INDIAN JOURNAL OF SCIENCE AND TECHNOLOGY

RESEARCH ARTICLE

Failure Rate Analysis of Full Bridge DC/DC Converter in Hard and Soft Switching Control Schemes

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OPEN ACCESS
Received: 27-01-2023
Accepted: 23-06-2023
Published: 28-07-2023

Citation: Chavan SB, Chavan MS (2023) Failure Rate Analysis of Full Bridge DC/DC Converter in Hard and Soft Switching Control Schemes. Indian Journal of Science and Technology 16(29): 2167-2175. https://doi.org/10.17485/IJST/v16i29.202

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Funding: None

Competing Interests: None

Published By Indian Society for Education and Environment (iSee)

ISSN
Print: 0974-6846
Electronic: 0974-5645

Abstract

Objectives: To calculate the failure rate of full bridge DC/DC converter for both hard and soft switching control schemes. **Method:** The analysis is done at same power level and same operating frequency. A 500 W photovoltaic system is simulated for experimentation on failure rate assessment of full bridge DC/DC converter with hard and soft switching control schemes. The individual component failure rates in hard switching control scheme and soft switching control scheme are calculated. Military handbook MIL-HDBK 217F is used to calculate the individual component failure rate. Then MTBF rates for both switching schemes is computed and compared. **Findings:** Reliability calculations are done for same input power and operating frequency of 10 KHz. Results have shown that semiconductor power switches, diodes and capacitor undergoes high stress in hard switching control scheme compared with soft switching scheme. The total failure rate for hard switched control scheme is 7.7910 while for soft switched control scheme total failure rate is 6.2715. The MTBF for hard control scheme is 128353.22 while for soft switched control scheme MTBF is 159451.48. Soft switched control schemes exhibited 81.92 % decrement in failure rate for IGBT, 68.16 % decrement for diodes and 50% decrement for capacitors. For transformer and inductor same failure rates are observed in both control schemes. This showed that soft switching control scheme offers lower failure rate and better reliability than hard switched control scheme. **Novelty:** This study has compared and calculated reliabilities for two different control schemes viz. hard switched and soft switched control schemes on same circuit platform. Individual component stress levels are computed for both control schemes and it is proved that stress on individual semiconductor components is lower in soft switched control scheme than in hard switched control scheme.

Keywords: Full Bridge DC/DC Converter Reliability; Soft and Hard Switching; Part Stress Method; Failure Rate Calculations; Converter Reliability Prediction

1 Introduction

Converters play significant role in power conversion for renewable energy systems. Nowadays, reliability issues of power electronic converters are becoming important due to fragile nature of components. Component level faults in converters may lead entire system to fail or work with lowered efficiency. According to survey(1) semiconductor power switches and capacitors are more failure prone components in converters. Various reliability assessment metrics and fault tolerant designs are presented in(2). Design issues for reliability improvement in photovoltaic power processing circuits are discussed in(3), authors says that avoiding electrolytic capacitors improves reliability of power processing circuits. H. Wang et al depicted need of systematic design approach to resolve reliability issues in power electronics circuits; environmental factors, manufacturing technology, material properties etc. should be considered at design stage(4). M. Pecht et al discussed physics of failure approach which deals with materials, defects and stresses on product reliability(5). Bin Lu et al discussed existing IGBT fault diagnosis and protection methods in inverters(6). Reliability oriented assessment of interleaved boost DC-DC converter for 1 KW PV application has been discussed in(7). Dhopale et al performed reliability assessment of fault tolerant DC-DC converter for PV application in which failure rate of power switches, diode and capacitors is determined using Markov model(8). Failure rate models are developed using Military handbook MIL-HDBK-217F. Reference(9) compares reliability of parallel combination of two discrete IGBTs and parallel combination of IGBTs in integrated power module, according to authors integrated power module provides more reliability compared with discrete combination. Reliability of interleaved boost power factor correction circuit in different modes and at different power levels is assessed, CCM mode is found more reliable than DCM and CRM(10). Model based strategy for power switch fault diagnosis in converter is described in(11). Redundancy based topology for H bridge converter is proposed in(12). Another fault tolerant converter topology for interleaved converter is presented in(13). A novel fault tolerant converter topology which automatically detects open circuit power switch faults and initiates corrective mechanism is presented in(14). The redundancy based fault tolerant converter systems automatically diagnoses the open or short circuit faulty power switches and activates alternative components in case of fault in main component. A new push pull converter topology based on 3 winding transformer is proposed(15), reliability and efficiency of the proposed converter and similar others is performed and described. Fourteen different converter topologies which can be used with solar PV source are analyzed and their performance against efficiency and stress is measured(16). A 3 level step up DC-DC converter for PV application is proposed and analyzed, the converter has high voltage gain, lower switching losses and higher efficiency(17). A novel converter based on "edge resonant switch capacitor" concept is presented and tested for PV input source(18). A review of MMC circuit topologies and their modelling techniques is presented(19). An ANF based PID control scheme is applied to a PSFB ZVS converter used in battery charging application, comparison results have shown that good optimization is obtained by this technique(20). A method is proposed for soft switched LLC-DAB converter to minimize backflow power(21). A reliability of single and double ended forward converters is predicted using fault tree diagram of the converters(22). Due to the brutal nature of the converters their reliability is analyzed using the Markov model(23). The reliability and MTBF of the boost converter applied for a PV system is computed(24). A reliable three port converter is presented for near space vehicles(25). A multi input DC/DC converter applicable for fuel cell and PV systems is described(26) . For a LLC converter reliability is calculated using the actual stress values(27). Reliability of multi-level fault tolerant inverter is computed and experimental results are presented(28). A low power DC-DC converter fabricated using 180nm process with soft charging technique is presented(29) which provides better performance. Because of the unknown uncertainties, the performance of the DC-DC converter may get deteriorate, to avoid this and bring more accuracy in control system, reinforcement learning algorithm from AI is used(30). Two RL agents are used for voltage control and system performance is monitored and compared. A new transformer less DC-DC converter for hybrid EV is presented(31) which offers several merits like high output voltage without any HF transformer.

