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Abstract **– This paper proposes a fully passive protection scheme for DC link inductors whose geometry is characterized by a substantial distance between the rectifier and inverter stations. Inductors of this type can be found intrinsically in very long high-power cables - as in HVDC transmission for example - as well as in DC-links for high-power current source inverters. In such applications the inductor must be duly protected against overvoltages as well as against overcurrents potentially occurring as consequence of an open-circuit or a short-circuit fault respectively. The distance between the inductor terminals prevents the use of well-known localized protections like, for example, simple freewheeling diodes. A key role in the protection scheme proposed by the authors is played by the largely available transient suppressor diodes (often commercially identified as "Tranzorbs") and the solution is kept very simple and reliable by employing only rugged diodes and thyristors. The protection relies only on the energy stored in the inductor without the need of any external supervision circuit or any information exchange between the distant inductor terminals. Experimental results are presented and a generalization of the scheme to a broader application is also introduced.**

I. INTRODUCTION

Often it is necessary to protect the insulation and mechanical integrity of large DC link inductors from damage caused by excessive overvoltages and/or overcurrents usually arising from open-circuit or short-circuit faults respectively. Such large inductors are a very expensive and important parts of the systems in which they operate. For this reason the task of designing a proper protection scheme for them must not be underestimated.

Often large DC current link applications are characterised by the fact that their terminals are located at very considerable distance apart (even several kilometers) as Figure 1 shows. The most common practical case occurs when the effective distribution of the inductance is over long distance, as may occur for high-power transmission cables or for inductors used as DC-link in high power current source inverters / rectifiers [1].

The inductors in Figure 1 have been drawn to call attention to the distributed nature of their inductance which is always a property of the overall loop in which the inductor current flows. Often the inductor constitutes the DC-link of current source converters in which the current i_L as well as the voltages v_A and v_B do not change sign.

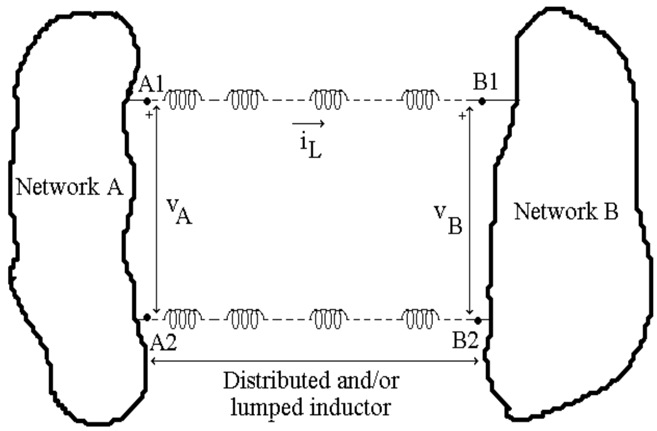

Fig. 1. Situation in which the effective terminals of a DC link inductor are distant from each other.

The distributed nature of the inductance leads one to approach the problem of protection of such inductors in a decentralized manner. Firstly, it is useful to observe that ultimately the portion of electrical network needing protection is the quadrupole A1-A2-B1-B2 identified in Figure 1 and not only a simple bipole.

As consequence the common protection against open-circuit faults constituted by a simple freewheeling diode can not be applied effectively. Indeed it is sufficient to observe that the effectiveness of two possible freewheeling diodes, one connected between the terminals A1 and B1 and the other between A2 and B2, would be jeopardized by the unavoidable large inductances of the diodes connections to A1 (A2) and B1 (B2). The magnitude of such undesired inductances would arise naturally as consequence of the large distance between the converter terminals. Furthermore a freewheeling diode would not provide any protection against overcurrents or overvoltages possibly arising at the ports A1-A2 and B1-B2 of the quadrupole.

In order to be as more reliable as possible, the protection scheme should be kept as simple as possible, since every added complexity introduces an additional risk of malfunction which is less and less tolerable as the cost of the inductor increases. In particular the protection scheme should possess the following features:

- Absence of any external supervision circuit.
- Independence from any external energy source.
- Capability to operate using only the energy stored in the inductor.
- Absence of information exchange between the two distant ports A1-A2 and B1-B2.

