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Estimation of Reliability of a Interleaving PFC Boost Converter

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Abstract: Reliability plays an important role in power supplies. For other electronic equipment, a certain failure mode, at least for a part of the total system, can often be employed without serious (critical) effects. However, for power supply no such condition can be accepted, since very high demands on its reliability must be achieved. At higher power levels, the continuous conduction mode (CCM) boost converter is preferred topology for implementation a front end with PFC. As a result, significant efforts have been made to improve the performance of high boost converter. This paper is one of the efforts for improving the performance of the converter from the reliability point of view. In this paper, interleaving boost power factor correction converter is simulated with single switch in continuous conduction mode (CCM), discontinuous conduction mode (DCM) and critical conduction mode (CRM) under different output power ratings. Results of the converter are explored from reliability point of view.

Keywords: Boost Converter, Reliability, Power factor correction (PFC), Simulation of converter and MIL-HDBK217.

1 Introduction

Reliability is the probability of operating a product for a given period of time without failure under specified conditions and within specified performance limits. It plays an important role in power electronic systems by which the number of system failures, repair costs, guarantee etc. are estimated [1].

Interleaved converters [2-5] are a result of a parallel connection of switching converters. They usually share the same output filter. Interleaved converters offer several advantages over single-power stage converters; a lower current ripple on the input and output capacitors, faster transient response to load changes and improved power handling capabilities at greater than 90% power efficiency. An interleaved converter can be realized by interleaving the control singles to each of the paralleled converters resulting in an effective increase in its switching frequency. They are used in applications where the loads demand low ripple tolerances. Such requirements are found in the new

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generation of personal computers, in which core voltages and currents of the central processing units are approaching 1V and 130A. Interleaving converters also find applications in switching audio amplifiers by interleaving series or parallel combinations of power inverters. Additionally, interleaving enables the converter to spread its components and the dissipated power over a larger area. Further, interleaving enables the converter to spread its components and the dissipated power over a larger area. Performance comparison of CCM and DCM fly-back converters is referred in [6]. Aspects compared to component stress, output voltage regulation and transient response due to step load and efficiency. The comparison was carried out experimentally on a 5V/25W, 50kHz prototype CCM and DCM fly-back converters which have been designed and built with similar circuit lay outs, components and power ratings. Tests performed on the prototype converter have shown that devices in the CCM fly-back converter sustain the same voltage stress, but lesser current stress than its DCM counterpart, when delivering the same output power. In this comparison, reliability is absent and is not considered, whereas reliability is a key necessity in power electronic devices which the life time, number of failures and associated cost are estimated. In [7, 8] effect of leakage inductance on reduction of reliability of switching power supplies is discussed. In [9], a boost converter is considered as the PFC part of a switching power supply the simulation and reliability calculation of boost converter within DCM and CCM modes operating in three different power ratings is done.

In this paper, a boost power factor correction converter is simulated with single switch interleaving technique in CCM, DCM and CRM modes at different output power ratings and results are compared. Reliability calculation is based on MIL-HDBK217 standard and in part counting method [10]. Results have shown that for an Interleaving boost converter as a PFC, working in CCM mode is better than DCM and CRM mode with reference to reliability.

2 Concept of Reliability

A Reliability definition

Reliability is a discipline that combines engineering design, manufacture, and test. An efficient reliability program emphasizes early investment in reliability engineering tasks to avoid subsequent cost and schedule delays. The reliability tasks focus on prevention, detection, and correction of design deficiencies, weak pans, and workmanship defects with the goal of influencing the product development process and producing products which operate successfully over the required life [1].

B Reliability function

The reliability of a component can be described as an exponential function. The probability of finding a component operating after a time period is defined as:

$$R(t) = \mathrm{e}^{-\lambda t}, \tag{1}$$

where, λ is the constant failure rate during the useful life period. The mathematical mean value of $R(t)$ occurs at t equal to $1/\lambda$. $1/\lambda$ is the mean time elapsed until a failure occurs or the ''Mean Time To Failure'', MTTF.

C MTBF (Mean Time between Failures)

As repair time (MTTR) normally can be neglected compared to MTTF for electronics, MTBF can be found as:

$$\mathrm{MTBF} = \mathrm{MTTF} + \mathrm{MTTR} \approx \mathrm{MTTF} = 1/\lambda .$$

MTBF or the failure rate can be calculated using different kinds of input data.

