Reliability Analysis of Transformer less DC/DC Converter in a Photovoltaic System

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Abstract *- Converter reliability depends upon robustness of individual component. Reliability assessment of converters is essential due to failure prone nature of few components. This communication describes design and reliability analysis of transformer less ZVS buck DC/DC converter. Transformer less converter omits disadvantages associated with transformer but provides isolation problems. In the presented work 125W DC/DC converter prototype is developed and its reliability is analyzed using part stress method. Over rated components are selected for design, analysis and experimentation. Reliability analysis reveals that power switch has highest failure rate*

Keywords – *transformer less converter design, converter reliability estimation, ZVS DC/DC converter, PV converter reliability, transformer less soft switched converter*

1. INTRODUCTION

Reliability of converters is an important issue due to failure prone nature of power semiconductor devices. Many authors have valuable contribution in reliability oriented assessment of power converters; many have developed fault tolerant schemes. Efforts of few authors who worked on reliability issues in converters are briefly discussed here. According to survey conducted by Shayong Yang et al semiconductor power switch in converters is most failure prone component. Capacitor ranked second after power switch. Failure of other components like diode and inductor is also reported [1]. Measurement metrics for reliability assessment are discussed in ref.[2]. Reliability issues in photovoltaic power processing circuits, problems and challenges in efficiency improvement are discussed in [3]. Faults occurring in IGBTs and existing protection methods in inverters are discussed [4]. An overview of faults occurring in IGBTs, present diagnosing and protection methods are discussed [5]. Experimentation on reliability assessment of parallel combination of power switches has done in ref.[6], authors of this paper reported higher reliability in parallel combination of power switches in integrated power module than for discrete power switches. Reliability assessment of power factor correction circuit is performed in [7]. Reliability oriented assessment of DC/DC converters in photovoltaic applications has been done [8][9].

Literature review reveals significance of converter reliability assessment. There is a trend to design transformer less converters to omit demerits like core saturation, bulkiness, power loss, cost etc. imposed by transformers. Considering the reliability aspects this communication describes reliability analysis of a transformer less DC/DC converter. The converter is designed with soft switched ZVS scheme and part stress method is used for reliability estimation. Section 2 present hardware design issues and reliability analysis is done in section 3.

2. DESIGN OF TRANSFORMER LESS CONVERTER

This section deals with design of transformer less ZVS DC/DC converter. Control scheme is shown in fig.1.

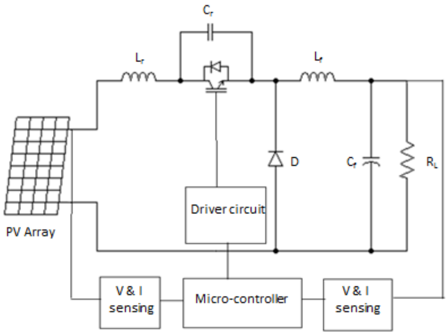

Figure 1- Converter control scheme

The resonant inductor and capacitor are selected using following expression [11].

$$f_{resonant} = \frac{1}{2\pi \sqrt{L_r C_r}}$$

Table 1 provides system specifications.

Table 1- Converter specifications

PV input voltage	19.37V
PV input current	800mA
Output voltage	12V
Output current	1.5A
Switching frequency	10KHz
Duty cycle	80%
R_L	50 Ω
Lr	115µH
C_r	2.2µF, 400V
L_f	0.28mH
C_f	470µF, 63V

TMS320F28335 microcontroller is used for monitoring and control action. Figure 2 shows gate driver pulses applied to IGBT. Voltage across resonant inductor is shown in fig. 3. Figure 4 shows collector to emitter voltage across IGBT.

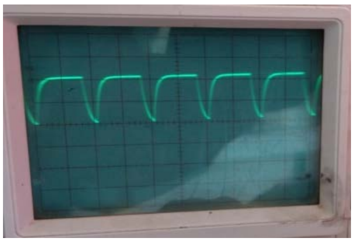

Figure 2- Gate driver pulses

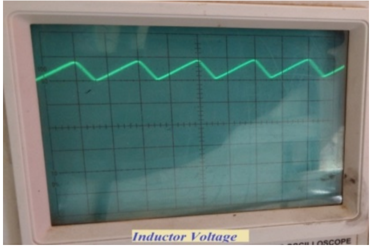

Figure 3- Voltage across inductor

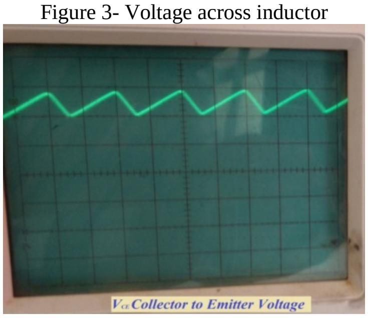

Figure 4- Collector to Emitter voltage across IGBT

Figure 5 shows converter prototype developed in laboratory.

Figure 5- ZVS DC/DC Converter prototype

3. RELIABILITY ANALYSIS

In this section failure rate of DC/DC converter circuit is analyzed. Control and sensing circuit is considered as ideal and fault free. Part stress method and Military handbook MIL-HDBK- 217F [12] is used for failure rate analysis.

