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Semiconductor Device Failures in Power Converter Service Conditions

Stefan Januszewski, Maria Kociszewska–Szczerbik, Henryk Swiatek, Grzegorz Swiatek*

Electrotechnical Institute, Pozaryskiego 28, 04-703 Warsaw, Poland
* Wasaw University of Technology, Institute of Control and Industrial Electronics, Plac Politechniki 1, 00-661 Warsaw, Poland

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Abstract

The failure analysis of power semiconductor devices (PSD) is valuable information to make some necessary converter circuit correction. Differences between PSD and signal device failures are described. Main failure mechanisms of SCR thyristors, GTO thyristors, IGBT transistors and power MOSFET's are discussed. Failures due a thermal fatigue are given as well. Selected results with example photos of PSD destroyed surfaces are presented. Expert systems used in PSD failure analysis are described.

Introduction

Most of the papers devoted to power semiconductor devices (PSD) failure analysis concern the subject from producers point of view. Then, the aim of such analysis is to improve the production technology to get higher reliability and more advantageous service parameters. Every producer values especially those pieces of information about PSD failures that take place in known but difficult to obtain during the research working conditions. PSD installed in power converters are subject to many exposures of different intensity levels. Occasional and unique dynamic working states that come out in semiconductor devices of the highest power in the time intervals previous to the failure appearances can be especially dangerous to cause PSD damages. Isolated cases of PSD failure during converters ordinary work can not be excluded as well (e.g. fatigue of materials). So, such considerations give the opportunity to verify technology level of PSD producers, in natural conditions.

A designer of power electronic equipment, who is not personally involved in the PSD production (Fig. 1), is not interested in their improvement. At the same time he can get familiar with devices of the same kind of other producers and deepen his knowledge during their exploitation. It concerns especially converters that work for a long time at frequently changing dynamic working states (e.g. high load changes) mainly [14, 15].

If PSD is damaged the important thing is the ability to both identify the cause of the failure and make an inspection of a silicon surface under a microscope. In most cases such a possibility does exists [12]. It leads to the improvement of converter protection system that will eliminate influences of the failure on a system. So, the failure analysis led by the designer tends to obtain the most reliable converter that satisfy customers requirements.

Typical differences between failure mechanisms of power semiconductor devices and signal devices

There are essential differences between failure mechanisms of power semiconductor devices and signal devices [14]. The size of silicon pellet of both devices is the main reason of differences between their failure mechanisms. The pellets of low power devices