D Calculation of MTBF for equipment [1]

When calculating the MTBF for equipment, its total failure rate λ_e must be found. By assuming the equipment or apparatus containing n components.

The probability to find n components in operation after the time t is:

$$R = R_1 R_2 \cdots\cdots\cdots R_n = \mathrm{e}^{-\lambda_1 t}\,\mathrm{e}^{-\lambda_2 t} \cdots\cdots\cdots \mathrm{e}^{-\lambda_n t} = \mathrm{e}^{-\lambda t} \tag{2}$$

and

$$\lambda = \lambda_1 + \lambda_2 + \lambda_3 + \cdots\cdots\cdots + \lambda_n . \tag{3}$$

The total failure rate for the equipment at specified conditions is accordingly achieved as:

$$\lambda_e = \lambda_{b1} c_1 + \lambda_{b2} c_2 + \cdots\cdots\cdots + \lambda_{bn} c_n . \tag{4}$$

By simply inverting this value, the MTBF figure for the equipment is found:

$$\mathrm{MTBF} = \frac{1}{\lambda_e} . \tag{5}$$

In this paper, the MOSFET is chosen as IXFH12N100Q/IXS, the Diode MUR850 and the input bridge KBPC_35_06.

3 Interleaved Boost Converter

Interleaved converters offer several advantages over single-power stage converters; a lower current ripple on the input and output capacitors, faster transient response to load changes and improved power handling capabilities at greater than 90% power efficiency. Another important advantage of interleaving is that it effectively increases the switching frequency without increasing the switching losses. The obvious benefit is an increase in the power density without the penalty of reduced power-conversion efficiency. There is still a penalty, however. Interleaving requires increased circuit complexity (greater number of power-handling components and more auxiliary circuitry), leading to higher parts and assembly cost and reduced reliability.

A Continuous conduction mode

Even though the inductor currents in I_{L1} and I_{L2} are discontinuous the input current which is the sum of two inductor currents is continuous [7]. So interleaving virtually eliminates discontinuity in the input current. The simulation of interleaved boost converter is shown in Fig. 1 and inductor current waveform after zooming is shown in Fig. 2.

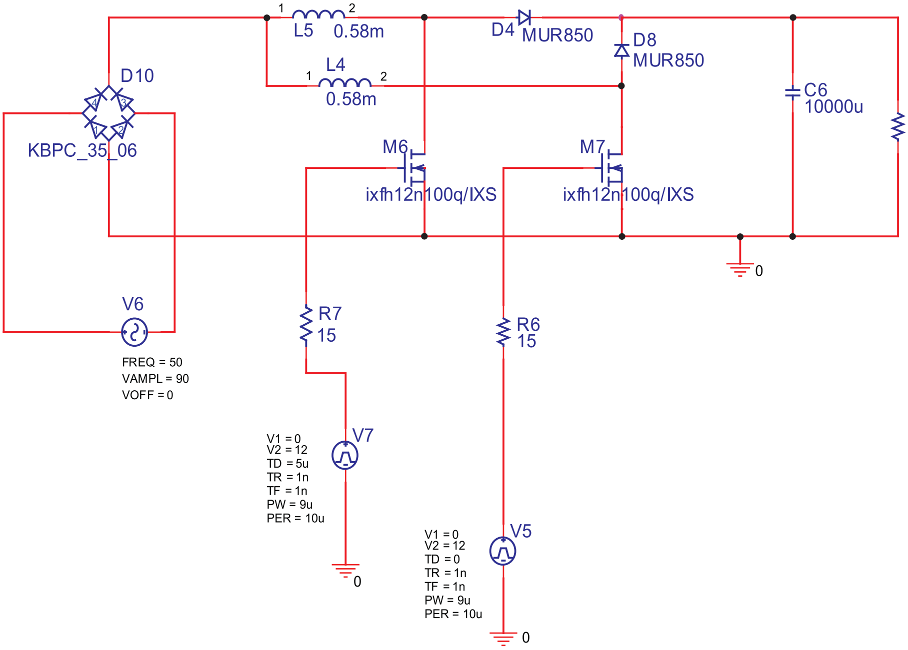

Fig. 1 – CCM *Interleaved Boost converter*.