3.1. Power switch reliability analysis

Power losses in power switch are calculated as below:

$$I_{RMS} = 757\text{mA}$$
$$V_{CE(sat)} = 2.5\text{V for selected IGBT}$$

IGBT conduction loss is given by

$$P_{ConductionLoss} = r_{CE}.(I_{rms})^2$$
$$= (104\ \text{m}\Omega).(757\text{mA})^2$$
$$= 0.059\text{W}$$

Switching loss is given by

$$P_{SwitchingLoss} = f_s\ C_d\ Vi^2$$
$$= (10\text{KHz}).(130\text{pF})(19.37)^2$$
$$= 0.00048\ \text{W}$$

Total power loss is

$$P_{TotalLoss} = P_{ConductionLoss} + P_{SwitchingLoss}/2$$
$$= 0.059 + 0.00024$$
$$= 0.059\text{W}$$

Considering case temperature, $T_c = 35^{O}C$

$$T_j = T_c + \theta_{jc}.P_{TotalLoss}$$
$$T_j = 35 + (0.27)(0.059) = 35.01\ ^{O}C$$

($\theta jc = 0.27$ for selected IGBT)

Temperature factor = π_T

$$\pi_T = e^{\left[-1925\left(\frac{1}{T_j+273}-\frac{1}{298}\right)\right]}$$

$$\pi_T = e^{\left[-1925\left(\frac{1}{35.01+273}-\frac{1}{298}\right)\right]}$$

$$\pi_T = e^{\left[-1925\left(\frac{1}{308.01}-\frac{1}{298}\right)\right]}$$

$$\pi_T = 1.21$$

Base failure rate $\lambda_b = 0.012$

Application factor $\pi_A = 4$ (rated output power is between 5W to 50W)

Environmental factor $\pi_E = 1$

Quality factor $\pi_Q = 5.5$

Part failure rate $\lambda_p = \lambda_b\ \pi_T\ \pi_A\ \pi_E\ \pi_Q$

$$= (0.012)(1.21)(4)(1)(5.5)$$
$$= 0.319\ \text{failures}/10^6\ \text{hours}$$

3.2. Filter capacitor reliability analysis

Base failure rate λ_b= 0.00040
Temperature factor = π_T

$$\pi_T = e^{\left[-Ea/8.617x10^{-5}\left(\frac{1}{T+273}-\frac{1}{298}\right)\right]}$$

where Ea= 0.15,

$$\pi_T = e^{\left[-0.15/8.617x10^{-5}\left(\frac{1}{35+273}-\frac{1}{298}\right)\right]}$$

$$\pi_T = e^{(0.1740)}$$

$$\pi_T = 1.19 \text{ at } 35^{O}C$$

Capacitance factor=π_C=C $^{(0.23)}$

$$= (470\mu F)^{(0.23)} = 0.171$$

$$S = \frac{\text{operating voltage}}{\text{Rated voltage}} = \frac{12}{63} = 0.190;$$

$$\pi_V = \text{Voltage stress factor } = \left(\frac{S}{0.6}\right)^{17} + 1$$

$$= \left(\frac{0.190}{0.6}\right)^{17} + 1 = 1$$

Voltage stress factor= π_V=1
Calculation of Series Resistance factor π_{SR}

$$\left(\text{CR} = \text{Circuit Resistance} = \frac{\text{Effective resistance between capacitor and power supply}}{\text{Voltage applied to capacitor}}\right)$$

$$\text{CR} = \frac{0.1}{12} = 0.0083$$

π_{SR} = 3.3 for CR between 0 to 0.1

Series resistance factor= π_{SR}= 3.3
Quality factor= π_Q=3
Environmental factor=π_E=1
Part failure rate $\lambda_p = \lambda_b\ \pi_T\ \pi_C\ \pi_V\ \pi_{SR}\ \pi_Q\ \pi_E$
= (0.00040) (1.19) (0.171) (1) (3.3) (3) (1)
= 0.00080 failures /10^6 hours

3.3. Resonant capacitor reliability analysis

Base failure rate λ_b= 0.00051
Temperature factor = π_T

$$\pi_T = e^{\left[-Ea/8.617x10^{-5}\left(\frac{1}{T+273}-\frac{1}{298}\right)\right]}$$

where Ea= 0.15,
Temperature factor π_T= 1.19 at 35^{O}C
Capacitance factor =π_C=C $^{(0.09)}$ = (2.2µF) $^{(0.09)}$
= 0.3096

$$S = \frac{\text{operating voltage}}{\text{Rated voltage}} = \frac{14}{400} = 0.035;$$

$$\pi_V = \text{Voltage stress factor } = \left(\frac{S}{0.6}\right)^{17} + 1$$

$$= \left(\frac{0.035}{0.6}\right)^{17} + 1 = 1$$

Voltage stress factor π_V=1
Series resistance factor π_{SR}= 3.3 for CR between 0 to 0.1
Quality factor π_Q=3
Environmental factor π_E=1
Part failure rate $\lambda_p = \lambda_b\ \pi_T\ \pi_C\ \pi_V\ \pi_{SR}\ \pi_Q\ \pi_E$
(0.00051) (1.19) (0.3096) (1) (3.3) (3) (1)
= 0.0018 failures /10^6 hours

