Reliability Analysis and Performance Degradation of a Boost Converter

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Abstract— **In general, power converters are being operated in closed-loop systems, and any characteristic variations in one component will simultaneously alter the operating point of other components resulting in a shift in overall reliability profile. This interdependence makes the reliability of a converter a complex function of time and operating conditions; and therefore, the application may demand periodic replacement of converters to avoid downtime and maintenance cost. By knowing the present state of health and remaining life of a power converter, it is possible to reduce the maintenance cost for expensive high-power converters. This paper presents a reliability analysis for a boost converter although this method could be used to any power converter being operated in closed-loops. Through the conducted study it is revealed that the reliability of a boost converter with control loops degrades with time, and this paper presents a method to calculate time varying reliability of a boost converter as function of characteristic variations in different components in the circuit. In addition, the effects of operating and ambient conditions have been included in the reliability model as well. It was found that any increase in the ON-resistance of the MOSFET or equivalent series resistance (ESR) of the output capacitor decreases the overall reliability of the converter. However, any variation in the capacitance has more complex impact on the converter's reliability. This conducted research is a step forward to the power converter reliability analysis because the cumulative effect of multiple degraded components has been considered in the reliability model.**

I. INTRODUCTION

The reliability and failure study of individual components used in power converters has been well conducted and can be found in literatures [1]-[4]. The bathtub curve of the failure rate is the most accepted model for any electronic component [5] [6], and this curve is shown in Fig. 1 (a). The infant failure of the components is generally linked to poor design, poor installation or misapplication, and constant failure rate defines the useful lifetime of the component. It has been shown in this paper that this constant failure rate changes due to any characteristic variation of the components because of the aging involved with the entire power converter. Therefore a proper maintenance program is required to ensure a safe, efficient and effective operation of a system having power converters.

Reactive maintenance is the most dominant type of maintenance program in industry, and in this method all converters and drives are allowed to run until they fail. Any replacement/repair is performed after the failure occurs. This results in highest downtime cost and may damage other components in the system. Other maintenance schemes attempt to predict the failure of any component and replace/repair the components before any failure takes place. A relative cost analysis for different pump maintenance schemes has been shown in Fig. 1(b) [5]-[7], and the reliability centered maintenance (RCM) is the most efficient maintenance program although it requires a sophisticated prognostics and diagnosis technique.

Most of the power converters are being operated in a closed-loop system in order to maintain expected voltage and currents at the input and output terminals. The control system also protects the converter from any potential overload or

(a) (b)

Fig. 1: (a) Bathtub curve for component failure rate (b) cost analysis for different maintenance schemes applied to electric pumps [5]-[7].

short circuit. Therefore, the operating condition of a power converter is affected by any variation in components' electrical parameters, input/output loading and ambient conditions. Any characteristics variation in one component will simultaneously affect the operating condition and the corresponding thermal stress. This may accelerate the aging process of that component as well as the remaining components of the converter.

Power switches and capacitors are the most failure prone components in a power converter [8] [9]. In this regard, variation in the reliability function as a function of MOSFET ON-resistance ($R_{DS(ON)}$), capacitance (C) and *ESR* of the capacitor in a closed-loop boost converter circuit has been analyzed in this paper. It has been shown in [2] that increased MOSFET ON-resistance of an interleaved boost converter operating in an open-loop system increases the reliability of the converter due to decrease in output voltage ripple across the capacitor. However, this analysis cannot be applied to boost converters being operated in closed loop and therefore needs modifications to accommodate the closed-loop operation of a converter. To the best knowledge of the authors, no analysis has been presented yet to address the reliability degradation of any closed-loop power converter.

II. RELIABILITY ESTIMATION OF A BOOST CONVERTER

A simple boost converter with a feedback control loop has been considered in this analysis. The schematic of the converter is shown in Fig. 2, and various circuit parameters are given in Table I. In this section, the component level variation has not been considered, and all the equations are presented together for better presentation.

