperature.

The over-temperature is limited to 150°C, so the converter ceases to operate beyond this temperature. For duty cycles higher than 51%, the junction temperature of the switch rises beyond the over-temperature. This shows the weakness of heatsink for cooling the module under thermal pressure. Using a more efficient heatsink will result in a decrease in the junction temperature and the extension of authorized period for increasing the duty cycle. The calculated power losses for the switch and diode (based on the rated parameters) are 145.02W and 89.69W, respectively. Also, the results illustrate that the switch junction temperature for a duty cycle of 42% and f_s=10 kHz is 117.29°C. The junction temperature of the diode is 122.27°C, and it has a higher value than the switch's temperature. This shows that greater thermal resistance can produce higher junction temperatures. Typically, the heat sink temperature is much lower than that at the junction of other components, and in reliability designs, a temperature of 40°C is considered a stable value for the temperature of the heat sink (Ma et al., 2014). However, the structure and design of the heat sink can affect its operating temperature. The simulation results showed that the heat sink temperature measured with the parameters rated was 69.32°C.

The reliability evaluation of buck converter

Estimated failure rates for each component under identical conditions are shown in Tables 2-5. Due to the rated active power of the converter, a value of 10 is considered to be the application factor. Values of π_Q and π_E were set for the components according to (Abdi et al., 2009).

Table 2: The estimated base failure rate for the switch

PLoss (W)	T_j (°C)	π_T	π_A	π_E	π_Q	λ_b	λ_P (failure/10^6 h)
145.02	117.29	4.60	10	6	5.5	0.012	18.216

Table 3: The estima ted base failure rate for the diode

PLoss (W)	T_j (°C)	π_T	π_C	π_S	π_E	π_Q	λ_b	λ_P (failure/10^6 h)
89.69	122.3	5.47	1	0.19	6	5.5	0.064	2.195

Table 4: The estima ted base failure rate for the capacitor

Value	T_A (°C)	π_{CV}	π_E	π_Q	λ_b	λ_P (failure/10^6 h)
1 µF	40	0.34	2	10	0.029	0.197

Table 5: The estima ted base failure rate for the inductor

T_A (°C)	T_{HS} (°C)	π_C	π_E	π_Q	λ_b	λ_P (failure/10^6 h)
40	69.32	1	4	20	6.22×10^{-4}	0.049

A value of 0.88 was considered to be the failure rate of the controller, similar to (Abdi et al., 2009), and the failure rate of the converter can be estimated by summing all of the failure rates. The failure rate of the entire system was calculated at 21.537 (*failure/10⁶h*). By reversing the failure rate, MTTF can be calculated as follows:

$$MTTF = \frac{1}{\lambda_{System}} = 46{,}432\ hours \qquad (19)$$

Conclusion

A new approach to reliability assessment based on thermal analysis of the switch and diode was presented. The thermal analysis of a buck converter with the basic characteristics shown in Table 1 was conducted by calculating the temperature at the switch and diode junction. The total failure rate of the converter was expressed by summing the failure rate of the components using the parts count method. The procedure employed for the reliability analysis was that given in the MIL-HDBK-217F handbook. The results of the simulation using Matlab Simulink showed that the buck converter analyzed will operate reliably for 5.3 years, which is an acceptable performance.

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