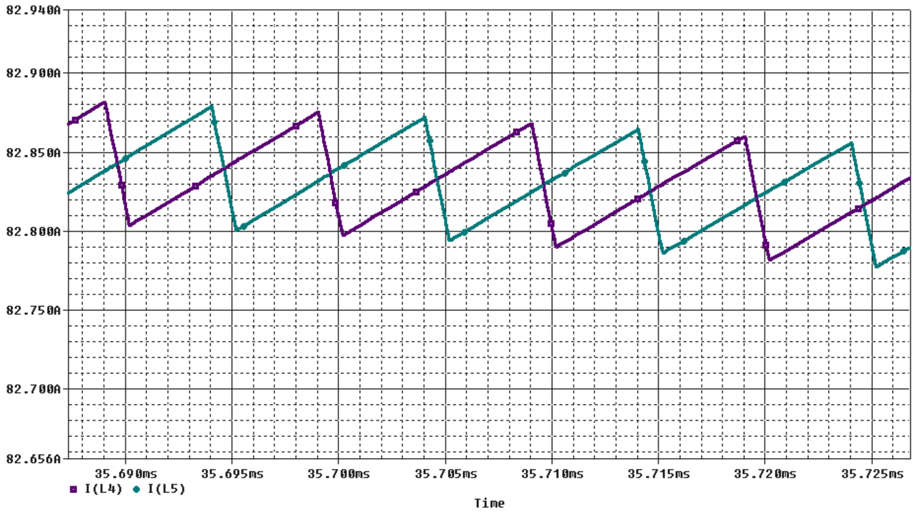

Fig. 2 – *Inductor current waveforms after zoom.*

B Discontinuous conduction mode

To operate interleaving configuration in discontinuous mode of operation the phase shift of 180^o is properly incorporated between the two inductor currents by using the delay. The simulation schematic of DCM interleaved converter is shown in Fig. 3 and inductor current waveform is shown in the Fig. 4.

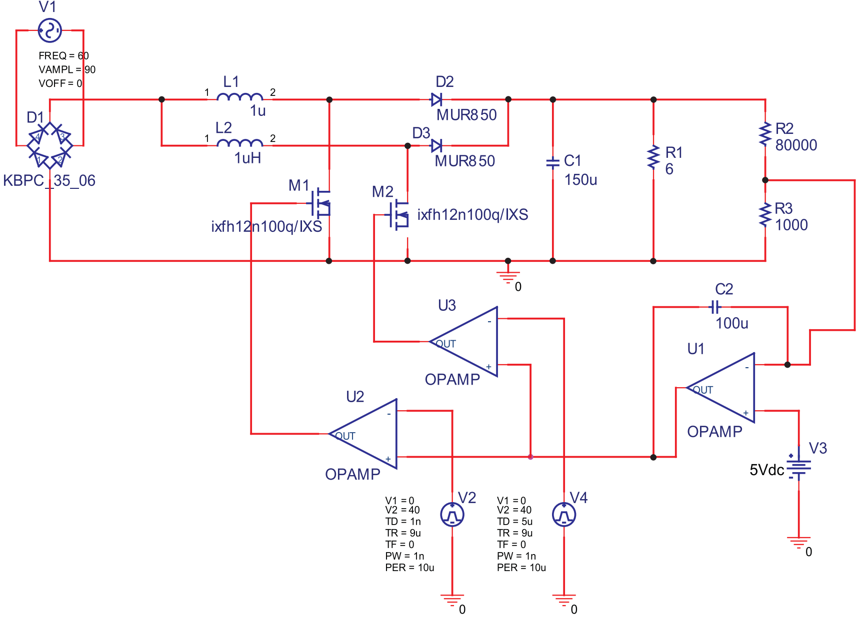

Fig. 3 – DCM *Interleaved Converter*.