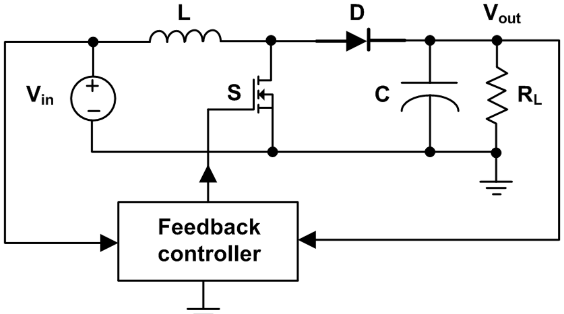


Fig. 2: Schematic diagram of the closed-loop boost converter.

$$R_s(t) = e^{-(\lambda_{SYSTEM} \times t)} \tag{1}$$

$$MTTF = \int_0^{\infty} R_s(t)dt = \frac{1}{\lambda_{SYSTEM}} \tag{2}$$

$$\lambda_{sw} = \lambda_B \pi_T \pi_A \pi_E \pi_Q \tag{3}$$

$$\begin{gathered}\pi_T = temperatue\ \ factor = exp\ [-1925\ (\frac{1}{T_J + 273} - \frac{1}{298})] \\ T_J = T_a + (\theta_{JA})P_{sw}\end{gathered} \tag{4}$$

$$\lambda_{sw0} = \lambda_B \pi_T \pi_A \pi_E \pi_Q = 0.012 \times \pi_T \times 8 \times 9.0 \times 8 = 6.912 \times \pi_T \tag{5}$$

$$\begin{gathered}T_J = T_a + (\theta_{JA})P_{sw} = 25 + (18 \times 1.3532) = 49.3576 \\ \pi_T = exp\ [-1925\ (\frac{1}{T_J + 273} - \frac{1}{298})]\ = 1.6292 \\ \lambda_{SW0} = 6.912 \times 1.6292 = 11.2610\, failure / million\ \ hours\end{gathered} \tag{6}$$

$$\begin{aligned}&\lambda_{SYSTEM0} = \lambda_{sw0} + \lambda_{CAP0} + \lambda_{DIODE0} + \lambda_{INDUCTOR0} \\ &= 6.912 \times exp\ [-1925\ (\frac{1}{T_a + (\theta_{JA})P_{sw} + 273} - \frac{1}{298}] \\ &+ 120 \times (0.0028 \times [(\frac{S_{CAP}}{0.55})^3 + 1] \times exp(4.09 \times (\frac{T + 273}{358})^{5.9})) \times \\ &0.495621 + 0.011664 \times exp\ [-3091\ (\frac{1}{T_a + (\theta_{JA})P_{diode} + 273} - \frac{1}{298})] \\ &+ 0.00108 \times exp\ [-\frac{0.11}{8.617\ x\ 10^{-5}}(\frac{1}{T_{HS} + 273} - \frac{1}{298})]\ = \\ &11.2610 + 4.2600 + 0.0283 + 0.9225 = 16.4718\, failure / million\ \ hours\end{aligned} \tag{7}$$

$$\begin{aligned}&MTTF = \frac{1}{\lambda_{SYSTEM}} = \frac{10^6}{16.4718} hours\ /\ failure \\ &= 6.930\ years\ /\ failure\end{aligned} \tag{8}$$

$$\lambda_{sw}(t) = \lambda_{sw0} \times f_1(\Delta R_{DS}) \tag{9}$$

$$\begin{gathered}\pi_{CV}(t) = \pi_{CV0} \times \Delta\pi_{CV} = \pi_{CV0} \times f_2(\Delta C) \\ \lambda_b(t) = \lambda_{b0} \times \Delta\lambda_b = \lambda_{b0} \times \\ f_3\left(\Delta C, T_a, \Delta T_{power\_loss\_in\_MOSFET\_diode,and\_ESRs}\right) \\ \lambda_{CAP}(t) = \lambda_{CAP0} \times f_2 \times f_3 = \lambda_{CAP0} \times f_4\end{gathered} \tag{10}$$

