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Article

An Analysis of Failures and Practical Possibilities of Diagnosing IGBT Transistors in Converter Circuits of Marine Propulsion Systems

Radosław Gordon [1,*] and Artur Bejger [2]

[1] Faculty of Mechatronics and Electrical Engineering, Maritime University of Szczecin, Wały Chrobrego 1-2, 70-500 Szczecin, Poland; r.gordon@am.szczecin.pl
[2] Faculty of Mechanical Engineering, Maritime University of Szczecin, Wały Chrobrego 1-2, 70-500 Szczecin, Poland; a.bejger@am.szczecin.pl
* Correspondence: r.gordon@am.szczecin.pl; Tel.: +48-509-113-573

Abstract: The article presents the results of tests related to failure analysis and finding ways to diagnose used semiconductor elements, among other, in power electronics converter systems on vessels and offshore facilities (drilling and production rigs, wind turbines). Diagnostic relationships were found between the temperature change in the above systems and the signals generated in form of elastic waves of acoustic emission.

Keywords: acoustic emission; sensor; transducer; gate turn-off thyristor; power electronics

1. Introduction to the Subject Matter

Modern sea-going ships are autonomous objects in terms of energy, with limited resources of energy and power. At present increasing number of ships gets equipped with electric propulsion systems powered by a diesel engine, much less frequently by a package of batteries. Newbuilds with electric high-power main propulsion generally utilize synchronous motors, installed for example in podded propellers [1]. From the power electronic perspective, they are controlled and powered by current and voltage converters. Semiconductor elements utilized in power electronic converters include half-controlled thyristors (SCR), gate turn-off (GTO) and integrated *gate-controlled* thyristors (IGCT), or integrated gate bipolar transistor (IGBT) and injection-enhanced gate transistor (IEGT). The power range of offered and already installed electric main propulsion exceeds 20 MW, which requires increasingly higher voltage of marine power plants, up to 15kV. At the same time, attempts are being made to employ greater currents of conduction at lower losses, higher reverse voltages and better dynamic properties (higher frequencies of switching) [2,3].

The lifetime of a power electronics system is determined by the characteristics of the system components such as the capacitors, gate drivers, insulated-gate bipolar transistors etc. [4,5]. Of these, the IGBT is the main component that affects the lifetime of the entire system. The current flowing across IGBT's determines the temperature variation, and the failure of the transistor structure depends on the thermal behavior [6,7,8]. The junction-temperature swing leads to repetitive thermomechanical stresses in the IGBT module, which accumulates as fatigue on the device [9,10,11].

The failure of bond wires distorts the current flowing to the IGBT module and accelerates the bond-wire liftoff and the cracking of the remaining bond wires [12]. These failures lead to open-circuit failure or catastrophic failures of switching devices such as thermal runaway and semiconductor-chip destruction. Additionally, the temperature variation leads to solder-joint fatigue [12,13]. There are two solder joints in the standard IGBT module: between the IGBT chip and the direct bonded copper (DBC) substrate and between the DBC substrate and the baseplate. Owing to the changes in the coefficient of thermal expansion caused by the temperature variation, thermomechanical stresses are applied to the solder joints, thus degrading the solder interface, e.g., causing cracks and delamination.

2. Marine power electronic switching systems

The need to find a solution of a switch and signal amplifier working faster with smaller conduction losses, relatively simple to make, brought considerable progress in research into IGBT transistors. In high power drives, the frequencies of IGBT switching oscillates between 1 kHz to 3 kHz. Increased frequency of switching reduces the current and unwanted voltage harmonics, as the voltage waveform gets closer to the sinusoidal. Increasing the frequency of switching results in greater losses, and consequent heating of the semiconductor element.

In power electronic propulsion systems, particularly in specialized offshore ships or drilling platforms, high reliability and protection of all critical infrastructure equipment is required. These critical units include propeller systems, positioning systems along with drilling and production processes, and few significant other.

A typical topology of a propulsion system equipped with podded propellers powered by power electronics converters is given in Figure 1.