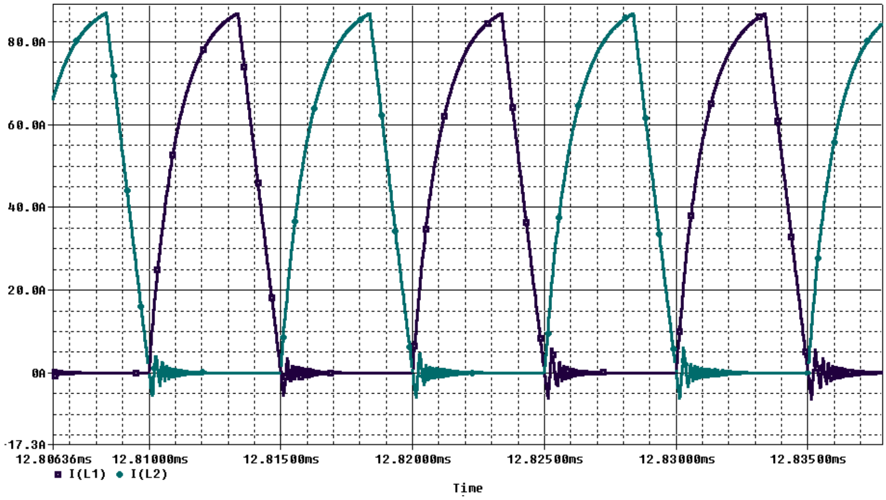

Fig. 4 – *Inductor currents waveforms.*

C Critical conduction mode

The interleaved switching converter, composed of parallel connection of switching converters, operating at same switching frequency, but each switching phase is sequentially shifted over equal fractions of the switching period [4]. The simulation schematic of CRM interleaved boost converter is shown in Fig. 5 and inductor current waveform is shown in Fig. 6.