$$\begin{aligned}&\lambda_{SYSTEM}(t) = \lambda_{sw}(t) + \lambda_{CAP}(t) + \lambda_{DIODE}(t) + \lambda_{INDUCTOR}(t) \\ &MTTF = \int_0^{\infty} R_s(t)dt = \int_0^{\infty} e^{-(\lambda_{SYSTEM}(t) \times t)}dt \neq \frac{1}{\lambda_{SYSTEM}(t)} \\ &MTTF = \int_0^{\infty} e^{-(\lambda_{sw}(t) + \lambda_{CAP}(t) + \lambda_{DIODE}(t) \times t + \lambda_{INDUCTOR} \times t)}dt \\ &= \int_0^{\infty} e^{-(\lambda_{sw}(t) \times t)} e^{-(\lambda_{CAP}(t) \times t)} e^{-(\lambda_{DIODE}(t) \times t)} e^{-(\lambda_{INDUCTOR}(t) \times t)}dt\end{aligned} \tag{11}$$

$$\begin{gathered}\lambda_{CAP0} = \lambda_{b0} \pi_{CV0} \pi_E \pi_Q \\ \lambda_{b0} = base\ \ failure\ rate = \\ 0.0028 \times [(\frac{S_{CAP}}{0.55})^3 + 1]\, exp(4.09(\frac{T + 273K}{358K})^{5.9}) \\ \pi_{CV0} = capacitancefactor = 0.32(C\mu F)^{0.19}\end{gathered} \tag{12}$$

Considering a constant failure rate ($\lambda_{SYSTEM0}$), reliability of the system can be calculated as shown in equation (1) [1] [3]. Where, $R_S(t)$ is the probability that the system will not fail by time t. The mean-time-to-failure (*MTTF*) can be calculated from the reliability probability function as shown in equation (2), and the failure rate of an N-channel MOSFET can be written in equation (3) [1]. The base failure rate λ_B is a constant equal to 0.012, and the application factor π_A and quality factor π_Q are both equal to 8 for switches rated at 135 W. Environment factor π_E is considered as 9 for equipment installed on wheeled or tracked vehicles [1]. Temperature factor and junction temperature can be calculated using equation (4) with ambient temperature T_a is set to 25ºC and junction to ambient thermal resistance θ_{JA} is set to 18.0 ºC/W for D2PAK packaging [13]. The total power dissipation (conduction loss + switching loss) of the switching device is P_{sw}. Considering the values stated above, failure rate of the MOSFET can be calculated using equation (5), and considering power loss (conduction loss + switching loss) in a switch is 1.3532 watt, failure rate of the MOSFET is calculated in equation (6). Similar analysis can be performed for the inductor, diode and capacitor. For the boost converter under consideration, the failure rate and MTTF of the converter is shown in equation (7) and (8), respectively.

III. EFFECT OF VARIATION IN DIFFERENT COMPONENT PARAMETERS

Variation of the reliability function as a function of any change in MOSFET ON-resistance ($R_{DS(ON)}$), capacitance (C) and ESR of the capacitor (ESR) in a simple Boost converter circuit operated in closed loop will be analyzed in this section.

A. Effect of Any Variation in $R_{DS(ON)}$

Any increase in $R_{DS(ON)}$ of a MOSFET is the dominant precursor of failure for a power MOSFET [8] [9], and variation in $R_{DS(ON)}$ has been well studied in several literatures [9]-[12]. For a fixed gate to source voltage, $R_{DS(ON)}$ of the MOSFET depends on the present value of $R_{DS(ON)}$, temperature, and the power loss in the MOSFET. Any increase in the value of $R_{DS(ON)}$ will affect the thermal stress on the switch, increases the junction temperature, changes the operating point of the converter and will decrease the reliability according to equation (4), and this corresponding effect is shown in Fig. 3(a).

