Influential Factors on Switch Power Losses of a Buck Converter: A Reliability Approach

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***Abstract*—Over the past several decades, with expanding utilization of power electronic devices, attention to the lifetime and reliability has become more momentous than before. Furthermore, different parameters can affect the reliability of devices. For this reason, a comprehensive assessment of influential factors needs to be conducted. In this paper, the switch power losses as the most significant factor in the reliability evaluation are studied. The simulation of the considered DC-DC buck converter was carried out using Matlab/Simulink. The results illustrate that the increase of switching frequency and the input voltage level leads to an increased switch power losses, whereas the opposite is true for the modulation index. Additionally, the results from the analysis conducted on three levels of output powers clarify that the power losses increases by higher output power, but the increasing rate is almost constant. However, the rising ratio of the power losses follows a downward trend with the increase of modulation index. A Gaussian function is able to model the junction temperature of the examined IGBT with an acceptable accuracy. This model can eliminate the need for additional calculations when new conditions for a buck converter are defined. The results obtained from this study confirmed that different criteria such as selecting the appropriate type of IGBT module must be considered for circuit design with reduced switching losses and longer lifespan.**

***Index Terms*—DC-DC Power Converters; Reliability; Semiconductor Device Reliability; Switching Loss.**

I. Introduction

In recent years, one of the major concerns of mankind has been energy supply. Today, the acute problem of global warming leads to human affairs, and the use of alternative energies is more momentous than before. It is worth mentioning that global warming is not the only factor affecting the utilization of alternative energy sources, but also environmental contaminations, such as air and water pollution, acid rains, wildland fire as a result of global warming, and ozone depletion have accelerated the renewable energy sources integration into power systems [1]. Wind turbines and photovoltaic panels have been the center of attention among governments because they exemplify clean and green energy sources. Thus, energy conversion systems play a crucial role for providing more efficient utilization of renewable energies. Nowadays, the power electronics can be defined as a bridge between renewable sources and utility grids. One of the commonly used power electronic devices that can be applied in photovoltaic systems is DC-DC converters. DC-DC converters are widely used in computers, communication systems, and adapters to produce the desired voltage levels [2].

Various types of DC-DC converters have been developed. The DC-DC converters based on the ratio of output voltage to the input voltage can be divided into three fundamental categories: buck, boost, and buck-boost. The proposed approach in this paper focuses on the buck converter. Buck converters are usually used in lightweight and easily portable equipment. Conventional buck converter is one of the simplest topologies of buck converters, which has only one switch and one diode in its circuit. Moreover, it operates in efficiency of at least 90%. A challenging issue in the field of power electronics is the reliability of the overall system. Many power electronic circuits do not include a backup or redundancy part; therefore, failure in a circuit's element leads to failure of the whole system. With regard to the importance of reliability in power electronic devices, various methods for reliability evaluation are introduced [3-6].

One of the most obvious factors related to reliability of a power electronic device is the thermal condition of its switches. Thermal condition depends on various device parameters, and changing any parameter that affects temperature changes can be effective on the power output quality. Related researches have explained the relationship of the power output quality with heat losses in different converters [7-9]. Usui and Ishiko presented a simple approach that practiced in steady state operation for thermal analysis of an IGBT module [10]. There are different approaches for thermal analysis of an IGBT module: One of these methods is Computational Fluid Dynamics (CFD), which determines heat transfer coefficients based on airflow conditions [11].

This paper presents a reliability approach for influential factors behind power losses of switch in a buck converter. The influential factors that can be effective on the switch power losses include switching frequency, modulation index, input voltage level and output power. Further, the effect of simultaneous changes in switching frequency and modulation index on the switch power losses, and the junction temperature related to the reliability is addressed for the first time in this study. The necessity of investigating power loss lies in the fact that it is directly related to the temperature junction and affects reliability. In addition, this paper describes an approximate relationship for determining the junction temperature of any desired buck converter. For this purpose, a Gaussian function is used to provide an accurate model for estimating the junction temperature of the used switch in the examined buck converter at four different frequencies.

