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Fault Tolerance Enhance DC-DC Converter Lifetime Extension

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Abstract

One of the most crucial renewable energy sources today is solar energy. Power convertors play an important role in adjusting the output voltage or current of photovoltaic (PV) systems. Using efficient and reliable switches for power converters and inverters is crucial for enhancing the safety and reliability of a platform. Generally, power converters suffer from failure mechanisms, such as wire bond fatigue, wire bond lift up, solder fatigue and loose gate control voltage, which mainly occur in power switches. In this paper, the junction temperature of the Insulated Gate Bipolar Transistor (IGBT) acting as a power switch used in the Impedance-Source DC-DC converter is estimated using an electro-thermal model in order to develop an adaptive thermal stress control (ATSC). The proposed stress control adjusts reference input of the PI control to extend the life expectancy of the device under the mission. The accuracy of results present using The Modified Coffin-Manson Law has been used to determine the life of IGBT and the lifetime has been successfully increased base on implementing imperative ATSC and comparing the result with the constant reference input of the PI controller. The result integrates with converter health management to develop advanced intelligent predictive maintenance.

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Keywords: **Power Electronic Converter, EV, IGBT, Condition Base Monitoring (CBM), Remaining Useful Life (RUL), Prognostics, System Health Management (SHM).**

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I. INTRODUCTION

Highly-efficient and cost-effective integrated power electronic modules are one of the key elements of making solar energy cost-competitive with non-renewable forms of energy. On the other hand, due to increased demands for dynamically-controlled safety systems from customers, requests for a continuous monitoring system which tracks and identifies trends in and sources of component degradations prior to failure has been provided. This is because high product availability which is one of the main demands of customers could not be fulfilled by conventional maintenance strategies, such as corrective and preventive maintenance strategies [1]. Therefore, the reliability of these power electronic modules is vital for the commercial success of various types of renewable energy sources and manufacturers. In addition, it is prerequisites for the components to be available in downtime lifecycles. Certainly, this requirement has put a lot of effort into diagnostic and prognostic systems in real time service to determine when a component will fail [2]. Due to harsh environment conditions, particularly in hostile environments such as power conversion applications and their operating load conditions, IGBTs will be subject to electro-thermal and mechanical stress in situations where the early life stage is rapidly degraded [3]. As a result, high reliability becomes an essential issue in power electronic modules, which are a significant part in renewable energy applications such as wind turbine farms, biomass and solar panel technologies [4]. On the other hand, prevention of power electronic module failure is impossible. Therefore, creating real-time early failure prediction and online estimation of remaining useful life of used power electronic switches in renewable systems are essential. This requires us to take challenges in a) decreasing stress level of the active switch when it is in failure region, b) life extension of critical devices, and finally, c) increasing efficiency for Maximum Tacking Power Point, MPPT. However, to meet all these requirements, it is necessary to expand knowledge and techniques in the following areas:

- Topology of converter
- Critical component
- Dominant failure
- Failure stresses analysis

In compare with traditional converters, SEPIC DC-DC converters have been introduced as a suitable candidate for reducing the overall stress of active power switches at hard operating conditions, Fig. 1. This is because these new topologies gain from coupled inductors make them promising for the high voltage applications at a small demanding duty cycle. As a result, the noise and the ripple current that are important factors for any DC-DC converter are incredibly reduced. Furthermore, it uses less number of power switches, which as an advantage reduces power dissipation, essential in increasing overall reliability. However in spite of key advantages of such converters, the reliability of the SEPIC DC-DC converter during the degradation process occurring in the switching device (IGBT) have not been well investigated for industrial application e.g. PV.

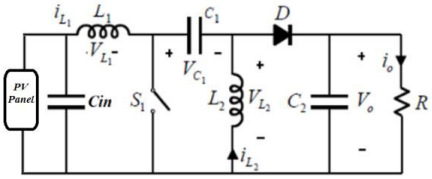


Fig. 1. SEPIC DC-DC Converter Topology.

It is widely known that power switches are the most critical components subject to thermomechanical stresses for any DC-DC converters including SEPIC converters. Potential of failure of various components used in the architecture of converters have been studied in the Military Handbook for Reliability of Electronic Equipment, MIL-HDBK-217F, summarized in table I [5]-[6]. As active switches are the dominant critical components subject to failure, so this paper mainly focuses on the reliability of power switches of SEPIC DC-DC converters. In this regard, experiments conducted by authors demonstrate qualitative thermal distribution at the surface of the SEPIC DC-DC converter using infrared Fluke thermal camera shown in Fig. 2. Our experiments have performed and corresponded to the input voltage 30V, 3A duty cycle 0.4, and 10 minutes duration. After the snapshot integration at the surface of PCB, the mean temperature is reading 64°C for the hotspot area detected around the IGBT and less amount of temperature reading for other components. This obviously ensures that IGBT is the critical component to high thermal cycling during its operation.