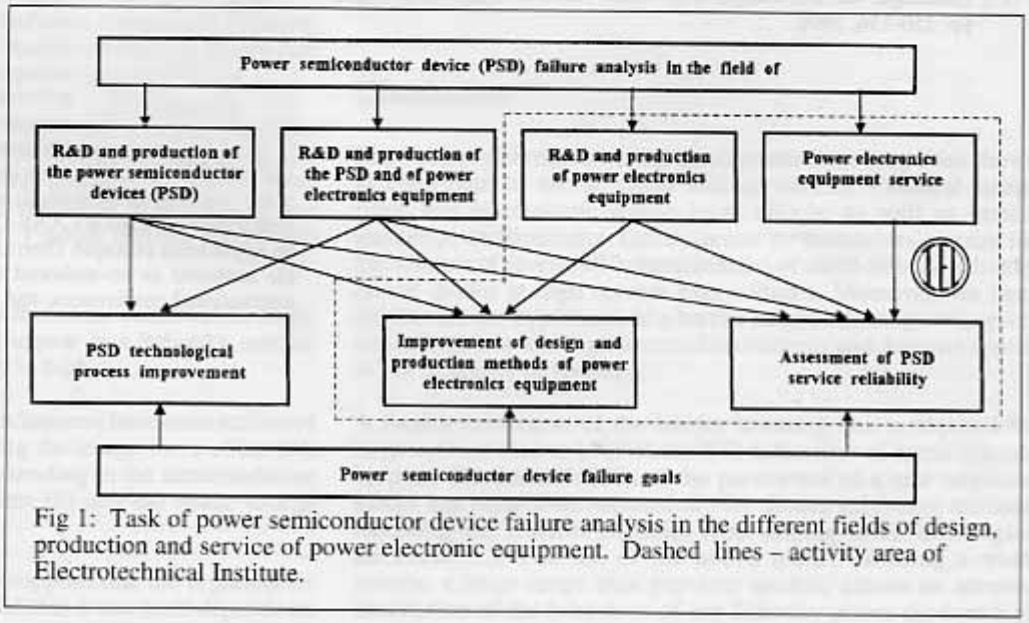


Fig 1: Task of power semiconductor device failure analysis in the different fields of design, production and service of power electronic equipment. Dashed lines – activity area of Electrotechnical Institute.

are of small size (few millimetres) and their physical features are homogenous. There is also easier to shape small dies more precisely, while the pellet diameters of the biggest PSD exceed 100 millimetres. It is much more difficult to set homogenous features for such big areas. It is also not possible to make parallel planes of PN junctions when using diffusion process. It results in greater current density in some parts of the junction. In PSD the level of electrical exposure is much higher then in signal devices. It is connected with greater nominal values of PSD parameters. In surge states exposure values can even exceed a few kV, tens of kA and device power can be greater than 10 to 20 MVA [8, 9]. Such conditions require taking into account an existence of electrodynamics forces. Their action cannot be ignored in the failure process of high PSD.

Damage reasons of power semiconductor devices

Modern fully controlled PSDs have multisegment structures. There are up to several hundred thousand segments in each PSD. Imperfection of manufacturing process causes both differences in their size and heterogeneity in structure. That gives differences of appropriate characteristics of individual segment and results in worsening of device's features in dynamic states. Heavy operating conditions as well as frequent and quick load changes (electric traction, welding processes) make the PSD failure probability increased.

All devices of load currents from a dozen to several hundred Amps are more tractable to damages. Non-homogeneity of current density makes it even worse. Values of current density in an individual silicon pellet may differ up to several tens times. According to the computer simulation distribution of current density in a particular PSD is constant and its maximum always appears in the same places of the pellet. A sudden load increase does not change the current density distribution as well. The above circumstances influence PSD persistence and cause their damage.

Heterogeneity of current density in dynamic states results in local temperature differences of a silicon pellet. Then, sudden load changes cause microscopic breaks in it. Passage of short-circuit impulses (switched off by appropriate protection devices) and their placement in the same parts of the silicon pellet make the breaks bigger and leads to the pellet damage.

The thermal fatigue of materials is one of very important PSD failure causes. It must be pointed out that a fast (1 µs, 1ms) temperature rise creates a temperature gradient such that the internal silicon portions are warmer and expand more than the outside [21]. This results in a tensile force in the external portions.

A degradation occurs due to thermal fatigue on macroscopic and microscopic basis (Fig. 2). Such phenomenon was particularly limiting when applying PSD operating over a wide temperature range. For silicon it has been shown that quenching in ice water (0°C) from temperature of 350°C results in micro cracs but quenching from 300°C does not.

SCR thyristor failures

Rectifier diodes and conventional thyristors are high reliability power devices and work correctly during long times. In the case of 3kV d.c. Polish rail traction service there are many rectifier diodes working some 20 years without damages or measurable changes of the initial parameters values [9].

Near 200 conventional thyristors that are continuously operated in rolling mill converters between 12-17 years are checked. Test results give 5% catastrophic failures and about 15% parameter initial value degradations [11]. In Table I some examples of most

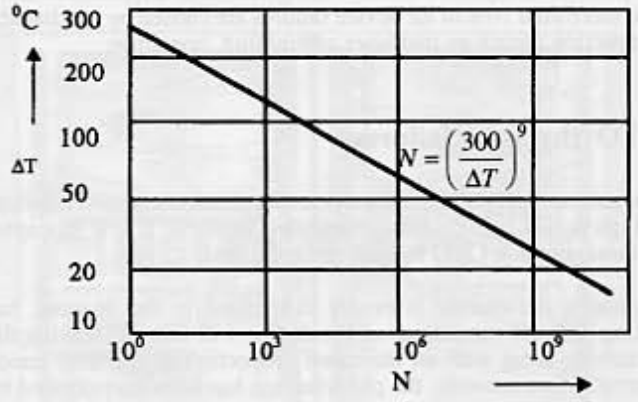


Fig. 2: Acceptable number of cycles N versus structure temperature excursion ΔT for specific size of power semiconductor devices [21].