The remainder of this paper is organized as follows: Section II demonstrates the desired buck converter, Section III represents the fundamental principle and different approaches of reliability, Section IV represents the utilized methodology for calculating the switch power losses, and in Section V, a comprehensive evaluation of influential factors on the switch power losses, is illustrated. Section VI is the conclusion.

II. THE BUCK CONVERTER

A simple scheme of the buck converter is shown in Figure 1. Buck converter is used as a step-down DC-DC converter, which also has higher conversion efficiency than the transformers. Buck converters are usually utilized in low and small power systems, computers and switch mode power supply circuits (SMPS). In this paper, an IGBT module is considered as switch coupled with a diode. The used IGBT model is Fuji module U-Series 600V/150A and the characteristics of the desired module can be found in [12].

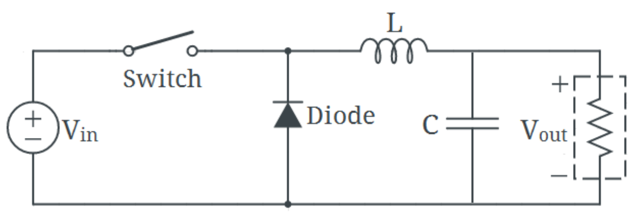

Figure 1: General structure of buck converter

A direct relationship in terms of duty cycle exists between the input and output voltage with regard to [13], which can be described as follows:

$$V_{out} = D \times V_{in} \tag{1}$$

where D is the duty cycle and its value is in the range of 0 to 1. As a result from Equation (1), it can be concluded that the output voltage is always lower than the input voltage. Furthermore, by decreasing voltage difference between input and output voltage for a conventional buck converter (typically for duty cycle more than 50%), the converter efficiency will be improved [14]. The proposed buck converter is implemented using an open loop simple pulse generator. The converter characteristics including the basic parameters are summarized in Table 1.

Table 1
Rated parameters for desired buck converter

Parameter	Value
Rated output active power P_o	12 kW
Input voltage V_{in}	300V DC
Output voltage V_{out}	125V DC ± 1.2% (Duty cycle = 42%)
Switching frequency f_{sw}	10 kHz
Inductor L	3 mH
Capacitor C	1 μF

III. RELIABILITY EVALUATION

Reliability is defined as the probability of an item to perform a particular function under specific operational conditions over an intended time period [15]. The common metrics for reliability evaluation include failure rate, mean time to failure (MTTF), mean time to repair (MTTR), mean time between failures (MTBF), and availability. However, failure rate and MTTF are enough to reasonably estimate the reliability [16]. Failure rate is the most important metric for reliability evaluation, which can be defined as the probability of occurring the first failure in a given component over the period of [t, Δt].

Reliability function is expressed by $R(t)$, which is simplified with the consideration of exponential distribution, as represented in Equation (2) [17]:

$$R(t) = \exp(-\lambda t) \tag{2}$$

In Equation (2), λ is the failure rate. Another effective metric for reliability is MTTF. In reliability analysis, MTTF is the average time that a component will function before a failure occurs. MTTF is widely used for reliability comparisons between various systems and topologies. MTTF relationship can be achieved from an improper integral of reliability function on the time interval of [0, ∞), which is simplified by substituting Equation (2) into the mentioned relation for MTTF. Thus, MTTF is presented as follows:

$$MTTF = \frac{1}{\lambda} \tag{3}$$

Over the past several decades, various organizations have offered different procedures for systems reliability evaluation based on their strategies. A comprehensive comparison between different procedures is presented in [18]. The most popular procedure (especially for power electronics field) is MIL-HDBK-217, which is also utilized in this paper [19].

Buck converter that has a series structure is considered as a case study in this paper. According to the parts count approach, the overall system failure rate can be attained by a summation of all components' failure rate. Equation (4) illustrates the total failure rate [20]:

$$\lambda_T = \sum_{i=1}^{N} \lambda_i \tag{4}$$

where N is the total number of components, and λ_i is the failure rate for each component.

