A novel parameter for the evaluation of protective circuits for IGBT explosion protection in submodules of MMC

Christoph Junghans, Hans-Guenter Eckel
UNIVERSITY OF ROSTOCK
Albert-Einstein-Str. 2
18059 Rostock, Germany
christoph.junghans@startmail.com
www.iee.uni-rostock.de

Keywords

«Modular Multilevel Converters (MMC)», «HVDC», «Short circuit», «Faults», «IGBT»

Abstract

Faults in high-power converters can cause sudden release of the energy stored in the charged intermediate circuit capacitor, destroying power semiconductors and causing secondary damage, such as the release of debris, the deformation of busbars and the emission of interference fields. This paper examines the effectiveness of certain protective circuits for the electrical explosion protection of IGBT modules in submodules of Modular Multilevel Converters (MMC) for HVDC applications and introduces a new parameter for the characterization of IGBT explosions. The protective circuits are arranged within the intermediate circuit of the submodule and are intended to reduce the surge current in the event of a fault and accordingly to dissipate or divert the energy of the storage capacitor and thus relieve the IGBT modules. The examinations indicate, that the connection of RL-combination and bypass thyristor can be recommended as protective circuit for IGBT explosion protection and surge current reduction used in MMC submodules with low switching frequencies. The newly introduced Explosion Integral XI improves the evaluation of electrical explosion protection measures. The parameter takes into account the thermal and magnetic mechanisms that cause the explosion of IGBT modules.

Introduction

Today MMC for high power HVDC transmission [1] surpass power levels of 1 GW and are constantly being further developed to increase the performance parameters. Occasional submodule faults in MMC are considered in the design and occur for different reasons (cosmic radiation, vibrations, thermal aging, fabrication defect, etc.). The submodules of the overall converter are designed in such a way that they are grouped out of the network with the help of a fast bypass switch in the event of a fault. The converter can then continue to work with redundant modules until a routine maintenance. The failure of one submodule must therefore not adversely affect other submodules or system components. A short circuit in the power semiconductors of the submodule induces the release of the energy stored in the intermediate circuit capacitor, which can cause surge currents and IGBT explosions to occur. These effects worsen with higher capacitor energy due to increasing MMC performance parameters. The electromagnetic as well as the mechanical effects of a fault must be restrained by appropriate technical measures like advanced semiconductor packages, reinforced semiconductor cells [2], interference shielding and additional protective circuits. The issue is quite important for the ongoing industrial converter evolution and widely ignored in the academic MMC sphere.

Two effects are responsible for the explosion of IGBT modules, which occur in combination during a surge current event and have a different degree of impact depending on the voltage class and module structure. On the one hand, it is the Lorentz force, which acts on the internal conductor structure of the IGBT module, on the other hand, it is the gas pressure that builds up as a result of electric arcs in the IGBT module. The arcs also cause the evaporation and decomposition of silicone gel that seals the internal electric structure.

The effect of the magnetic force component is considered in [3] for an IGBT module of the same package size as in this paper. However, the energy available in this study of the module explosion is relatively small at 10 kJ and the effect of gas formation is not taken into account. For the measurements, IGBT modules in the so-called IHV housing (IGBT High Voltage) with a base plate in the dimensions 140 mm x 190 mm are used. The IGBT modules are connected as a half-bridge and arranged in a closed and mechanically reinforced semiconductor cell, that is a modified version of a commercial MMC submodule semiconductor cell.

Different parameters can be used to evaluate the effectiveness of protective circuits in the intermediate circuit of a submodule. In this paper, the peak value of the fault current, the I²t-value, the energy conversion inside the IGBT module, the mechanical warpage of the IGBT heat sink and the novel parameter Explosion Integral XI are used. This paper is based on excerpts of [4]. Extensive experimental results, researched detailed design as well as simulation of the transient electrical and mechanical behaviour (e.g. interference fields, deformation of busbars with Ansys Workbench) can also be found there.

1. MMC-submodule fault and type of protective circuits

The MMC submodule considered here consists of the storage capacitor C, the IGBT half-bridge T1/D1 + T2/D2 and the bypass switch BPS (Fig. 1a). For the examination, the serious fault case is assumed, in which the majority of the energy of the storage capacitor is released in the IGBT module T1/D1. This occurs when the IGBT modules of the submodule are no longer switching (e.g. due to driver failure or signal interruption) and the storage capacitor C is reaching an unacceptably high voltage. If this case is detected by the monitoring electronics, the submodule is grouped out by closing the high-speed bypass switch BPS [5]. The freewheel diode D1 of the upper IGBT module T1/D1 is hard switched off and destroyed by the reverse recovery current. In this way, the charged intermediate circuit capacitor is short-circuited so that the surge current flows via T1/D1 and the bypass switch (red arrows, Fig. 1a).

