A review on real time physical measurement techniques and their attempt to predict wear-out status of IGBT

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This work is carried out to implement online voltage monitoring method to find out the wear-out status of power modules in converter operation. The work is conducted under the Intelligent Efficient Power Electronics (IEPE) and Center of Reliable Power Electronics (CORPE) project framework at Aalborg University, Denmark.

Keywords

«wear-out», «IGBT failures», «failure criteria», «lifetime model» », «real time measurement»», « V_{ce} measurement topologies»», «power converter»

Abstract

Insulated Gate Bipolar Transistors (IGBTs) are key component in power converters. Reliability of power converters depend on wear-out process of power modules. A physical parameter such as the on-state collector-emitter voltage (V_{ce}) shows the status of degradation of the IGBT after a certain cycles of operation. However, the V_{ce} mainly shows the wear-out of bond wire lift-off and solder degradation. The V_{ce} is normally used to estimate the junction temperature in the module. The measurement of V_{ce} is sensitive to the converter power level and fluctuations in the surrounding temperature. In spite of difficulties in the measurement, the offline and online V_{ce} measurement topologies are implemented to study the reliability of the power converters. This paper presents a review in wear-out prediction methods of IGBT power modules and freewheeling diodes based on the real time V_{ce} measurement. The measurement quality and some practical issues of those measurement techniques are discussed. Furthermore, the paper proposes the requirements for the measurement and prognostic approach to determine wear-out status of power modules in field applications. The online V_{ce} measurement for a selected topology is also shown in the paper.

Introduction

Monitoring an on-state voltage of switching devices is a potential method of preventing catastrophic failures of power modules and warning for the pre-failure replacement of devices. An online measurement is critical and difficult mainly due to a requirement of high degree of accuracy in small signal measurements in the kV and kA current switching for high power converters. The V_{ce} measurement gives early indication of bond wire failures, but it requires a accurate measurement due to a small change in the voltage on each bond wire lift-off as shown in Figure 1. The measurement of thermal resistance gives hint for the detection of a solder wear-out. In IGBT, the temperature sensitive electrical parameters (TSEPs) are on-state voltage drop, threshold voltage, breakdown voltage, saturation current, leakage current, trans-conductance and turn-on or turn off energy loss with respect to time [1]. Among them, the on-state V_{ce} allows determining virtual junction temperature of the IGBT chip [2].

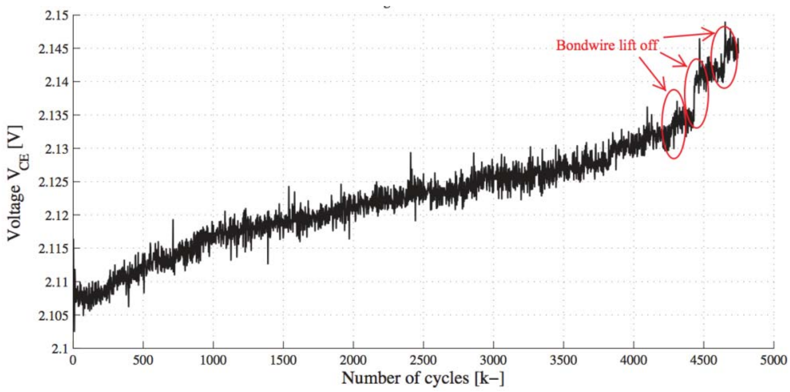


Fig. 1. Measurement of IGBT's on-state V_{ce} during power cycling (1000A, 1700V IGBT module) [3]

Power cycling tests are used to generate thermo-electrical stresses in accelerated lifetime test methods. The tests apply rated or higher level currents either rectangular or 100Hz half sign wave shape, to create thermal cycles in the device [4]. In power modules, the change in junction temperature has a bigger influence on the device life than the actual junction temperature [4]. In contrary to other research, the power cycling life of diodes is shown shorter than that of the IGBTs [5]. Specifically, the purpose of the power cycling test is to understand ageing and failure mechanisms of power modules in a short period of time. Hence, the wear-out data obtained from the short period test is useful to monitor and find the status the module in a field application. In most cases, it is better to de-rate the converter power level (or stop operation) after obtaining indications of a certain wear-out of the power modules. This kind of de-rating is only possible with some sort of advance prediction of the wear-out status. The online wear-out measurement of the power modules for the field applications are not discussed yet. Some difficulties for online measurement in PWM switching power converters are discussed by Smet et al. [6].

