Reliability evaluation of non-isolated high gain interleaved DC-DC converter

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ABSTRACT

A high gain DC-DC converter is the crucial part in renewable energy systems (RES) and in electric vehicular systems. The reliability of those high-gain converters needs to be assessed for the long-term operation of renewable energy systems. This article presents the reliability analysis of non-isolated high gain interleaved DC-DC converter. The analysis primarily relies on calculating the mean time between failures (MTBF). Based on military handbook (MIL-HDBK-217) criteria, the reliability calculation is performed. Stress factors and predicted failure rate for each component of presented converter is evaluated and tabulated. Reliability evaluation is performed for 1.5 kW hardware prototype. Based on reliability evaluation results, a reliable converter with better operating life time has been introduced.

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NOMENCLATURE

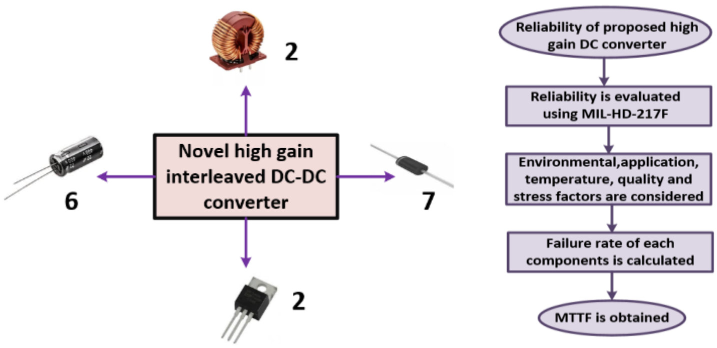
$\lambda_{Converter}$: failure rate of converter (FIT)
λ_{MOSFET}: failure rate of MOSFET (FIT)
λ_{Diode}: failure rate of diode (FIT)
$\lambda_{Capacitor}$: failure rate of capacitor (FIT)
$\lambda_{Inductor}$: failure rate of inductor (FIT)
$P_{Switch\ Loss}$: switching loss of MOSFET (W)
P_{Diode}: loss of diode (W)
$P_{Capacitor\ Loss}$: loss of capacitor (W)
P_{CI}: loss of coupled inductor (W)
T_J: worst case junction temperature (°C)
T_C: case temperature (°C)
θ_{JC}: junction to case thermal resistance (°C/W)
P_d: power dissipation (W)
λ: failure rate
λ_b: base failure rate
π_T: temperature factor
π_A: application factor
π_Q: quality factor
π_E: environmental factor
π_S: voltage stress factor
π_C: construction factor
π_{CV}: capacitance factor
S: ratio of operating to rated voltage
T_{HS}: hot spot temperature (°C)
T_A: inductive device ambient operating temperature (°C)
W_L: power loss of inductor (W)
A: radiating surface area of case (in^2)
ΔT: average temperature rise above ambient (°C)

1. INTRODUCTION

High gain DC-DC converters and inverters plays a vital role in renewable energy systems (RES) and in electric vehicular systems [1]–[6]. Many types of converters were dealt in [7]–[9]. The employed DC-DC converters and inverters should be reliable to guarantee the sustainability of renewable energy systems and electric vehicular systems. The converters are built with semiconductor switches, inductors and capacitors in [10]–[13]. When DC-DC converters are put through any applications, there is a possibility that they will break down by many factors like switching losses of semiconductor switches, high reverse recovery problem of diodes, high capacitor stress, operative temperature of inductors and other external environmental conditions. Renewable energy applications rely on both converters and inverters. In particular, inverters play a crucial role in the overall process. Many types of inverter were proposed in [14]–[18]. Renewable energy-based converters must operate reliably for many years. Thus, it is imperative to evaluate the reliability of a DC-DC converter.

Efficiency, reliability, and price are the performance criteria for evaluating power converters which are presented in [19]–[24]. The probability of a system functions satisfactorily over time and under particular operational and environmental conditions is the standard way to assess dependability is given in [20]–[22]. The reliability study enables comparison of various design techniques, evaluation of the system design process, and definition of preventive maintenance plans. Reliability analysis is performed for conventional and interleaved DC–DC boost converters in [19]. The performance and reliability enhancement of modular DC converter were analysed in [20]. Many conventional dc converters are reconfigured and restructured their reliability performance are discussed in [21], [22]. The reliability assessment for multilevel DC converters are analyzed in [23]. Likewise, many articles in [19]–[23] have evaluated the reliability of DC converters. Life time extension of many converters can be made possible by using multistate markov analysis elucidated in [24].