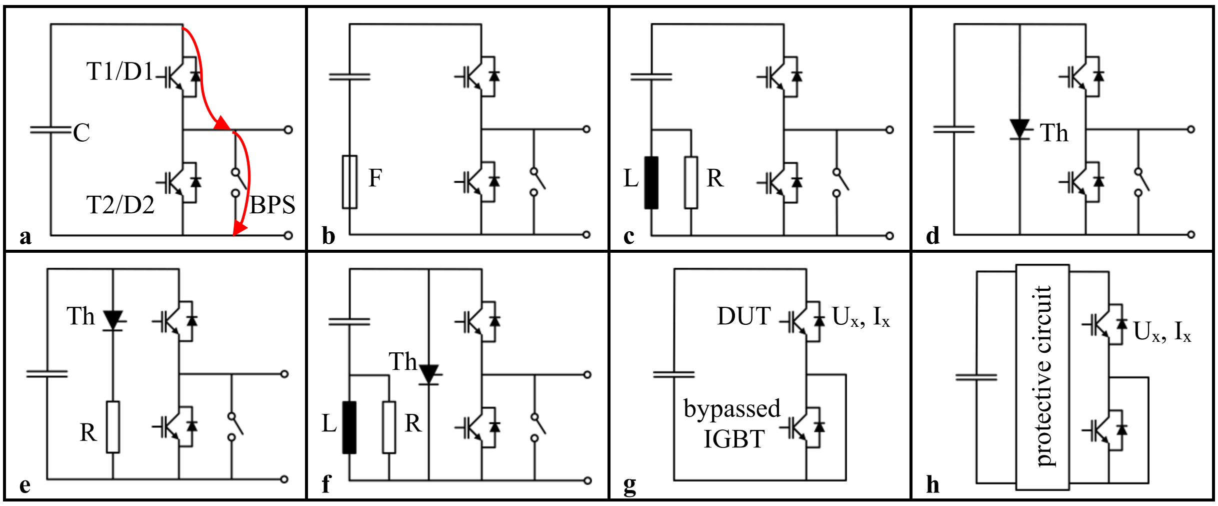

Fig. 1 a-h: Schematics of submodule, protective circuits and experimental setup

The IGBT modules CM900HC90 (CM900) and CM1200HC90 (CM1200) from the manufacturer Mitsubishi are used in the experiments. The modules belong to the voltage class 4.5 kV and the rated current is 900 A and accordingly 1200 A. The experiments show that the CM900 builds up more voltage during a failure and that the explosion effect is greater than that of the CM1200. This is a consequence of the unequal internal structure and the different nominal current ratings. For the examination of the fault event, the storage capacitor has a capacitance of 13 mF and is charged to a voltage of 4 kV, so that an energy of 104 kJ is available. The alternating current in the intermediate circuit under normal operating conditions in this design is defined to 1 kA_{rms}, even if this would be too high for the IGBT modules used. The switching frequency of the exemplary submodule is rated at 150 Hz.

Based on the energy content and the nominal current of the intermediate circuit used, according to the current state of the art, a commercially used submodule would each be equipped with two IGBT modules for T1/D1 and T2/D2 connected in parallel. In the event of a fault, it cannot be assumed that both modules connected in parallel fail at the same time and that the released energy is evenly distributed among the modules. The examinations with only one IGBT module used therefore not only show a case of particularly high module stress, but also anticipate a further increase in the power density of IGBT modules due to technical progress. With a comparable intermediate circuit, only one module of the reviewed housing category could be sufficient in the future as a power semiconductor for the formation of a half-bridge consisting of a total of two IGBT modules.

The examined protective circuits in the intermediate circuit are high-speed fuses (F, Fig. 1b), the series connection of a parallel RL-combination (R+L, Fig. 1c), a thyristor (Th, Fig. 1d) bypassing the IGBT half-bridge without or with a discharge resistor (Th+R, Fig. 1e) and an integration of RL-combination and bypass thyristor (Th+R+L, Fig. 1f). Benchmark measurements without protective circuits (Fig. 1g) are used for comparison. The experiments are started by switching on T1 ("0" on the diagrams x-axis), as the experimental effort for destroying D1 by hard switching off is too great. After switching on T1, the IGBT desaturates for a few microseconds and is then destroyed. The IGBT module is mounted in a semiconductor cell on an aluminium alloy heat sink, which is 20 mm thick and pierced with cooling channels for water cooling. The IGBT module explosion induces recoil as well as an increase in pressure in the semiconductor cell, causing the heat sink to warp. The semiconductor cell is a modified commercially used package containing two IGBT modules as a half-bridge. One of the IGBT modules is bridged with busbars, so that only the failure of a single module (DUT, T1/D1) is subject to consideration (U_x+I_x, Fig. 1g+1h). Hereinafter selected tests are presented, an overview of the conducted experiments is given in Table I.

2. Details on the measurements

2.1 Benchmark tests (Fig. 1g)

The benchmark tests are conducted without protective circuits, voltage and current curves of the IGBT modules CM900 and CM1200 are shown in Fig. 2. U_x is the voltage drop of the semiconductor cell (IGBT module + internal busbars), I_t is the surge current, 9 or 12 stands for CM900 and CM1200 respectively. Fig. 5a shows a damaged semiconductor cell (the two IGBT modules are mounted inside) of a benchmark test with the IGBT CM900, the upper deformed heat sink is the one of the DUT, the lower one is the least deformed heat sink of the bridged IGBT module T2/D2.

