Fuse Protection of IGBT Modules against Explosions

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Abstract. The demand for protection of power electronic applications has during the last couple of years increased regarding the high-power IGBT modules. Even with an active protection, a high power IGBT still has a risk of exhibiting a violent rupture in the case of a fault if IGBT Fuses do not protect it. By introducing fuses into the circuit this will increase the circuit inductance and slight increase the over-voltage during the turn-off of the diode and the IGBT. It is therefore vital when using fuses that the added inductance is kept at a minimum. This paper discuss three issues regarding the IGBT Fuse protection. First, the problem of adding inductance of existing High-Speed and new Typower fuses in DC-link circuit is treated, second a short discussion of the protection of the IGBT module is done, and finally, the impact of the high frequency loading on the current carrying capability of the fuses is presented.

Keywords: IGBT protection, IGBT fuses, added inductance, high-frequency loading

I. INTRODUCTION

More power electronic converters use a voltage source dc-link and new applications are added every year, with variable speed drives and UPS systems as two of the main applications. Due to the significant improvement in device technology with IGBT's, the voltage and current ratings have increased and IGBT-based high power applications already exist, both by paralleled and series connections. A disadvantage with the higher power is that the dc-link capacitors store more energy, which in many cases cause a higher risk of IGBT case rupturing when a circuit failure condition occurs [1]-[6]. In some cases the rupture can be extremely destructive, raising the following problems: damage of converter, drive down-time, personal injury and troubles with drive certifications. Most failures are caught by an active over-current protection, which turns off the switches when a fault is detected. However, there are cases where the active protection is not sufficient and where the consequences may be catastrophic for the converter and its surroundings.

A solution to this problem could be a fuse protection, which will not prevent the IGBT destruction but it will prevent a case rupture. There may naturally be a reluctance to use fuse protection in IGBT converters because it takes up extra space, it is an extra cost, it introduces extra losses and finally, a fuse will add some extra stray inductance into the circuit. These drawbacks may, however, be counterbalanced by the advantages such as no rupture, lesser problems with certification and no need for a special explosion chamber in the design.

Some publications have discussed fuses in dc-link applications [1]-[12] and this paper will give an overview of the three main topics in the IGBT fuse protection, added inductance in the circuit, the IGBT module protection and the high frequency loading of the fuse in a DC-link circuit.

II. ADDED INDUCTANCE IN IGBT CIRCUITS

In Fig. 1 are some obvious locations of the IGBT Fuse shown as well as how conventional fuses can be used in an adjustable speed drive. The fuse will have to protect the IGBT modules against the stored energy in the capacitor bank. It can also be seen that the IGBT Fuse will introduce extra inductance in all proposed positions, which will influence the operation of the inverter.

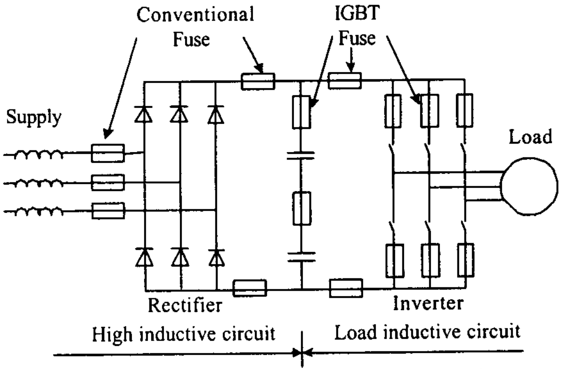

Fig. 1. Possible fuse protection of adjustable speed drives.

One of the influences of the added inductance L_{st} is shown in Fig. 2a. During turn-off of the IGBT switch the added inductance will increase the over-voltage of the IGBT. If the inductance is significantly increased, the switching frequency has to be lowered in order to keep the same power losses, which impacts the output performance alternatively the IGBT-module should carry less current.