Table I: Conventional thyristor typical failures

Failure reason	Failure reason	Failure symptoms and other explanations
Excessive value of di/dt		A burn near the surrounding of gate periphery
Surge current		Thyristors damaged by surge current have a large burned out area, at any part of the cathode surface
Over-voltage		A burn near the device periphery indicates an overvoltage failure
Thermal runaway		A burn area is depending on the velocity of over-current protection
Excessive gate power		A burn on the gate surface near its contact

frequent SCR thyristor failures are given. Our experiences show that more than 10% of all device failures are caused by mechanical destruction during an improper assembling operation.

GTO thyristor failures

The gate turn-off (GTO) thyristors are the dominant turn-off devices at high power conversion applications. In Table II few examples of most common GTO failures are presented.

Typically, the current is evenly distributed in the on-state, but during turn-off some areas of the device will turn-off leaving the remaining areas with an increased proportion of the total anode current. More recently, the phenomenon has been investigated by a non-invasive magnetic field measurement method [17] that allows mapping of the current density as the turn-off transient proceeds. The results demonstrate that dynamic current redistribution occurs as a consequence of differences in the many physical parameters affecting device performance. Redistribution of current during turn-off results from relative differences in the switching speed of the individual segments of a GTO. The segment which turns-off last is responsible for the turn-off failure [4].

It was confirmed that progressive shrinking of the conduction channel with the shape of the cathode finger takes place during the turn-off storage period [5]. At the beginning of the fall-time period, the conduction area shrinks or collapses in the cathode length direction until it assumes a cylindrical shape. A high density drift current is flowing in the conduction channel, thus forming a current filament. In this way a destructive filament formation could occur. Other GTO failures (Table II) – like in SCR thyristors – were connected with overcurrent and overvoltage phenomena or an excessive rise of *di/dt* values. Two examples of destroyed GTO's with comments are given in Fig. 3 and Fig. 4.

IGBT transistor failure

Insulated gate bipolar transistors (IGBT) combine the high gate impedance and high switching frequency of MOSFET's and the low saturation voltage of BJT transistors.

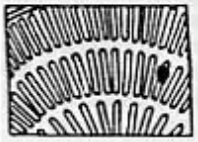
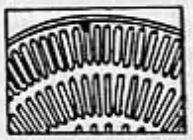
The IGBT transistor has an internal parasitic thyristor structure. If this structure latches up the collector current can no longer be influenced over the gate and the device is destroyed. A proper protection system should prevent such circumstances.

At first the failed IGBT modules were opened nondestructively. Then some electrical parameters such as threshold voltage $U_{GE(th)}$, on-state voltage $U_{CE(on)}$, blocking voltage U_{CE} were examined chip by chip. In this way the failed chip and its degraded parameter could be identified. The microscope and other equipment were used in failure analysis to define the failure mechanisms.

Wire lifting failure (Fig. 5)

Wire bonding is usually considered as one of the weakest areas of device packaging, which is especially true for power IGBT modules because thick wires of 0,25 - 0,5 mm in diameter are used in IGBT to conduct high current. Bonding pressure and temperature are two sensitive factors determining bonding quality. With a poor bonding pressure it is impossible to form a good contact between wire and bonding pad. This fact may lead to a low fracture strength at the bonding interface. Moreover, bonding wires are subject to a tensile stress due to the changes of temperature during power cycling.