This paper focuses on the effective factors on performance of an IGBT, thus we only consider switch failure rate according to MIL-HDBK-217, which is presented as follows [20]:

$$\lambda_{Switch} = \lambda_b \pi_T \pi_A \pi_Q \pi_E \tag{5}$$

where, λ_b is the base failure rate, which according to the MIL-

HDBK-217 standard, it is 0.012 and 0.064 *failure/10⁶h* for switch and diode, respectively. π_A is the application factor that has a constant value of 10 for output powers more than 250W. π_Q and π_E are quality and environment factor that are normally neglected. π_T is the temperature factor and is calculated using Equation (6) for switches [20].

$$\pi_T = \exp\left(-1925 \times \left(\frac{1}{T_j + 273} - \frac{1}{298}\right)\right) \quad (6)$$

In the above equation, T_j is the temperature junction. Given that one-cell Cauer network model has been chosen as the thermal model for heat transfer between junction and case, T_j is determined by Equation (7):

$$T_j = T_C + \theta_{jc} \times P_{loss} \quad (7)$$

where T_C is the heat sink temperature, θ_{jc} is the thermal resistance (This value is assumed 0.25 according to the used IGBT's datasheet), and P_{loss} is the power loss in switch.

IV. METHODOLOGY

As previously mentioned, power loss has a direct relationship with temperature junction that can affect overall reliability. In order to analyze 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 [12]. IGBT power losses can be categorized into conduction losses, switching losses, and blocking losses (which are usually neglected) [21].

A. Conduction Losses

The instantaneous IGBT conduction loss is determined using a simplified Equation (8) [22]:

$$P_{Cond}(t) = V_{CE}(t).I_C(t) \quad (8)$$

where, V_{ce} is IGBT on-state voltage, when IGBT is completely on. I_C is also the Collector current. A simple model for the used IGBT, taking into account a series of coupled DC voltage source (V_{CE0}), a Collector-Emitter on-state resistance (r_C), and I_C as the collect current can be expressed as [22]:

$$V_{CE} = V_{CE0} + r_C I_C \quad (9)$$

The instantaneous IGBT conduction loss is calculated by substituting Equation (9) into Equation (8) [21-22]:

$$P_{Cond}(t) = V_{CE0}(t).I_C(t) + r_C(I_C(t))^2 \quad (10)$$

In order to perform power loss assessment, the average of Equation (10) is needed, which can be attained by the integration of IGBT conduction losses over the switching period of [0, T_{sw}).

Assuming that I_{cav} and I_{crms} are respectively the average and rms values of IGBT current, the average losses can be expressed as follows [22]:

$$P_{Cond} = V_{CE0}.I_{cav} + r_C.I_{crms}^2 \quad (11)$$

B. Switching losses

The IGBT switching losses are divided into turn-on and turn-off losses [21-22]:

$$P_{Cond} = (E_{on} + E_{off})f_{sw} \quad (12)$$

where, f_{sw} is the switching frequency and E_{on} and E_{off} represent the turn-on and turn-off energy losses in IGBT.

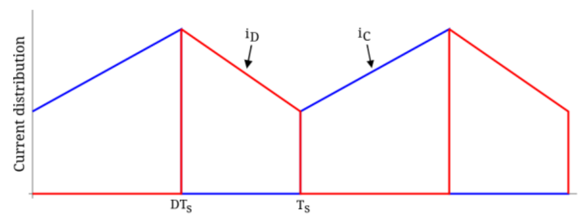

Figure 2: Currents distribution for the buck converter

With regard to Figure 2, the parameters of power losses in buck converter can be calculated. The detailed explanations of these calculations are drawn in [22].