Table I: Critical Components in Power Electronics Applications

Component	Type
Active Switches	IGBT, MOSFET
Diodes	Schottky power diodes
Capacitors	Dry aluminum electrolytic capacitors

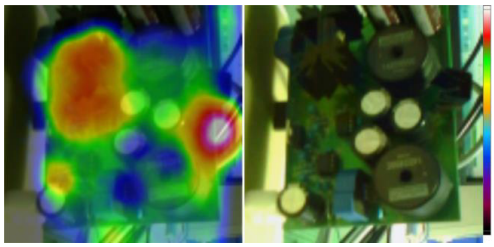


Fig. 2. Temperature measurement of proposed converter using Fluke Thermal Camera.

Reliability estimation of IGBT needs consideration during exposure to failure injection in a similar fashion to wire bond joint failure as the dominant failure in IGBT packaging. Increasing junction temperature with high-temperature change exposure causes die attached solder failure in short period and by long-term exposure to small temperature change causes wire bond solder joint failure. Therefore, each of these failure mechanisms has the different potential of failure rate and model base failure which increase the cost to have the overall lifetime estimation of the device in service. The current state of the art failure mechanisms of power electronics module (PEM), notably dominant failure based on packaging failures is wire bond lift off under cyclic thermal loading condition [7].

In order to enhance the reliability of SEPIC DC-DC converter, this paper aims to employ a physics of failure model of the active switch for reliability testing and implement stress reduction algorithm has fused with the critical control unit to improve the lifetime. This ultimately reduces the power dissipation for improving life cycle. To meet these key advantages, the main term vision of this paper contributes in:

- Reliability assessment by using the Coffin-Manson rule based physics of failure (PoF) model, which integrates the junction temperature of the device with the model. As a precursor parameter for monitoring the health state, the junction temperature is derived from the electro-thermal model to extend the lifetime of the IGBT in downtime [8].
- Stress minimization by introducing a radically novel approach to the development of an adaptive algorithm control for deceleration of the junction temperature stress. It focuses on the degradation data collected from simulation failure propagation conducted particularly for the power switch in the PV module applications under degradation process happening in the packaging failure mechanism.

In order to validate the result of ATSC, empirical equation Modified Coffin-Manson Law is used for calculation of the remaining useful life that improves design processes in making robust maintenance schedule policy and efficient reliability assessment presented for the life extension of the device.

Section 2 discusses damage profile model using physics of failure model (Coffin-Manson Law) for the IGBT life estimation. Section 3 describes control strategy for reducing the effect of thermal stress. The results of successfully lifetime extension after embedding control strategy are discussed in section 4. Conclusion remarks and future work is discussed in section 5.

II. Damage Profile Modelling Approach

The damage profile collection needs to run in real power cycles to test the lifetime of the device, which is impractical and requires long aging test time as IGBT life expectancy can last for millions of cycles. Since, the novelty of the paper is about to extend the lifetime of the SEPIC DC-DC converter by decelerating failure mechanisms; therefore, the damage profile collection needs to be run in real power cycles to test the lifetime of the device, which is impractical and requires long ageing test time as IGBT life expectancy can last for millions of cycles. Hence, in simulating, the aging mode is mainly related to wire bond failure has induced in a similar fashion to crack progression at solder joint by increasing the on-state resistance from 0.3Ω-0.75Ω. Junction temperature increases at 1 sec gradually as result of the potential of solder joint fatigue as an important failure mechanisms process in power electronic switches, as shown in Fig. 3.

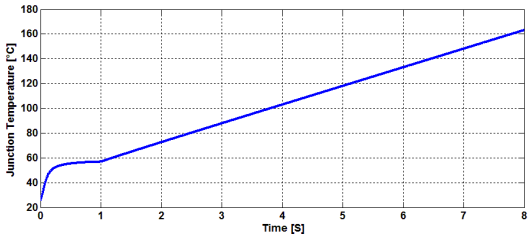


Fig. 3. Junction temperature estimation.