Table II: GTO thyristor typical failures

Failure reason	Failure result	Failure symptoms and other explanations
Excessive turn-off energy		Burns near the center of a cathode segment are characteristics of turn-off energy failures
Excessive value of *di/dt*		A burn near the periphery of a cathode segment indicates a *di/dt* problem
Over-current (overload short-circuit)		A surge failure is characterised by a large burn spreading symmetrically over a localised "hot spot" area
Segment current concen-tration		A burn area near the device periphery indicates a turn-off failure (Fig. 3)

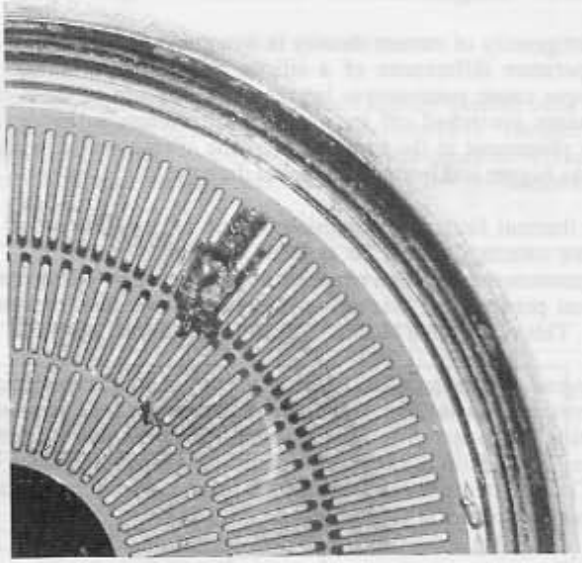


Fig. 3: GTO thyristor (0.6 kA; 2,5 kV). The diameter of silicon pellet 40 mm. In the peripheral ring there is a main region of molten silicon containing three cathode segments. There is a second smaller failure region between the two internal rings. The failure was caused by to long short-circuit current flow.

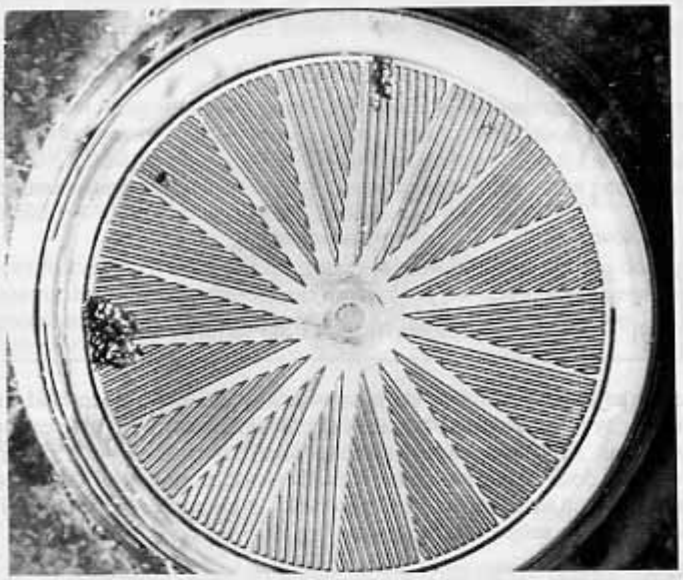
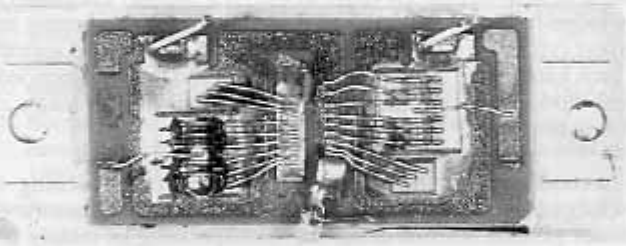


Fig. 4: GTO thyristor (1 kA, 4,5 kV). The diameter of silicon pellet 53 mm. In four of cathode cell groups (near the pellet edge) there are regions of molten silicon spread over few cathode segments.

a)