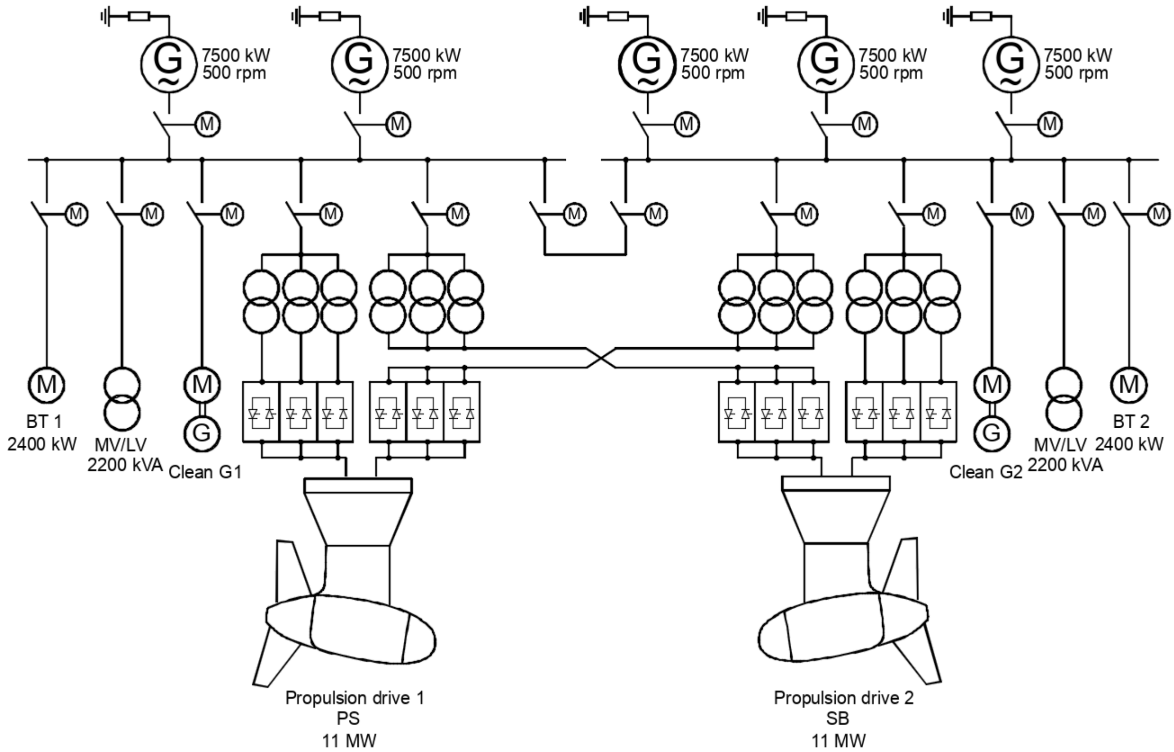

Figure 1. An example diagram of pod thruster propulsion components his is a figure.

Although most critical marine power electronics devices are doubled, i.e. at least one identical system is installed in parallel, allowing instant switching to take over the load, the specific conditions lead engineers to seek even higher reliability of electronic systems in use. Difficult working conditions of these devices are an additional factor increasing the research problem. The harsh marine environment (high humidity, salt content in the atmosphere) also affects the failure rate of the systems.

The possibility of diagnosing the above modules or anticipating the condition of devices is an essential problem from the economic and safety perspectives, raised by many

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operators. Figure 2 presents the range of marine power electronic system parameters [3, 14].

An analysis of the working range of marine power electronic instruments shown in the Table 1 indicates clearly that these factors are an important element of marine converting devices.

IGBT transistors are commonly used in ship propulsion control systems, medium power converters and power management control systems and active filters in compensation systems.

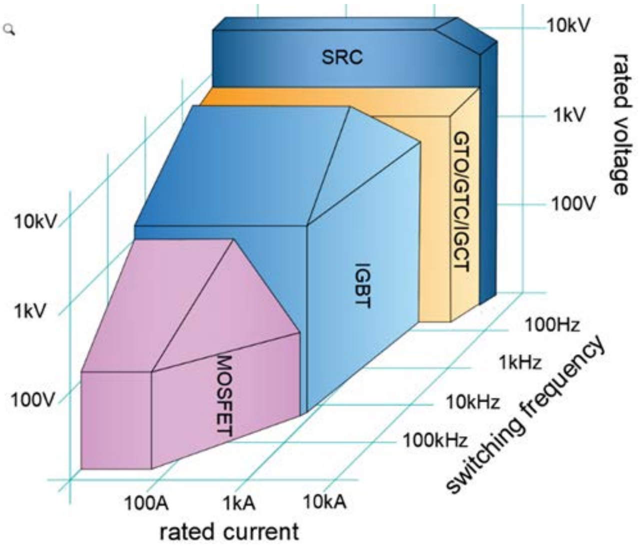

Figure 2. The range of marine parameters of silicon power electronic devices [3, 14].

There is a growing need for research in pursuit for the possibility of diagnosing semiconductor circuits (those used at sea) while operation. In the [15] the effects of turning off current on the low and high frequency components of generated internally acoustic emission waves were studied. Linear relationship was found between the low frequency component and the turn-off current, and the low frequency component could closely follow the change of turn-off current, showing that the low frequency component was strongly related with turn-off current. The research herein presented confirms the results related to the use of acoustic emission signals in examining IGBT transistor switching. The stability and operation of the IGBT evaluated by measuring the saturation voltage drop, the off current and the switching off time as the measurement parameters was presented in [16]. A comparative study of SiC based MOSFETs and Si based IGBTs regarding changes in their junction temperature in a PV inverter application along with the junction temperature of semiconductors, which allow determining and comparing the thermal constraints in SiC type MOSFET and Si based IGBT power modules was shown in [17]. The presence of electromagnetic interferences in the AE measurement and its contribution to the signals obtained in the GTO thyristor was shown in the [21].