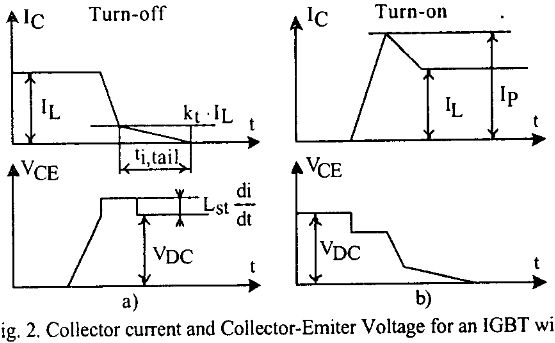

Fig. 2. Collector current and Collector-Emiter Voltage for an IGBT with an added inductance: a) during turn-off and b) during turn-on.

The added inductance will increase the switching losses according to the general equations for turn-off [7]:

$$E_{T,sw}\Big|_{off} = \frac{V_{DC}^2 \cdot I_L}{2\left(\frac{dv}{dt}\right)_{off}} - \left(\frac{V_{DC}}{2} - L_{st}\left(\frac{di}{dt}\right)_{off}\right)\frac{I_L^2}{\left(\frac{di}{dt}\right)_{off}} + \frac{1}{2}k_t \cdot I_L \cdot t_{i,tail} \quad (1)$$

where:

$E_{T,sw}\big|_{off}$ - turn-off switching losses,

L_{st} - stray inductance of the circuit,

I_L - load current, k_t - tail current factor,

$t_{i,tail}$ - duration of tail current,

$\left(\frac{di}{dt}\right)_{off}$ - current gradient turn-off,

$\left(\frac{dv}{dt}\right)_{off}$ - voltage gradient turn-off,

V_{DC} - DC-link voltage.

The turn-on losses can be expressed, according to Fig. 2b, as [7]:

$$E_{T,sw}\big|_{on} = \left(\frac{V_{DC}}{2} - L_{st}\left(\frac{di}{dt}\right)_{on}\right)\frac{I_P^2}{\left(\frac{di}{dt}\right)_{on}} - \frac{I_L \cdot V_{DC}^2}{2\left(\frac{dv}{dt}\right)_{on}} \quad (2)$$

where:

$E_{T,sw}\big|_{on}$ - turn-on switching losses,

I_P - allowed peak current,

$\left(\frac{di}{dt}\right)_{on}$ - current gradient turn-on,

$\left(\frac{dv}{dt}\right)_{on}$ - voltage gradient turn-on.

It is obviously that the added inductance will increase the switching losses during the turn-on and a poor utilization of the power device is obtained.

III. TEST SETUP FOR MEASURING ADDED INDUCTANCE

In order to measure the added inductance a test setup has been established. The setup is simulating the real switch regarding to current level, di/dt, voltage and physical design of the bus bar and fuse connection.

The test setup consists of a DC capacitor, a bus bar with a positive and negative rail, and an IGBT half-bridge as shown in Fig. 3. The bus bar is changeable, and a fuse can be mounted onto it. This makes it easy to test different fuses and different ways of mounting them on the bus bar. The copper bars are 2 mm thick and there is 02 mm isolation between the positive and negative rails.

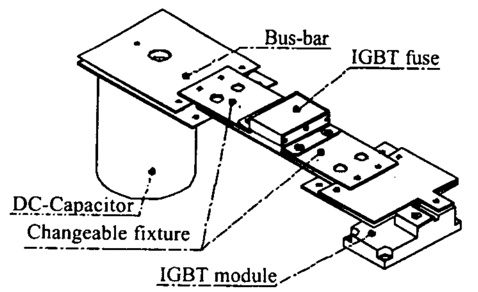

Fig. 3. Test setup for measuring added inductance in an IGBT circuit.

An electrical diagram of the setup is shown in Fig. 4.

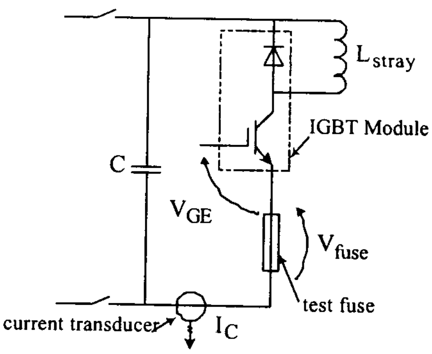

Fig. 4. Electrical diagram for test circuit to determine added inductance in a fuse.