In this simulation, the ambient temperature is fixed to 24° C and for the switching frequency 16 KHz. The thermal stress fatigue is considered as the damage profile, which caused by cyclic temperature in solder joint. This phenomenon is susceptible to high-temperature thermal cycles, which initiate micro crack propagation incorporates the effect of the contraction going and compression going. The elastic strain stress law (e.g. the magnitude of thermal cycle ΔT) built up in the solder by n number of given ΔT over the entire temperature scale which can be extrapolated using Modified Coffin-Manson Law. This model incorporates a power law (e.g. Arrhenius model) to correspond the fatigue failure model, which can be expressed in Equation 13 [1].

$$N_f = f^{\beta}.\lambda.(\Delta T)^{-\alpha} \exp\left[\frac{E}{K.T}\right] \quad (1)$$

where f is the frequency of the stress cycle and, α, β are exponent term as the coefficients of the best fit for the model life time. The coefficient α range from 2 to 3 describe the effect of severity of the temperature change whereas, λ is the constants for material properties. In physic term as an exponential term is considering the Arrhenius effect E, K and T as the activation energy in eV, the Boltzmann constant ($1.38\times 10^{-23}\frac{J}{K}$) and the temperature of failure, respectively. The IGBT lifetime

consumed for different spectrum loading conditions (ΔT) as a stress is estimated by means of using Miner's linear cumulative damage rule, which states the failure phase as the following condition is met as shown in Equation 14[2]:

$$\sum_{i=1}^{k} \frac{n_i}{N_{f(i)}} = 1 \qquad (2)$$

where i is index, which varies within the range of the number of load in a spectrum $(1 \leq i \leq k)$ and n_i is the number of cycle IGBT that is exposed to i^{th} temperature swing whereas $N_{f(i)}$ is the fatigue lifetime for i^{th} load condition. In this paper, the effective stress range can be also identified using rainflow counting method, which is best suitable algorithm for counting the stress cycle from fatigue damage profile. The cycle counting presented in Fig. 4 for IGBT junction temperature shown in Fig. 15, which the number of cycle is expressed with the temperature swing amplitude by applied load profile within 1 second.

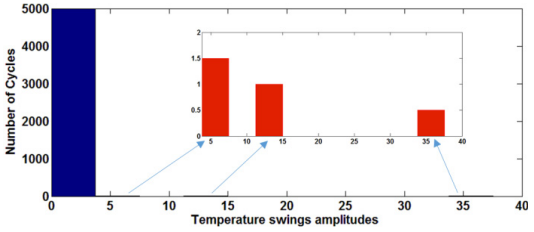


Fig. 4. The main flow histogram of IGBT junction temperature variations before applied stress control.

The life usage of the IGBT for the mission profile with predominant temperature stress swings is given in table II. The percentage lifetime consumed calculation for each thermal cycle stress uses Eq. 2 to estimate the fraction of total life. Apparently, The total IGBT life usage is significantly due to thermal variation stress smaller than 7.5 in this case which certainly has a number of thermal cyclic. To increase power cycling lifetime of the device requires adaptive algorithm as the thermal stress amplitude and the number cycle to failure proportionally reduces [11]-[12].

Table II: IGBT Lifetime calculation results

Temperature Swings	7.5<**ΔT**°C<11.3	11.3<**ΔT**°C<15	33<**ΔT**°C<37	**< 7.5**
Number of Cycles(n_i)	1.5	1	0.5	5000
Mean Temp°C	153	112	63	45
Number of Cycle to failure($N_{f(i)}$)	4.1370e+5	4.8743e+5	6.609e+5	1.7332e+5
Life Consumed%	3.6258e-4	2.0516e-4	7.5632e-5	2.8849
Life Consumed after 8 seconds	Almost 3%			

III. Adaptive Thermal Stress Control

In this paper, the stress control algorithm renders to mitigate the junction temperature variation, which generates a non-uniform distribution of hot spots and thermal stress. This approach assumes that IGBT is degraded as the switching losses relatively increases; that consequently raises Tj. This can refer to the process of the crack propagation in the solder as such the failure rate rapidly and significantly increases the PV downtime and maintenance cost. Observing junction temperature enables Adaptive Thermal Stress Control (ATSC) to manipulate with duty cycle (D) when the healthy state of device progress to a degraded state after a one-second simulation run. The duty cycle will be reached to 0.36 switching on at normal operating condition and after failure injection without affecting the adaptive control, see Fig. 5.

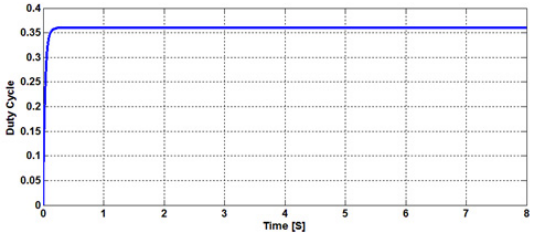


Fig. 5. Converter Duty cycles without control implementation.