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Table 1. The Range Of Working Parameters Of Marine Power Electronic Silicon Devices [3,14].

Device name	Highest rated voltage	Highest rated currents	Application
SCR thyristors	to 18 kV	to 6 kA	Highest power converters (to 100 MVA) used in transmission systems, DC high voltage
Light-triggered thyristors (LTT)	to 8 kV	to 4 kA	
Gate turn-off thyristors (GTO)	to 6 kV	to 6 kV	Highest power converters (to more than 10 MVA) used mainly in controllable AC drive systems and transmission networks
IGBT transistors	from 0.6 kV to 6.5 kV	from 10 A to 3.5 kA	Medium power converters (to several MVA) mainly for propulsion systems and active compensation systems
IEGT transistors	to 4.5 kV	to 1.5 kA	
MOSFET transistors	from 20 V to 1.5 kV	from 1 A to 500 A	Low power converters (below 100 kVA)

3. Power electronics modules and their properties

Power modules are generally designed and produced so that they meet the typical operational and service life requirements. Following technical requirements (e.g. electric, thermal, mechanical, costs, dimensions, etc.) one typically attempts to solve the problem by using one objective of optimization, i.e. the maximization of IGBT modules lifetime when only one specific failure is considered. In practice, the IGBT module is usually subject to combined effects of vibrations, fatigue, and temperature.

Third generation IGBT transistors allow the junction to work in higher temperatures. Commonly, catalogue data indicate a working range up to 150°C. This is essential due to problems with heat transfer and dissipation. Thermal resistance between the junction and the housing is similar in MOSFET transistors (in the same kind of case), which results from the similarity of the semiconductor structure. The temperature impact on all electrical parameters is also important so the manufacturers must provide efficient way of cooling semiconductor structures. Table 2 presents various failure mechanisms of the IGBT module. As it is shown in [9,13] temperature issues (T and ΔT) are the main cause of power electronics devices damages.

Bipolar transistors show a negative voltage saturation coefficient (MOSFET transistor - positive resistance coefficient of the switched-on channel). For an IGBT, the temperature coefficient of this parameter is close to zero while slightly negative in the low current area, and slightly positive in high currents. The most important, however, is the conclusion that IGBT transistors of the same type and parameters can be connected to work in parallel. These transistors are also more resistant to destruction due to thermal runaway, as no current density concentration occurs in the 'hotter' area of the transistor channel. IGBTs also do not have a parasitic connection, forming an 'anti-parallel' diode. Depending on the application, this can act as an advantage or drawback of a structure. Usually, the semiconductor switch works in the circuits of commutation with inductive load. Such a diode is required to recover energy collected in inductance when transistor off-state. In the case of IGBT switches, an external freewheeling, fast recovery diode is required.

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Table 2. Failure for mechanism of the IGBT module [13,18].

Failure mechanism	Failure Site	Failure Mode	Main cause
Bond-wire fatigue	Bond wires	Open circuit	*ΔT, T*
Metalization	IGBT and diode	Open circuit	*ΔT, T*
Solder fatigue	Solder joints	Open circuit	*ΔT, T*
Gate-oxide failure	IGBT oxide	Closed circuit	*T, V, E*
Burnout failure	IGBT and diode	Closed circuit	*T, E,* overvoltage

Where: ΔT – temperature swing; T – temperature; E – electric field

The reliability of IGBT transistor depends, inter alia, on well-devised protection circuits. Practically every failure of a device working in the switch mode ends up with a failure of the switching component. The IGBT transistor is a voltage-controlled element. From electrical point of view, it can be roughly stated that gate circuit represents capacitance, and this parasitic parameter should be examined for possible transistor failure. The capacitance is not constant and contributes to the emitter-gate and gate-collector junctions. The former should be quickly recharged due to fast control, while the latter is the cause for the negative feedback phenomena which additionally slows down the process of gate overcharging.

In the case of high current switching at relatively significant frequencies, the gate driving is quite complicated process. With mid to high switching frequencies due to internal parasitic capacitance gate currents can get notably high within wide voltage range. To optimize the control process, the voltage source along with resistance in the gate circuit can be applied, which is shown in Figure 3.

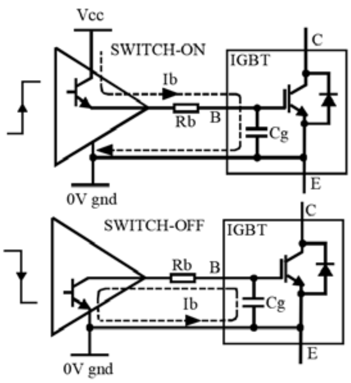

Figure 3. The circuit of gate voltage type driver, recharging internal gate capacity.