II. PROPOSED PROTECTION SCHEME

As mentioned, it is common that the inductor represents the DC-link of high-power current source converters with the quantities i_L , v_A and v_B having constant sign that can be assumed positive under normal operating conditions. Unless stated otherwise these assumptions will be at the basis of the subsequent discussion.

All quantities i_L , v_A and v_B clearly have design limits and considering the requirements listed in the previous paragraph the authors propose the circuit solution shown in Figure 2 as a decentralized protection scheme. The symbols F_{A1}, F_{A2}, F_{B1}, F_{B2} represent fuses that might be fast acting or slow acting depending on the application. The tripole identified as "Thyristor trigger circuit" senses the voltage v_B and triggers the thyristor T_B whenever v_B exceeds the design value considered as the symptom of a fault.

Observing Figure 2 it is possible to analyze how the protection scheme operates in the different possible fault conditions.

I) An open-circuit fault either occurring in network A or consequence of the intervention of fuses F_{A1} and/or F_{A2}, causes the current i_L to flow into the diode D_A and the voltage v_A to equal the negative forward voltage drop of D_A. The current i_L decreases after the fault because of the action of the voltage v_B.

II) An open-circuit fault either occurring in network B or consequence of the intervention of fuses F_{B1} and/or F_{B2} , causes the voltage v_B to rise until its fault value is reached. At this instant the thyristor T_B is ignited through the trigger circuit and the terminals B1 and B2 are almost short circuited.

If the positive voltage v_A is not reduced considerably after this event, the current i_L raises under its presence until at least one of the fuses F_{A1} and F_{A2} intervenes, because its time-integral of the current squared has been exceeded. In this case the current i_L is diverted to flow in D_A.

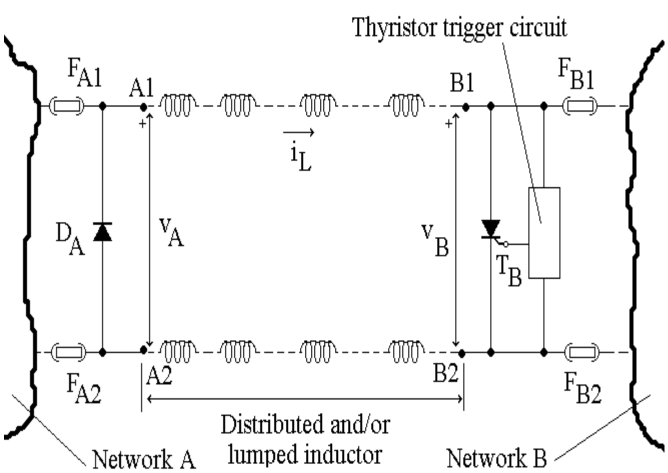

Fig. 2. Basic principle of decentralized protection scheme.

The short circuit produced by the thyristor T_B at the port B1-B2 ultimately leads to the intervention of at least one of the fuses F_{B1} and F_{B2} unless additional possible – but not required - protection policies operating on the network B prevent this from happening. If this is not the case the ultimate operating mode of the inductor is the one in which the current i_L may flow in D_A and T_B only while its value decreases towards zero under the action of the forward voltage drops of these devices.

III) Any faulty operating condition creating an overcurrent i_L which exceeds the I^2t rating of the fuses will ultimately melt at least one of them. As consequence, from that instant onwards the protection scheme behaves like one of the previous cases I or II.

The scheme provides also fast protection for the inductor against overvoltages at port B1-B2 because such an event invokes the intervention of the thyristor trigger circuit and the consequent behaviour as described by the previous case II. On the other hand an overvoltage condition at the port A1-A2 is detected indirectly and with slower dynamics because it must create a rise of the current i_L or - if a controls system for i_L is present in the network B - an elevation of the voltage v_B.

This differentiation between the mode of intervention for overvoltages in v_A and v_B is justified by the hypothesis under which this principle scheme has been developed. Indeed when the inductor constitutes the DC-link of a current source converter operating with positive i_L, v_A and v_B, as assumed, the network A, which is the generating side, may be more affected by short spike voltages that should be ignored.

