Fusing IGBT-based Inverters

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Abstract. The number of applications based on the dc-link voltage source converter is in a continuous growth. Due to the fact that the power level increases more energy is stored in the dc-link. Even with an active protection, a high power IGBT still has a risk of exhibiting a violent rupture in the case of a fault. In order to avoid the rupture a possible solution is to use a fuse protection of the converter. From failure analysis of a three-phase inverter, a dc-link location for fuses might assure a protection against all faults. Experiments made with 400 A, 1200 V IGBT switches show that rupture can be avoided by the use of high-speed fuse protection. The problem of added inductance in existing High-Speed Fuses is discussed, and new IGBT Typower fuses in the dc-link circuit are treated. Finally, some considerations about current distribution in dc-link fuses and spectral analysis of these currents are discussed when high-frequency components are present in the current.

Introduction

The dc-link voltage source converter topology covers currently a wide range of power applications, with variable speed drives and UPS as the main ones. Due to the significant improvement in IGBT technology, the voltage and current ratings have increased and IGBT-based high power applications already exist, both parallel and series connected. A drawback with the higher power is that the dc-link capacitors store more energy. This causes a higher risk of IGBT case rupturing when a circuit failure condition occurs [1], [2]. The rupture can be extremely destructive in some situations, and it brings up certain problems such as damage of converter, drive down-time, personal injury, troubles with drive certifications – only few have been mentioned here. 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 an unwillingness 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 in the circuit. These drawbacks may, however, be compensated by the advantages such as no rupture, reduced problems with certification and no need for a special explosion chamber in the design and thereby reduced manufacturing cost.

This paper will first present an overview concerning the failures in a dc-link inverter and possible location of the fuses. Then, a study of the rupture phenomena and how a fuse protects an IGBT is shown. Next, some experimental measurements regarding the value of added inductance by fuses for different types of bus-bars will be presented. Finally, based on experimental results the high-frequency current distribution and spectral analysis within dc-link fuses will be presented.

Failure analysis in dc-link inverters

A typical three-phase voltage source dc-link inverter is shown in Fig. 1

![Fig. 1. Three-phase inverter with voltage source dc-link and IGBT's.](image)

The rectifier side is high-inductive whereas the inverter side is very low-inductive. The capacitor
bank typically consists of several individual capacitors in series and parallel, and the same can be true for the IGBT-modules, although only paralleling is relevant because the low voltage level is considered here. It is common practice to connect the mid-point of the capacitor bank to ground.

Several incidents can cause a huge over-current in the IGBT devices, and different cases are indicated in Fig. 2.

The discussion is mainly focused on drives application but it could easily be other applications too. The first is the dc-link shoot through as shown in Fig. 2a. This can happen in the case of a fault in the control circuit or an interior fault in an IGBT-module. A dangerous case happens if a fault is detected by the over-current protection and the converter is put into operation again because the user subsequently has ignored the error message.

The next cases in Fig. 2b and Fig. 2c are short-circuits between two phases. A reason could be failure of the insulation in the motor windings. The two cases are principally similar, but the amount of inductance in the current path determines the current rise-time and how the fault evolves. The last cases shown in Fig. 2d and Fig. 2e are earth faults. These could also be caused by e.g. bad motor winding isolation. The difference between the earth faults and the phase-to-phase faults is that the short circuit current only appears in one of the dc-link rails.

Possible location of Fuses in IGBT Inverters

Some possible locations of the fuses in a voltage source inverter [1], [2] are shown in Fig. 3. Only those solutions are presented which have fuses both in the upper and in the lower part of the inverter, because it is the only way to give a full protection of the inverter.

Fig. 3. Possible fuse configurations in a voltage source inverter: a) dc-link, b) in series with the capacitors, c) in series with the IGBT-modules, d) modular paralleling of half-bridges to increase the converter power rating.