The presence of negative voltage is usually a problem. Practice shows that the collector currents up to 100 A, negative voltage is practically not present. Manufacturers catalogues usually give strict recommendations in this respect, while the resultant driver is the simplest possible one (Fig. 4). However, there are at least two problems here. One is the presence of capacitance between the gate and collector, known as Miller capacity, due to the Miller effect of this capacitance.

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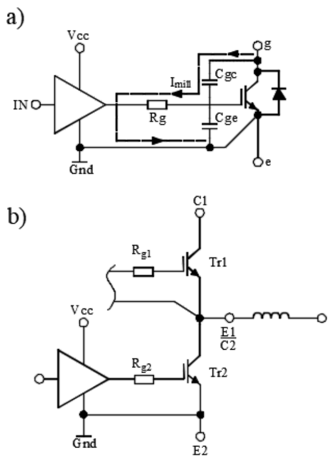

Figure 4. The example of the IGBT transistor driver with marked parasitic capacitances (a) and (b) parasitic inductances in the emitter circuits of keying transistors.

This is an effect of local negative feedback, which slows down switching process. Moreover, transistors switches in high power circuits usually work in pair utilizing bridge or half-bridge configurations. In such cases, turning off one transistor may cause false switching on the other, due to Miller capacitance. C_{gc} which makes up a divider along with R_g. If the voltage on this divider exceeds the threshold level of gate voltage, the transistor will turn on. The risk of unwanted firing up transistor increases as temperature rises, because in such condition the threshold level slightly decreases.

That is main reason the lowest possible values of resistance R_g should be used to prevent this phenomenon and when this is insufficient, negative voltage should be used. This is one of the practical conclusions, resulting from the mentioned theory. A similar risk giving the same effect inevitably results from the parasitic inductance present in the transistor emitter structure, particularly significant for currents reaching hundreds of amps and pulse steepness expressed in kV/μs. Even when the transistor is switched off, considerable currents can flow, recovering energy through freewheeling diodes. The dI/dt in the circuit of one key will be transferred to the circuit of the other, inducing negative voltage on its emitter. The result may be similar: false turn-on of an IGBT transistor which may suffer damage because of uncontrolled current flow. Proper assembly is essential in this context. Therefore, in high power circuits the reference potential of the driver should be directly connected to the transistor emitter that it controls.

Similarly, to get protection from damage due to inductance in the collector circuit, so called snubber circuits are used. The transistor can also be protected by local feedback from the collector to the driver. However, one should expect greater power losses in the semiconductor switch, so this kind of safeguard has limited applications. Another type of protection is short circuit that monitors the voltage of the collector (sometimes the emitter current is measured). When the transistor gets out of saturation, after a delay of a few microseconds, it turns off the transistor excluding damage due to very high energy emitted in the collector circuit. This type of protection also prevents the transistor from latch-up effect.

It should be noted that 3rd generation IGBT transistors (Trench-Field-Stop IGBT) do not show as many losses of power as IGBT1 and IGBT2. They show a shorter lasting 'current tail' in the turning-off stage and slightly lower saturation voltage. IGBT transconductances are generally higher than those of MOSFET transistors. In the working component the essential relationship is that between temperature and saturation voltage (Fig. 5). In a low range of collector current the temperature coefficient is negative (like for BJT), in the high current range.

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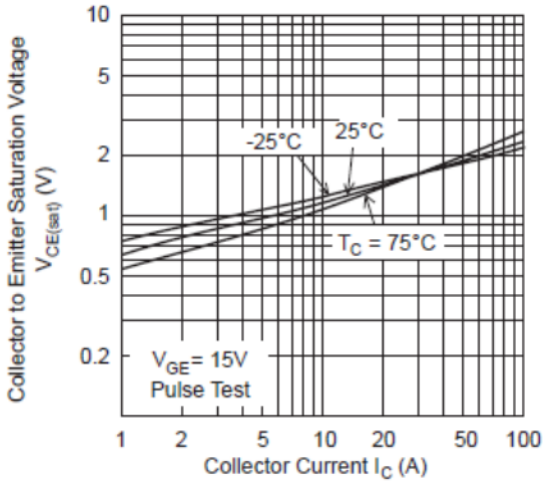

Figure 5. The characteristics of IGBT transistor and temperature impact on the voltage of saturation [2].

4. Description of the research object

Because IGBT transistors have a strictly specific range of allowable working temperature, the authors focused on seeking diagnostic relationships that could be used in monitoring the conditions where the transistor gets close to the maximum working temperature.