It should be observed that the proposed scheme strongly favors the protection of the inductor over the networks A and B. This choice arises from the original assumption that the inductor is a highly valuable component whose integrity and survivability deserve the highest priority.

III. STRUCTURE OF THE THYRISTOR TRIGGER CIRCUIT

Thus far only the function of the thyristor trigger circuit has been addressed but not its detailed structure and accompanying design choices. First of all it should be observed that when the occurring faulty condition ultimately leads to the operating mode II described in the previous section, the inductor current i_L cannot be diverted instantaneously into the thyristor T_B because of its finite commutation time. Consequently the thyristor trigger circuit must be able to withstand the entire fault value of i_L until T_B goes in full conduction.

Additionally, in general, it is not possible to identify a single value of i_L that could be used as decisive threshold for triggering the thyristor. This is because an open circuit fault in network B could occur for reasons completely independent from i_L and its value. These observations together with the requirements listed at the end of section I restrict the set of possible components that can be used in the trigger circuit.

The authors have adopted the structure and components shown in Figure 3 to realize the trigger circuit enclosed in the red rectangle for sake of clarity. In order to satisfy the requirement of operating only with the energy stored in the protected inductor, the circuit employs only passive components and does not require any external energy source.

It should be further observed that such a feature is very important because it assures protection even in case of catastrophic fault of the entire system, with consequent loss of all energy sources. In a scenario like this, one can rely only on the energy stored in the inductor. The trigger circuit uses only the local information represented by the voltage v_B and does not require other additional external supervision circuits.

The key detail for the correct circuit operation is the utlization of the nowadays widely available unidirectional Transient Voltage Suppressors (TVS) diodes which are often denominated with the conventional name of "Tranzorb". These components clamp the voltage to a maximum value close to their nominal one with effects similar to a zener diode. Nonetheless, very differently from the zener diodes, they can withstand and dissipate very high instantaneous powers for few microseconds and, furthermore, their first failure mode is guaranteed to be a short circuit [2].

Tranzorbs rated for 1.5 kW – 3kW of dissipated power are commonly produced by many manufacturers and nowadays devices rated for 30 kW and 6 kA peak current are emerging produced, for example, by Sussex Semiconductors [3]. The manufacturer usually specifies the waveform of the surge current that a Tranzorb can withstand safely as an asymmetrical bell-shaped curve having a rise time of 10 µs and a fall time, to ½ of the peak current, of 1000 µs.

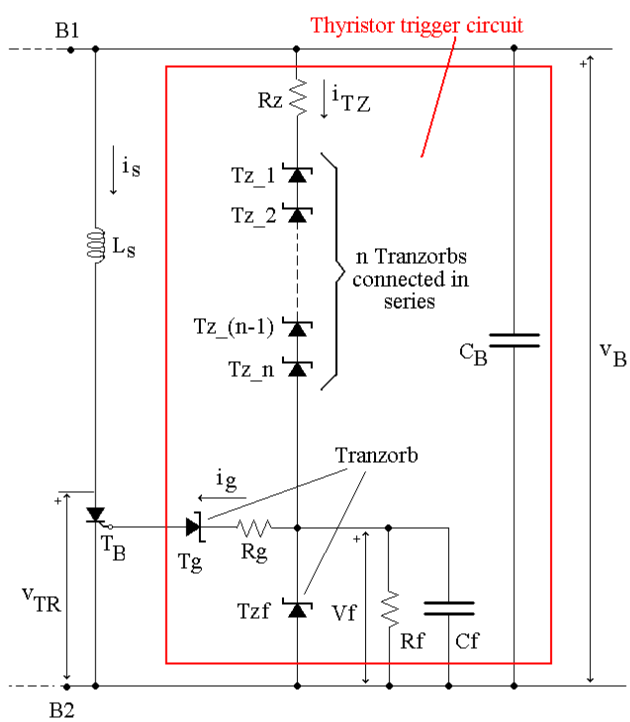

Fig. 3. Structure of the fully passive thyristor trigger circuit.