3.4. 3Filter inductor reliability analysis

T_{HS}= T_A+ 1.1 (ΔT)
Considering ΔT= 5^{O}C
T_{HS}= 40.5^{O}C
Base failure rate λ_b= 0.000030

$$\pi_T = e^{\left[-0.11/8.617x10^{-5}\left(\frac{1}{T_{HS}+273}-\frac{1}{298}\right)\right]}$$

$$\pi_T = e^{\left[-0.11/8.617x10^{-5}\left(\frac{1}{40.5+273}-\frac{1}{298}\right)\right]}$$

$$\pi_T = e^{\left[-1276.54\left(\frac{1}{313.5}-\frac{1}{298}\right)\right]}$$

$$\pi_T = e^{[-1276.54\,(0.0031-0.0033)]}$$

$$\pi_T = 1.29$$

Temperature factor π_T= 1.29
Quality factor π_Q=1
Environmental factor π_E=1
part failure rate λ_p= $\lambda_b\ \pi_T\ \pi_Q\ \pi_E$
= (0.000030) (1.29) (1) (1)
= 0.0000387 failures /10^6 hours

3.5. Resonant inductor reliability analysis

For resonant inductor calculated part failure rate is same as filter inductor part failure rate λ_p= $\lambda_b\ \pi_T\ \pi_Q\ \pi_E$ = 0.0000387 failures /10^6 hours

3.6. Diode reliability analysis

V_f= 1.1 V, R_f=0.73Ω
$I_{DiodeRMS}$ = 1.4mA
λ_b = Base failure rate=0.0030
Diode power loss due to R_f is given by,

$$P_{diode_{Rf}} = R_f \cdot \left(i_{D1_{rms}}\right)^2$$

$$= (0.73)\ (1.4mA)^2$$

$$= 1.43x10^{-6}\ W$$

Power loss associated with diode due to V_f is given by

$$P_{diode_{Vf}} = V_f\ i_{Davg}$$

$$= (1.1)\ (0.7mA)$$

$$= 0.00077\ W$$

Total loss in each diode is given by,

$$P_{TotalDiodeLoss} = P_{diode_{Rf}} + P_{diode_{Vf}}$$

$$= 1.43x10^{-6} + 0.00077$$

$$= 771\ \mu W$$

At $T_c = 35^{o}C$

$$T_j = T_c + \theta_{jc}.P_{TotalLoss}$$

$$= 35+[(1.5)\ (771\ \mu W)]$$

$$= 35.001^{o}C$$

(where $\theta_{jc} = 1.5$)

Temperature factor $=\pi_T$

$$\pi_T = e^{\left[-1925\left(\frac{1}{T_j+273}-\frac{1}{298}\right)\right]}$$

$$\pi_T = e^{\left[-1925\left(\frac{1}{35+273}-\frac{1}{298}\right)\right]}$$

$$\pi_T = e^{[0.1975]}$$

$$= 1.21$$

$$V_s = \text{Voltage stress ratio} = \frac{\text{Applied voltage}}{\text{Rated Voltage}} = \frac{12}{1000}$$

$$= 0.012$$

Electrical stress factor $\pi_S = (Vs)^{2.43}$
$= (0.012)^{2.43}$
$= 0.000021$

Contact construction factor $\pi_C = 2$
Quality factor $\pi_Q = 5.5$
Environmental factor $\pi_E = 1$
Part failure rate $\lambda_p = 0.223$
Part failure rate $\lambda_p = \lambda_b\ \pi_T\ \pi_S\ \pi_C\ \pi_Q\ \pi_E$
$= (0.0030)\ (1.21)\ (0.000021)\ (2)\ (5.5)\ (1)$
$= 0.0000008385$ failures $/10^6$ hours

Table 2- Converter failure rate analysis

Device	Part failure rate	Number of devices	Total failure rate (λ) (failure $/10^6$ h)
Power switch	0.319	01	0.319
Capacitor (resonant)	0.0018	01	0.0018
Inductor (resonant)	0.0000387	01	0.0000387
Capacitor (filter)	0.00080	01	0.00080
Inductor (filter)	0.0000387	01	0.0000387
Diode	0.0000008385	01	0.0000008385
Converter failure rate			0.3216 failures $/10^6$ h

MTBF= MTTF + MTTR
(Neglecting MTTR as MTTR <<< MTTF)
MTBF = 1/ λ
MTBF = 3109452.73 hrs

4. CONCLUSION

This paper assessed reliability of transformer less DC/DC converter. For this a converter prototype is built for experimentation using over rated components. From failure rate analysis it can be seen that the mean time between failures of the designed converter is 3109452.73 hours. It is found that power switch have highest failure rate among all components. Use of over rated components improves converter reliability.

5. ACKNOWLEDGEMENT

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