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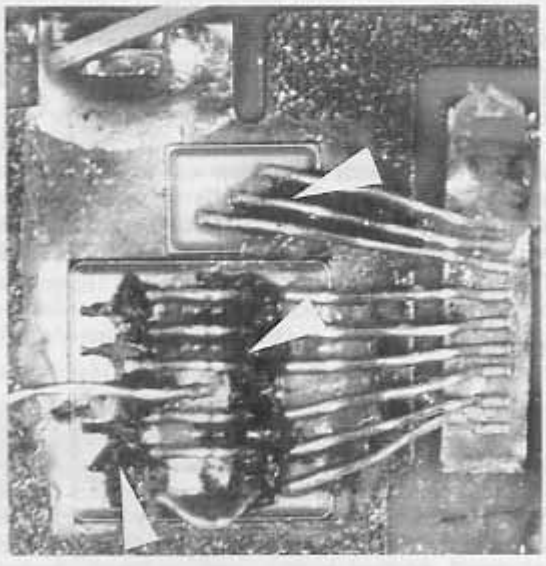
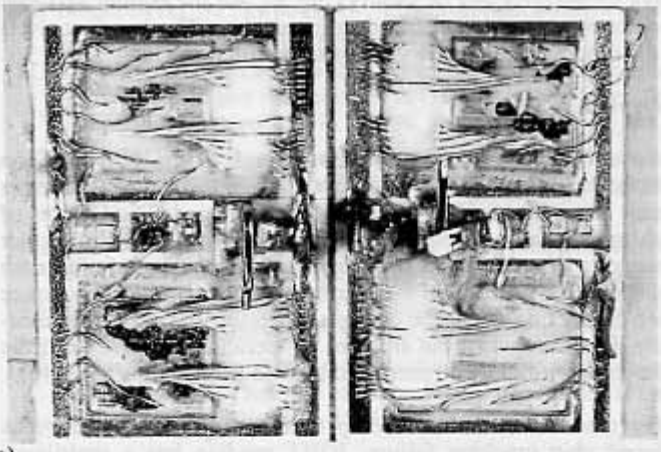


Fig. 5: Powerblock composed with two IGBT transistors and two fast diodes (50 A, 1200 V) - 30 × 90 mm. The top of the case was removed. The arrows point destroyed parts on a surface of the structure. The failure was caused by too long short-circuit current flow: a) all structure view, b) fragment of failed structure.

a)



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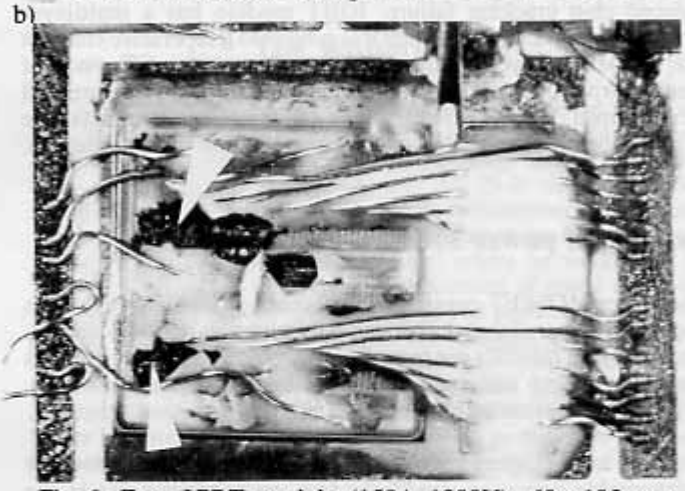

Fig. 6: Four IGBT module (150A, 1200V) - 60 x 105 mm. The top of the case was removed. The arrows point destroyed areas caused by long short-circuit current flow: a) all structure view, b) fragment of failed structure.

Electromigration failure in bonding wires

Electromigration in thick wire like that in a bulk metal might happen at a current density of about 10^4 A/cm^{2}and at high temperature. If the current distributes non uniformly among the IGBT chips, or wire debonding occurs at first, then the current density in some wires will be much higher than the average value mentioned above. Besides, high temperature plays a more important role in thick wire electromigration than in thin metal film migration. At high temperature the silicon gel surrounding emitter wires (Fig. 6) was solidified so as to keep the wire at high temperature. This circumstance accelerates the migration process.