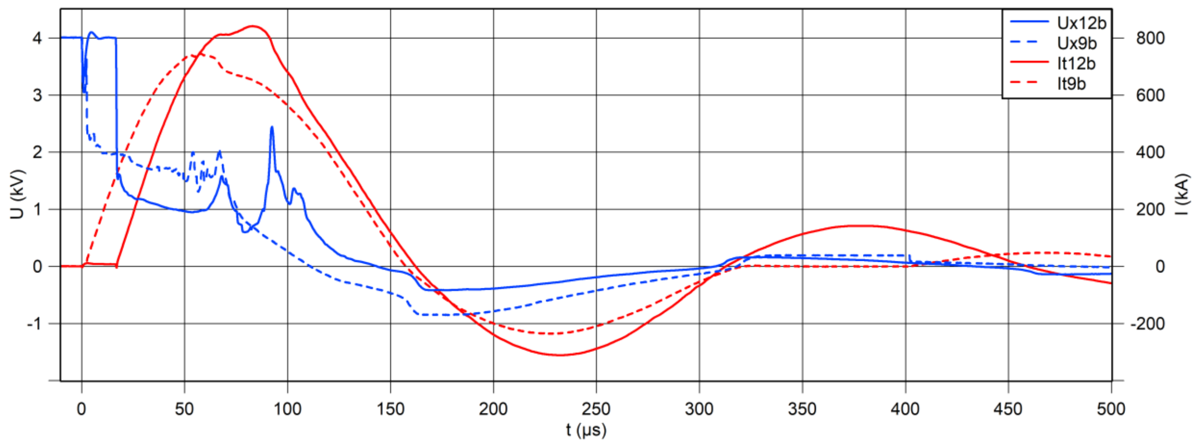

Fig. 2: Benchmark tests of the IGBT modules CM900 and CM1200

2.2 High-speed fuses (Fig. 1b)

The examination of high-speed fuses as a well-known variant of IGBT explosion protection [6, 7] is carried out with two parallel fuses of the type PC123UD25C500TF from the manufacturer Mersen/Ferraz with a nominal voltage of 2.5 kV_{rms} (3.6 kV_{peak}) and a rated current of 500 A each. The design depends on the nominal AC current of the intermediate circuit and the appropriate voltage drop to be built up by the fuses in a surge current event. For a practical design, the fuses should have a higher rated current in order to maintain safety reserves. The IGBT module CM900 is destroyed and the housings of the fuses crack (Fig. 5b). Nevertheless, the purpose of IGBT explosion protection is fulfilled with this protective circuit, as the heat sink is not deformed. The commercial availability of types of high-speed fuses suitable for the current and voltage values in MMC submodules is limited. The diagram in Fig. 3 shows the curves of the voltage drop of the IGBT semiconductor cell U_{x9f} and of the fuses U_{f9f} as well as the total fault current I_{t9f}.

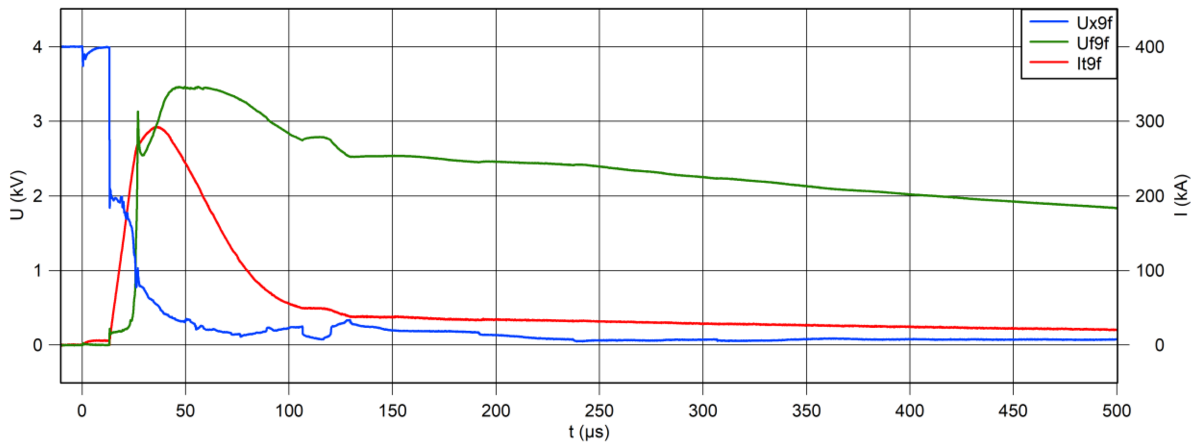

Fig. 3: Test of submodule with high-speed fuses and CM900

2.3 RL-combination (Fig. 1c)

The combination of a resistor and an inductor connected in parallel (RL-combination) in the intermediate circuit of a submodule is known from [8]. The RL-combination causes losses in normal operation which increase with the switching frequency. The RL-combination is suitable for surge current limitation during a fault for semiconductors in disc housings and is examined here for IGBT module explosion protection.

The newly introduced RL-transformer [9] (so-called Hochenergie-Stossstrombegrenzer) as a compact derivative of the RL-combination with two primary windings and one secondary winding would also be suitable. The electrical behaviour is identical to the RL-combination. The short-circuited secondary winding is placed within the primary windings and crosses them. The secondary winding represents the inductively coupled parallel resistor and is made of stainless steel (V2A). To avoid saturation effects, the RL-transformer has no core material.

In the RL-combination with a design at the values 6 mΩ and 430 nH as well as with aforementioned nominal AC current and switching frequency, losses of approx. 120 W including the skin effect are to be expected in normal operation of the submodule. The inductor consists of one winding of a formed busbar (Fig. 5c) with a cross-section of 100 mm x 5 mm and a diameter of about 340 mm. The resistor is made up of a folded stainless steel (V2A) sheet with insulating intermediate layers of synthetic mica sheets (Fig. 5d). The IGBT module CM1200 is completely destroyed in the test, the heat sink warpage is at 3 mm. The diagram in Fig. 4 shows the curves of the voltage drop of the semiconductor cell U_{x12rl} and of the RL-combination U_{rl12rl} as well as the total current I_{t12rl}, the current of the inductor I_{12rl} and the current of the parallel resistor I_{r12rl}.