Literature survey reveals that reliability assessment of power converters is important for reliable system design. Considering reliability aspect, in this communication, failure rate assessment of full bridge DC/DC converter for hard and soft switching control schemes is discussed and compared. The reliability calculations gives general idea about the failure rate of the circuit under the known and considered circumstances. But calculating converter reliability after design ensures the working duration of the circuit. From literature review it seems that no work is done on reliability estimation and comparison of hard and soft switching approaches.

2 Methodology

In this work following methodology is used from failure rate computation.

a) Simulation model is developed as per the system specifications shown in Table 1.

b) Control scheme is developed for hard switching and pulses are applied to gates of IGBTs

c) V_{CE}, IGBT currents, output voltage and currents are monitored. Based upon the electrical stress factors the failure rate of each component is calculated. Finally total failure rate of converter for hard switching control scheme is calculated.

d) Soft switched control scheme is developed and pulses are applied to gates of IGBTs.

e) V_{CE}, IGBT currents, output voltage and currents are monitored. Failure rate of each component is calculated. Total failure rate of converter for soft switching control scheme is calculated.

f) Component wise failure rates and total failure rate in hard and soft switching control schemes is compared.

Figure 1 shows full bridge DC/DC converter topology. In hard switching scheme diagonally connected power switches are driven with gate pulses of same phase and frequency. In soft switching scheme gate drive pulses have phase change of $\Delta\Phi$ and transformer leakage inductance of L_{lk}.

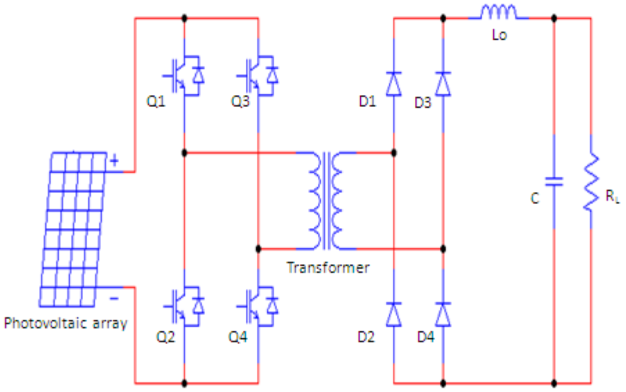

Fig 1. Full bridge DC/DC converter topology

This section presents simulation results obtained in hard and soft switching control schemes for full bridge DC/DC converter. System specifications are shown in Table 1.