Realizing the above mentioned fact, this paper presents a review of online measurement technique to estimate life time of high power IGBT modules. Initially, this paper highlights the wear-out parameters in the power modules and criteria to indicate wear-out prior to breakdown. Then, previous online measurement techniques are discussed. The selected V_{ce} measurement topologies are presented to highlight the issues for the field implementation. Furthermore, the detection of wear out status and a review of analytical lifetime models are presented. Finally, the requirements of the real time measurement and prognostic methods are discussed.

Wear-out and failure criteria

The structure of power IGBT modules consist of multi layers of different packaging materials with coefficients of thermal expansion (CTE) that are not perfectly equal. The CTE varies from $2.6\cdot10^{-6}$/K for silicon to $223.5\cdot10^{-6}$/K for aluminum [7]. The major failures in standard IGBT modules are: bond wire lift off, solder fatigue joint, bond wire heel cracking, aluminum reconstruction, Cosmic ray induced failures [8] and in press pack IGBT modules: fretting damage, spring fatigue, spring stress relaxation, cosmic ray induced failures [9].

The failure occurs at different components of the IGBTs, which depend on the thermo-electrical loading such as average temperature, temperature swing and the voltage. The known failure mechanisms, failures and corresponding thermo-electrical stresses are summarized in Table I.

Table I IGBT failures and major stressors

Failures	Thermo-electrical stress	Failure mechanisms
Bond wire lift-off	ΔT, Tm, ΔT/dt	Bond wire fatigue
Solder joint	ΔT, Tm, ΔT/dt, ΔH	Solder joint fatigue
DCB substrate	ΔT, Tm, ΔT/dt, ΔH	Ceramic cracks
Metallization	T, J	Electro-migration

Where, ΔT: temperature swing, Tm: mean temperature, ΔT/dt: temperature slope, ΔH: humidity and J: current density

Table II shows the wear-out and failure criteria for IGBT based on two major TSEPs measurement. A clear distinction should be made between the ageing limit for the safe operation of the module and the failure criteria. A failure criterion is the critical limit of the ageing, further operation after the criterion is malfunctioned the module [10].

Table II. Wear-out status and failure criteria

Increment in on-state voltage	Failure criteria	Increment in junction to case thermal resistance	Failure criteria
3%	Wear-out started	5%	Wear-out started
5%	Early failure	10%	Early failure
10%	Early failure	20%	Failure criteria
20%	Failure criteria		

The wear out detection and failure criteria for different TSEPs are summarized in Table III.

Table III. Wear-out detection criteria of IGBT

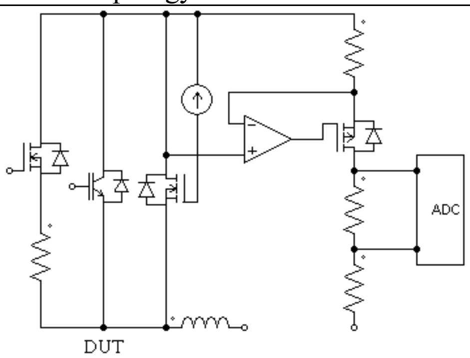
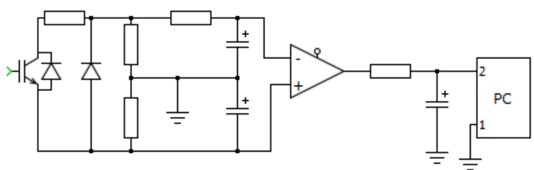
Parameter	Failure Criteria	Remarks
V_{ce} measurement [3]	Increase in 40mV is detected in power IGBT module before it is failed. The module is rated at 1000A, 1700V. 20% increase in V_{ce} from its original value is considered in [6]. General rule of thumb is, $\Delta V_{ce}\ \% = 1500/I_{rated}[A]$ For 300Amodule, failure criteria is 5% increment on V_{ce} [10]	Offline measurement of V_{ce} on each cycle. The measurement needs more operating points of the cycle to identify the wear-out status in the voltage versus number of cycles curve.
V_{ce} and junction to base plate thermal resistance [11]	V_{ce} has risen by 2 – 3% and R_{th} has risen by 10%.	Smaller voltage change has chosen to reduce the test duration. Bond wire lift-off and heel cracking damages are related to the V_{ce} [11]
Forward diode voltage measurement [5]	Increase in voltage on each bond wire lift-off.	This is not useful for a simple DC power cycling test
Chip/Junction temperature measurement [12] V_{ce} as TSEP [12]	Build junction temperature versus number of cycles to failure.	The module needs to calibrate separately prior to the test. Calibrate module at different temperature.

