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Explosion Tests on IGBT High Voltage Modules

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***Abstract*-In this paper we report on surge current experiments with IGBT modules in low inductance, snubberless circuits. We give design guidelines for robust modules and robust converter designs, discuss scenarios of consequential damage and propose worst-case test conditions for explosion safety.**

For wire-bonded modules, the limit for material ejection is at a stored capacitive energy of about 10 kJ. In a good design the shock wave trajectory is defined and no metallic parts are obstructing the plasma expansion. The worst-case damage occurs, if initially a single chip fails. Press-pack modules can be designed to contain the plasma inside the housing in the case of a short circuit.

Simple protective measures are sufficient ot protect personnel.

I. INTRODUCTION

In the case of thyristor or GTO based circuits, di/dt is limited by a snubber inductivity. This limits the surge currents in the case of a short circuit. IGBT based circuits, in general, do not use snubbers. Parasitic inductivities are typically less than 100 nH. At a line voltage of 3000 V this results in a di/dt of 30kA/µsec or more and peak currents exceeding 100 kA. For wire-bonded modules this leads to explosions with potential ejection of module fragments with high kinetic energy. Severe consequential damage may result if no precautions are taken. In this paper we report on tests performed on wire bonded and press-pack type modules. We discuss the scenarios of consequential damage and how to minimize it by module design, converter design and by protective measures.

I. TEST CIRCUITS AND SAMPLES

If a module suffers a short circuit, then most of the stored energy in the system is discharged into the module. The prime source of such energy is the DC line capacitor. Due to the very low parasitic inductance, the characteristic time for the discharge of energy is only 30 - 100 µsec. Other parts of the system may have larger stored energies (e.g. transformers, motors). However, their characteristic time for discharge is considerably longer. They play an important role if the module barely survives the line capacitor discharge or is slightly pre-damaged. If already the fast discharge of the line capacitor leads to massive destruction, then the subsequent slower release of energy is of no importance for the damage scenario. For this reason we consider only the energy stored in the line capacitor in the explosion tests reported in this paper.

Figure 1 gives the basic test set up. It consists of a two-quadrant converter with two identical IGBT modules. Ls denotes the parasitic inductance. Rs is a fuse resistor which in most experiments is set to zero. The line capacitor C can be charged up to 3.5 kV. Two auxiliary switches are used to establish the desired load current and to induce a short circuit failure.

A first test sequence (Test A) consisted of closing the lower of the two auxiliary switches in Fig. 1. The sequence of events of Test A is the following: The high side module is turned on and the load current increases as defined by the load inductance Lload. After Iload has exceeded the safe operating area (SOA) for turn-off of the high side module HS, it is attempted to turn off HS. The initial part of the turn-off process takes place, the current in the module HS is reduced and part of the current is commuted to the diode of the module LS. The module HS then undergoes a turn-off failure. The diode in the low-side module LS carries substantial current at this instant. The failure forces the diode to turn off at virtually unlimited di/dt. This is outside the diode SOA and the diode also fails.

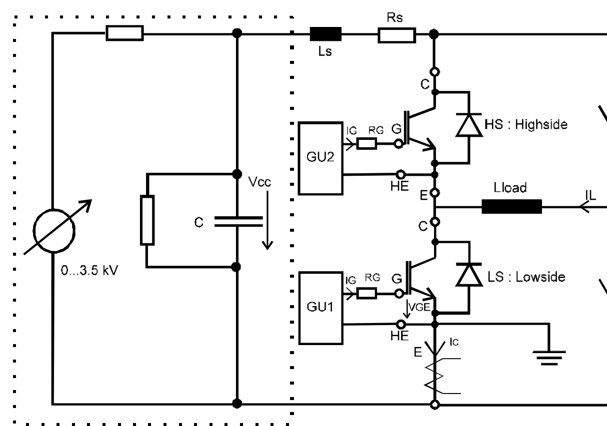

Fig.1 Test circuit for explosion tests. The fuse resistor Rs was omitted in most cases and the parasitic inductance Ls varied between 40 nH and 250 nH.

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A second test scenario (Test B) was also studied. In this test the module HS is turned on until a substantial load current is reached. At this moment the module LS, which sees the full voltage is induced to fail. The module HS then goes into desaturation and also fails. In reality such a failure could be due to cosmic rays [1-3] or due to thermal overload. It can be artificially induced by e.g. mixing one chip with high leakage current into a set of pre-tested chips of good performance.