Table 1. System specifications

Input PV voltage	97V
PV output current	5.5 A
Converter output voltage (Hard switched)	92.32V
Converter output current (Hard switched)	4.85A
Converter output voltage (Soft switched)	76.05V
Converter output current (Soft switched)	4.0 A
Capacitor	1500μF, 600V
IGBT	30A, 600V, $V_{CE(sat)}$ = 2.5V, θjc= 0.27
Diode	V_f= 0.7V, 10A
Inductor	10μH
Transformer (hard switched)	1:1, leakage inductance=0
Transformer (soft switched)	1:1, leakage inductance=0.1μH
R_L	19 Ω
Frequency	10KHz

2.1 Hard switching

Figure 2 shows collector-emitter voltage across IGBT and current through IGBT in hard switching control scheme. It can be seen that current and voltage across IGBT changes instantaneously. In OFF state voltage across power switch equals input PV voltage while in ON state it equals transistor saturation voltage ($V_{CE(sat)}$).

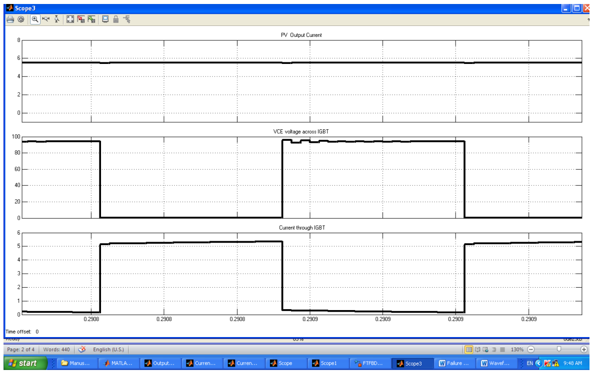

Fig 2. Hard switching control scheme waveforms 1) voltage across IGBT 2) Current through IGBT

Figure 3 shows voltage across diode and current through diode in hard switching scheme.

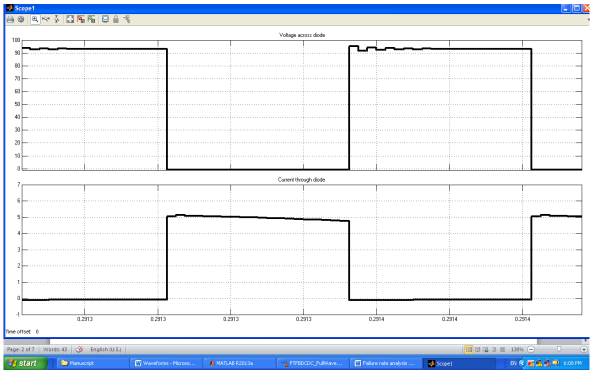

Fig 3. Hard switching control scheme 1) Voltage across diode 2) Current through diode

2.2 Soft switching

Figure 4 shows voltage across IGBT and current through IGBT in soft switching control scheme.

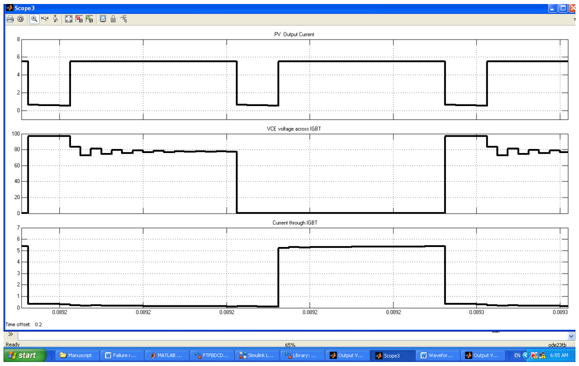

Fig 4. Soft switching control scheme waveforms 1) voltage across IGBT 2) Current through IGBT

Figure 5 shows voltage and current waveforms at diode in soft switching scheme.

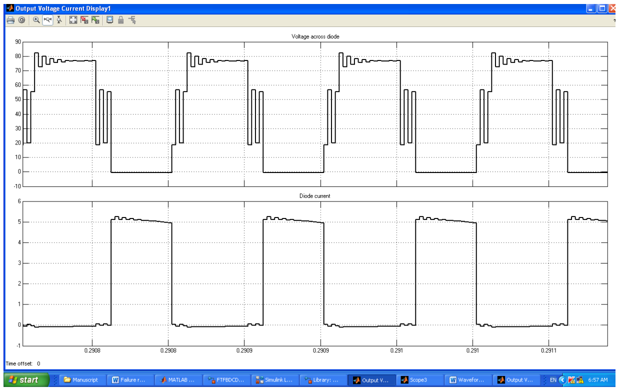

Fig 5. Soft switching control scheme 1) Voltage across diode 2) Current through diode

2.3 Failure rate calculations

In this section component failure rates are calculated for both hard and soft switching control schemes. Input PV power level is kept constant and measurements are taken. Power switches, diode and capacitor undergo different levels of electrical stress at same input power level for different switching schemes. Component failure rates are calculated using Military handbook MIL-HDBK 217F⁽³²⁾.