The failure rate of the MOSFET can be updated as shown in equation (9) where, λ_{sw0} is the failure rate of the MOSFET considering no change in $R_{DS(ON)}$ over time. The function f_1 depends on the change in MOSFET's ON-resistance. In addition, increased thermal stress changes the gate capacitance of the MOSFET which may cause degraded switching performance, and it may result in higher thermal stress because of the elevated switching loss. Therefore, reliability of a switch is highly dependent on the prolonged operation of the converter and cannot be accurately predicted by assuming a constant rate of failure.

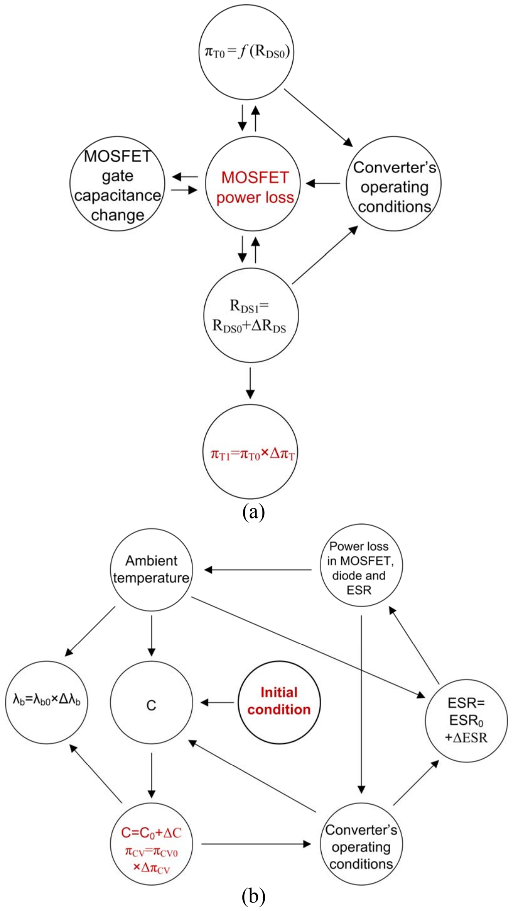
B. Change in Capacitance (C) and ESR

A state diagram for characteristic variation of a capacitor used in a power converter has been shown in Fig. 3 (b). Both the base failure rate and the capacitance have been considered as time varying in this model. The time dependent failure rate of the capacitor is shown in equation (10). π_{CV0}, λ_{b0} are the capacitance factor and base failure rate of the capacitor considering no variation in capacitance over time.

Gradual change/degradation in capacitance depends on the type of capacitor used, and this change is highly dependent on the ambient temperature. Thermal stress is the dominant reason for electrolytic capacitor failure, and power loss in other components (MOSFET, diode, equivalent series resistance of the inductor, ESR of the capacitor itself) may increase the ambient temperature of the capacitor. Output

TABLE I: CIRCUIT PARAMETERS OF THE BOOST CONVERTER

Symbol	Description	Value
V_{in}	Input voltage	40 V
V_{out}	Output voltage	100 V
L	Inductance	1 mH
r_L	Equivalent series resistance (ESR) of	0.1 Ω
$R_{DS(ON)}$	MOSFET ON resistance	0.034 - 0.044 Ω
r_D	Diode on resistance	0.05 Ω
V_f	Diode forward	0.5 V
C	Output capacitance	5-10 μF
ESR	ESR of the	0.1-0.18
R_{out}	Output load	50 Ω
f_{sw}	Switching	10 kHz
P_{rated}	Rated power of the	215 W



(a)

(b)

Fig. 3. (a) Effect of $R_{DS(ON)}$ variation of the MOSFET on the reliability of the converter, (b) effect of capacitance (C) and ESR variation on the reliability of the converter.