It may seem most obvious to place two fuses in the dc-link (a) as they can protect against all faults. However, placement in series with the capacitor bank (b) provides in principle the same protection. The advantage here is that fuses in series with the capacitor do not carry the active power producing current but only ac-current. The solution in (c), where one fuse is used in series with each IGBT seems at first sight most expensive, but the current in each of the six fuses is smaller than in the dc-link fuses. There is no fixed ratio between the fuse currents for case a) and c) because the dc-link mainly carries active power whereas a fuse in series with an IGBT carries both active and reactive power to the load.

Short-circuit test

Tests with short-circuit of an IGBT have been performed in order to study the rupture phenomena and how a fuse protects an IGBT. A diagram of the basic test facility is shown in Fig. 4. The tests are made with a 1200 V, 400 A standard single switch IGBT-module and a 660 V, 200 A Bussmann High-Speed Fuse. The tests are performed as a simple short-circuit of an isolated capacitor bank through the IGBT. The dc-link capacitance is 4.7 mF and the parasitic
The inductance of the circuit without the fuse is 30 nH. Both values correspond well to what is used in practical converters together with 400 A IGBT’s.

![Diagram of the IGBT short-circuit test facility](image)

**Fig. 4.** Diagram of the IGBT short-circuit test facility with indication of the measured values.

The normal dc-link voltage used with 1200 V components is around 560-700 V, but the test is performed at 800 V which is considered as a worst case that occurs in the case of e.g. a fast breaking of a motor. The tests are carried out at 20°C. The current is measured with a PEM CWT 1500 Rogowski coil transducer with a bandwidth of 7.5 MHz, having an inserted inductance of a few pH. The voltages are measured with normal voltage probes by an oscilloscope. The sampling rate is 50 MHz.

![Graph of VCE and Ic](image)

**Fig. 5.** Short circuit test of an 1200 V, 400 A IGBT switch without a fuse.

The results for the direct IGBT short-circuit test are shown in Fig. 5, and the results for the test with an inserted fuse are shown on Fig. 6. The **I^2t-values in the two cases are compared in Fig. 7.**

![Graphs of IGBT power, Vfuse, VCE, and I^2t](image)

**Fig. 6.** Short circuit test of an 1200 V, 400 A IGBT switch with a 200 A high-speed fuse.

The conclusion of the short-circuit tests is that a fuse can prevent a rupture of an IGBT switch and furthermore makes it much easier to protect the driver circuits from being destroyed by over-voltage. For this example with a 400 A single switch IGBT and a 200 A fuse there is a security factor of 550/200 = 2.75 against rupture in terms of energy, and 6.5/1.5 = 4.3 in terms of I^2t, see Fig. 7.

![Graphs of I^2t values with and without fuse](image)

**Fig. 7.** I^2t-values for tests with and without a fuse.

**Added inductance by fuses in dc-link circuit**

Another major aspect is the inductance value added in the dc-link circuit by using fuses. A test setup for measuring the circuit inductance has been developed. The test setup consists of a dc
capacitor, a bus-bar with a positive and negative rail, and an IGBT half-bridge. The setup is shown in Fig. 8. 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 a 0.2 mm insulation between the positive and negative rails.

![Diagram of test setup](image1)

Fig. 8. Test setup for measurement of the added inductance using a fuse.

An electrical diagram of the test setup is shown in Fig. 9.

![Electrical diagram](image2)

Fig. 9. Electrical diagrams of the test-circuit for measuring added inductance using a fuse.

The operating principle of the circuit is as follows: The capacitor C1 is initially charged to a preset voltage (e.g. 130 V). A very short pulse is applied on the IGBT’s gate (about 60 μs). Then the IGBT is turned off very rapidly. The fuse inductance is calculated based on measured voltages and currents from the circuit during turn-off. Varying the gate-resistance R_G as shown in Fig. 9 the current gradient di/dt during turn off can be controlled.

An example of a measured current during turn-off is shown in Fig. 10. The corresponding voltages are shown in Fig. 11. Two measured voltages are shown as well as the calculated difference between them, which is the bus-bar voltage drop. It is seen that initially, when the di/dt is zero, the voltage drop is only a few volts. This means that the resistive voltage drop can be ignored when the large inductive voltage drop is considered during turn-off. So, the voltage peak at 0.8 μs is entirely due to (L*di/dt) in the circuit.