One of the tested objects was a voltage source inverter (VSI). VSIs are mainly used with electric induction motors, but can also be used for synchronous machines, including permanent magnet motors. At present, the power of propulsion fed by VSI is limited to 8-10 MW, due to available power electronics elements that can work at high frequency. The most often used method of inverter control is pulse width modulation (PWM) and space-vector sensor less control where the inverter switches work in the frequency ranging from 1 to 20 kHz. In marine high power propulsion systems, the switching frequency of IGBT transistors is approximately 1 kHz to minimize switching loses and heat emission. It is known that with increasing of inverter switching frequency the electric motor current gets more like a sinusoid but at the same time switching losses (mainly on heat) increase [3,14].

The transistor working conditions, i.e. values of constant voltage polarizing the base-emitter and base-collector junctions without the presence of a variable input signal, determine how the transistor will respond to a variable input signal. The bipolar junction transistor demonstrates current gain, IGBT is a transconductive element; the input parameter is the gate voltage, the output signal is the collector current (Fig. 6).

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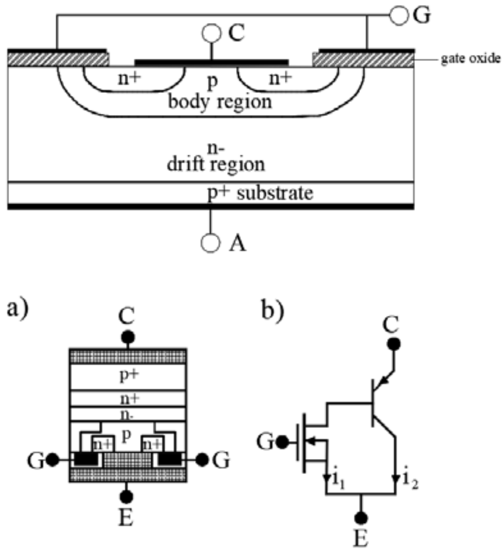


Figure 6. Example of IGBT transistor structure [19], cross section silicon section [20].

The measurement circuit of the transistor tested in laboratory conditions is shown in Figure 7.

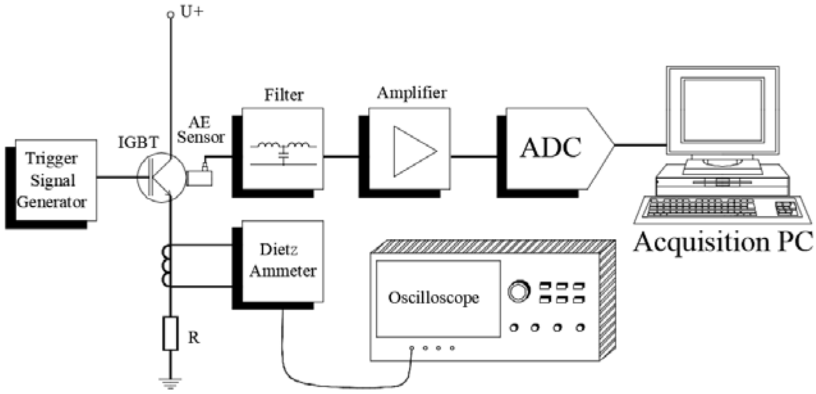


Figure 7. The measurement circuit of IGBT transistor of the WSα.

Measurement circuit utilizes a wideband acoustic emission WSα sensor from Physical Acoustic Corporation (MISTRAS), characterized by high sensitivity and wideband frequency range shown in the Fig. 8. Wideband AE sensors are useful where frequency analysis of the AE signal is required and in helping determine the predominant frequency band of AE sources for noise discrimination and selection of a suitable lower cost, general purpose AE sensor. In high fidelity applications, various AE wave modes can be detected using wideband sensors, providing more information about the AE source and distance of the AE event. A 30-degree angle at the bottom edge of the sensor cavity reduces the risk of electric shorts from the sensor cavity to conductive test surfaces. The signal was recorded using AE recorder designed at the Maritime University of Szczecin, and additionally, the measurement results were confirmed by a two-channel AE recorder from the MISTRAS (Pocket AE-2).

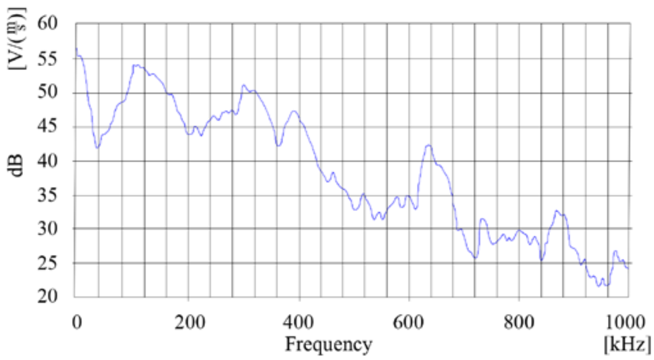


Figure 8. Frequency response of the WSα. Calibration based on ASTM E1106 [21].