The nominal peak surge current is roughly equal to the rated power of the device divided by its nominal clamping voltage. The Tranzorbs are widely used as protection devices against overvoltages (especially induced by lightning) since they can clamp the voltage much more effectively than Varistors [4]-[5] and they are guaranteed to fail as a short circuit providing an ultimate protection that is generally used to blow a fast acting fuse.

The features of the Tranzorbs are particularly suitable for the thyristor trigger circuit because they are components of reduced size which are nevertheless able to withstand a large impulse current. This is exactly the situation occurring in the trigger circuit inside the time interval between the inception of the fault and the instant when T_B goes in full conduction. In this interval the surge current i_{TZ} in the Tranzorbs becomes higher than i_L and the devices must be chosen so that their peak current is not lower than the maximum i_L that can occur in the worst case fault condition. Zener diodes could not be used as substitute of Tranzorbs because there is no guarantee on their clamp voltage and failure mode for peak currents well above their absolute maximum rating.

Following these considerations, it can be observed in Figure 3 that the branch composed by the series of low-value resistor Rz, Tranzorb Tzf and n Tranzorbs Tz_1 – Tz_n, constitutes a path in which the inductor current i_L can flow - until T_B reaches the full conduction - without risk of being abruptly interrupted with consequent onset of potentially destructive values of v_B. The number of Tranzorb diodes in series implies the maximum overvoltage for v_B after which the circuit ignites T_B. As soon as a specific Tranzorb device has been selected according to additional criterion, such as availability for example, the desired maximum v_B determines the number n+1 of devices needed in series.

The layout of the trigger circuit must be as compact as possible and lie as close as possible to the port B1-B2 in order to minimize the parasitic series inductance on the path of i_L. To relax in some extent such a requirement and to protect T_B against excessive dv_B / dt the very low series impedance capacitor C_B is introduced and it is mounted as close as possible to the T_B terminals.

From Figure 3 one can infer the succession of events which lead T_B into conduction after an open circuit fault of type II. Before the fault inception the voltage v_B has a positive value lower than the threshold defined by the number of Tranzorbs in series and their avalanche voltage. As soon as the open circuit fault occurs the current i_L flows into the capacitor C_B and the voltage v_B raises linearly up to the maximum clamping voltage defined by the series of n Tranzorbs Tz_1 – Tz_n. At such instant these Tranzorbs conduct and the voltage v_B remains almost clamped. As consequence, the current i_{TZ} becomes equal to i_L because the capacitor voltage is practically constant. Not later than when the voltage of the small filtering capacitor Cf reaches the clamping voltage of the Tranzorb Tf, a gate current ig appears and its peak is set by the difference of the clamping voltages of Tzf and Tg as well as the resistor Rg. As soon as ig exceeds the thyristor gate trigger current, T_B reaches the full conduction after the delay time specified by the manufacturer which is usually below 5 µs. At this point the thyristor current i_S starts to rise with a slope determined by the clamping voltage of the series of Tranzorbs and the turn-on snubber inductance Ls. The inductor Ls must always be present to limit the maximum di/dt for which the thyristor is rated. Ultimately i_S will become equal to i_L, i_{TZ} will drop to zero ending so the commutation process and the surge current in the Tranzorbs. It is important to choose a thyristor whose I^2t is greater than the one characterizing the fuses chosen. By selecting properly the components the whole area of the pulse current in the Tranzorbs remains easily inside the safe limits specified by the manufacturer.

IV. EXPERIMENTAL SETUP AND RESULTS

An experimental setup has been built to test the effectiveness of the proposed protection circuit. The setup is part of a wider one aimed at testing topologies for high power wind turbines. Figures 4 and 5 show the portion of the setup regrouping the power semiconductors and thyristor trigger circuit while the 67 mH inductor to be protected is not shown because collocated far away from the other components.

The components shown in Figure 2 and 3 are highlighted in figures 4 and 5 for sake of explanation and clarity. The capacitor C_B is composed by one extremely low inductance 470 nF snubber capacitor mounted directly on the terminals of the thyristor T_B together with additional two 1nF and 600 pF capacitors mounted on the trigger circuit board. The Tranzorb Tz_1 – Tz_n and Tzf used are devices 1N6284A (1.5KE36A) rated for 1.5kW and 36 V breakdown voltage while the Tranzorb Tg is a 1N6272A (1.5KE11A) rated for 11.5 kW and 11 V breakdown voltage.