![Graph of measured current](image3)

Fig. 10. Measured current during turn-off. The dots indicate all the points in which di/dt is evaluated.

![Graph of measured voltages](image4)

Fig. 11. Measured capacitor and IGBT voltages, and the calculated difference between them.

The current gradient can be calculated based on the experimental data shown in Fig. 10. The bus-bar inductance is calculated by evaluating the di/dt in a number of points around the voltage peak. A simple division of the bus-bar voltage with di/dt gives the circuit inductance.

The test-setup has been realized in the laboratory with maximum focus on flexibility. Thus, it can be changed and tested with different sizes of bus-bars and fuses.

The inductance for three types of reference bus-bars: 50 mm, 70 mm and 120 mm width have been measured without a fuse. Fig. 12 shows the 50 mm bus-bar used during the test. The results are summarized in table 1.

![Test bar](image5)

Fig. 12. 50 mm reference bus-bar.
Table 1. Inductance values for the reference bus-bars at \( \frac{di}{dt} = 4.3 \text{kA}/\mu\text{s} \)

<table>
<thead>
<tr>
<th>Bus-bar width [mm]</th>
<th>Bus-bar inductance [nH]</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>21</td>
</tr>
<tr>
<td>70</td>
<td>20</td>
</tr>
<tr>
<td>120</td>
<td>20</td>
</tr>
</tbody>
</table>

Next, the added inductance for different types of fuses, have been measured for the considered bus-bars. Fig. 13 and Fig. 14 shows two types of Typower IGBT fuses.

![Typower IGBT Fuse, no. 2828.](image)

![Typower IGBT Fuse, no. 2805.](image)

In Table 2 are presented the values of added inductance for Typower IGBT Fuses mounted on 70 mm bus-bar.

Table 2. Added inductance for Typower IGBT Fuses mounted on 70 mm bus-bar

<table>
<thead>
<tr>
<th>Fuse no.</th>
<th>Rated current [A]</th>
<th>Rated voltage [Vdc]</th>
<th>Added inductance ( \Delta L ) [nH]</th>
</tr>
</thead>
<tbody>
<tr>
<td>280</td>
<td>350</td>
<td>800</td>
<td>12</td>
</tr>
<tr>
<td>282</td>
<td>350</td>
<td>800</td>
<td>12</td>
</tr>
<tr>
<td>288</td>
<td>350</td>
<td>800</td>
<td>12</td>
</tr>
</tbody>
</table>

Table 3 shows the added inductance for Standard High-Speed Fuses mounted on 50 mm bus-bar.

Table 3. Added inductance for Standard High Speed Fuses mounted on 50 mm bus-bar

<table>
<thead>
<tr>
<th>Fuse no.</th>
<th>Rated current [A]</th>
<th>Rated voltage [Vdc]</th>
<th>Added inductance ( \Delta L ) [nH]</th>
</tr>
</thead>
<tbody>
<tr>
<td>280</td>
<td>180</td>
<td>800</td>
<td>19</td>
</tr>
<tr>
<td>280</td>
<td>380</td>
<td>800</td>
<td>21</td>
</tr>
</tbody>
</table>

From the above measurement results it can be concluded that by introducing Typower IGBT Fuses into the dc-link 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 3), whereas by introducing a Typower IGBT Fuse the added inductance can be reduced to around 12 nH (see Table 2). 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).

Current distribution in fuse

The current distribution in a fuse placed in the dc-link circuit of a three-phase voltage source inverter is affected by eddy currents as a result of time variation of the electromagnetic field [6], [7]. The high-frequency currents generate two phenomena in conductors: skin effect and proximity effect. Due to the skin effect the current, which flow through the conductor, is pushed towards the surface. When the current is divided among a group of parallel conductors the sharing of the total current between them is generally unequal. As this phenomenon is dependent on the distance between conductors, it is called direct proximity effect. Furthermore, if 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 \((L = 0.47 \text{mH})\) as shown in Fig. 15.
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 0.2 mm insulation between the positive and negative rails.