The first series of test samples consisted of wire bonded modules specifically designed to minimize consequential damage. In such modules four chips are mounted on ceramic subassemblies which in turn are placed onto a massive metallic ground plate. The stripline-type terminals do not obstruct the room above the subassemblies. As a result the explosion shock wave has a well defined trajectory and no massive parts (terminals) are along this trajectory. After filling the module with silicon gel, the windows are covered with a thin and flexible rubber foil. The design concept is, that only very fragmented and soft particles consisting of gel and rubber should be ejected in a defined direction in the case of an explosion.

Tests were also performed on press-pack type modules. Here the design requirements are that no consequential damage should occur in case of a short circuit. In particular for series connected press-pack modules this means that the stack integrity has to be conserved.

II. TEST RESULTS

We first consider the situation of Test A at a relatively modest level of stored energy. The circuit parameters for this experiment were: V = 1500 V, C = 6.4 mF, Ls = 250nH, Rs = 0. This corresponds to a stored energy of 7.2 kJ. The test modules had four subassemblies with a total of 24 IGBT chips and 8 diode chips. The rating is 2500 V and 1200 A (single switch).

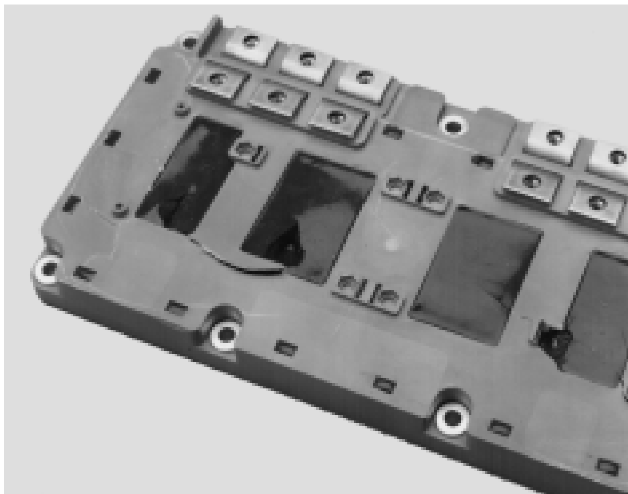

Fig. 2: High side module HS after a test with 7.2 kJ stored energy (Test A). Note the four windows under which the subassemblies carrying the chips are located. The rubber covers of all 4 windows are broken. No material is ejected.

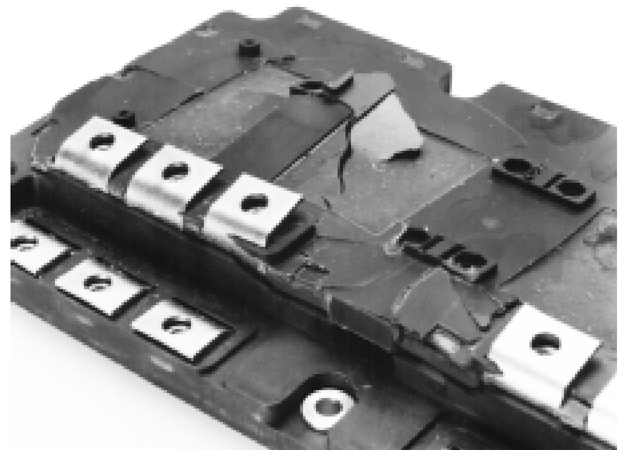

Fig.3 Damage to the low side module LS after the same test as in Fig.2. The damage to the low side module is more severe. No material is ejected but the terminals are bent.

The results of the first test are shown in Figs. 2 and 3. The HS module (Fig. 2) exhibits relatively small damage. In particular the overall mechanical integrity is conserved and no material is ejected. It is evident that chips in all four subassemblies were destroyed. The low side module (Fig. 3) exhibited slightly more damage. But also for the LS module no material was ejected.

Increasing the stored energy rapidly increases the damage. The limit for particle ejection is at about 10 kJ for this type of modules. Fig. 4 shows a detail of a module tested at 10 kJ (Test A, V = 2000 V, C = 5 mF, Rs = 0, Ls = 40 nH). The module is mechanically identical to the one of Figs. 2 and 3, except that the internal wiring is such that it is a phase leg. One half acts as HS and the other as LS. Correspondingly the rating is 2500 V and 2 x 600 A. A minor ejection of material is observed.