Based on the measured voltage drop on the fuse and the fuse current, the added inductance can be calculated as shown in Fig. 5.

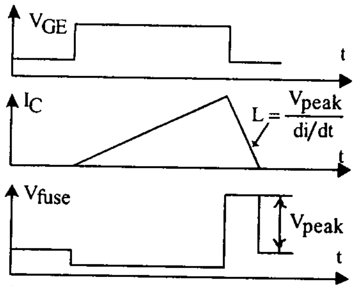

Fig. 5. Calculation of inductance from voltage drop and current gradient.

IV. TEST OF ADDED INDUCTANCE

The inductances for three types of reference bus-bars: 50 mm, 70 mm and 120 mm width have been measured without a fuse. Fig. 6 shows the reference 50 mm bus-bar used during the test. The experimental results are summarized in Table 1.

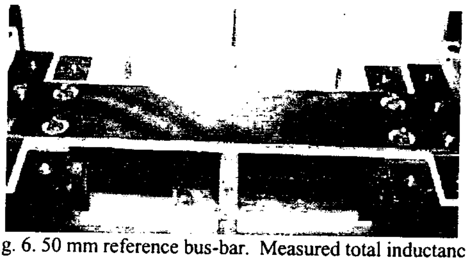

Fig. 6. 50 mm reference bus-bar. Measured total inductance: 21 nH @ di/dt = 4.3 kA/µs.

Table 1. Inductance values for the reference bus-bars at di/dt = 4.3 kA/µs

Bus-bar width [mm]	Bus-bar inductance [nH]
50	21
70	20
120	20

Then, a number of tests on different types of Standard High-Speed and Typower IGBT fuses have been carried out on the test setup. All tested fuses are compared with the reference bus-bar shown in Fig. 6.

Measurement of the added inductance of a Typower IGBT Fuse for protection of IGBT modules is shown in Fig. 7.

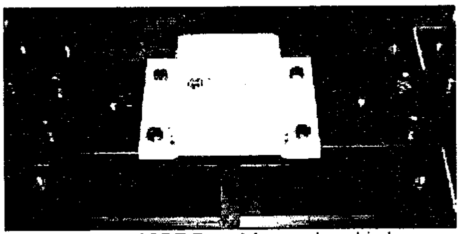

Fig. 7. Typower IGBT Fuse. Measured total inductance: 32 nH @ di/dt = 4.1 kA/us ~ ΔL = 12 nH.

In Table 2 are presented the values of added inductance for Standard High-Speed Fuses mounted on 50 mm bus-bar.

Table 2. Added inductance for Standard High Speed Fuses mounted on 50 mm bus-bar.

Fuse no.	Rated current [A]	Rated voltage [Vdc]	Added inductance ΔL [nH]
2806	180	800	19
2803	380	800	21

The values of added inductance for Typower IGBT Fuses mounted on 70 mm bus-bar are presented in Table 3.

Table 3. Added inductance for Typower IGBT Fuses mounted on 70 mm bus-bar.

Fuse no.	Rated current [A]	Rated voltage [Vdc]	Added inductance ΔL [nH]
2805	350	800	12
2828	350	800	12

From the above measurement results it can be concluded that by introducing Typower IGBT Fuses into the DC-link circuit the level of inductance will increase with only very small values. The Standard High-Speed Fuses mounted on the top of the bus-bar will add around 20 nH of inductance to the inverter circuit (see Table 2), whereas by introducing a Typower IGBT Fuse the added inductance can be reduced to around 12 nH (see Table 3). It is believed that if the distance between the fuse, fuse element and the return conductor can be reduced; the value of the added inductance will be even smaller. Variation on the width of the bus-bar seems to have only negligible effect on the inductance (see Table 1).

V. IGBT PROTECTION

Case rupturing protection of the IGBT module with Typower IGBT fuses has also been investigated. Testing of different power modules, manufacturers, types and sizes, are showing that the energy dissipated in the IGBT can be reduced dramatically by using a Typower IGBT fuse as shown in Fig. 8. By values in A^2s the reduction is in the area of a factor 3-4.