5. The experimental results

During the tests, the authors confirmed the influence of the transistor's working temperature on its amplitude-frequency spectrum of acoustic emission signal. The narrow range of 'safe temperatures' was considered. The tests were conducted with temperature increases from 25°C to 75°C (10°C increments). Due to limited volume of this paper, the results are given for 25°C, 45°C and 75°C. The AE time signal clearly indicates the pulse of the transistor switching (Fig. 10). As previously stated, analyzing the catalogue data of bipolar transistors it can be observed that the maximum allowable working temperature of these elements should not exceed 150°C. Therefore, the amplitude-time-frequency analysis was made for the rising temperature. The results indicate that the higher transistor working temperature generates additional AE waves in the frequency band characteristic of transistor work (Fig. 11).

In the case of discrete acoustic emission (during transistor switching), the theoretical Rayleigh distribution can be used where the frequency of the occurrence of event rate N_z for maximum signal amplitudes A_m can be written as:

$$N_z(A_m) = \frac{N_c A_m}{\zeta^2}\, exp\left(-\frac{A_m^2}{2\zeta^2}\right) \quad (1)$$

Where:

ζ is the maximum value of the threshold of discrimination A, N_c total rate of events of various amplitude.

The N_z is a Rayleigh distribution with shape forming parameter ζ. The probability density function for different shape parameters ζ is shown in Figure 9.

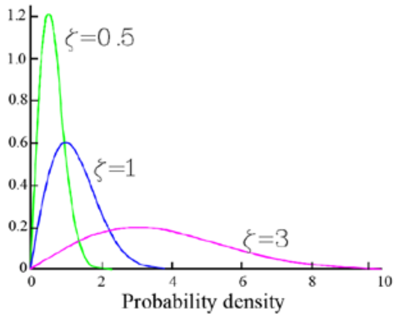


Figure 9. Probability density for 3 different shape parameters.

The distribution of event rate of any amplitude for expression (1) can be determined by integrating this expression by relative to *Am*.

Assuming that for the curves of amplitude distribution of event rate it is possible to approximate these curves with the power function:

$$N_z(A) = \beta\ A^{\gamma} \tag{2}$$

Where: $\beta,\ \gamma$ – empirically chosen constants.

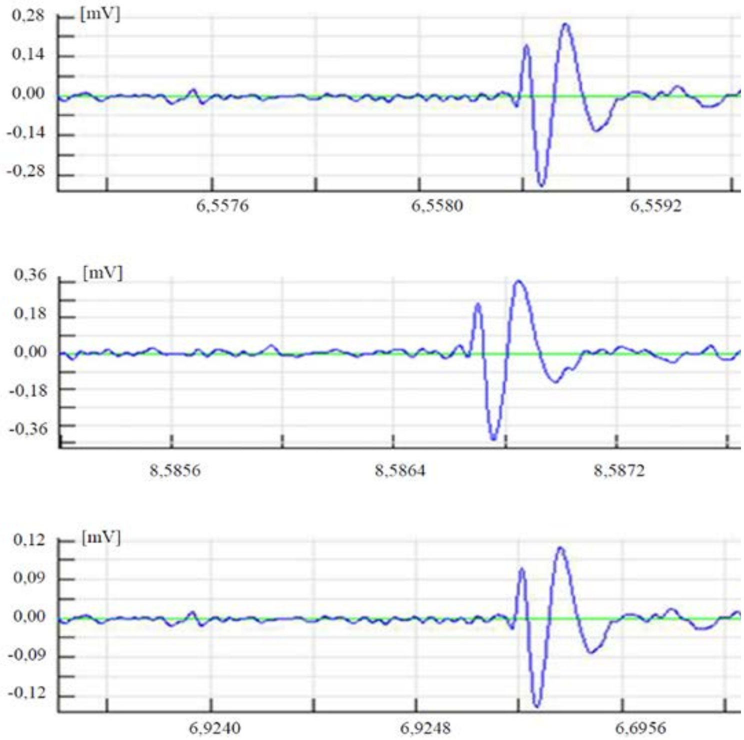
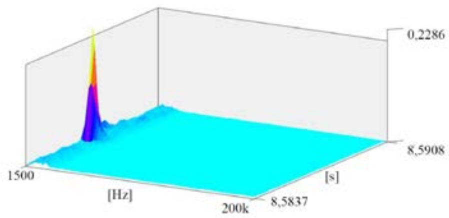
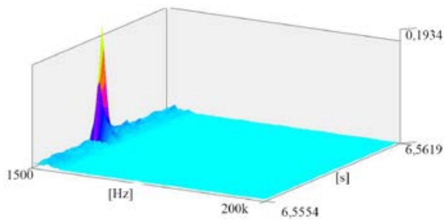