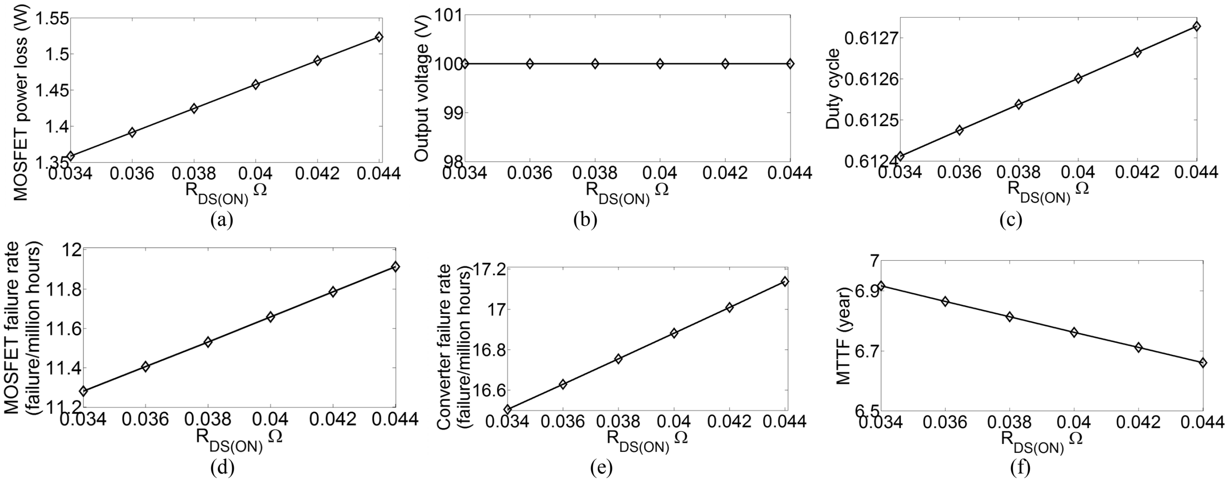
voltage ripple increases with any decrease in capacitance, and it increases the voltage stress in the capacitor as well. Higher voltage and ripple current stress play significant roles to increase the ESR, and any increase in ESR results in higher power loss and ambient temperature rise [14] [15]. f_1, f_2, and f_3 are the unknown functions and needs to be identified.

Let us consider the boost converter shown in Fig. 2. The following analysis will consider variations in device parameters and define reliability of the converter as a time varying function. Therefore, the failure rate of the converter (λ_{SYSTEM}) and *MTTF* will no more be a constant, and can be expressed as shown in equation (11).

This approach works for circuits with a limited number of components, and this is why the reliability analysis of power converters could be benefitted from this method. An initial reliability of a converter can be estimated based on the measurable quantities such as $R_{DS(ON)}$, *ESR*, *C* and so on, and it can be updated periodically by measuring those parameters with a regular interval. Variation of reliability function with the variation in $R_{DS(ON)}$, *C* and *ESR* of the closed-loop boost converter has been presented in section IV.

IV. SAMPLE RELIABILITY MODEL: A TEST CASE

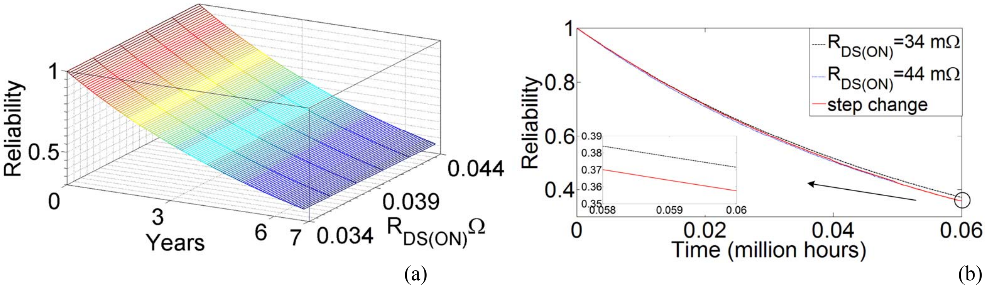
Reliability of the closed-loop boost converter for the change in MOSFET's ON-resistance from 34 mΩ to 44 mΩ, capacitance variation from 5μF to 10μF and ESR variation from 0.1 Ω to 0.18 Ω will be presented here.