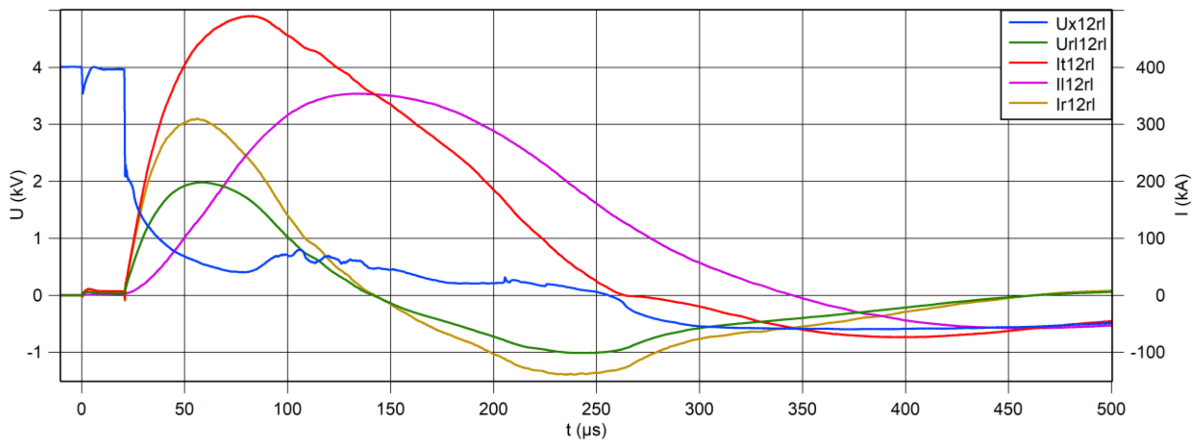

Fig. 4: Voltages and currents when testing the RL-combination with the IGBT CM1200

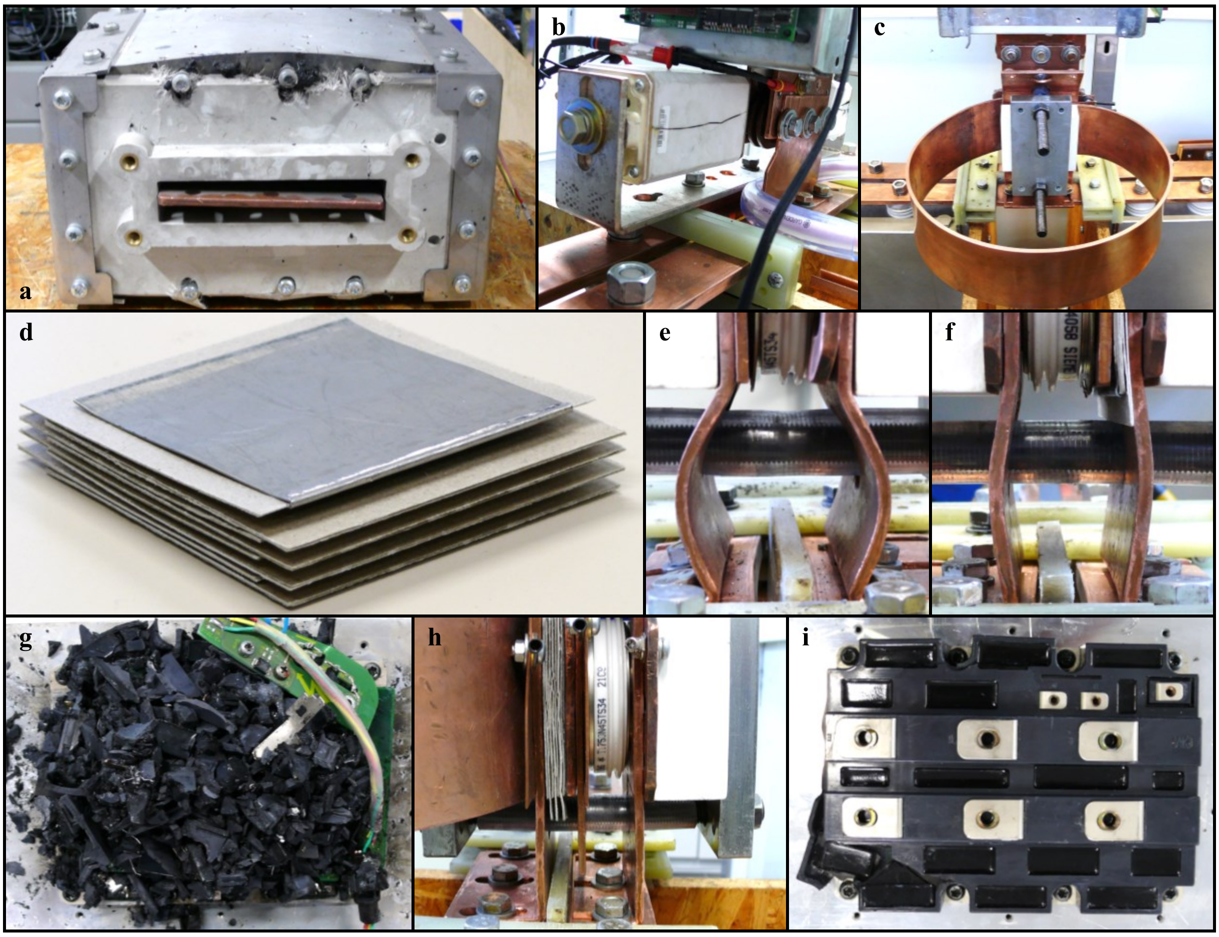

Fig. 5a-i: Photographs of the experiments

2.4 Bypass thyristor parallel with the semiconductor cell (Fig. 1d)

A bypass thyristor is intended to short-circuit the intermediate circuit and thus relieve the IGBT module in case of a failure [10]. The thyristor in a disc housing is turned on approximately one microsecond after the failure of the IGBT module by a controller that detects the subsequent current increase as the IGBT is destroyed after desaturation. The module housing of the CM900 is slightly damaged after the experiment. No deformation of the heat sink can be detected. The amplitude of the fault current of the IGBT module is limited to 65 kA.

The diagram in Fig. 6 shows the voltage drop U_{x9bp} of the semiconductor cell, the total surge current I_{t9bp} and the fault current of the IGBT module I_{x9bp}. The total surge current with a peak value of 1300 kA is greater than in the benchmark test, the thyristor disc housing burst due to high internal pressure. The effect on 5 mm x 120 mm busbars is shown in Fig. 5e.