This paper presents the reliability evaluation of high gain interleaved DC-DC converter. The operation, steady state analysis, power loss and efficiency of proposed converter were presented in [25]. The military manual MIL-HDBK-217F [26] is used to assess the reliability. This handbook is a basic supporting tool for the prediction of reliability of any electronic system. The stress factors and predicted failure rate of presented high gain interleaved DC-DC converter is calculated under normal operating conditions. Figure 1(a) shows the components of proposed converter included in reliability evaluation and Figure 1(b) shows the steps to be followed for the reliability evaluation. Typically, failure rates for each component are determined separately and then summed to determine the failure rate.



(a) (b)

Figure 1. Reliability evaluation: (a) components included and (b) steps of reliability analysis

2. NOVEL NON-ISOLATED INTERLEAVED HIGH GAIN DC-DC CONVERTER

The operation, steady state analysis, power loss and efficiency calculations of proposed non-isolated interleaved high gain DC-DC converter is presented in [25]. The presented converter has interleaved structure, switched capacitor (SC) cell, passive clamp circuit and voltage multiplier unit (VMU). Through the use of the interleaving technique, the distribution of currents is optimized, and the occurrence of ripples is minimized. The SC cell improve the overall output voltage. Clamp circuits can reduce switching losses and voltage spikes caused by power switches being turned off. VMU further improves the overall voltage gain of the converter. It can able to obtain the output voltage of 515 V from 30 V input. The voltage gain of proposed converter is found to be 17.5 at a nominal duty ratio $D = 0.6$. The reliability evaluation is performed for the 1.5 kW hardware prototype. Figure 2 shows the circuit of non-isolated interleaved high gain DC-DC converter.

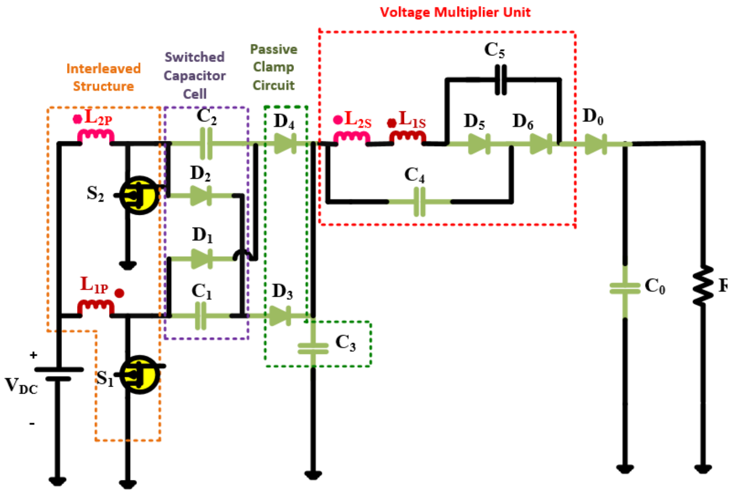


Figure 2. Circuit of non-isolated interleaved high gain DC-DC converter [25]

3. RELIABILITY EVALUATION

The reliability of the proposed converter is determined using the MIL-HDBK-217F military manual. The impact of power loss on the failure rates of converter components has been evaluated, and the failure rates of components are determined through practical calculations. In order to conduct a reliability analysis, it's important to know the component ratings of the converters. The components considered for reliability evaluation are illustrated in Figure 1(a), consisting of 2 coupled inductors, 2 MOSFETs, 7 diodes, and 6 capacitors. The reliability evaluation is conducted in accordance with the steps outlined in Figure 1(b). Reliability analysis of proposed converter is calculated under normal operating and environmental condition. Reliability of converter depends on manufacturing process and material used in devices and has an indirect impact by the working environment. The MTTF is estimated by (1) and (2):

$$Mean\ Time\ of\ Failure = \frac{1}{\lambda_{Converter}} \tag{1}$$

$$\lambda_{Converter} = \sum_{i=1}^{2} \lambda_{MOSFET} + \sum_{j=1}^{7} \lambda_{Diode} + \sum_{k=1}^{6} \lambda_{Capacitor} + \sum_{l=1}^{4} \lambda_{Inductor} \tag{2}$$

Failure rates and stress factors are dependent on environmental conditions. For the calculations of failure rate and stress factors, the power loss equations must be derived by using hardware parameters. The power loss values for switches ($P_{Switch\ Loss}$), diodes ($P_{Diode\ Loss}$), coupled inductor ($P_{CI\ Loss}$) and capacitor ($P_{Capacitor\ Loss}$) were calculated. Power loss equations and its values of proposed converter is shown in Table 1. For determining the MTTF of proposed converter, the failure rate of individual components like MOSFET's, diodes, capacitors and inductors of proposed is determined based on the equations tabulated in Table 2. Those equations are taken from MIL-HDBK-217 military handbook [26].