Figure 10. Source signal (time) of AE during the IGBT transistor switching for temperature increases: a) 25°C, b) 45°C, c) 75°C

a)



b)



c)

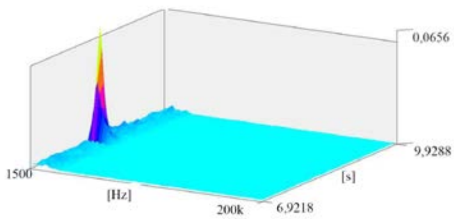


Figure 11. AE signal obtained from IGBT transistor switching for temperature variations: a) 25°C, b) 45°C, c) 75°C

The tests were conducted with the same current- voltage parameters. The only variable value was the temperature of the plate / board where the IGBT transistor was mounted. Figure 12 presents the results of spectrum and amplitude-time-frequency characteristics for selected working temperatures of IGBT transistors.

a)

b)

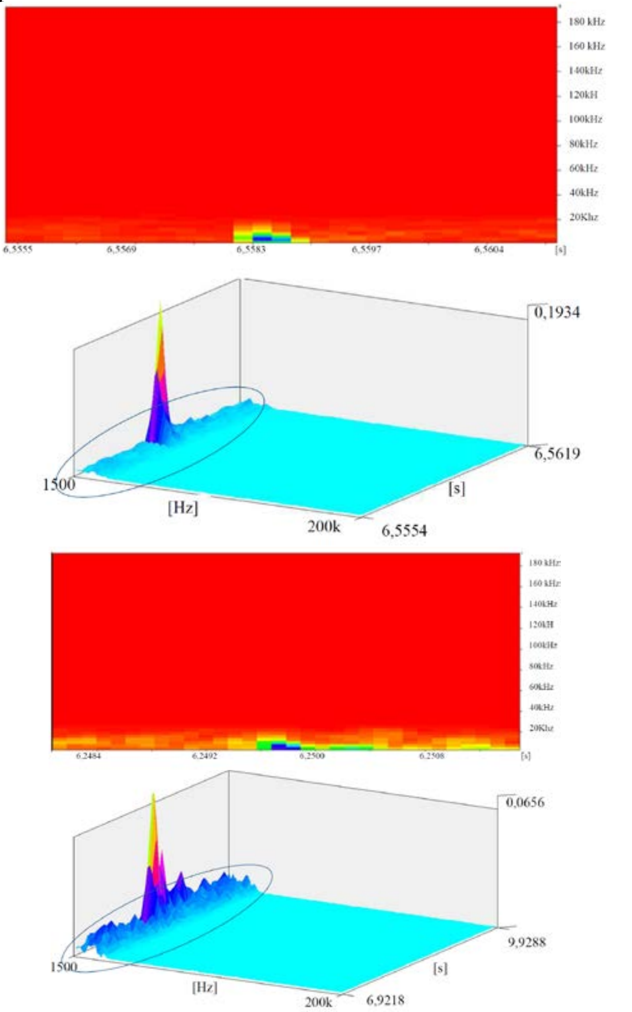


Figure 12. Amplitude-time-frequency analysis and the spectra for a bipolar transistor at different temperatures: a) 25°C, b) 75°C

As the temperature increases, apart from a visible peak related to the transistor switching, additional wave signals occur, generating a frequency rise dependent on the transistor working temperature.

5. Conclusions

Analyzing causes of IGBT transistor failures, the authors found diagnostic relationships characterizing increasing working temperature of an object. This relationship can be used in monitoring the condition and the temperature getting close to the maximum working temperature of the transistor. As the temperature of the semiconductor element increases, additional characteristic frequencies appear apart from a visible rise of AE signal frequency amplitude related to transistor switching, their value (amplitude) increases as the working temperature of the circuit rises.