2.3.1 Component failure rates in hard switching scheme

For hard switching control scheme component failure rates are calculated as below.

2.3.1.1 IGBT failure rate. I_{rms} = 3.73 A, $V_{CE(sat)}$ = 2.5V for selected IGBT

$\lambda_p = \lambda_b\ \pi_T\ \pi_A\ \pi_Q\ \pi_E$ failures /10^6 hours
Base failure rate = $\lambda_b = 0.012$
$P_{Static\_Loss} = V_{CE(sat)}$ X I_{rms} = 9.325 W
$P_{Dynamic\_Loss} = V_{avg}$ X I_{avg} X T_{on} X F_s =64.26 W
$P_{Total\_Loss} = P_{Static\_Loss} + P_{Dynamic\_Loss}$ =73.58W
At Tc= 30°c
Tj= Tc + (θjc X P_{Total_Loss})= 49.86°C
where θjc= 0.27
π_T = exp [-1925(1/Tj+273 - 1/298)]
= 1.78
Application factor $\pi_A = 10$
Quality factor $\pi_Q = 8$
Environmental factor $\pi_E = 1$
Part failure rate = λ_p = 1.7088

2.3.1.2 Diode failure rate. $\lambda_p = \lambda_b\ \pi_T\ \pi_S\ \pi_C\ \pi_Q\ \pi_E$ failures /10^6 hours

V_f= 0.7V, I_{rms} =3.5 A
λ_b = Base failure rate=0.0030
$P_{Static\_Loss} = V_f$ X I_{rms} = 2.45 W
$P_{Dynamic\_Loss} = V_{avg}$ X I_{avg} X T_{on} X F_s =56.26 W
$P_{Total\_Loss} = P_{Static\_Loss} + P_{Dynamic\_Loss}$ =58.71 W
At Tc= 30°C
Tj= Tc + (θjc X P_{Total_Loss})= 118°C
(where θjc= 1.5)
π_T = Temperature factor
= exp [-1925(1/Tj+273 - 1/298)]
= 4.66
Electrical stress factor $\pi_S = 1$

Contact construction factor π_C = 2
Quality factor π_Q = 8
Environmental factor π_E = 1
Part failure rate λ_p= 0.223

2.3.1.3 Capacitor failure rate. $\lambda_p= \lambda_b\ \pi_T\ \pi_C\ \pi_V\ \pi_{SR}\ \pi_Q\ \pi_E$ failures /10^6 hours

C= 1500μF, rated capacitor voltage = 600 V
Base failure rate λ_b = 0.00040
Temperature factor π_T = 1.1 at 30°c
Capacitance factor π_C = C $^{0.23}$= (1500x10-6) $^{0.23}$ =0.22
Voltage stress factor π_V = 2
Series Resistance factor π_{SR} = 1
Quality factor π_Q = 3
Environmental factor π_E = 1
Part failure rate λ_p = 0.00058

2.3.2 Component failure rates in soft switching scheme

For soft switching control scheme component failure rates are calculated as below.

2.3.2.1 IGBT failure rate. $\lambda_p= \lambda_b\ \pi_T\ \pi_A\ \pi_Q\ \pi_E$ failures /10^6 hours

I_{rms} = 3.35 A, $V_{CE(sat)}$ = 2.5V for selected IGBT
Base failure rate = λ_b= 0.012
P_{Static_Loss} = $V_{CE(sat)}$ X I_{rms}= 8.3 W
$P_{Dynamic\_Loss}$= V_{avg} X I_{avg} X T_{on} X F_s =34 W
P_{Total_Loss}=P_{Static_Loss}+$P_{Dynamic\_Loss}$=42.39W
Tj= Tc + (θjc X P_{Total_Loss})= 41.44°C
π_T = exp [-1925(1/Tj+273 - 1/298)]
= 1.46
Application factor π_A = 10
Quality factor π_Q = 8
Environmental factor π_E = 1
Part failure rate = λ_p= 1.40