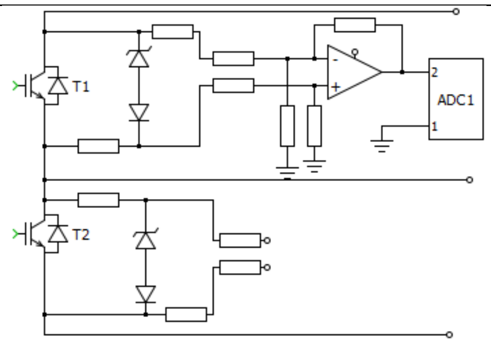
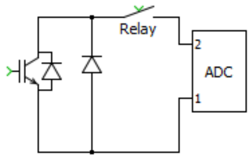
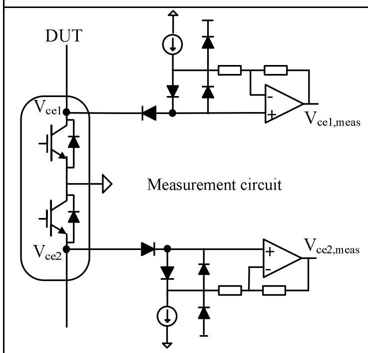
Junction to case and junction to water thermal resistances measurement [13] Junction to case thermal resistance	A lowest failure criterion is when the junction to water thermal resistance is increased by 10% of the initial value. The failure criterion is 20% increment of the junction to case thermal resistance [14, 15].	A detail thermo electrical model is required. This is a failure indicator for the DCB delamination and the solder layer fatigue. A potential error in the case temperature measurement due to non-uniform distribution.
The on state V_{ce} voltage drop by 17% and followed by instant increment [16]	The solder joint degradation due to increase in junction temperature before the bond wire lift-off.	The V_{ce} shows a negative temperature coefficient for this range. This is the unique measurement.
Ringing characterization [17]	More damped ringing characterization for the wear-out module.	This method is useful to diagnose the wear out of module separately.

V_{ce} measurement topologies

In field applications, the power module experiences different stresses due to external factors such as environment, temperature, vibration etc. The online measurement topology built for the field application should take consideration of the irregularly changing external factors. Table IV summarizes the circuit topologies used for the V_{ce} measurement of power devices in laboratory tests. Most of the literatures do not mention further provision to apply those techniques for the field applications.

Table IV. Circuit topology for measurement

Circuit topology	Operating limitations
 Fig. 2 V_{ce} measurement circuit using MOSFET	Two stages, one for high side IGBT and another for low side IGBT. Includes V_{ce} clamp to limit the measured voltage in the off state, current sink for an indirect temperature measurement and voltage to current converter [11]. The risk is that the false switching of a MOSFET may short circuit the power module.
 Fig. 3 V_{ce} measurement circuit using diode clamp	The voltage variation across the diode during high temperature variation creates measurement error [18].

 Fig. 4 V_{ce} measurement circuit using diode and thermal compensation	The zener diode will be useful for the thermal compensation of the power diode. The zener adds limitation for the high voltage measurement [19].
 Fig. 5 V_{ce} measurement circuit fast switching relay	The relay switching is not fast enough to record the on-state voltage of the IGBT. Fast switching is necessary to record the on-state voltage during power conversion in a real time [3].
 Fig. 6 V_{ce} measurement circuit for online measurement	The circuit is able to block high voltage and protect from the switching transients. The clamping diodes limit the voltage magnitude in the worst case switching situations.

As discussed above, the measurement circuit needs to design carefully in order to reduce the intrinsic and extrinsic noises in the real converter operation. During an operation, the circuit components mainly suffer from the following noises as listed below.