(a) (b) (c)

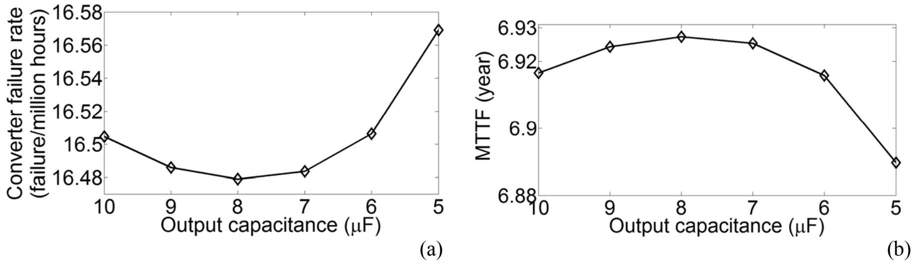
(d) (e) (f)

Fig. 4: Effect of $R_{DS(ON)}$ variation on the operating condition and reliability of the closed-loop boost converter, (a) variation in power loss in MOSFET, (b) output voltage, (c) duty cycle variation, (d) failure rate of the MOSFET, (e) converter failure rate, and (f) MTTF of the converter as a function of $R_{DS(ON)}$.



(a) (b)

Fig. 5. (a) Reliability probability function of a closed loop boost converter for the variation in $R_{DS(ON)}$, (b) reliability probability function variation for step change in $R_{DS(ON)}$.



(a) (b)

Fig. 6. (a) converter failure rate vs. output capacitance, *C*, (b) MTTF of the converter vs. output capacitance, *C*.

A. Change in MOSFET ON-Resistance ($R_{DS(ON)}$)

The boost converter shown in Fig. 2 has been simulated in PSIM and the results have been imported to MATLAB to calculate the reliability. The feedback controller was implemented using a simple proportional-integrator (PI) controller with gain 0.1 and time-constant was set to 0.001. Output capacitor's capacitance and ESR were set to 10 μF and 0.1 Ω, respectively. $R_{DS(ON)}$ of the MOSFET was varied from 34 mΩ to 44 mΩ. This variation of ON-resistance is consistent with the experimental data reported in [9] (as a result of accelerated thermal aging process of a MOSFET).

The simulation results are shown in Fig. 4. Fig. 4(a) shows that power loss in the MOSFET (sum of the switching and conduction loss) increases with any increase in ON-resistance, and Fig. 4(b) and Fig. 4(c) show the output voltage and duty cycle of the converter respectively. The PI controller maintains a fixed output voltage by changing the duty ratio to compensate any variation in $R_{DS(ON)}$. Failure rate of MOSFET increases with the increase of $R_{DS(ON)}$ due to increased thermal stress, and thereby increases the failure rate of the converter as well. These are shown in Fig. 4(d) and Fig. 4(e) respectively. It should be noted that increased $R_{DS(ON)}$ in a closed-loop system do not increase the reliability of the converter as opposed to the open-loop system discussed in [2]. MTTF of the converter is reduced by about 2,238 hours (0.2556 years) for the variation in $R_{DS(ON)}$ from 34 mΩ to 44 mΩ, and this is shown in Fig. 4(f).

Reporting a real time characteristics variation of a power converter may take years of continuous observation in a controlled ambient condition, and this is not feasible. Therefore, a test case is considered here. Assuming a rate of increase in $R_{DS(ON)}$ of 2 mΩ/10,000 hours, the results have been plotted in Fig. 5. There is about 3.75% variation in reliability after 60,000 hours of operations or 2,238 hours variation in MTTF if the variation in MOSFET's ON resistance is taken into account.