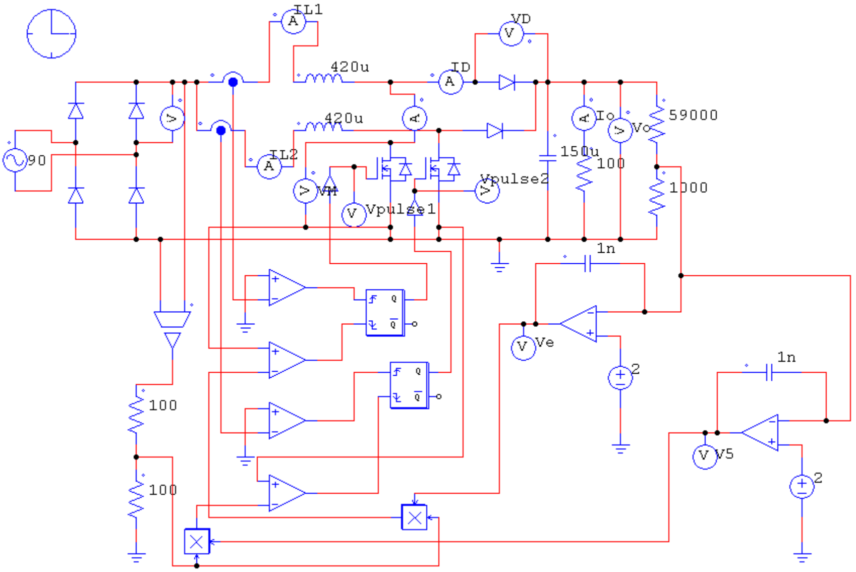

Fig. 5 – *Simulation schematic of* CRM *interleaved converter.*

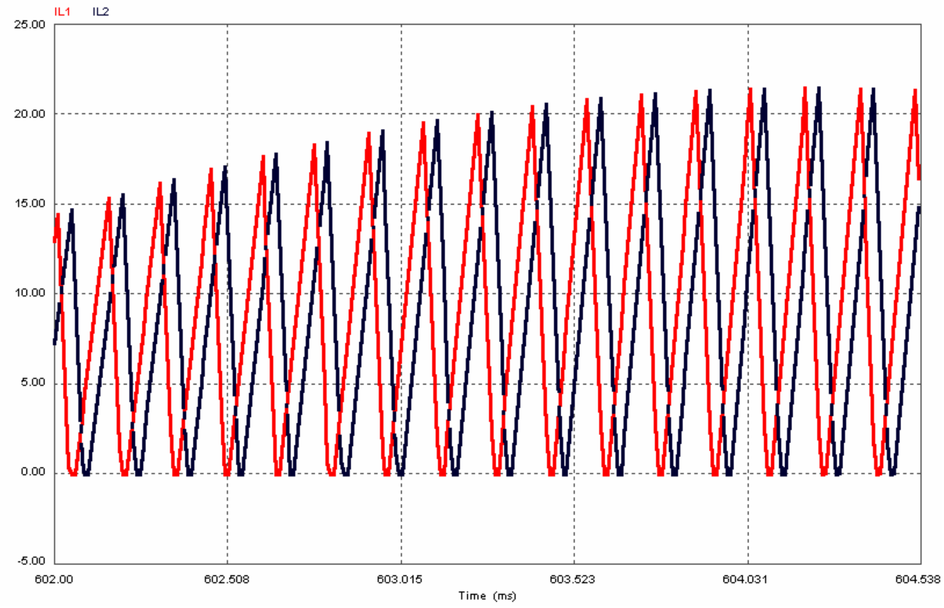

Fig. 6 – *Inductor Current waveform.*

4 Reliability Calculations

In this section, reliability of the boost converter for different output power is calculated and presented in detail. For different output powers and operating modes, the results of reliability calculations are shown in **Table 1**. The part counting method [10] is used to calculate reliability. In this approach, first the failure rate of each element in the converter structure is obtained individually and then the value of the converter's MTBF is calculated from equations (4) and (5), where "*N*" is the number of consisting parts. For these calculations the following assumptions are made:

- The ambient temperature is 27°C;
- The control structures of these converters are not the same whose reliability can be neglected for comparing the reliability of main components;
- To calculate the reliability, first the dynamic and static losses of MOSFET and Diodes should be calculated for different output powers working in three operating modes namely CCM, DCM and CRM;

$$P_{dynamic} = V_{avg} \times I_{avg} \times t_{ol} \times f_s , \tag{7}$$

$$P_{static} = V_{on} \times I_{avg} \times t_{on} \times f_s , \tag{8}$$

$$P_{loss} = P_{static} + P_{switching} , \tag{9}$$

It should be noted that if the converter is operating in DCM mode, then before further turn-on of the switch, the inductor current should reach zero. So there will not be turn-on loss. But in CCM operating mode, the current should be transferred from diode to the switch. The turn ON overlap and turn OFF overlap is shown in Figs. 7 and 8 respectively.

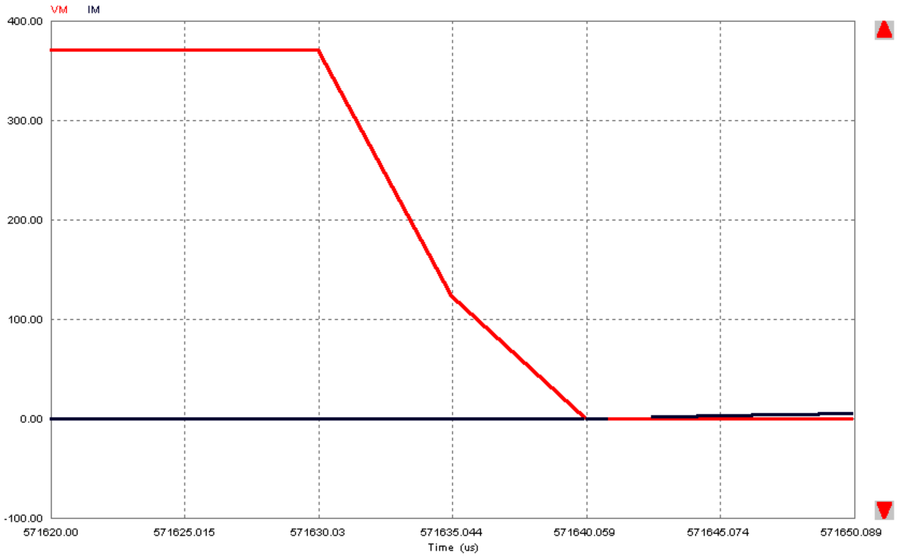

Fig. 7 – *Turn on Overlap*.