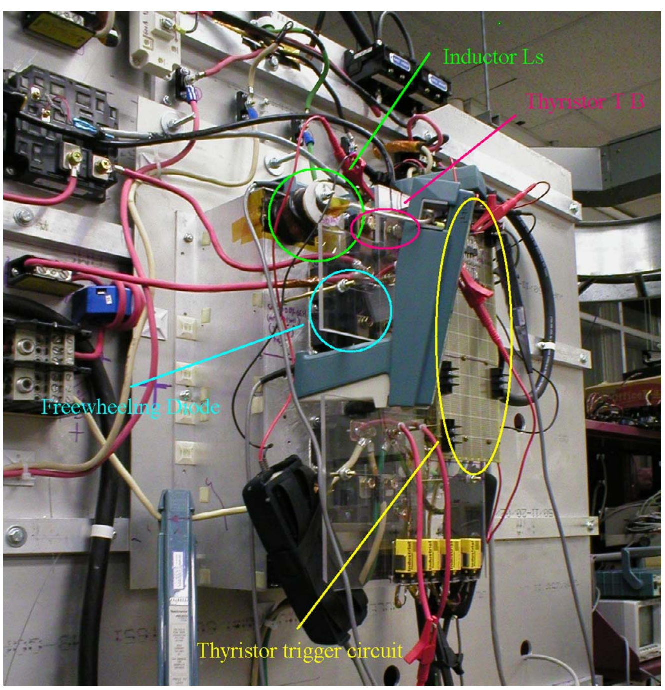

Fig. 4. Particular of the experimental setup.

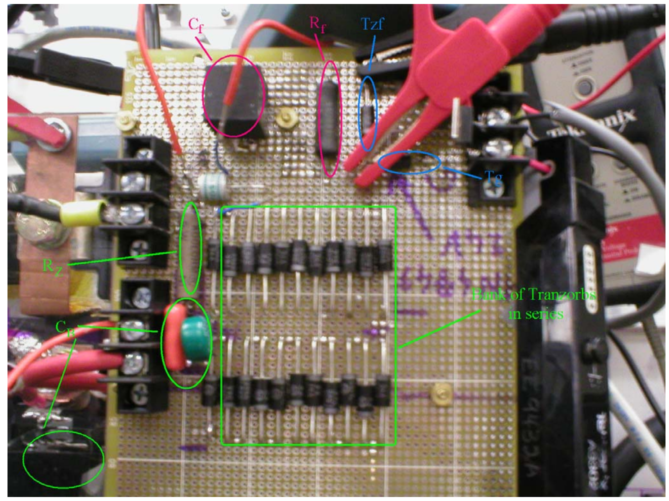

Fig. 5. Detail of the thyristor trigger circuit showing the components.

On the trigger board shown in Figure 5 there are two groups of 11 Tranzorbs each, all connected in series, for a total possible breakdown voltage of 792V. In the test performed only one group has been used setting so the intervention voltage of the trigger circuit was close to 400 V. The resistor Rf and the capacitor Cf have values of 100 Ω and 0.1 µF respectively, both selected for low inductance. The resistors Rg and Rz are 22 Ω and 1 Ω respectively, again both are antiinductive. The thyristor T_B is a device TD310N from Eupec and the turn-on snubber inductance Ls used has a value of 30 µH to limit the di/dt at 13.4 A/µs (with 400V maximum V_B voltage) well below the 120 A/µs which is the device limit.