Based on the previous discussion, junction temperature is affected by power losses, which are dependent on the power demands. In order to regulate the desired output SEPIC DC-DC converter, the output voltage is sensed and compared with V_{ref} as error input through PI controller to generate D in which then regulates a pulse width modulation (PWM) with the fix ±15 gate voltage (Vg). Switching frequency and gate emitter on state voltage are given from the power switch specification. Under the degradation process, the ratio between the on-state duty cycle and off-state duty cycle can be varied, and thus the power allocations. The control strategy is required under the failure propagation where the on and off duty cycle will be allocated properly in ATSC according to severity of the thermal stress, and varied by adjusting V_{ref} as a feedback parameter receiving from the output voltage of the MPPT. Thus, PI controller effectively is fed with updated V_{ref} according to the reference junction temperature ($T_{j_{ref}}$) which is set to a particular value depending on the IGBT characteristics. As a result, the estimated junction temperature gradient declines for entire target simulation in comparison with $T_{j_{ref}}$ for determined eight-second simulation performance. This results in improving the converter life expectancy in downtime by reducing thermal stress and has great interest in DC-DC power converters, as shown in Fig. 6.

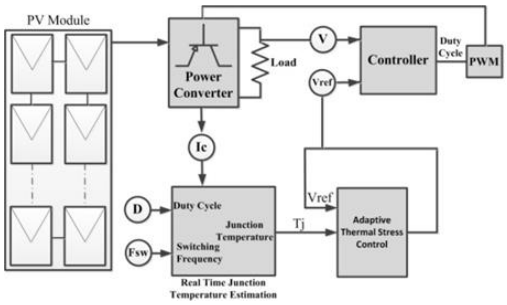


Fig. 6. Proposed schematic diagram of sensorless thermal stress reduction control.

The dominant failure mechanism of IGBT such as bond wire lifts up due to solder fatigue progression is injecting after one second, and it is noted that T_j of IGBT will raise up with slope at 15 and will exceed above the defined safe margin value (e.g. 125℃) as show in Fig. 3. The proposed ATSC is illustrated in Fig. 7 assumes thermal stress can be controlled after estimated T_j reaches to 60℃ where IGBT is in the normal operating region correspond to time before it is subjected to deterioration at around 1 sec. The PI control maintains duty cycle; see Fig. 5 before T_j rises above 60℃. To increase converter life time and maintain consistency with the IGBT operating in failure condition, the control region is designed to reduce the extreme operating condition from over temperature as duty cycle was regulated between 0.35 and 0.3 (see figure 8) which reduces a total of 40 ℃ for T_j. In order to intuitively decelerate the temperature rising with this slope, the proportional slope rate is given which V_{ref} is adapted and tuned in term of effective switching frequency (f_{sw}) rate 16.5 kHz of the device.

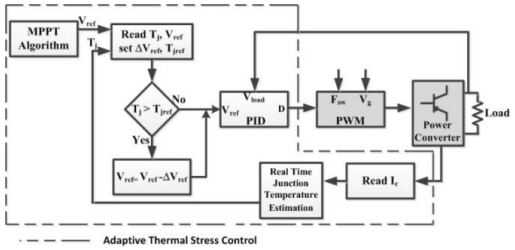


Fig. 7. Proposed schematic diagram of adaptive thermal stress reduction control algorithm.

IV. Lifetime Extension Results Discussion

As the slope is observed, ATSC immediately reduces junction temperature's slope, see Fig. 9 and clamp slope at 10 if the estimated junction temperature rises above $T_{j_{ref}}$ at 60℃. This will be happen by adjusting V_{ref} at 150V from MPPT algorithm with its dynamic response value ΔV_{ref}; however following the design specification, the output voltage's limitation does not halted under the appropriate value which distorts the power demand, as shown in Fig. 10. The adaptive stress control part keep the temperature below 125℃ which allows the IGBT operates in normal less stress condition till mission is on demand. Fig. 9 shows that the slope of T_j is successfully decelerated; wherein, the lower limits of the output voltage is set base on minimum acceptable output voltage performance as the least limitation of the load demand. Fig. 10 shows this lower bound has been set to 120V depending on the duty cycle, ensuring that minimum power can be guaranteed from the PV module, in addition reduces the risk of failure from thermal stress conditions. To compare ATSC has extended the lifetime of the IGBT. Furthermore investigation needs to perform by applying rainflow algorithm to junction temperature profile for calculating the device lifetime usage, as it is shown in Fig. 11. Interestingly, the device is incredibly consumes more lifetime cycle in the form of the inverse-exponentially dependent on the thermal stress variation amplitude as it is shown in Fig. 4.