V. RESULTS AND DISCUSSION

As mentioned earlier, this paper presents a study of the factors affecting the power losses in the used Fuji IGBT. The selection of factors influencing the switch power losses would be limited with respect to the issue that the buck converter only consists of an IGBT module, a filter, and an output load. Therefore, these factors include input voltage, output voltage (or modulation index), output power, and the characteristics of the used IGBT. In this study, a fixed IGBT is utilized, thus other items should be investigated. All effective factors are described separately.

A. Effects of switching frequency and modulation index on power losses

Figure 3 displays the effects of switching frequency and modulation index on the desired buck converter for a 200V input voltage and 12kW output power. From Figure 3, it is obvious that the increasing switching frequency produces more power losses in the IGBT. It should be noted that this increase is almost a linear trend. The effect of changing modulation index on the power loss is non-linear, which leads to an abnormally increased power loss in 20%-30% of modulation index. However, in other modulation indexes power loss follows a downward trend.

B. Effect of input voltage level

In the previous section, the variations of the switch power losses in terms of switching frequency and modulation index were represented when the input voltage and output power of the converter were selected 200V and 12kW, respectively. Considering a constant 12kW output power for the converter, the effect of changing input voltage value due to the increase in the input voltage from 200V to 300V DC is as shown in Figure 4.

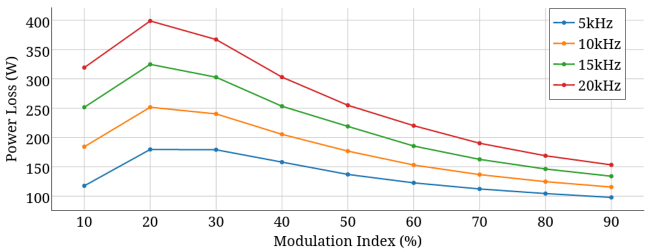

Figure 3: Switch power losses versus switching frequency and modulation index (200V input voltage)

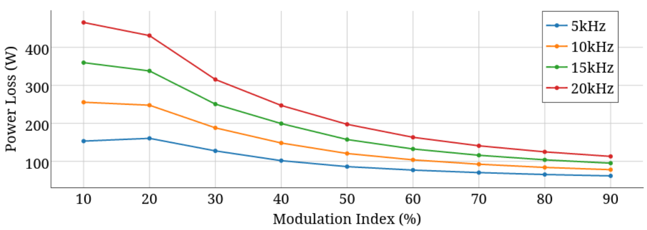

Figure 4: Switch power losses in 300V input voltage

Figure 4 illustrates that the increase in the input voltage level of the converter from 200V to 300V causes more power losses in the switch for low modulation indexes. The power losses will decrease by an average of 33W for 300V in 5 kHz switching frequency. Additionally, this ratio is about 30, 25 and 19W for 10, 15 and 20 kHz, respectively.

C. *Effect of output power of the converter*

To show the effect of different converter output powers on the IGBT power losses, three different output powers (4, 8, and 12 kW) have been considered for the analysis. Figure 5 to 7 demonstrate the effect of changing the output power on the power losses; moreover, the contour plots are provided to make the changes more obvious.

Assuming that there is a fixed switching frequency (for example 20kHz for all power output levels), the rising ratio of the power losses is normally descending with the increase of the modulation index, but the rising percentage of the power losses is almost constant and has an average of 37.16% and 55.93% for increasing output power from 4kW to 8kW, and 8kW to 12kW, respectively. It can also be concluded that the value of IGBT power losses will grow by increasing the switching frequency and reducing the modulation index.