Two LeCroy digital scopes have been used to perform the measurements. The first scope, a model LT354, (four channels, 500 MHz) is used to monitor the waveforms of the trigger circuit v_{TR} (CH1,blue), i_{TZ} (CH2,green), Vf (CH3, red) and ig (CH4, magenta) and a capture of its screen during a test with i_L = 10 A is shown in Figure 6. The second scope, a model 9304 (four channels, 175 MHz) monitors the waveforms v_A (CH1, magenta), i_L (CH2,blue), v_B (CH3, red) and i_S (CH4, green). The two scopes were connected with the 9304 acting as trigger master on the voltage v_B and the LT354 as trigger slave

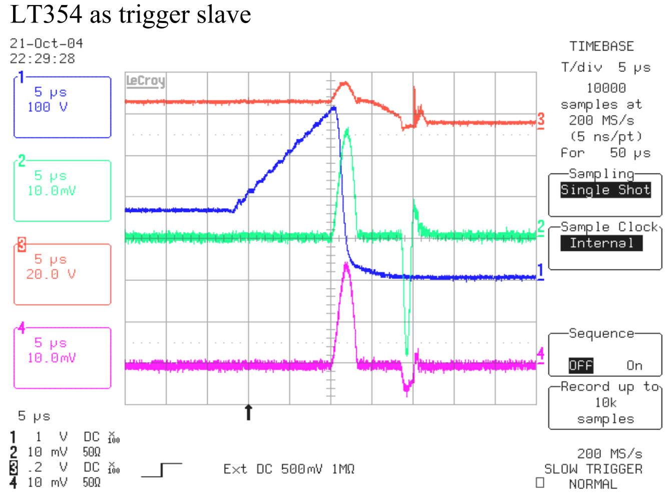

Fig. 6. Display of the LT354 scope with waveforms of the trigger circuit.

Two tests were performed on the experimental setup and in both the network A was constituted by a six-pulse diode rectifier whose input was a 60 Hz three-phase symmetrical system of sinusoidal voltages regulated in amplitude by a Variac. The network B was a 16 Ω power resistor. Between the network A and the fuses F_{A1}, F_{A2}, as well as between the fuses F_{B1},F_{B2} and the network B, solid state switches (high-power IGBTs) were inserted to realize very "clean" open-circuit fault conditions.

The first test was performed by creating an open-circuit condition at the port B1-B2 after that the inductor current i_L had reached the steady state value of 10 A. The scopes were triggered for a 200V value with positive slope sensed on the voltage v_B and the waveforms recorded on a time base scale of 5 μs/div are shown in Figure 7. The upper graph of Figure 7 presents the waveforms of v_A, i_L, v_B, i_S recorded by the scope 9304 while the waveforms of v_{TR}, i_{TZ}, Vf, ig recorded by the scope LT354 are presented in the lower graph.

By analyzing the traces it is possible to observe the operation of the circuit. After the open circuit occurs at the port B1-B2 The voltage v_B raises linearly starting from about 160 V. When it reaches a value close to 400 V the Tranzorbs Tz_1 – Tz_n begin to conduct. Simultaneous and equal peaks occur in the currents i_{TZ} and ig starting at +10 μs because the Tranzorb Tg (11 V) allows the flow of the gate current before than Vf reaches the clamping value of 36V.