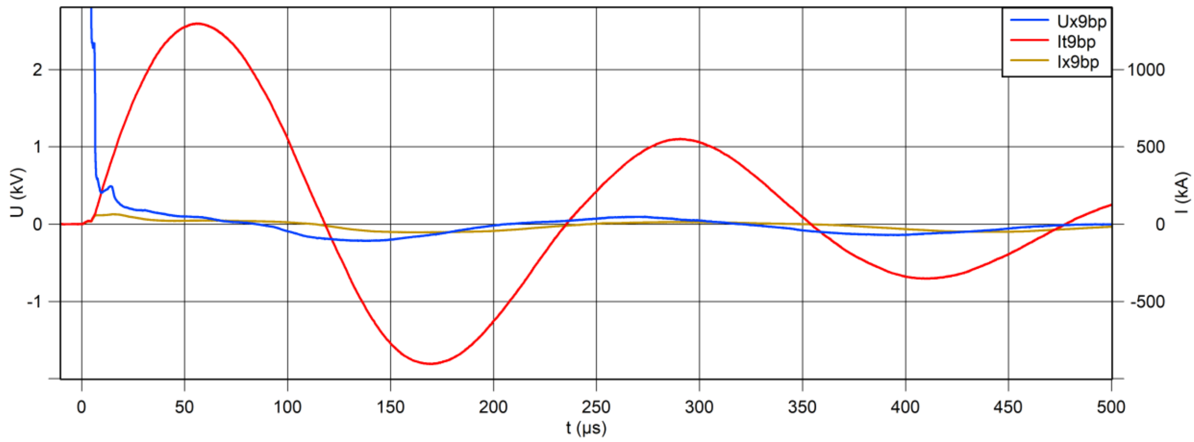

Fig. 6: Current and voltage curves when tested the bypass thyristor with the CM900 IGBT module

2.5 Bypass thyristor with discharge resistor (Fig. 1e)

Parallel to the IGBT semiconductor cell, a series connection of thyristor and discharge resistor is arranged, which is a simplified arrangement of [11] without inductance. The thyristor is turned on when the IGBT module fails. Then the thyristor and discharge resistor take over a part of the surge current and thus partly relieve the IGBT module. The resistor thermally dissipates a part of the energy stored in the intermediate circuit capacitor. The rating of the resistor value is based on the balancing between the maximum permissible surge current in the intermediate circuit and the distribution of energy and current to both paths.

The discharge resistor is dimensioned to a value of 1.2 milliohms for the transfer of the larger proportion of current and is designed as a folded stainless steel (V2A) sheet resistor. As with the bypass thyristor without discharge resistor, this protective circuit does not cause any additional losses during normal submodule operation. The measurements are conducted with the CM900 and CM1200 IGBT modules. The IGBT modules are destroyed (CM900 in Fig. 5g) and the heat sink is warped 1 mm. The busbars between the bypass and the capacitor bank are less widened (Fig. 5f) by I^2t-value than the same place when using a thyristor without discharge resistor (Fig. 5e). Fig. 7 shows the measurements with a CM1200 IGBT module. U_{x12bpr} is the voltage of the semiconductor cell, I_{t12bpr} stands for the total surge current of the intermediate circuit, I_{x12bpr} is the fault current of the IGBT module and $I_{th12bpr}$ represents the current of the bypass consisting of thyristor and resistor.

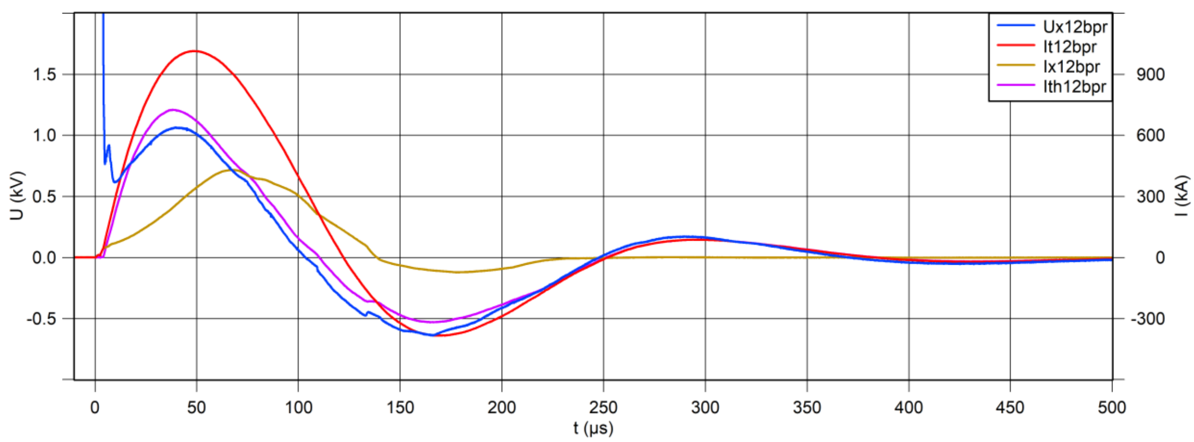

Fig. 7: Measurements on bypass thyristor with discharge resistor and IGBT CM1200

2.6 RL-combination joined with bypass thyristor (Fig. 1f)

RL-combination or RL-transformer can be connected to the bypass thyristor, thus combining IGBT explosion protection and surge current limitation [12]. The RL-combination with a resistance of R = 6 mΩ and an inductance of L = 430 nH is accommodated with the bypass thyristor in a clamping device located between the semiconductor cell and the capacitor bank. Fig. 5h shows the setup after the test, the busbars between capacitor bank an protective circuit are barely bended.