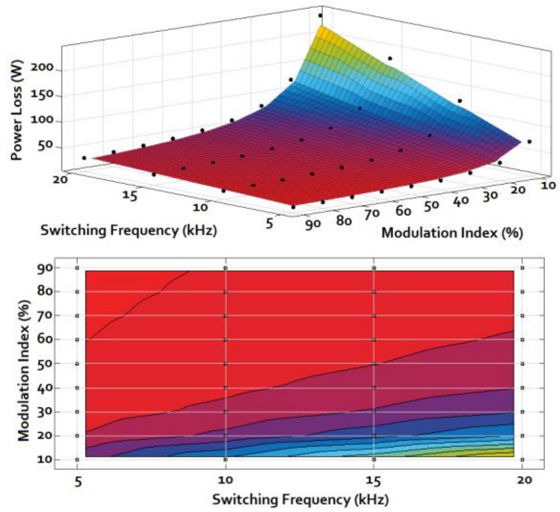

Figure 5: 3D and contour plot of the power losses at 4kW output power

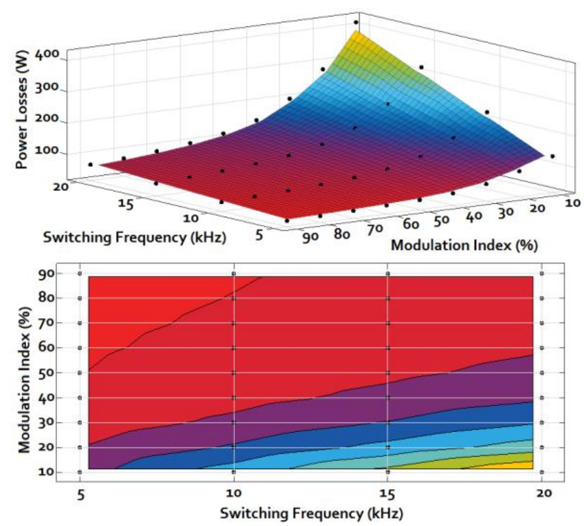

Figure 6: 3D and contour plot of the power losses at 8kW output power

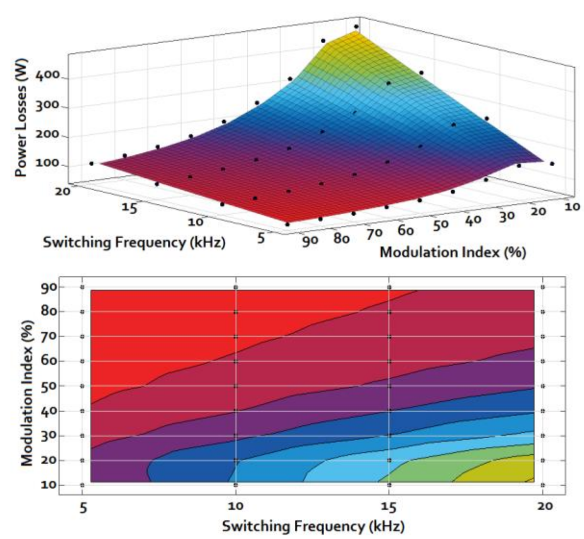

Figure 7: 3D and contour plot of the power losses at 12kW output power

D. *Effects of switching frequency and modulation index on switch junction temperature*

A Matlab simulation is performed to find the accurate value of the switch junction temperature. As shown in Figure 8, the results of the simulation are represented by a 3D curve for the junction temperature with the switching frequency on the x-axis and the modulation index on the y-axis. In this simulation, a temperature of 150°C is set as the limit for the junction temperature.

Given Figure 8, it is clear that the converter can operate at lower switching frequencies with higher modulation indexes without exceeding temperature limit. To obtain a reasonably accurate estimation of the junction temperature, we practiced the Gaussian function to make a good fit. Assuming fixed values for switching frequencies, the junction temperature depends only on modulation index value. Then, a Gaussian function has been used to achieve an appropriate fit. The use of this function leads to an acceptable model that can be extended for any buck converter with different output powers and input voltages. Therefore, this model reduces the input values for calculating the junction temperature and eliminates the need to calculate iterative determinations for another buck converter.