1. Thermal noise: This noise is generated by random motions of electrons and the magnitude of thermal noise increases with the temperature.
2. Radiated noise: This noise is generated from the switching operation of the IGBT and the emitted electro-magnetic interference (EMI) noise couples with the signal.
3. Offset voltage: The operational amplifier introduces offset voltage. This amplitude varies with the temperature.
4. Ground loop: The noises coupled with the signal through ground loop in the measurement circuit.

The on-state voltage drop of IGBT is a function of the junction temperature, the collector current and the gate-source voltage as shown in equation 1 [20]. The on-state voltage of IGBT is a combination of both voltages with a positive and a negative temperature coefficient. At low current, the voltage is the negative temperature coefficient. Hence, for real time measurement, the TSEP should be calibrated in the converter. However, the accurate calibration is difficult to obtain due to self-heating of the high current injection and the parasitic. [20, 21, 22]

$$V_{ce} = V_{be(th)} + R_{on(th)} \times \frac{I_{ce}}{1+\beta_{PNP}} \quad (1)$$

The online V_{ce} measurement circuitry should fulfill the following criteria for the field application,

1. Voltage level: The voltage blocking components should withstand module rated collector-emitter voltage level
2. Physical distance in the measurement board: Minimum requirement is 10mm for 1000V
3. Self-protection circuit: Protect measurement circuit from high transient current and voltage
4. Isolate circuit during fault (avoid fusing): Circuit should stop operation after a fault in the measurement circuit
5. Not sensitive to thermal coupling to other components: Avoid offset voltage due to change in the ambient temperature
6. Less offset voltage: No offset in the measurement
7. Low impedance: Circuit should not change the behavior of gate impedance of the IGBT

The circuit shown in Figure 6 is built to meet the primary requirement for the online V_{ce} measurement. The circuit do not introduces noises in the existing gate driving circuit. The circuit is tested at the H-bridge converter, which is built to realize similar stress as the converter for the DFIG in wind power converter. [3] [23] The converter parameters are given below,

DC link voltage: 1000V, Load voltage: 315V$_{(RMS)}$, Load current: 890A$_{(peak)}$, Output frequency: 6Hz, Switching frequency: 2.5kHz, Water cooling temperature: 80±1°C

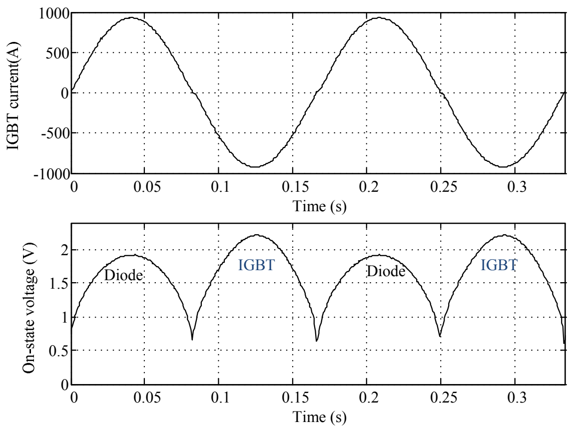


Fig. 7 Real time measurement of the current and on-state voltage for low side IGBT, freewheeling diode

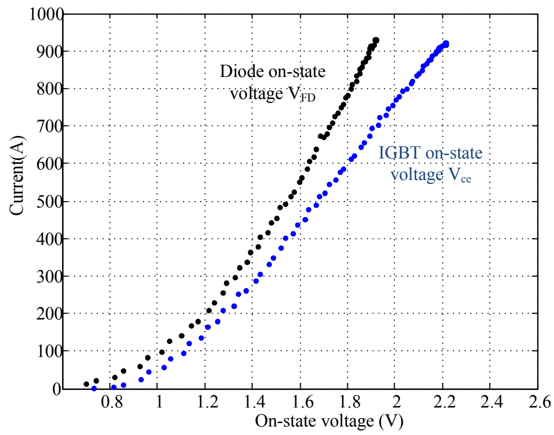


Fig. 8 Real time measurement of output characteristics of IGBT and diode on the low side

Figure 7 shows the real time on-state voltage drop on a low side of the half bridge IGBT module at 70°C water cooling temperature and the gate-emitter voltage is at 15V. The half bridge IGBT module is rated at 1000A and 1700V. Figure 8 shows the output characteristics of the half bridge module for the IGBT and freewheeling diode while the converter is in the operation.