The housing of the IGBT module CM900 remains largely intact (Fig. 5i). The heat sink of the IGBT module has no deformation. Fig. 8 shows the voltages of IGBT semiconductor cell U_{x9bprl} and RL-combination $U_{rl9bprl}$ as well as the total surge current I_{t9bprl} of the intermediate circuit, the fault current I_{x9bprl} of the IGBT module and the current curve $I_{th9bprl}$ of the bypass thyristor.

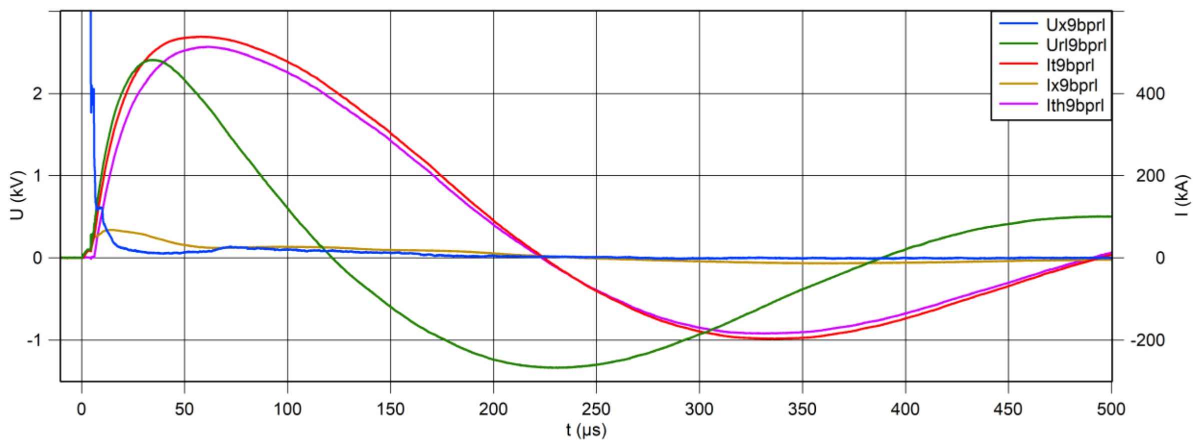

Fig. 8: Currents and voltages of joined RL-combination and bypass thyristor with IGBT CM900

3. The Explosion Integral XI

The quantification of the explosion effect of IGBT modules based on the mechanical impact on the semiconductor cell is associated with high material effort and error-prone. Usually most of the components must be renewed for each additional measurement. For instance, this includes deformed, damaged or weakened heat sinks, screws, mounting assemblies, busbars, reinforced plastics and - of course - the destroyed IGBT modules. The Explosion Integral XI should therefore make it possible to induce from electrical measurements the effectiveness of protective circuits for IGBT explosion protection and thus to reduce experimental expenses.

The I^2t-value and the energy E converted during an IGBT failure are not in a fixed relationship to each other even with identical IGBT modules, but depend on the slope of current rise, the level of the surge current and the duration of the surge current event. This is due to the fact that the energy conversion of the IGBT module depends not only on the surge current, but also on the arc voltage, which develops after the mechanical or thermal destruction of the internal electrical connecting components of the IGBT module. Therefore, not one of the parameters alone is sufficient for the characterization of the explosion behaviour of IGBT modules. For the better evaluation of protective circuits, it is therefore proposed to use a characteristic parameter that includes both the magnetic component from the I^2t-value, as well as the thermal component from the energy E. Thus, the two integral expressions for I^2t and E can be combined to form the Explosion Integral XI.

The formation of the Explosion Integral XI is not a derivation but a definition:

I^2t-value: $$\mathrm{I}^2\mathrm{t} = \int \mathrm{i}^2\mathrm{dt} \quad (1)$$

Energy: $$\mathrm{E} = \int \mathrm{uidt} \quad (2)$$

Explosion Integral: $$\mathrm{XI} = \int \sqrt{\mathrm{i}^2}\,\mathrm{uidt} = \int |\mathrm{i}|\mathrm{uidt} \quad (3)$$

Unit XI: $$[\mathrm{XI}] = \mathrm{A}^2\mathrm{Vs} = \mathrm{AJ} \quad (4)$$

The current “i” and the voltage drop “u” are the electrical quantities of the IGBT module or rather the semiconductor cell during the fault event. The absolute value formation of one share of the fault current ensures that the energy temporarily stored in the stray inductance of the semiconductor cells’ busbars is not affecting the Explosion Integral XI. This makes it possible that the measurement of the voltage does not need to be taken directly on the terminals of the IGBT module. For the calculation of the Explosion Integral XI, it is also conceivable to weight the proportions of the magnetic and thermal components differently, since both effects can have an unequal share of the IGBT explosion behavior.

4. Results

Fig. 9 shows the fault currents in the intermediate circuit for all tests with the IGBT CM900: benchmark test (It9b), high-speed fuse (It9f), RL-combination (It9rl), bypass thyristor (It9bp), bypass thyristor with resistor (It9bpr) and the connection of RL-combination with bypass thyristor (It9bprl).