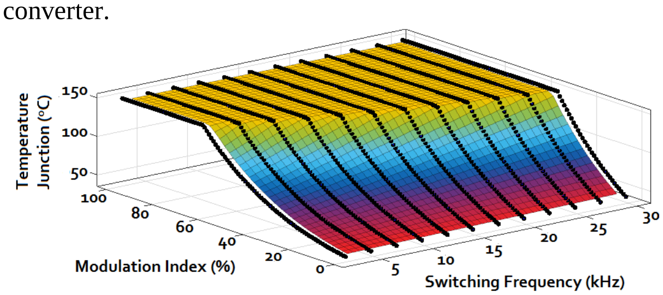

Figure 8: Temperature junction versus switching frequency and modulation

The relationship of the two-peaks Gaussian is as follows:

$$f(x) = a_1 \exp\left(-\left(\frac{x-b_1}{c_1}\right)^2\right) + a_2 \exp\left(-\left(\frac{x-b_2}{c_2}\right)^2\right) \quad (13)$$

Six parameters (a_1, b_1, c_1, a_2, b_2, c_2) of this function should be identified. Moreover, all parameters do not follow a particular sequence and should be determined separately. Thus, the analysis is executed for four different switching frequencies, and the calculated values for each switching frequency are shown in Figure 9.

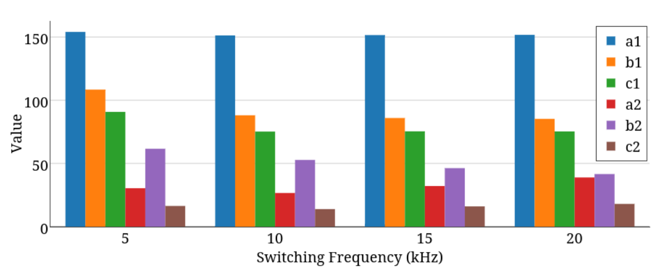

Figure 9: The calculated parameters for the Gaussian function at different switching frequencies

To draw a comparison between the actual data and the predicted data, indicators of RMSE (root mean square error) and R^2 (coefficient of determination) are utilized [23]. From Table 2, it is further observed that the Gaussian function delivers a proper performance.

Table 2
The statistical parameters for Gaussian fit at different frequencies

Switching Frequency (kHz)	R^2	RMSE
5	0.9987	1.4905
10	0.9992	1.1025
15	0.9986	1.4607
20	0.9976	1.8090

Therefore, the switch junction temperature at different switching frequencies for a 300V input voltage, and its characteristics provided in Table 1 can be estimated using the proposed function with an appropriate accuracy.

VI. CONCLUSION

Generally, power electronic circuits and devices are without power backup circuit or redundancy, thus failure in one of their parts leads to the failure of the whole system, and reliability evaluation becomes even more essential. According to the mentioned relationships, variation in the power losses affects the system reliability. In this paper, a buck converter was considered, and MIL-HDBK-217 reliability approach was used to assess the influential factors on the switch power loss. The results showed that switch power losses grew as switching frequency increased. Also, the switch power losses were reduced by increasing the modulation index and decreasing the input voltage level. An analysis of the three different values of output power was performed, and the results indicated that the rising ratio of the power losses is normally descending with the increase of the modulation index, but the increasing power losses from a power output to other value is almost constant. Furthermore, a Gaussian function was used to produce a predictable model of the switch temperature junction in the buck converter, and the values of statistical parameters validated the accuracy of the estimates.

To the extent of our knowledge, this is the first time that a comprehensive evaluation of effective factors on the switch power losses from the viewpoint of reliability is carried out. A good avenue of research for the future works would be to assess other important converters such as boost converters using both theoretical and experimental validations. Additionally, the influence of using various models of IGBT modules with different characteristics seems to be interesting for future studies.

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REFERENCES

[1] I. Dincer, "Renewable energy and sustainable development: a crucial review," Renew. Sustain. Energy Rev., vol. 4, no. 2, pp. 157–175, 2000.

[2] S. Chander, P. Agarwa, I. Gupta, "Auto-tuned, discrete PID controller or DC-DC converter for fast transient response," Int. Conf. Power Electron., pp. 1-7, 2011.

[3] J. Jones and J. Hayes, "Estimation of system reliability using a 'non-constant failure rate' model," IEEE Trans. Reliab., vol. 50, no. 3, pp. 286 – 288, 2001.