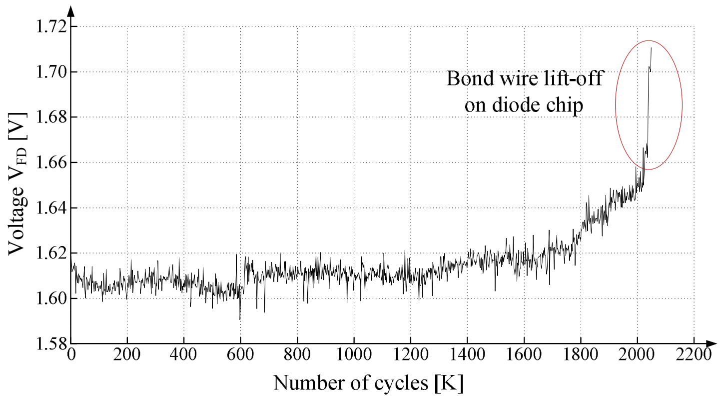


Fig. 9 Diode voltage increases before the module explodes

Figure 9 shows the on-state forward voltage (V_{FD}) of the diode after 96 hours of the converter operation. The measurement is taken in an unregulated room temperature. The V_{FD} is increased suddenly close to 50mV after $2.6 \cdot 10^6$ cycles of the operation. The step increased in voltage shows the sign of bond wire lift-off before the module is exploded. In this test, the diode is failed earlier in the module.

Wear-out status and lifetime

A gradual degradation of IGBT can be assessed after long hours of operation at normally loaded conditions. Usually, the wear-out of IGBT is classified as a chip related and a package related failures. Both the failure mechanisms are associated with each other. However, the package related failures such as bond wire lift-off and solder fatigue are predominant cause of failures in wind power converters. Therefore, in comparison to the chip related failures, the package related failures are used to monitor the wear-out of the IGBT modules. Normally, a prognostic health monitoring approach is used to obtain the wear-out status and to predict the failures of the IGBT. The ageing parameters for the failure mechanisms are given in Table V.

Table V IGBT failures and corresponding wear-out parameters

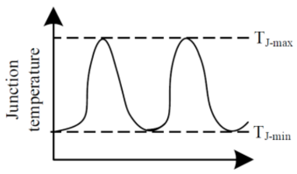
Failures	Failure parameter	Wear-out	Test methods
Time dependent dielectric breakdown and gate oxide degradation	Gate threshold voltage, capacitance voltage and leakage current [24, 25, 26]	An increase in temperature leads to a decrease in the band-gap of the silicon, which reduces the threshold voltage.	Offline
Bond wire lift off	V_{ce} and R_{on}	The ageing increases the on-state voltage drop and the resistance.	Online and offline
DCB and solder fatigue	Thermal resistance	The ageing increases the thermal resistance.	Online and Offline

As discussed earlier, materials and solder joint degradations are the weakest parts in IGBTs due to the thermo-electrical stresses. Based on the stresses and material properties, some analytical lifetime models are developed to estimate the number of cycles to failure of the power modules [27]. The analytical models give estimation of number of cycles to failure corresponding to the major stressors. The analytical models are listed below.

1. Coffin-Manson model: main stressor is a junction temperature swing

2. Modified Coffin-Manson model: main stressors are junction temperature swing and mean temperature
3. Norris-Landzberg model: main stressors are junction temperature swing, mean temperature and frequency
4. Bayerer's model: main stressors are junction temperature swing, mean temperature. This model also uses other model parameters such as on-state time, current, voltage and duty cycle.