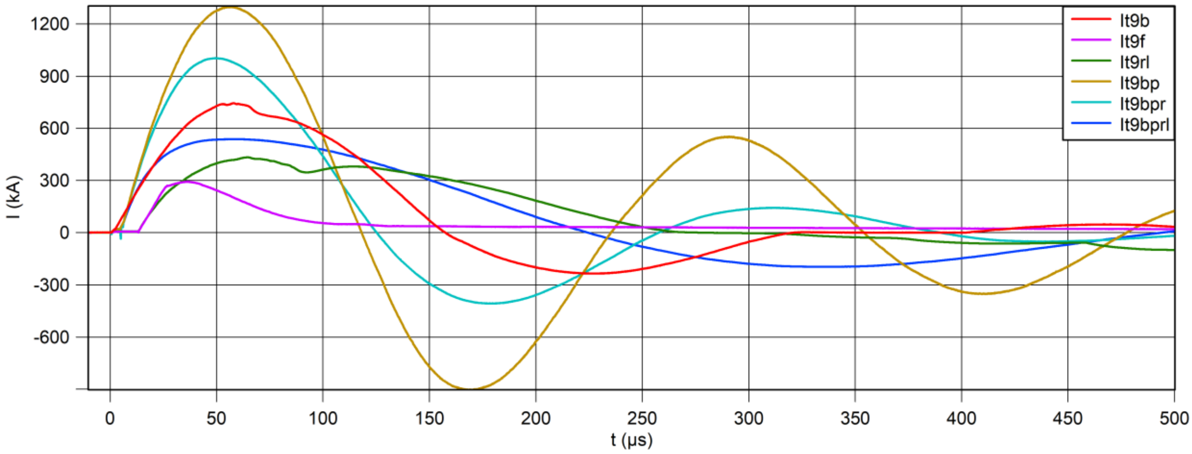

Fig. 9: Overview of fault currents in the intermediate circuit with IGBT module CM900

The IGBT current curves with the module CM900 in which the heat sink was warped by 1 mm or less are shown in Fig. 10: high-speed fuse (Ix9f), bypass thyristor (Ix9bp), bypass thyristor with resistor (Ix9bpr) and the connection of RL-combination with bypass thyristor (Ix9bprl).

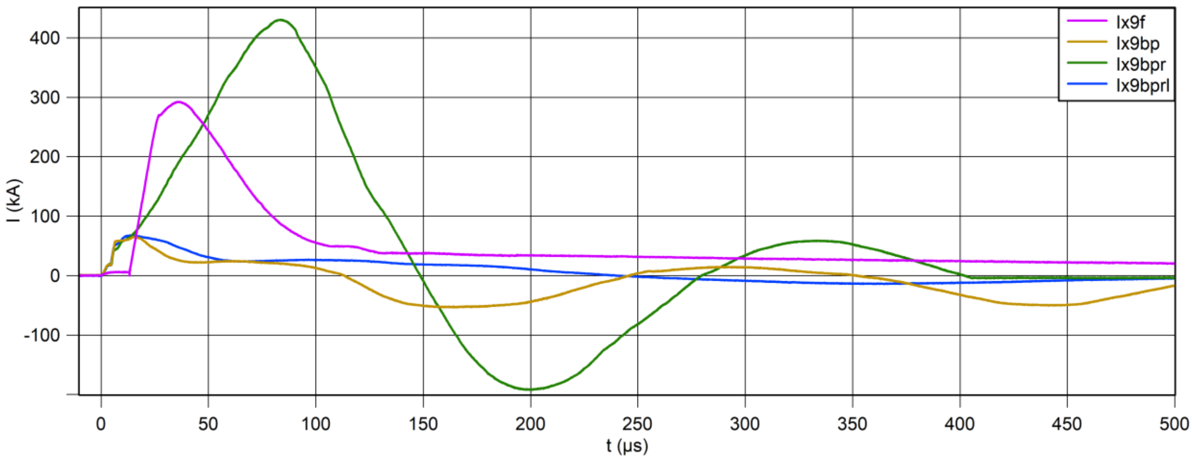

Fig. 10: CM900 IGBT module current of experiments with heat sink deformation by 1 mm or less

Table I: Overview of the measurement results

Protective circuit #	Unit	IGBT	I_{tmax}	I^2t_t	I_{xmax}	I^2t_x	E_x	E_{pc}	Δ_{hs}	XI	Remarks
#	Unit		kA	MA²s	kA	MA²s	kJ	kJ	mm	GAJ	
Benchmark											
1		CM900	746	46	746	46	87	-	14	49	
2		CM1200	843	55	843	55	78	-	12	49	
High-speed fuse											
3		CM900	300	4	300	4	10	83	0	2	
RL-combination											
4		CM900	434	23	434	23	55	41	8	18	Folded V2A-resistor
5		CM1200	491	26	491	26	46	51	3	14	Folded V2A-resistor
6		CM1200	505	28	505	28	41	56	3	14	Graphite disc resistor
Bypass thyristor											
7		CM900	1301	173	65	0.5	2	-	0	0.08	Thyristor disc burst
Bypass thyristor + discharge resistor											
8		CM900	1004	71	431	13	20	43	1	5	
9		CM1200	1016	70	431	11	20	44	1	6	
Bypass thyristor + RL-combination											
10		CM900	540	38	68	0.2	1	82	0	0.04	

Table I gives an overview of all measurement results: intermediate circuit surge current peak value I_{tmax}, intermediate circuit I^2t_t-value, DUT (IGBT module) surge current peak value Ixmax, DUT I^2t_x-value, DUT energy conversion E_x, protective circuit energy conversion E_{pc} (without losses of bypass thyristor, if any), deformation of heat sink Δ_{hs} and Explosion Integral XI. The bound of integration for I^2t-value, energy and Explosion Integral is about one millisecond from switching on T1.

Fig. 11 indicates the relation of the heat sink warpage Δ_{hs} to energy conversion E_x, I^2t_x-value and Explosion Integral XI. Regression lines (subindex “r”) are derived from the respective measuring points. In order to evaluate the significance of E_x, I^2t_x and XI for the relationship with Δ_{hs}, the determination coefficient R^2 of the measuring points for the respective regression line is determined. The Explosion Integral XI has the highest determination coefficient with a value of $R^2_{XI} = 0.94$, followed by the energy conversion E_x with $R^2_{Ex} = 0.90$ and the I^2t_x-value with a $R^2_{I^2tx} = 0.83$.