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References

1. Bejger A.; Kozak M.; Gordon R., The use of acoustic emission elastic waves as diagnosis method for insulated-gate bipolar transistor, *journal Of Marine Engineering And Technology*. **2020**, doi.org/10.1080/20464177.2020.1728875.
2. Świerc K. Tranzystory IGBT – budowa, parametry i ich obwody sterowania. *Serwis Elektroniki*. **2011**
3. Mysiak P.; Strzelecki R.; Energoelektronika na obiektach morskich, *IX Konferencja Naukowo-Techniczna – i-Mitel* **2016**
4. Liu, H.; Ma, K.; Qin, Z.; Loh, P.C.; Blaabjerg, F. Lifetime estimation of MMC for o shore wind power HVDC application. *IEEE J. Emerg. Sel. Top. Power Electron*. **2016**, *4*, 504–511. **DOI:** 10.1109/JESTPE.2015.2477109
5. Choi, U.M.; Blaabjerg, F.; Lee, K.B. Study and handling methods of power IGBT module failures in power electronics converter systems. *IEEE Trans. Power Electron*. **2015**, *30*, 2517–2533. DOI: 10.1109/TPEL.2014.2373390
6. Haleem, N.M.; Rajapakse, A.D.; Gole, A.M. Improved circuit model for simulating IGBT switching transients in VSCs. J. *Power Electron*. **2018**, *18*, 1901–1911.
7. Wang, Z.; Qiao,W. A physics-based improved cauer-type thermal equivalent circuit for IGBT modules. *IEEE Trans. Power Electron*. **2016**, *31*, 6781–6786. DOI: 10.1109/TPEL.2016.2539208
8. Ji, B.; Song, X.; Sciberras, E.; Cao, W.; Hu, Y.; Pickert, V. Multi objective design optimization of IGBT power modules considering power cycling and thermal cycling. *IEEE Trans. Power Electron*. **2015**, *30*, 2493–2504. DOI: 10.1109/TPEL.2014.2365531
9. Choi, U.M.; Blaabjerg, F.; Lee, K.B. Study and handling methods of power IGBT module failures in power electronics converter systems. *IEEE Trans. Power Electron*. **2015**, *30*, 2517–2533. DOI: 10.1109/TPEL.2014.2373390
10. Choi, U.M.; Blaabjerg, F.; Jorgensen, S. Power Cycling Test Methods for Reliability Assessment of Power Device Modules in Respect to Temperature Stress. *IEEE Trans. Power Electron*. **2018**, *33*, 2531–2551. DOI: 10.1109/TPEL.2017.2690500
11. Smet, V.; Forest, F.; Huselstein, J.J.; Rashed, A.; Richardeau, F. Evaluation of Vce monitoring as a real-time method to estimate aging of bond wire-IGBR modules stressed by power cycling. *IEEE Trans. Ind. Electron*. **2013**, *60*, 2760–2770. DOI: 10.1109/TIE.2012.2196894
12. Kim, S.M.; Lee, K.B. Control method of power cycling test setup for submodule reliability investigation of modular multilevel converters. *In Proceedings of the ICEE 2018 Conference, Seoul, Korea*. **2018**.
13. Choi, U.M.; Blaabjerg, F.; Jorgensen, S. Power Cycling Test Methods for Reliability Assessment of Power Device Modules in Respect to Temperature Stress. *IEEE Trans. Power Electron*. **2018**, *33*, 2531–2551. DOI: 10.1109/TPEL.2017.2690500
14. Napieralski A.; Napieralska M.; Starzak Ł. ; Zubert M., "Modern high power semiconductor devices", *ELTE 2013, Ryn, Poland, April 16-18*, **2013**, Vol. 8902, ISBN 9780819495211, s. 890203-1, 890203-17
15. Li M., He Y., Meng Z., Wang J., Zou X., Hu Y. and Zhao Z., Acoustic Emission Based Experimental Analysis of Mechanical Stress Wave in IGBT Device *IEEE Sensors Journal*. **2020**, vol. 20, no. 11, pp. 6064-6074, 1 June1, 2020, DOI: 10.1109/JSEN.2020.2974312.
16. Jo S-R., Kim S-M., Cho S. and Lee K-B, Development of a Hardware Simulator for Reliable Design of Modular Multilevel Converters Based on Junction-Temperature of IGBT Modules. *Electronics* **2019**, *8* (10), doi.org/10.3390/electronics8101127
17. Cai X ; Bian J ; Wang Y, Design of IGBT Parameter Automatic Test System Based on LabVIEW, *2019 IEEE Symposium Series on Computational Intelligence (SSCI) Xiamen, China, December 6-9* **2019.**
18. Dbeiss M, Avenas Y. and Zara H, Comparison of the electro-thermal constraints on SiC MOSFET and Si IGBT power modules in photovoltaic DC/AC inverters, *Microelectronics Reliability Volume 78*. **2017**, Pages 65-71, https://doi.org/10.1016/j.microrel.2017.07.087
19. Dodge J. and Hess J., IGBT Tutorial, *Advanced Power Technology, Application Note APT0201, rev. B*. **2002**.
20. Mohan N., Undeland T.M., Robbins W.P., Power electronics converters, applications and design. *Wiley* **2003**
21. Kozak, M.; Bejger, A.; Tomczak, A. Identification of Gate Turn-Off Thyristor Switching Patterns Using Acoustic Emission Sensors *MDPI Sensors*. **2021,** *21(1), 70*.

22. Bejger A.; Drzewieniecki, J.B., A New Method of Identifying the Limit Condition of Injection Pump Wear in Self-Ignition Engines, *Energies*, **2020**, Vol.: 13 Issue: 7, DOI: 10.3390/en13071601