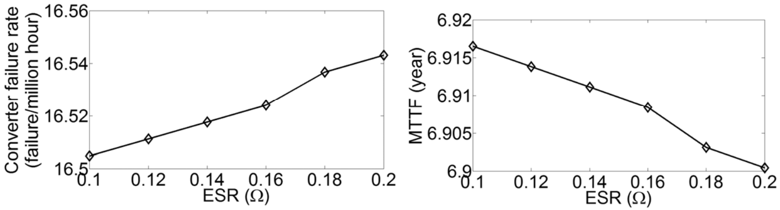
B. Change in Capacitance(C)

Effect of capacitance variation on the reliability and MTTF of the converter has been discussed in this section. The output capacitance of the converter was varied from 10 μF to 5 μF in steps of 1μF. $R_{DS(ON)}$ and *ESR* were set to 34 mΩ and 0.1 Ω, respectively. The failure of an aluminum electrolytic capacitor is shown in equation (12). Here, λ_b is the base failure rate and is a function of ripple voltage across the capacitor. π_{CV} is the capacitance factor and depends on the capacitance of the capacitor.

Starting from 10μF, decreasing capacitance increases voltage ripple across the capacitor and thereby increases base failure rate. However, the capacitance factor decreases with any decrease in capacitance. Therefore, failure rate of the converter decreases with any reduction in capacitance and starts to increase when the base failure rate becomes dominant over the capacitance factor. Failure rate and MTTF of the converter vs. output capacitance is shown in Fig. 6. MTTF of the converter is reduced by about 330 hours for the variation of in *C* from 10 μF to 5 μF. However, any variation in the output capacitance does not have any significant effect on the failure rates of other components of the converter.

C. Change in ESR of the Output Capacitor

Effect of capacitor's *ESR* on the reliability and MTTF of the converter have been discussed in this section. *ESR* of the output capacitor was varied from 0.1 Ω to 0.2 Ω in steps of 0.02 Ω. $R_{DS(ON)}$ and *C* were set to 34 mΩ and 10 μF respectively. Similar to $R_{DS(ON)}$ variation, failure rate of the converter increases with any increase in *ESR*. However,



(a) (b)

Fig.7. (a) Converter failure rate vs. *ESR*, *C*, (b) MTTF of the converter vs. *ESR*.

TABLE II. SYSTEM FAILURE RATE FOR CHARACTERISTICS VARIATION OF $R_{DS(ON)}$, *C* AND *ESR*

$R_{DS(ON)}$ (mΩ) *C*=10μF, *ESR*=0.1Ω	System failure rate (λ_{SYSTEM}) (failure/million -hours)	Capacitance (μF) $R_{DS(ON)}$ = 34 mΩ *ESR*=0.1 Ω	System failure rate (λ_{SYSTEM}) (failure/million -hours)	ESR (Ω) C=10 μF, R_{DS} (ON) = 34 mΩ	System failure rate (λ_{SYSTEM}) (failure/million -hours)
34	16.5048	10	16.5048	0.10	16.5048
36	16.6294	9	16.4860	0.12	16.5112
38	16.7551	8	16.4789	0.14	16.5177
40	16.8817	7	16.4836	0.16	16.5241
42	17.0094	6	16.5065	0.18	16.5367
44	17.1380	5	16.5690	0.20	16.5432

failure rate of the converter is less sensitive to *ESR* compared to $R_{DS(ON)}$. Failure rate and MTTF of the converter vs. *ESR* is shown in Fig. 7. The MTTF of the converter is reduced by approximately 140 hours for the variation in *ESR* ranging from 0.1 Ω to 0.2 Ω.

V. CONCLUSIONS

Reliability degradation of a boost converter being operated in closed loop has been presented in this paper. Components used in this converter exhibit parameter variations due to aging of the entire converter. Therefore, the effect of any variation in MOSFET ON-resistance ($R_{DS(ON)}$), capacitance (C) and *ESR* of the output capacitor on the reliability of the power converter have been analyzed, and a summary is presented in Table II. The MTTF of the closed-loop converter decreases with the gradual increase in both $R_{DS(ON)}$ and *ESR*. However, any variation in $R_{DS(ON)}$ impacts the reliability of the entire converter the most. In addition, the reliability of the converter varies in a more complex manner while it is expressed as a function of the capacitance C. However, the impact of any variation associated to one component on the remaining components has been studied as well. Authors believe that this technique could be applied to many other high power converters where predicting the failure rate and reliability is critical.

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