Degradation in emitter bonding pads

Surface degradation in emitter bonding pads was observed when seeking for the reason of wire lifting failure. With power cycling the metalization surface became rough and hillocks were formed because of recrystaliozation and electromigration of Al metalization. This would be accelerated by thermomechanical stress due to the difference in thermal expansion coefficients of Al and Si.

IGBT chip failures

Power IGBT module is a multichip device. Therefore current imbalance in IGBT chips, due to the differences of electrical parameters such a threshold voltage $U_{GE(th)}$, on-state voltage $U_{CE(on)}$ and switching time t_{on} and t_{off}, might cause thermal failure of

IGBT. Most of IGBT chips of the failed modules are burned out either catastrophically or locally (Fig. 6). All the emitter and gate bonding wires are either fused or lifted-open. The bonding wires of the diodes (upper arrow) are partially liften-open.

Overvoltage

An overvoltage will create punch through in the IGBT silicon structure and this will be a future short circuit for the converter circuit and a lot of component will be damaged. The failures of such mode usually occur in the corner of the IGBT rectangular structure where the electric field is most critical. These failures are essentially the function of the thermal characteristics of the device when conducting avalanche currents. Therefore the avalanche capability decreases when the ambient temperature increases and the failures can normally be predicted by safe avalanching areas [6].

Other mechanism of IGBT chip failure may be thermal stress induced chip cracking failure. IGBT module has a multilayer structure in its packaging. When it is subject to temperature changes like in the load cycling, thermal stress due to the difference of thermal expansion coefficient of each material in the structure will be developed (bimetal effect), which can result in a fatigue failure in soft solder and make silicon chip break because of its brittleness.

Failures of power MOSFET transistors

The power MOSFET consists of thousands of identical segments connected in parallel and operates only with the majority carrier. The power MOSFET's are free of such problems as storage effects during switching and are well suited for high-speed, low-loss, large power applications.

From the technological viewpoint segments that can be actived by unfavourable operating conditions (e.g. an excessive rise in the voltage between drain and source) cause an uncontrolled transition of the MOSFET into the on–state [2, 3, 10]. In such a case it is impossible to turn this transistor off, even by applying a negative gate-to-source voltage. The controllability of the MOSFET is then lost. This mechanism is the most often cause of a MOSFET transistor failure [19, 20]. If the parasitic bipolar structure in a single cell or in a few cells becomes activated then the current density can become high enough to destroy the device.

Another reason of destroying a MOSFET may by a decrease in the gate threshold voltage with increasing temperature. This fact also causes the device to lose its controllability and in consequence its destruction.

Field effect MOSFET transistors operate usually at high frequencies. This makes it difficult to eliminate the phenomena mentioned above by using protection systems because of short rise times of the fault processes. The failure mechanisms of MOSFET transistors have not been fully investigated yet, particularly in the case of high power devices [1].

Experiences show that almost 50% of failed MOSFET had the gate short. Typical cause of these was excessive voltage applied to the gates. The next cause (about 30%) was to fail with the safe operating area infringement. The rest of MOSFET failures was connected with excessive transient current overload and other ones.

Expert system

An expert system "shell" was used for PSD failure analysis [15]. This tool was chosen because expert systems are the most stable

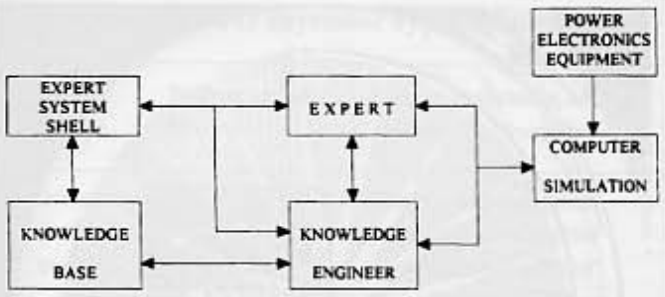

Fig. 7: Expert system structure in PSD failure analysis

and the most developed domain of artificial intelligence, and the majority of knowledge-based systems applications are also expert systems. Moreover expert system "shell" is ready-to-use system with all desired components like: inference engine, user interface, explanation tool, knowledge editor etc., which allow to focus only on the main subject of the work (Fig.7).