Table 1. Power loss equations and its values [25]

S. No	Equations	Loss values (W)
1.	$P_{Switch\ Loss} = I_D^2 . R_{DS(ON)} + P_{Switch\ (on)} + P_{Switch\ (off)}$	17.95
2.	$P_{Diode\ Loss} = V_{Diode\ (ON)} . I_{Diode\ Avg} + I_D^2 . R_{diode}$	15.97
3.	$P_{CI\ Loss} = I_{LP}^2 . R_{LP} + I_{LS}^2 . R_{LS} + P_{Core\ Loss}$	9.11
4.	$P_{Capacitor\ Loss} = I_{C(RMS)}^2 . ESR$	18.2
	Total loss	61.23

The essential parameters and selected values of hardware components for failure rate for reliability assessments are given in Table 3. The failure rate calculations can be determined by the hardware components are as follows; IXTK 62N 25 for two MOSFET's, RF1001 for diodes D1, D2, D3 and D4, MUR1560 for D5, D6 and D0, electrolytic type for C1, C2, C3 and C0 and aluminium type for C4 and C5. The values of supporting parameters like $R_{DS\ (ON)}$, T_C, θ_{JC}, TJ and θ_{JC} are taken from the data sheets of hardware components.

Table 2. Failure rates and stress factors [26]

Components	Equations of failure rate	Equations of stress factor
MOSFET	$\lambda = \lambda_b \pi_\tau \pi_A \pi_Q \pi_E\ Failures/10^6$	$\pi_\tau = exp\left[-1925\left(\frac{1}{T_J+273}-\frac{1}{298}\right)\right]$ $T_J = T_C + \theta_{JC}.P_d$
Diode	$\lambda = \lambda_b \pi_\tau \pi_S \pi_C \pi_E\ Failures/10^6$	$\pi_\tau = exp\left[3091\left(\frac{1}{T_J+273}-\frac{1}{298}\right)\right]$ $T_J = T_C + \theta_{JC}.P_d$
Capacitor	$\lambda = \lambda_b \pi_{CV} \pi_Q \pi_E\ Failures/10^6$ $\pi_{CV} = 0.34C^{0.18}$	$\lambda_b = \left[\left(\frac{s}{0.5}\right)^2\right].exp\left[5.09\left(\frac{T_A+273}{378}\right)^5\right]$
Inductor	$\lambda = \lambda_b \pi_Q \pi_E \pi_C$	$\lambda_b = 0.00035\ exp\left(\frac{T_{HS}+273}{409}\right)$ $T_{HS} = T_A + 1.1\Delta T, \Delta T = \frac{125\ W_L}{A}$

The junction temperature of switches S1, S2 and all diodes from D0 to D6 of proposed converter can determined by using:

$$T_J = T_C + \theta_{JC}.P_d \tag{3}$$

where T_J is worst case junction temperature (°C), T_C is case temperature (°C), θ_{JC} is junction to case thermal resistance (°C/W) and P_d is power dissipation (W). The stress factors for all the components of proposed converter is determined by referring MIL-HDBK-217 military handbook [26] and specifications of hardware components in Table 3. By substituting the failure rate of hardware components in (2). The failure rate of converter can be determined by, $\lambda_{Converter} = 40.78 \times 10^6$ hours.

$$MTBF = 24520 \text{ hours}$$

The stress factors and predicted failure rate of hardware components are tabulated in Table 4. The predicted failure rate of switches S1, S2 are 0.768 $10^{-6}h^{-1}$, the diodes D1, D2, D3, D4 are 6.72 $10^{-6}h^{-1}$, diodes D5, D6, D0 are 1.232 $10^{-6}h^{-1}$, the capacitors C1, C2 are $1.33 \times 10^{-3}\ 10^{-6}h^{-1}$, the capacitor C3 are $1.209 \times 10^{-3}\ 10^{-6}h^{-1}$ capacitors C0 are $31.89 \times 10^{-3}\ 10^{-6}h^{-1}$ and inductors are $2.52 \times 10^{-3}\ 10^{-6}h^{-1}$. The mean time between failures of proposed high gain converters are found to be 24520 hours. The results show that the proposed high-gain converter is moderately reliable. A novel and high-gain converter has been developed and tested for renewable energy applications, and perhaps it is generally reliable.