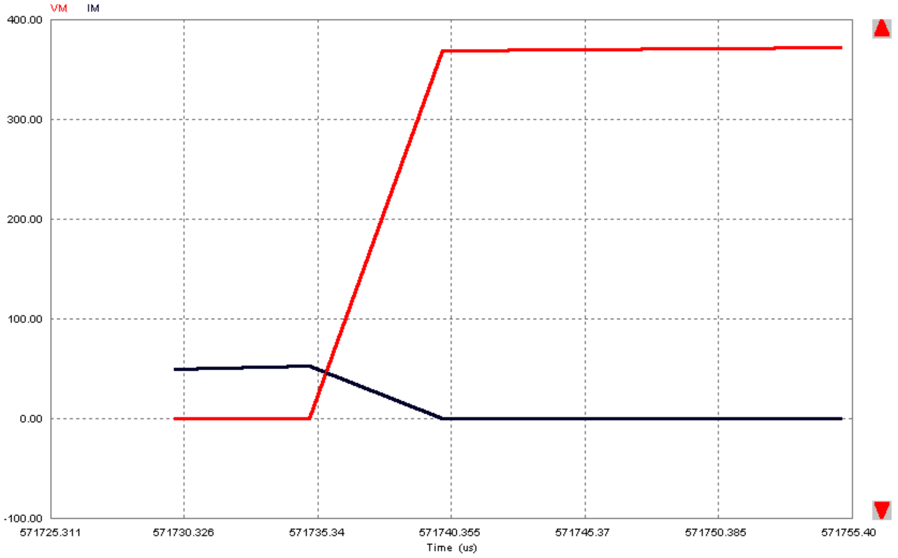

Fig. 8 – *Turn off Overlap*.

Table 1
Reliability calculations for CCM, DCM *and*
CRM *operating modes of interleaving boost* PFC.

Output Power	800W			1000W		
Operating Mode	CCM	DCM	CRM	CCM	DCM	CRM
λ_p (MOSFET)	76.686	256.9	261.11	90.92	390.41	391.16
λ_p (Output Diode)	0.200	2.030	3.145	0.5810	2.776	3.1293
λ_p (Input Bridge)	0.103	0.124	0.139	0.1421	0.169	0.181
λ_p (Input Inductor)	0.509	0.363	0.362	0.5099	0.362	0.362
λ_p (Output Capacitor)	0.060	0.060	0.060	0.0713	0.071	0.071
λ_p (Output Resistor)	0.0297	0.0297	0.0297	0.0297	0.0297	0.0297
Total λ_p	77.59	259.46	264.85	92.25	93.82	394.94
MTBF (hours)	12888	3854	3775	10839	10658	2532

5 Results

From the results noted in the Table-I, the following points are observed. The boost converter has highest reliability in CCM operating mode compared to DCM and CRM modes of operation. The peak and rms values of current are higher in DCM and CRM modes, when compared with CCM, as a result, they offer higher current stress on switching devices. Hence, switching devices have highest failure rate in DCM and CRM modes when compared with CCM mode.

6 Conclusion

In this paper, a boost PFC converter is simulated under three output power ratings and CCM/CRM/DCM operating modes. Reliability calculation of the converter is done based on MIL-HDBK-217 and in part count method. Results have shown that switches have the highest failure rate in the converter structure in both CCM/DCM operating modes and different output powers. It is observed that, with reference to reliability, boost converter as a PFC, working in CCM mode is better when compared with DCM and CRM modes of operation.

7 Appendix

In this section, the sample calculation for failure rate for each component is presented:

a) Calculation of Failure rate λ_p for MOSFET (IXFH12N100Q/IXS):

$$V_n = 1000\,\mathrm{V},\ \theta_{jc} = 0.42\,^0\mathrm{C/W},\ \theta_{ca} = 1\,^0\mathrm{C/W}$$

$$T_c = T_a + \theta_{ca} \times P_{loss} = 27 + 1 \times 69.163875 = 96.163875$$

$$T_j = T_c + \theta_{jc} \times P_{loss} = 96.163875 + 0.42 \times 69.163875 = 125.2127$$

$$\pi_T = \exp\left(-1925 \times \left(\frac{1}{T_j + 273} - \frac{1}{298} \right) \right) = 5.08162$$

$$\lambda_b = 0.012, \pi_E = 6,\ \pi_A = 10\ ,\ \pi_Q = 5.5$$

$$\lambda_p = \lambda_b \times \pi_Q \times \pi_E \times \pi_A \times \pi_T = 0.012 \times 5.5 \times 6 \times 10 \times 5.08162 = 20.1232.$$