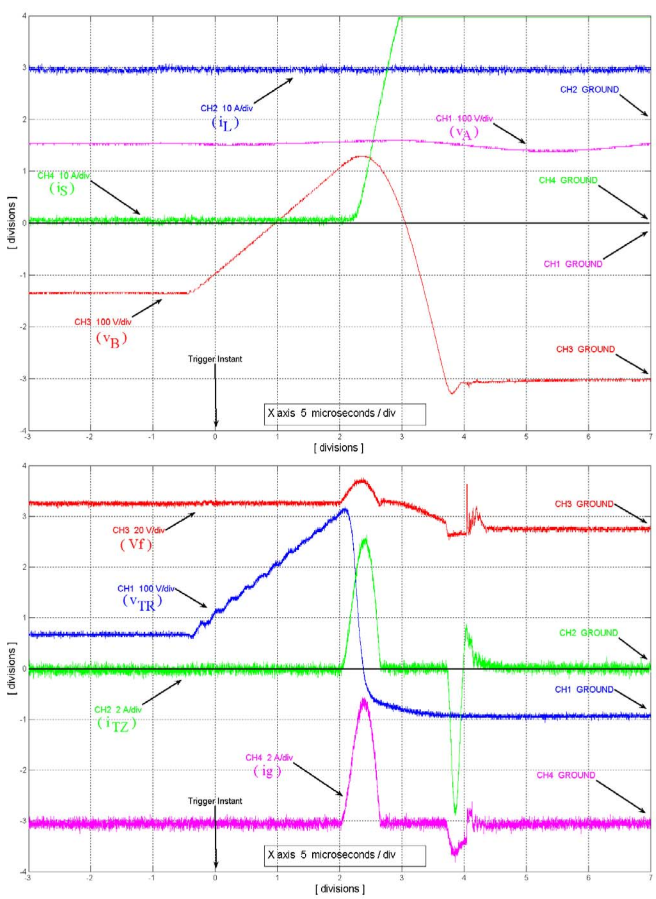

Fig. 7. Waveforms for the test with 10A of inductor current.

The thyristor voltage v_{TR} drops abruptly after ig has reached the ignition value. As consequence of the short-circuit created by T_B the capacitor C_B begins a discharge thyristor transient current through L_S and indeed one can observe that the ramping in the current i_S due to this event. After L_S has been charged, it will perform a partial discharge transient also in the series connection of all Tranzorbs until i_S assumes the same value of i_L.

During this transient the Tranzorbs are directly polarized acting as normal diodes. The negative peak observable in i_{TZ} is due to this process. It is important to observe that the waveform of the current i_L does not show any appreciable transient, confirming that i_L commutates smoothly from the network B to the short circuit created by the triggered thyristor T_B; i.e. the protection scheme has accomplished its task of preventing abrupt changes in the inductor current.

The second test performed was aimed at testing the effectiveness of the protection in case the inductor current i_L was of limited value, i.e. in the range of tenths of Amperes. Figures 8 and 9 show the waveforms of i_L, v_B, i_S recorded during this test repeated on two different time base scales. In Figure 8 one can observe that although the open circuit fault occurs when i_L is small, nevertheless, v_B rises and fires the thyristor through the trigger circuit.

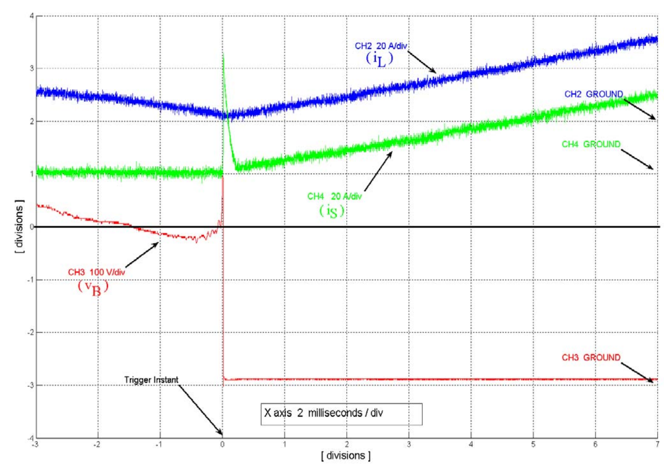

Fig. 8. Waveforms for the test with low inductor current.

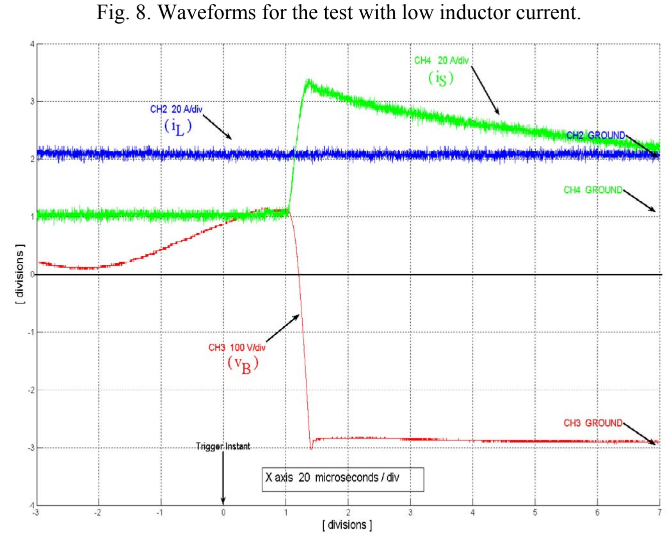

Fig. 9. Test with low inductor current repeated with magnified time base.