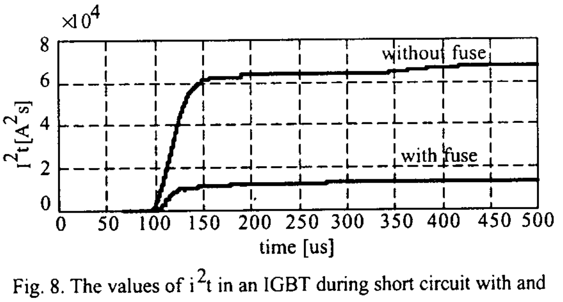

Fig. 8. The values of i^2t in an IGBT during short circuit with and without an IGBT fuse.

VI. HIGH FREQUENCY LOADING OF FUSES

As a result of time variation of the electromagnetic field, the current distribution in a fuse placed in the DC-link circuit of a three-phase voltage source inverter is affected.

The high-frequency currents generate two phenomena in conductors: skin effect and proximity effect. Due to the skin effect the current, which flows through the conductor, is pushed towards the surface. When a current carrying conductor is brought near the parallel conductors (e.g. return bus-bar), the distribution of the current is affected. This phenomenon is called inverse proximity effect since opposite currents flow in the return conductor and the group of parallel conductors.

A test setup for studying current distribution in fuse-strips has been developed. The test setup consists of an auto-transformer (AT), a three-phase rectifier bridge (RB), a dc capacitor bank, a bus-bar with a positive and negative rail, an IGBT half-bridge and an inductive load (L = 0.47 mH) as shown in Fig. 9. The bus-bar is changeable, and a fuse can be mounted onto it. This makes it easy to test different fuses and different ways of mounting them on the bus-bar. The copper bars are 2 mm thick and there is 02 mm insulation between the positive and negative rails.

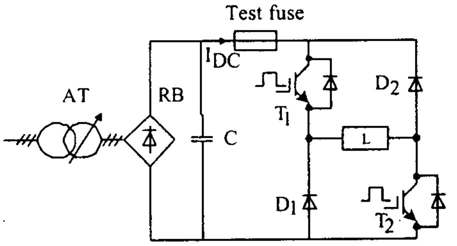

Fig. 9. Electrical diagram of the test setup for high-frequency loading of fuses.

The current distribution through different strips of the fuse can be measured with a Rogowski Current Transducer, as shown in Fig. 10. During the tests of current distribution, two types of fuses have been used. The first one is a Standard High-Speed Fuse, which has four parallel strips placed vertical, 16 mm width, 70 mm length and 0.1 mm thickness, as shown in Fig. 10. The distance between bus-bar / strip and strips is 10 mm.

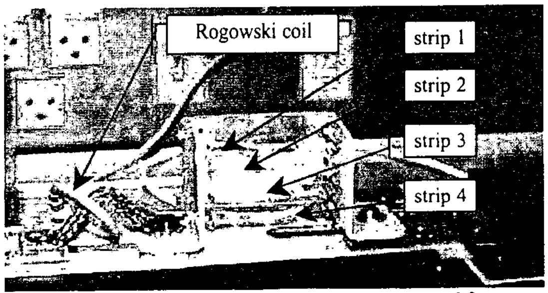

Fig. 10. Open model of a Standard High-Speed Fuse used for current distribution test.

The second tested fuse is an open model of a Typower IGBT Fuse, which has five parallel strips placed horizontal, 7 mm width, 50 mm length and 0.2 mm thickness as shown in Fig. 11. The distance between bus-bar and strips is 17 mm, and there is 5 mm between the strips.

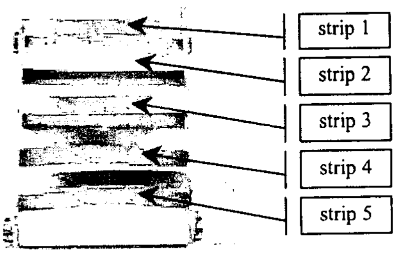

Fig. 11. Open model of a Typower IGBT Fuse used for current distribution test.