Table 3. Essential parameters and selected values for failure rate assessments

Components	Parameters and values
MOSFET's S1, S2	IXTK 62N 25 ($R_{DS\,(ON)}$ = 35 mΩ, T_C = 25 °C, θ_{JC} = 0.3 °C/W)
The diodes D1, D2, D3, D4	RF1001 (T_C = 25 °C, T_J = 150 °C, θ_{JC} = 3.5 °C/W, P_d = 8.98 W)
The diodes D5, D6, D0	MUR1560 (T_C = 25 °C, TT_J = 175, θ_{JC} = 1.5 °C/W)
The capacitors C_1, C_2, C_3	Electrolytic (200 V, 5 A) (1–10 μF)
The capacitors C_4, C_5	Aluminum type (300 V, 10 A), 650 nF
The capacitors C_0	Electrolytic type (250 V, 5 A) 470 μF

Table 4. Stress factors and predicted failure rate for each component

Stress factors	Switches S1 and S2	Diodes D1, D2, D3, D4	Diodes D5, D6, D0	Capacitors C1, C2	Capacitors C3	Capacitors C4, C5	Capacitors C0	Inductors
λ_b	0.012	0.069	0.069	0.031	0.031	0.031	0.031	5.38×10^{-4}
π_A	8	–	–	–		–	–	–
π_S	–	0.58	0.77	–		–	–	–
π_C	–	1	1	–		–	–	1
π_Q	8	8	1	0.1	0.1	1.0	1.0	4
π_E	1	1	1	1.0	1.0	1.0	1.0	1
π_T	1.08	21	23.2	–	–	–	–	–
π_{CV}	–	–	–	0.43	0.39	0.314	1.029	–
Predicted failure rate $10^{-6}h^{-1}$	0.768	6.72	1.232	1.333×10^{-3}	1.209×10^{-3}	9.734×10^{-3}	31.89×10^{-3}	2.52×10^{-3}

3.1. Effect of failure rates of components

Figure 3 shows the contributions of each component to the converter failure rate of proposed high gain converter. The contribution of failure rate of switches S1, S2 are 8.8%, diodes D1, D2, D3 and D4 are found to be 77.06%, D5, D6, D0 are 14.12%, C1 and C2 is 0.15%, C3 is 0.01%, C0 is 0.36% and inductors 0.29%. In the presented reliability assessments, the failure rates corresponding to the diodes have higher chances of failure. Therefore, diodes with different characteristics are to be selected for better reliability.

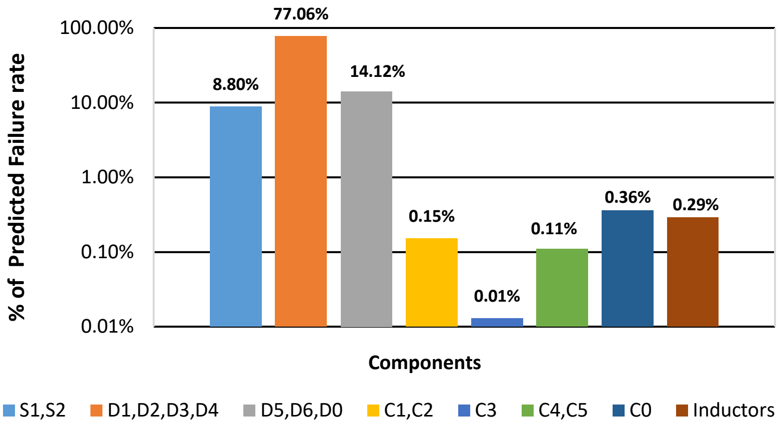


Figure 3. Contributions of each component to the converter failure rate

4. CONCLUSION

In this paper, the reliability of a novel high-gain converter is investigated. The reliability of DC converters is influenced by a variety of elements, including component quality, design considerations, operating circumstances, and maintenance procedures. The reliability evaluation of the proposed converter is done and it is found that the diodes have the highest failure rate. The failure rate of the proposed topology is calculated using the military handbook and it is observed that the failure rate is 24520 hours. The results show that the proposed high-gain converter is moderately reliable and reliability can be improved by replacing the diodes with different characteristics. However, reliability is a dynamic, ever-evolving characteristic rather than a static one. To guarantee that these systems operate reliably in their intended applications, regular evaluations and enhancements are required.

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