[4] A. Høyland and M. Rausand, *System reliability theory: models and statistical methods*. Wiley, 2009.

[5] P. Wikström, L. Terens, and H. Kobi, "Reliability, availability, and maintainability of high-power variable-speed drive systems," IEEE Trans. Ind. Appl., vol. 36, no. 1, pp. 231–241, 2000.

[6] E. Strangas, S. Aviyente, J. Neely, and S. Zaidi, "Improving the reliability of electrical drives through failure prognosis," in Proc. IEEE Int. Symp. Diagn. Electron. Mach., Power Electron. Drives, Sep. 2011, pp. 172–178.

[7] A. Stupar, D. Bortis, U. Drofenik, and J. W. Kolar, "Advanced setup for thermal cycling of power modules following definable junction temperature profiles," in Proc. IPEC, Sapporo, Japan, pp. 962–969, 2010.

[8] M. T. Zhang, M. M. Jovanovic, and F. C. Lee, "Design and analysis of thermal management for high-power-density converters in sealed enclosures," in Proc. 12th Annu. Appl. Power Electron. Conf. Expo., vol. 1, pp. 405–412, 1997.

[9] M. Bašić, D. Vukadinović, and M. Polić, "Analysis of Power Converter Losses in Vector Control System of a Self–Excited Induction Generator," J. Electr. Eng., vol. 65, no. 2, pp. 65–74, 2014.

[10] M. Usui, M. Ishiko, "Simple Approach of Heat Dissipation Design for Inverter Module," Proc. of Int. Power Electron. Conf. (IPEC), pp. 1598-1603, 2005.

[11] T. Y. Lee and M. Mahalingam, "Application of a CFD Tool for System-Level Thermal Simulation," IEEE Trans. Comp. Pack. Manuf. Tech., vol. 17, no. 4, pp.564 -571, 1994.

[12] Fuji IGBT Module U-Series 2MBI150U2A-060 Datasheet. (Available: www.fujielectric.com)

[13] R. W. Erickson and D. Maksimovic´, *Fundamentals of Power Electronics*, 2nd ed. Boston, MA: Kluwer, 2000.

[14] V. R. Tintu and M. George, "Tapped inductor technology based DC-DC converter", Proc. ICSCCN, pp.747 -753, 2011.

[15] H. Wang, K. Ma, and F. Blaabjerg, "Design for reliability of power electronic systems," in Proc. IEEE Ind. Electron. Soc. Annu. Conf., pp. 33–44, 2012.

[16] M.R. Lyu, *Handbook of Software Reliability Engineering*. McGraw-Hill, 1996.

[17] R. F. Stapelberg, *Handbook of Reliability, Availability, Maintainability and Safety in Engineering Design*, Springer-Verlag, London, 2009.

[18] M. G. Pecht, F. R. Nash, "Predicting the Reliability of Electronic Equipment," In Proceedings of the IEEE, vol. 82, pp. 992-1004, 1994.

[19] Military Handbook - Reliability Prediction of Electronic Equipment, MIL-HDBK-217F Notice 2, Feb 28, 1995.

[20] B. Abdi, A. H. Ranjbar, G. B. Gharehpetian, and J. Milimonfared, "Reliability considerations for parallel performance of semiconductor switches in high-power switching power supplies," IEEE Trans. Ind. Electron., vol. 56, no. 6, pp. 2133–2139, Jun. 2009.

[21] N. Palumbo. "Thermal Analysis of an Integrated Power Electronics Module," PhD Diss. Rensselaer Polytechnic Institute, 2012.

[22] D. Graovac, M. Pürschel, "IGBT power losses calculation using the data-sheet parameters," Infineon Application Note, January 2009, pp. 1–17.

[23] C. W. Dawson, R. J. Abrahart, L. M. See, "HydroTest: a web-based toolbox of evaluation metrics for the standardised assessment of hydrological forecasts," Environ. Modell. Software, vol. 22, no. 7, pp. 1034–1052, 2007.