The measurements have been performed with a square wave shape of the DC-link current at different switching frequencies and at constant current 100 A, for both considered fuses. The RMS values of the currents in each strip of the fuse were measured with the Rogowski current transducer connected to a LeCroy oscilloscope.

The current distributions into the open models of Standard High-Speed Fuse and Typower IGBT Fuse for the tested frequencies f_{sw} = 2.7-14 kHz are summarized in Fig. 12 and Fig. 13 respectively.

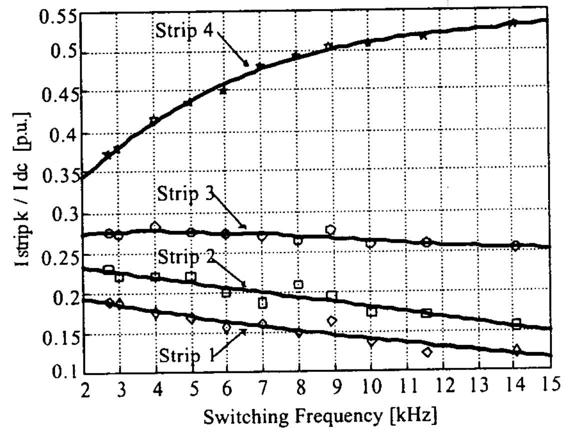

Fig. 12. Current distribution between strips for the open model of Standard High-Speed Fuse.

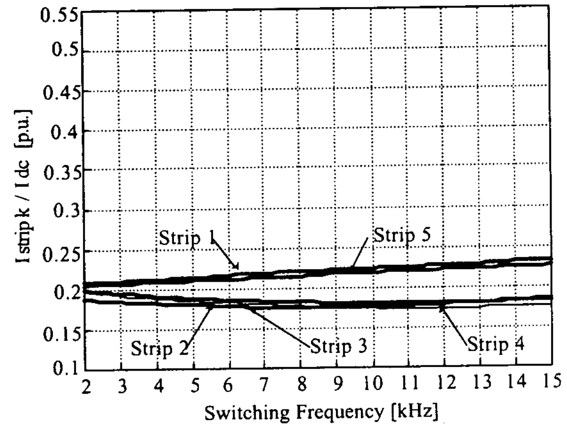

Fig. 13. Current distribution between strips for the open model of Typower IGBT Fuse.

Due to the inverse proximity effect the current distribution in a Standard High-Speed Fuse is affected even for lower frequencies. The strip located near the bus-bar carry a significant amount of the total current 40-50 %, whereas the remote strip carries just 10-20 % of it. For a Typower IGBT Fuse the current is distributed almost equal between the strips. The both sideways strips are loaded with a higher current than the other ones, but the difference is only around 5%. Result: the low-inductive IGBT-fuse has superior capability under high frequencies. In the final paper some consideration regarding the waveform of the strip currents and harmonic content will be presented.

The experiments have been continued with the analysis of temperature distribution for both considered fuses. The thermo-graphic equipment Agema Thermovision ® 9000 TE with a 20° x 12.5° Field of View lens has been used for tests.

The copper strips of the fuses and the bus-bars have been painted with a special black paint for accurate measurement. This black paint has an emissivity (ε) of 0.92. The accuracy of the measurements is ± 1°C for range scale -10°C - 80°C. The interval between each measurement has been chosen to 5 minutes so that the temperatures of the strip is at steady state. Due to the natural cooling effect the measured temperature on the edge strip might be lower than the real one.

The temperature distribution test has been performed for the same switching frequencies and DC-link current as in current distribution test shown in Fig. 12 and Fig. 13.

Fig. 14 and Fig. 15 show the thermo-graphic images of the tested fuses for 5 kHz switching frequencies.