Failure analysis of power diodes, thyristors and transistors was the first part of the research work. It was based on the results of the long-term research on converter equipments which was carried out in Electrotechnical Institute. A lot of experts in the domain was interviewed in order to posses appropriate knowledge. Thanks to such prepared knowledge base, knowing the basic parameters of the area such as location, shape, size and granulation, it was possible to determinate the cause of the PSD failure. The prototype knowledge-base was the result of these interviews, and many tests of expert system on collected data were made. After tests it appeared that such knowledge is too much contextual and that the knowledge of real working environment of the device should be taken into consideration.

The second part of the work was devoted for widening the knowledge-base. This time, equipment designers were interviewed to posses general rules of designing and operating of widely used semiconductor converters. Next, the knowledge base was completed with the new rules that joined the failure area parameters with general model of a plant in which the failure plan worked. The completion decreased the diagnose reliability. This make expert system much more reliable especially in such cases when structure of equipment cannot be known because of license rights. Since power devices are very expensive, further testing of the expert system was based on computer simulation of chosen converters. The main aim of computer simulation was to reconstruct failure circumstances, which enabled to verify knowledge-base of the expert system. Experiments and tests confirmed correctness of operation of the expert system in the domain of PSD failure analysis.

Conclusions

The causes and mechanisms of semiconductor power device failures are very complicated because they are affected by various factors. Laboratory simulation of abnormal operation states of converters especially those conducted in order to verify correct operation of the protection systems developed is a serious hazard to the new generation devices used. In such cases the stresses (mainly the electrical ones) applied to the semiconductor devices can significantly exceed their ratings. Device failure of fatal nature can occur sometimes.

These circumstances allow the type of failure to be correlated with real factors that caused the phenomenon discussed. Acquisition of such information facilitates identification of failure causes in the case of analysing devices damaged in unknown stress conditions.

Some additional benefits are also obtained in the form of test results that can verify the limit strength of devices in abnormal operation conditions.

Different diagnostic systems installed in contemporary more complex power electronic units are very useful tools for PSD failure analysis. Application of shell expert systems for this goal probably gives new very convenient way to resolve some problems dealing with power converter design.

Identification of PSD failure causes is valuable information during converter prototype laboratory tests. It is possible to make some necessary converter circuit correction in the aim of known PSD failure elimination.

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The authors

Stefan Januszewski received the B.Sc. and M.Sc.Eng degress in electrotechnics from Warsaw University of Technology in 1953 and 1960 respectively and the Ph.D. degree in power electronic eng. from the Electrotechnical Institute in 1973. In 1952 he joined the Electrotechnical Institute (Warsaw) where he worked on the research and development of power electronics equipment and power semiconductor device measurements. He is author and co-author of more than 110 papers and 7 books in these fields. He is the chairman of Power Electronics Standard Group in the Polish Standard Comitte as well. He participates in the works of IEC (TC 22 Power Electronics). Presently, he is assistant professor in the Power Converter Department of the Electrotechnical Institute.

Henryk Swiatek received the B.Sc. degree in electrotechnics from Warsaw Univ. of Technology in 1964 and M.Sc. in organization and menagement from Warsaw University in 1980. In 1960 he joined the Electrotechnical Institute (Warsaw) where he worked on the research and development of power semiconductor device measurements. He organized the design and manufacturing of 7 kinds of industrial power semiconductor device testers. He is author and co-author of more than 60 papers and 7 books in these fields.

Maria Kociszewska–Szczerbik received the M.Sc.Eng degree in electronics from Warsaw University of Technology in 1964. In 1964 she joined the Electrotechnical Institute (Warsaw) where she worked on the research dealing the failure analysis of power semiconductor devices mainly in service conditions. She is author and co–author of more than 20 papers in this field.

Grzegorz Swiatek received the M.Sc. degree in control theory from Warsaw University of Technology in 1988. In 1986 he joined the Institute of Control and Industrial Electronics in the Warsaw University of Technology. Currently he is working as research assistant in the field of artifical intelligence and expert systems.