$$N_f = a.(\Delta T)^{-n}.e^{\left(E_a/K*T_m\right)} \qquad (2)$$



$$\Delta T = T_{J-max} - T_{J-min}$$
$$T_m = T_{J-min} + \Delta T/2$$

Figure 10: Junction temperature

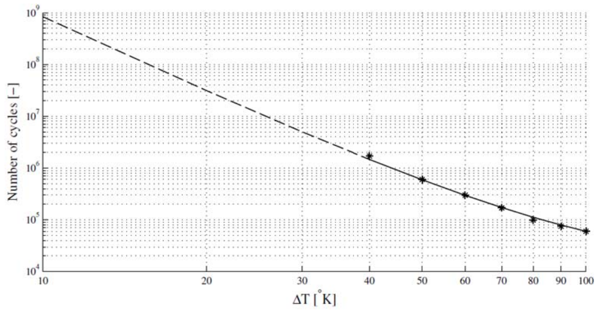


Figure 11: Coffin-Manson law plot

The lifetime of the power modules is highly dependent on the stress level. During accelerated life time test, the stress is increased by raising the accelerated factor. However, in the field application, the stresses vary with the types of load. The shape of temperature cycles strongly effects to the lifetime of the IGBT [28]. The modified Coffin-Manson relation as in equation 2 is close to reflect the lifetime, which uses cyclical stress and temperature change as stressors [8]. Figure 10 shows a trend of number of cycles to the failure with respect to temperature as estimated from figure 11. However, the Coffin-Manson does not consider the frequency and slope of the junction temperature for the lifetime estimation. Moreover, it doesn't include other parameters and characteristics of the converter. The Bayerer's analytical model uses influence of the various parameters from the power cycle test including module characteristics but the model doesn't comply with the experimental results [29]. The estimation of number of cycles to failure of power modules based on above analytical models may vary due to various reasons.

1. The analytical models are developed under specific loading conditions, which do not necessarily comply with the field conditions.
2. The parameters required for the model are not available in every test.
3. The interactions between the failure mechanisms are not included in the model.

A combination of physics of failure analysis and online measurement of the power module is essential to obtain the wear out and lifetime estimation of power modules. Recently, to meet above mentioned requirements a new fusion prognostic method is proposed. This method monitors the weakest parameter of the device and uses them to estimate the remaining useful life based on the healthy and long term test data [30]. However, for a real life application, this method needs an accurate measurement and should consider the effect of change in the ambient temperature.

General diagnostic approach such as cause of failures, failure at bonding, emitter metallization and solder are specified when V_{ce} is increased by a few percentages by Smet. et.al [11]. The number of cycles were recorded on each level and predicted failure mechanism such as bond wire lift-off, heel cracks etc. The criteria as mentioned in the Table I, help to detect degradation status of power modules. However, the V_{ce} monitoring method most provides the wear-out indication sufficiently in advance to the failure of the module to protect it from further destruction.

Discussion

The real time wear-out monitoring is essential to increase the reliability of power converters for the filed operation. In addition to the above mentioned requirements, the accuracy of the V_{ce} measurement is expected close to 5mV for high power IGBT module. However, it is a challenge to obtain millivolts accuracy, because the off-state voltage crosses typically 100V to 1200v for 1700V IGBT module. The V_{ce} measurement circuit as shown in figure 6 is designed to meet the requirements for the online measurement in the converter operation.

Power cycling test applies square wave thermal cycle in the power device. However, in the field operation, the thermal cycling will not be the same always. Similarly for steady-state PWM switching operation, the fundamental thermal cycle of a DC-AC converter will vary with the fundamental frequency of the output voltage (and current). Therefore, the measurement technique in figure 6 is tested to know the wear-out status in the realistic operation.

The material degradation and wear-out of a power module is inevitable due to the CTE mismatch between dissimilar materials and the temperature cycling. The accurate measurement and prediction of the degradation of the module will allow to stop or to de-rate the converter in a smart way, which can be used to increase the operating period of the system. Thereby, it could be possible to avoid severe damage, and perhaps also non-scheduled service. The smart de-rating functionalities must be adopted for the different types of application, e.g. wind turbines, tractions, marines etc.

Conclusion

This paper highlighted a review of the major failures and failure criteria to detect the degradation in high power IGBT modules. The measurement topologies to detect the wear-out and failure of the IGBT for online and offline implementations are shown. The major limitations for the measurement circuits are to block the high voltage during off-state, avoid short circuit during the switching operation and not to add additional noises in the switching gate pulse. The online V_{ce} measurement for the selected measurement topology is presented. The previously developed analytical models to calculate the number cycles to failure and their shortcomings for the online implementation are discussed. At the end, a recently emerging prognostic approach is mentioned, which is implementable for the real time wear-out measurement of the high power module in comparison to other methods.

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