Fig.4 Discharge of 10 kJ into a phase-leg module (Test A). This module contains the high and low-side in one package.

Superficially one could argue that depositing 10 kJ into a single module (Fig. 4) is about the same as depositing 20 kJ in two modules. The experimental results prove the contrary.

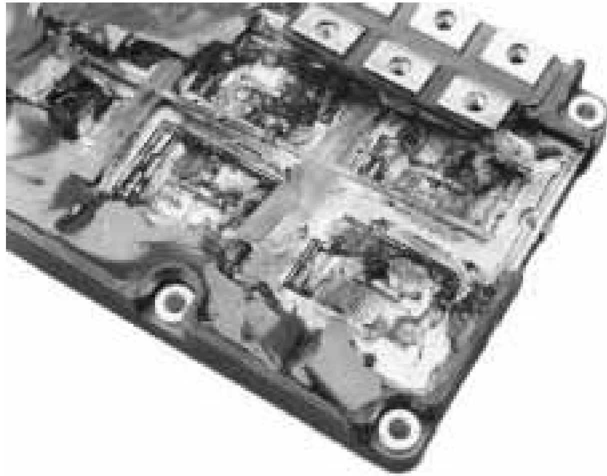

Fig. 5 LS module after a discharge of 20.3 kJ (Test B). Massive ejection of gel and rubber particles occurs. The terminals are bent, but still in place.

In the next experiment (Test B, Fig. 5) the diode of the LS module was destroyed while HS was turned on and the load current was flowing in HS. The module had a 1800 V, 1800 A rating and consisted of 20 IGBT and 12 diode chips. The circuit parameters were V = 1300 V, C = 24 mF, Ls = 40 nH, Rs = 0. The stored energy was 20.3 kJ. Both HS and LS were heavily destroyed with massive ejection of rubber and gel fragments and signs of electrical arcing in the module. However, no massive parts were ejected. The terminals are somewhat bent but still in place. The results are shown in Fig. 5.

In summary we can say that even for wire bonded modules specifically designed for explosion robustness, ejection of particles is unavoidable for energies higher than about 10 kJ. What can be achieved by a good design is, that no massive parts are ejected which can cause severe consequential damage.

We have demonstrated that it is possible to dramatically reduce the damage by the use of fuses or current limiting shunt resistors Rs. In particular, particle ejection can be prevented and thus little or no consequential damage is expected. In order to be useful, however, shunt resistors of a few tens of mΩ have to be used. This leads to unacceptable losses. Fuses also increase the parasitic Ls. We therefore do not believe this is a practical solution.

It is found that the damage depends substantially on the initial conditions of the module. The worst case is, if one chip is pre-damaged and if the full discharge energy is released in the vicinity of the pre-damaged chip. A short circuit affecting all chips simultaneously has much less consequences. To a lesser extent, the damage depends also on the location of a pre-damaged or "weak" chip in the module. Explosion test results do thus in general not reflect the worst case, unless the chips are specifically selected, such that a single chip fails initially.

We stress that the problem of individual chips failing cannot be overcome by having a set of virtually identical chips in the module. External impacts such as cosmic ray induced failures [1-3] will lead to single chip failure also for perfectly matched and homogenous chip sets.