b) Calculation of failure rate (λ_p) for Ouput diode:

$$V_n = 1000\,\mathrm{V}\ ,\ \theta_{jc} = 2\,^0\mathrm{C/W}\ ,\ \theta_{ca} = 1\,^0\mathrm{C/W}\ , P_{loss} = 1.99056\mathrm{W}$$

$$T_c = T_a + \theta_{ca} \times P_{loss} = 27 + 1 \times 1.99056 = 28.99056$$

$$T_j = T_c + \theta_{jc} \times P_{loss} = 27 + 1 \times 1.99056 = 32.97168$$

$$\pi_T = \exp\left(-1925 \times \left(\frac{1}{T_j + 273} - \frac{1}{298} \right) \right) = 1.183291$$

$$\lambda_b = 0.069, \pi_E = 6,\ \pi_Q = 5.5,\ \pi_C = 1$$

$$V_S = \frac{90}{500} = 0.18 \Rightarrow \pi_S = V_S^{\ 2.43} = 0.01549$$

$$\lambda_p = \lambda_b \times \pi_Q \times \pi_S \times \pi_E \times \pi_T \times \pi_C =$$

$$= 0.069 \times 5.5 \times 0.015 \times 6 \times 1.183291 \times 1 = 0.041735\,.$$

c) Calculation of failure rate (λ_p) for Input Bridge:

$$V_n = 1000\,\mathrm{V}\ ,\ \theta_{jc} = 1.6\,^0\mathrm{C/W}\ , P_{loss} = 3.8808\ \mathrm{W}$$

$$T_c = T_a + \theta_{ca} \times P_{loss} = 27 + 1 \times 3.8808 = 30.8808$$

$$T_j = T_c + \theta_{jc} \times P_{loss} = 30.8808 + 1.6 \times 3.8808 = 37.09008$$

$$\pi_T = \exp\left(-1925 \times \left(\frac{1}{T_j + 273} - \frac{1}{298} \right) \right) = 1.286413$$

$$\lambda_b = 0.069, \pi_E = 6,\ \pi_Q = 5.5,\ \pi_C = 1$$

$$V_S = \frac{304}{1200} = 0.2533 \Rightarrow \pi_S = V_S^{\ 2.43} = 0.03554$$

$$\lambda_p = \lambda_b \times \pi_Q \times \pi_E \times \pi_C \times \pi_S \times \pi_T =$$

$$= 0.069 \times 5.5 \times 6 \times 1 \times 0.03554 \times 1.286413 = 0.104102 .$$

d) Calculation of failure rate (λ_p) for Inductor:

$$T_{HS} = T_A + 1.1 \times \Delta T = 27 + 1.1 \times 11 = 39.1$$

$$\lambda_b = 0.0016 \times \left(\frac{T_{HS} + 273}{329} \right)^{15.6} = 0.70282\,\text{m}$$

$$\pi_E = 6,\ \pi_Q = 20$$

$$\lambda_p = 0.070282 \times 10^{-3} \times 6 \times 20 = 0.08433 .$$

e) Calculation of failure rate for Capacitor:

$$\Pi_{CV} = 0.34 \times C^{0.18} = 0.34 \times (917\mu)^{0.18} = 0.09653$$

$$\pi_E = 2,\ \pi_Q = 10$$

$$\lambda_p = \lambda_b \times \pi_Q \times \pi_E \times \pi_{CV} = 0.13 \times 10 \times 2 \times 0.09653 = 0.250978.$$

f) Calculation of failure rate for Resistor:

$$\pi_R = 1,\ \pi_E = 2,\ \pi_Q = 10,\ \lambda_b = 0.000066$$

$$\lambda_p = \lambda_b \times \pi_Q \times \pi_E \times \pi_R = 0.00066 \times 10 \times 2 \times 1 = 0.0297$$

Therefore the total system failure rate will be:

$$\lambda_{system} = \sum_{n=1}^{N} \lambda_{part} = 20.634 \ \left(\text{failures} / 10^6 \text{ hours}\right)$$

$$\Rightarrow \text{MTBF} = \frac{1}{\lambda} = 48463.70 .$$

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