The life usage of the IGBT for the mission profile after stress control applied with predominant temperature stress swings has been calculated and is given in table III.

Table III: IGBT Lifetime extension calculation results

Temperature Swings	2.2<**ΔT**℃<4.5	13.5<**ΔT**℃<15.8	20.4<**ΔT**℃<22.6	<2
Number of Cycles	**2**	**0.5**	**0.5**	**5000**
Mean Temp℃	**51**	**102.6722**	**64.2527**	**64.5008**
Number of Cycle to failure	**6.5700e+05**	**1.8921e+06**	**1.9934e+06**	**1.5279e+06**
Life Consumed %	**3.0442e-06**	**2.6425e-05**	**2.5083e-05**	**0.33**
Life Consumed after 8 seconds	**Almost 0.33%**			

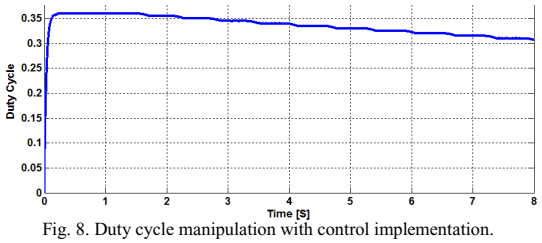


Fig. 8. Duty cycle manipulation with control implementation.

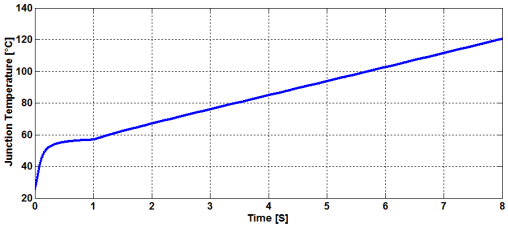


Fig. 9. Junction temperature reduction with control implementation.

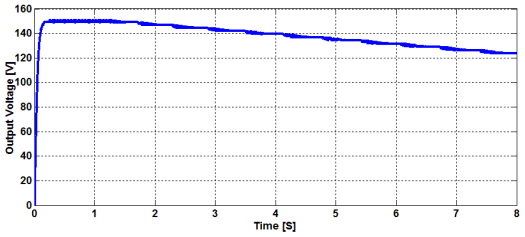


Fig. 10. Output voltage demands with control implementation.

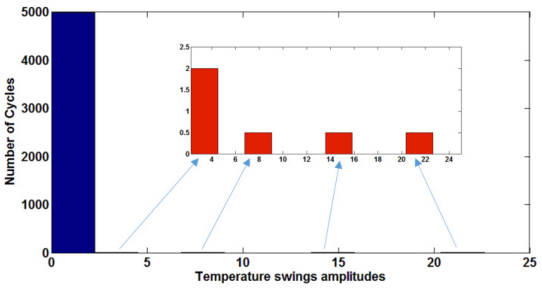


Fig. 11. The main flow Cycle counting for IGBT junction temperature stress in the PV after stress control.

The results show that the total life consumed by the device using thermal stress control is about 0.33% would mean the lifetime is extended by 9 times which extremely high improvement compared with when the duty cycle is not a function of thermal stress. Using proposed control approach has succeeded to minimize the temperature swings to less than 2. This will avoid converter reaches to catastrophic failure region, which reduce huge maintenance cost.

V. Conclusion

The main contribution of this paper successfully presented the development and implementation of thermal stress control for IGBTs with using the junction temperature as a reference input for the proposed adaptive thermal stress control (ATSC). Furthermore, it is proven an increasing life expectancy of the device by performing the Modified Coffin-Manson Law using estimated junction temperature as a precursor parameter. The IGBT model simulation is propagated with degradation model as function of on-state resistance ($R_{s_{on-state}}$) and switching frequency (f_s) and which causes the junction temperature (T_j) swings rapid. The life usage calculation is proved that the life relatively is extended by comparing with the results of without implementing thermal stress control. It is concluded that ATSC algorithm is adjusted V_{ref} for PI control to minimize the thermal stress. In contrast current state of the art thermal stress control, this paper presents an adaptive algorithm base on junction temperature variation to decelerate stress condition which improves the life usage during failure condition.

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