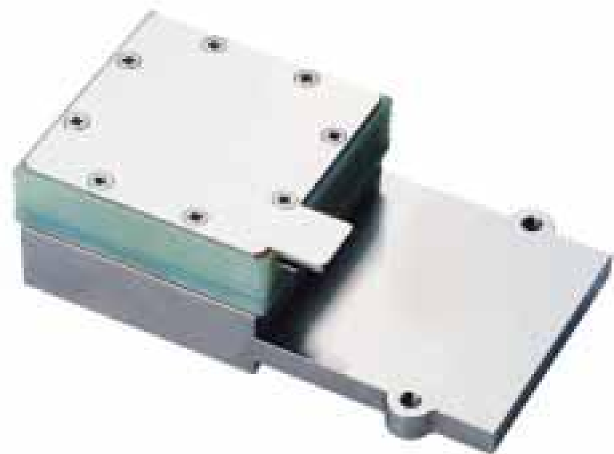

Fig. 6 Press-pack module, 2.5 kV, 700 A used for explosion tests

Similar tests were performed for press-pack modules (Fig.6). The modules had a rectangular shape which makes the confinement of the pressure resulting from the plasma more difficult compared to a hockey-puck design. In the press-pack case the strategy was not to provide a defined discharge trajectory for the explosion, but to confine the short circuit induced plasma inside the housing. In the axial direction the confinement is supported by the clamping forces. In the in-plane direction the housing has to withstand the full pressure. This is possible with a proper design and a proper choice of the structural materials. We have succeeded in designing press-pack type modules which can withstand discharge energies of more than 10 kJ.

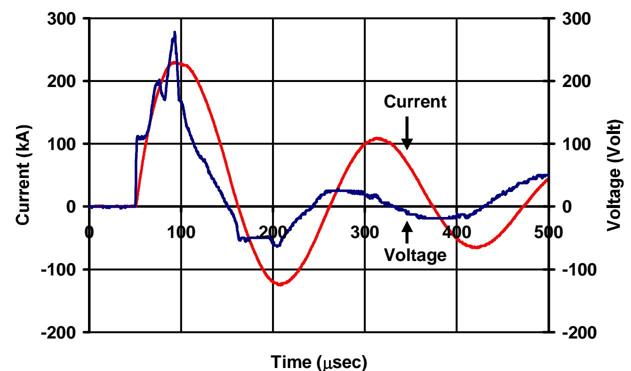

Fig. 7 Current and voltage as a function of time for a short circuit discharge of 8.7 kJ into a press-pack module

Fig. 7 exhibits the current voltage curve of a 8.7 kJ discharge into a 2.5 kV, 700 A press-pack module of ABB

Semiconductors. The module survived the discharge without external damage. The parameters were: C = 6.4 mF, V = 1650 V, Ls = 190 nH, Rs = 0. The peak current exceeds 200 kA and the characteristic time ($1/\omega$) for the oscillation is about 35 μsec.

The effects of energy, other than the one stored in the line capacitor, is of importance only if the structure survives the first rapid and intense current pulse. This is not the case for wire-bonded modules but for properly designed press-packs.

In explosion tests for press-packs it is thus not sufficient to test only for effects of the discharge of the line capacitor but to include also other sources of stored energy which may feed energy into the structure with a much longer time constant but with higher total energy. Typical for many systems are pulses on the 10 msec and 10 kA scale which follow the initial rapid discharge. We have performed such tests but will not report on them in this paper.

III CONSEQUENTIAL DAMAGE

The consequential damage caused by the explosion of a module very much depends on the design of the module and of the converter. A first type of damage is caused by the emitted gases. This is relatively short range and easy to control by proper converter design. The second type is caused by emitted aerosols consisting of finely dispersed gel and rubber particles. Even if no mechanical damage is caused, such material will form a sticky layer on objects in the vicinity of the module. This implies costly cleaning operations. If heavy parts are emitted, then severe mechanical damage may occur.

Personnel has to be protected by shielding. Another potential hazard is the extremely loud noise of the explosion which may lead to hearing impairment. In particular during explosion tests personnel has to wear an ear protection.

For some module types a protection from consequential damage by a protective and energy absorbent fabric can be of help. Fabrics such as the ones used for bullet-proof vests are well suited.

IV CONCLUSIONS

It seems to be impossible to protect wire bonded modules against explosion in the case of a short circuit. If elementary precautions are disregarded, then severe consequential damage may occur and even personal injury or death is not excluded. Using suitable precautions, the risks for personnel can be excluded and the risks for equipment drastically reduced.

The damage depends not only on the stored energy but also on the distribution of energy inside the module. The worst case corresponds to a module with a single pre-damaged chip such that the discharge is concentrated on this chip.

Fuses are effective in reducing the effects of a short circuit. They add substantially to the losses, increase the parasitic inductivity Ls and have their own reliability issues. For this reasons we do not believe this is a realistic solution.

Press-pack type modules offer the possibility to confine the plasma formed by the short circuit inside the package. This is only true, if proper attention is paid to the design of the housing and to the choice of the structural materials.

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