The current distribution through different strips of the fuse can be measured with a Rogowski Current Transducer as shown in Fig. 16. 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. 16. The distance between bus-bar / strip and strips is 10 mm.

The second one is a 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. 17. The distance between bus-bar and strips is 17 mm, and there is 5 mm between the strips.

Because each strip has different value of mutual inductance, big differences between the current waveform and RMS current in the strips can be observed. The current distribution in each strip of this type of fuse, for the tested frequencies (f_{sw} = 2.7-14 kHz), is summarized in Fig. 20.
Fig. 20. Current distribution in Standard High-Speed Open Fuse for different switching frequencies.

The current waveform for each strip of the Typower IGBT Fuse is shown in Fig. 21.

Fig. 21. Currents waveform in each strip of Typower IGBT Fuse with 5 kHz switching frequency.

The current distribution in each strip, for the same switching frequencies as in precedent case, is summarized in Fig. 22.

Fig. 22. Current distribution in Typower IGBT Fuse for considered switching frequencies.

Due to the inverse proximity effect the current distribution in a Standard High-Speed Fuse is affected even for lower frequencies and 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.

Spectral Analysis of Currents

Based on the dc-link current and the strip currents for both considered open fuses a spectral analysis has been performed. The harmonic currents magnitude are related to the dc component of the dc-link current spectra as follows:

- Harmonic spectra of the dc-link current: 
  \[ I_{h_{dc}} / I_{dc} \], where: \( I_{dc} \) is the dc component of the dc-link current spectra and \( I_{h_{dc}} \) is the magnitude of the harmonic components.

- Harmonic spectra of strips currents: 
  \[ I_{h_{strip_k}} / I_{dc} \], where \( I_{h_{strip_k}} \) is the magnitude of the harmonic currents for \( k^{th} \) strip, \( k = 1, \ldots, n \).

Fig. 23 shows the harmonic spectra of the dc-link current and Fig. 24 the harmonic spectra for each strip current in the open Standard High-Speed Fuse.

Fig. 23. Harmonic spectra of the dc-link current with 5 kHz switching frequency.
Ih strip 1 / Idc

Fig. 24. Harmonic spectra of the strip currents in open Standard High-Speed Fuse.

The harmonic spectra of the strip currents, for open model of Typower IGBT Fuse, are shown in Fig. 25.

Fig. 25. Harmonic spectra of the strip currents for open model of Typower IGBT Fuse.

From the above investigation it can be concluded that, in the harmonic spectra only odd harmonics order have to be taken into account. The even harmonics have a small magnitude because of the dc-link current shape (see Fig. 23). For both tested fuses only 1st to 9th odd harmonics have a significant magnitude, the rest can be neglected.

The spectral analysis of the strip currents offers a foundation in studying the influence of skin effect on the current distribution in each strip.

Conclusion

It is explained how an IGBT-based inverter circuit can be protected against IGBT case rupture by introducing fuses in the circuit. Different types of faults and possible protection methods are discussed. Furthermore, this paper shows that by introducing Typower IGBT Fuses instead of Standard High Speed Fuses in the dc-link the level of inductance will increase with only very small values. A method to measure realistic values of added inductance is given and values for different fuse types are published.

It is shown how inverse proximity effect affects the current distribution in a Standard High-Speed Fuse and a Typower IGBT Fuse.

Proximity effect has a great impact on the current distribution among the fuse strips. Some of the strips may carry more than the normal share of the rated current. As a consequence the fuse rated current must be de-rated accordingly. As this effect depend on the distances between bus-bar and strips, and switching frequency, it can be minimized only by modifying the fuse geometry. From the test shown in this paper it is obvious that using a fuse with paralleled strips placed horizontally and small distance between them and the return conductor (a Typower IGBT fuse), the value of the added inductance decreases and the current distribution is only slightly affected by the inverse proximity effect.

References

[2]. F. Abrahamsen, C. Klumpner, F. Blaabjerg, K. Ries, H. Rasmussen - Fuse protection of IGBT's against rupture, Proceed. of NORPIE 2000, pp.64-68;