2.3.2.2 Diode failure rate. $\lambda_p= \lambda_b\ \pi_T\ \pi_S\ \pi_C\ \pi_Q\ \pi_E$ failures /10^6 hours

I_{RMS} =3.21 A, Vf= 0.7V
λ_b = Base failure rate=0.0030
P_{Static_Loss} = V_f X I_{rms}= 2.247 W
$P_{Dynamic\_Loss}$= V_{avg} X I_{avg} X T_{on} X F_s =39.92 W
P_{Total_Loss}=P_{Static_Loss}+$P_{Dynamic\_Loss}$=42.16 W
At Tc= 30°C
Tj= Tc + (θjc X P_{Total_Loss})= 93.24°C
(θjc= 1.5)
π_T = Temperature factor
= exp [-1925(1/Tj+273 - 1/298)]
= 3.17
Electrical stress factor π_S = 1
Contact construction factor π_C = 2
Quality factor π_Q = 8
Environmental factor π_E = 1
Part failure rate λ_p= 0.152

2.3.2.3 Capacitor failure rate. $\lambda_p = \lambda_b\ \pi_T\ \pi_C\ \pi_V\ \pi_{SR}\ \pi_Q\ \pi_E$ failures /10^6 hours

C= 1500μF, rated capacitor voltage = 600V
Base failure rate λ_b = 0.00040
Temperature factor π_T = 1.1 at 30^{o}c
Capacitance factor π_C = C $^{0.23}$= (1500x10-6) $^{0.23}$ =0.22
Voltage stress factor π_V = 1
Series Resistance factor π_{SR} = 1
Quality factor π_Q = 3
Environmental factor π_E = 1
Part failure rate λ_p = 0.00029

Inductor and transformer failure rates are associated with environmental and quality factors hence their failure rates are same for both control schemes and are calculated as below.

2.3.2.4 Inductor failure rate. $\lambda_p = \lambda_b\ \pi_T\ \pi_Q\ \pi_E$ failures /10^6 hours

Base failure rate λ_b = 0.000030
Temperature factor π_T = 1.29 at T$_{HS}$ =46.5
Quality factor π_Q = 1
Environmental factor π_E = 1
Part failure rate λ_p = 0.0000387

2.3.2.5 Transformer failure rate. $\lambda_p = \lambda_b\ \pi_T\ \pi_Q\ \pi_E$ failures /10^6 hours

Base failure rate λ_b = 0.049
Temperature factor π_T = 1.29 at T$_{HS}$ =46.5
Quality factor π_Q = 1
Environmental factor π_E = 1
λ_p = Part failure rate= 0.06321

3 Results and Discussion

In this section total failure rate of converter is calculated,

3.1 Converter failure rate in hard switching scheme

Table 2. System failure rate in hard switching scheme

Device	**Part failure rate**	**Number of components**	**Total failure rate (λ)(failure /10^6 h)**
IGBT	1.7088	04	6.8352
Diode	0.223	04	0.892
Capacitor	0.00058	01	0.00058
Transformer	0.06321	01	0.06321
Inductor	0.0000387	01	0.0000387
Total failure rate			**7.7910**

MTBF= MTTF + MTTR (neglecting MTTR as, MTTF >>> MTTR)
= 1/ λ
= 128353.22
For hard switching control scheme, MTBF= 128353.22

3.2 Converter failure rate in soft switching scheme

MTBF= MTTF + MTTR (neglecting MTTR as, MTTF >>> MTTR)
= 1/ λ
= 159451.48
For soft switching control scheme, MTBF= 159451.48

Table 3. System failure rate in soft switching scheme

Device	Part failure rate	Number of components	Total failure rate (λ)(failure /10^6 h)
IGBT	1.40	04	5.6
Diode	0.152	04	0.608
Capacitor	0.00029	01	0.00029
Transformer	0.06321	01	0.06321
Inductor	0.0000387	01	0.0000387
Total failure rate			**6.2715**

Reliability calculations shows that converter has lower failure rate in soft switched control scheme at same power level and conditions.

4 Conclusion

Semiconductor devices used in high power applications like power switches, diodes and other devices like Capacitor are failure prone because they have to work on higher power levels. Continuous switching action of power switches makes them unstable and they become faulty. These semiconductor devices pass current in series through them. Once any single device becomes faulty it results in malfunction of the system. Hence, any control scheme having lesser chances of failure and with higher reliability is always a good choice for the power generation systems located at remote places. To address the issue, this study considered hard and soft switching control schemes and their effect on converter reliability. Soft switching scheme is more superior to hard switching due to lowered values of electrical stress on devices. Failure rate analysis reveals that soft switching offers better reliability over hard switching scheme. Failure rate of components like power switch, semiconductor diode and capacitor is higher in hard switching when compared to soft switching scheme, at same power level. Hence, soft switching control action in converters working at higher power levels, will help to enhance the system reliability.

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