The waveform of i_S shows a peak due to the discharge of C_B through the thyristor as explained before. Subsequently i_S decreases by flowing in the directly polarized Tranzorbs until it reaches the same value of i_L. The peak of i_S, its subsequent decrease and the evolution of v_B are magnified in Figure 9. The inductor remains always connected to the voltage source at the port A1-A2 while the thyristor T_B provides the recirculation path for the current i_L. As consequence the inductor currents i_L and i_S begin to rise as clearly shown by Figure 8 and ultimately i_L would provoke the intervention of at least one of the fuses F_{A1}, F_{A2} and the diode D_A as explained in section II, thereby completing the sequence of events for the protection of the inductor.

V. GENERALIZED PROTECTION SCHEME

The protection scheme presented in the previous sections was shown to be valid for unidirectional power flow from network A to network B when the current i_L as well as the voltages v_A and v_B assumed only positive values. The authors consider it worthwhile to propose a generalization of the scheme able to operate also in the common cases where a bidirectional power flow is required by reversing the signs of the voltages v_A and v_B while i_L continues to remain always positive.

The generalized protection scheme under these assumptions is shown in Figure 10. The group composed by the thyristor T_B and its trigger circuit has been replicated at the port A1-A2 but its polarity has been reversed to allow the flow of the current i_L during a fault condition. The unidirectional voltage blocking capability of the chosen Tranzorbs imposes one additional diode (Dta, Dtb) be provided in series to each trigger circuit at both ports. Without this diode the voltage at each port could not reverse its polarity because the Tranzorbs would immediately enter the forward conduction mode.

In the worst fault case, during a hypothetical simultaneous open circuit fault at the ports A1-A2 and B1-B2, the current i_L will flow initially in the capacitors C_B of both trigger circuits until sufficient capacitor voltages are reached to ignite the thyristors T_A and T_B. It is worthwhile to note that the capacitor voltages rise independently and simultaneously because the path provided by them is the only one in which i_L can flow initially.

As consequence T_A and T_B are eventually ignited, but always independently, and still without the need of any communication between the circuits located at the two ports. As well it is possible to observe how this protection scheme provides overvoltage protection of both signs although each specific port is capable of sensing only one specific voltage polarity.

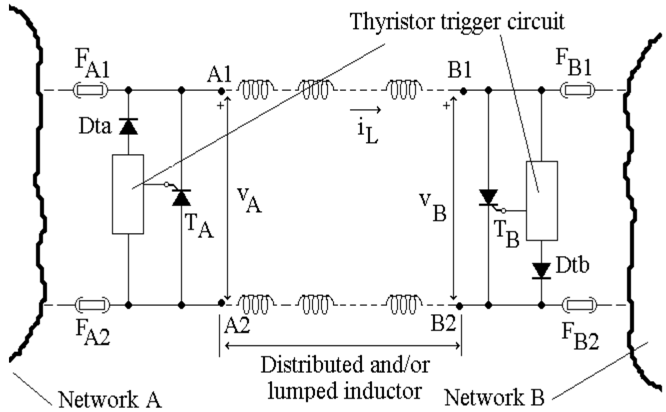

Fig. 10. Decentralized protection scheme for bidirectional power flow.

VI. CONCLUSIONS

A decentralized protection scheme designed to protect geometrically large DC-link inductors from overvoltages and overcurrents has been presented. The protection of the DC-link inductor is considered as a priority choice in case of fault. The proposed protection scheme does not require any supervision circuit or communications between the distant terminals of the inductors to be protected and uses passive devices only, without any need of external power sources, as it exploits the same energy stored in the inductor before the fault event. An experimental setup has been realized to test the effectiveness of the protection scheme and the related results have been presented. Additionally, a possible generalization of the scheme capable to operate also in case of bidirectional power flow across the DC-link inductor has been proposed.

VII. REFERENCES

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