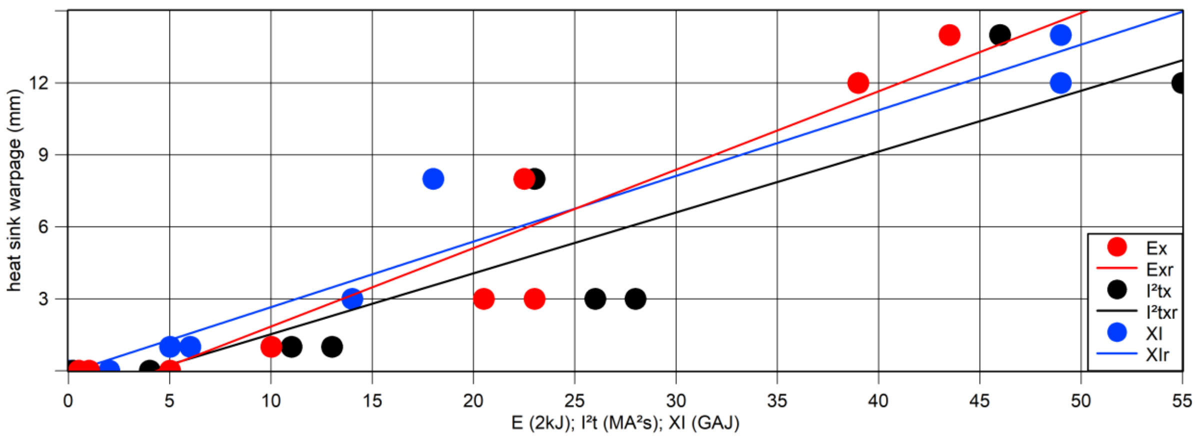

Fig. 11: heat sink warpage Δ_{hs} in relation to energy conversion E_x, I^2t_x-value and Explosion Integral XI

Conclusion

The connection of RL-combination and bypass thyristor can be recommended as protective circuit for IGBT module explosion protection and surge current reduction in MMC submodules with low switching frequencies. The parallel bypass thyristor reduces the voltage drop over the IGBT module to a minimum to avoid an explosion. RL-combination or RL-transformer may be designed for optimal trade-off of surge current reduction in the intermediate circuit and additional losses in normal operation. RL-combination or RL-transformer are freely scalable and can be manufactured from commercially available standard materials.

The newly introduced Explosion Integral XI is suitable for the evaluation of the effectiveness of protective circuits for IGBT explosion protection because it combines the magnetic and thermal components of the fault event. Based on the results of the examinations, it can be assumed that the Explosion Integral XI as a parameter for describing the explosion behaviour of IGBT modules is superior to the I^2t-value and the energy E. For further verification, examinations should be carried out with other IGBT module types and differing converter characteristics.

References

[1] R. Marquardt, A. Lesnicar: „An Innovative Modular Multilevel Converter Topology Suitable for a Wide Power Range“, IEEE Bologna Power Tech Conference Proceedings, ISBN: 0-7803-7967-5, 2003

[2] M. Billmann, D. Malipaard, H. Gambach: „Explosion Proof Housings for IGBT Module Based High Power Inverters in HVDC Transmission Application“, PCIM Conference, 2009

[3] D. Li, F. Qi, M. Packwood, A. Islam, L. Coulbeck, X. Li, Y. Wang, H. Luo, X. Dai, G. Liu: „Explosion Mechanism Investigation of High Power IGBT Module“, 19th Interntl. Conf. on Thermal, Mechanical and Multi-Physics Simulation and Experiments in Microelectronics and Microsystems (EuroSimE), 2018

[4] C. Junghans: “Zur Beherrschung von Stoßstromereignissen bei Fehlerfällen in Submodulen von Modularen Mehrpunktumrichtern”, Dissertation, Universität Rostock, 2022

[5] J. Bürger, J. Dorn, T. Kübel, R. Renz, A. Stelzer, A. Zenkner: „Kurzschlussvorrichtung mit pyrotechnischer Auslösung“, Patent WO/2009/092621A1, Siemens AG, 2009

[6] F. Iov, F. Abrahamsen, F. Blaabjerg, K. Ries, H. Rasmussen, P. Bjornaa: „Fusing IGBT-based Inverters“, PCIM Conference, 2001

[7] D. Braun, D. Pixler, P. LeMay: „IGBT Module Rupture Categorization and Testing“, IEEE IAS ‘97, ISBN: 07803-4070-1/97, 1997

[8] H.-G. Eckel, H. Gambach, F. Schremmer, M. Wahle: „Submodul mit Stromstossbegrenzung“, Patent WO/2014/090272A1, Siemens AG, 2014

[9] H.-G. Eckel, C. Junghans, D. Schmitt: „Hochenergie-Stossstrombegrenzer“, Patent WO/2017/097351, Siemens AG, 2017

[10] M. Billmann, J. Dorn, H. Gambach, M. Wahle: „Kurzschlussstromentlastung für Submodul eines Modularen Mehrstufenumrichters (MMC)“, Patent WO/2013/044961A1, Siemens AG, 2013

[11] A. Zuckerberger, F. Bolgiani, J. Eckerle: „Spulenbauelement zur Verwendung in einer Crowbar-Schaltung“, Patent EP2109122A1, ABB AG, 2009

[12] H.-G. Eckel, C. Junghans, D. Schmitt: „Modul für Modularen Mehrpunktumrichter mit Kurzschließer und Kondensatorstrombegrenzung“, Patent WO/2018/149493, Siemens AG, 2018