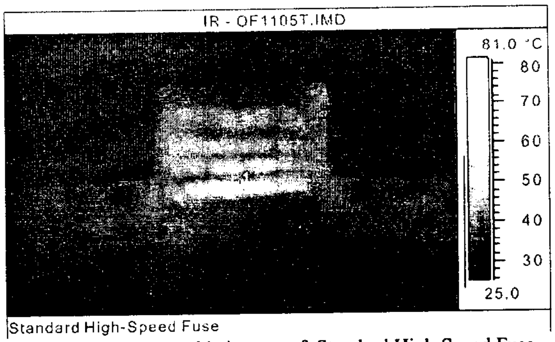

Fig. 14. Thermo-graphic images of Standard High-Speed Fuse at 5 kHz switching frequency

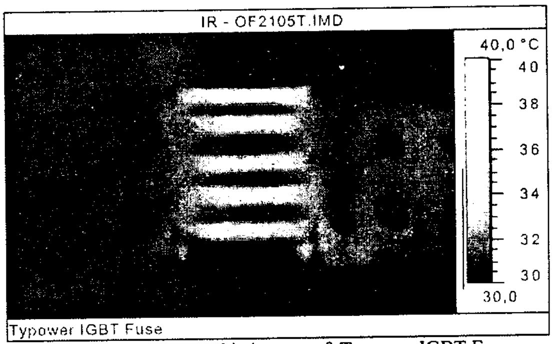

Fig. 15. Thermo-graphic images of Typower IGBT Fuse at 5 kHz switching frequency

In Fig. 16 are shown the temperature profiles of each stripas a function of the width for the open model of Standard High-Speed Fuse at 5 kHz switching frequency.

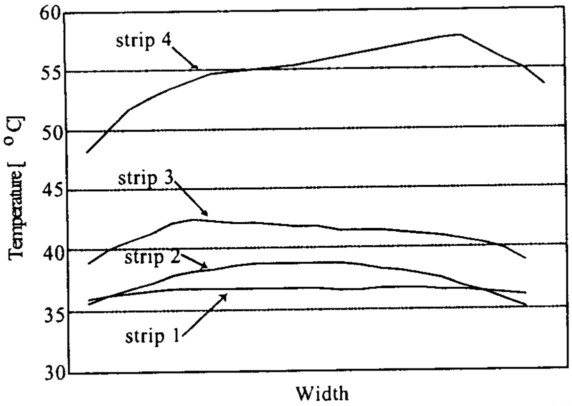

Fig. 16. The temperature profile as a function of width for Standard High-Speed Fuse at 5 kHz switching frequency

The width temperature profiles for strip 1, 2 and 3 of the Typower IGBT Fuse at 5 kHz are shown in Fig. 17. The others strips have the same temperature profile.

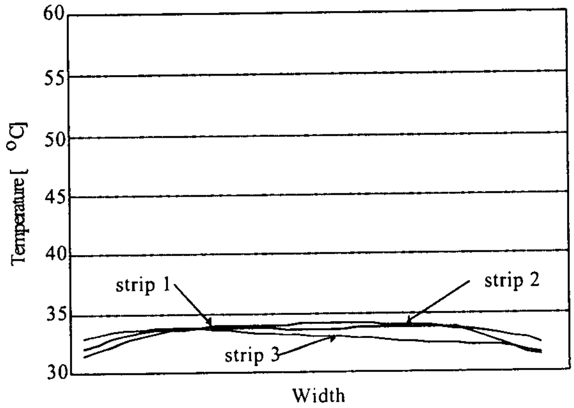

Fig. 17. The temperature profile as a function of width for Typower IGBT Fuse at 5 kHz switching frequency

The temperature width profile seems to be affected only by the proximity effect. For both considered fuses there is a small difference between the temperature on the strip edges and the middle one, but the thickness is 0.2 mm. If the skin effect affects the strip current distribution there should be a significant temperature difference between the edge and the middle of the strip. From measurements the difference is very small (0.5°C - 1°C).

VII. CONCLUSION

This paper shows that by introducing fuses in the dc-link circuit of an IGBT based inverter the level of inductance will increase with very small values. A method in order to measure realistic values of added inductance is given. Furthermore, based on current distribution measurements and analysis of temperature distribution the paper shows how high-frequency currents affect the current distribution into fuses.

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