Power Semiconductor Switches for Current Impulse Generators

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Abstract: In current impulse generators for currents in the range of several kilo-Amperes, time durations up to several milliseconds and charging voltages in the range of 50 kilo-Volts, usually triggered spark gaps are used as switches. Well-known problems of spark gaps are the need for gap spacing adjustment depending on the charging voltage, a high sound level in case of high currents and severe erosion of the electrodes in case of high charge transfer. Also, if the impulse generator is mismatched the current may oscillate to values of opposite polarity. In general, a spark gap has the disadvantage that current my flow bidirectional, so mismatch of the load will result in a current oscillation after zero-crossing.
With semiconductor switches all these disadvantages can be avoided. Main problems of semiconductor switches, however, are the uneven voltage distribution across the many components that have to be connected in series and the limited current and voltage capability. One individual impulse may damage the whole semiconductor stack, whereas a spark gap can handle very high overcurrents for many times without damage, and overvoltages are not a problem.
Special attention has to be paid to the triggering of many serially connected semiconductors. If the trigger impulses are not exactly synchronous very high overvoltages may occur at the last triggered components.
This contribution reports about a self designed and optimized thyristor switch for a long-duration (LD) current impulse generator for testing high-voltage energy metal oxide varistors with a maximum charging voltage of 50 kV and a maximum current of 6 kA (1 ms) and 2 kA (4 ms), respectively. This switch is currently in a test phase and has operated so far very satisfyingly. A second view is taken on a thyristor switch for an ac current impulse test transformer, also used for testing high-voltage energy varistors. Maximum primary voltage is 6 kV, and maximum short-circuit current is 2 kA (50 Hz). Here, a vacuum breaker has been replaced in order to minimize the inrush current when energizing the transformer and to have only one half-cycle of short-circuit current when a breakdown of the test sample occurs.

1 INTRODUCTION

In electrical power supply systems semiconductor switches still have too many disadvantages, usually making them unattractive as replacement for mechanical switches or breakers, although they are much faster and do not require any maintenance. Most important disadvantages are limited overcurrent capability, high continuous power losses, insufficient insulating properties under the aspect of personal safety and concerns about service reliability.

In laboratory test circuits these requirements in most cases do not exist. For safety issues, separate insulating links and earth switches can be provided, and only expert staff is using the equipment. The test circuits have short-circuit currents that are mostly not much higher than the test currents. The turn-on time is usually very short, such that power losses do not constitute a problem. Especially for current impulse tests very high currents are present but for very short time only. Therefore, generally, active cooling of the semiconductors is not necessary. For the proper selection of the type of semiconductors current amplitude and the time duration of current flow are the most important parameters. IGBTs have the advantage of being able to chop a current at any time, but the maximum overcurrent capability is in the range of only two times the continuous current. Bipolar transistors are more or less “dead” MOSFET transistors; they are very fast, but are not available for high voltages and very high currents. GTOs and IGCTs are still "exotic" and expensive components and are therefore not a good choice for building commercial switches. Finally, thyristors are able to handle overcurrents in the range of 10 times the continuous current and even more for 10 milliseconds, and they are commercially available components "from the stock". Their only disadvantage is that they can interrupt currents only if there is a natural zero-crossing. But due to the fact that in impulse tests there is always a natural zero crossing this type of semiconductor is perfect for these applications.

For testing the energy handling capability of metal oxide (MO) varistors depending on impulse current amplitude and wave shape, as e.g. reported in [1], impulse capacitors and ac test transformers are used. A high-voltage energy MO varistor of 45 mm height has a typical residual voltage in the range of 15 kV to 20 kV, dependent on the current amplitude. For very high currents (up to 200 kA) and short impulse durations (microseconds) charging voltages up to 100 kV are required. However, the impulse charge is not very high compared to long–duration current impulses (milliseconds time duration) and alternating current. But it would be very expensive to design semiconductor switches for this special application. Therefore, main attention is given to long-duration (LD) current impulse test generators and alternating current test transformers. The required impulse time duration for LD current impulses is in the range of 1 ms to 4 ms, and the current amplitude may reach values of 6 kA. For generating these impulses pulse forming networks (PFNs) are used. When a PFN is switched to a matched load half of the charging voltage will appear across the load, thus required charging voltages for these tests are in the range of 20 kV to 50 kV. This allows using semiconductor switches instead of spark gaps.

The alternating current tests are performed to determine the behavior of energy varistors in the current range of several amps to less than 1 kA. The supply voltage of the transformer is below 10 kV, so it is comparatively easy to replace the existing mechanical switches (vacuum circuit breakers) by thyristor switches.

In the following sections 2 and 3, the existing test circuits are introduced, and then the alternative solutions by making use of semiconductor switches is presented starting from section 4.

2 LD CURRENT IMPULSE GENERATOR

2.1 Test circuit

The PFN test circuit consists of an LC ladder network and has an energy content of 250 kJ (20 x 10 μF at maximum 50 kV). It can be adjusted to generate rectangular current impulses of 1 ms, 2 ms or 4 ms time duration. **Figure 1** shows the equivalent circuit and **Figure 2** a photo of the setup.

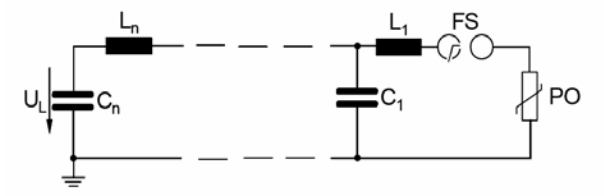

Fig. 1: PFN circuit for LD current impulse testing. FS = triggered spark gap, PO = test object

2.2 Impulse wave shape

Depending on the load and the degree of matching the generator surge impedance to the load an oscillation may occur after current zero-crossing. The spark gap will not interrupt this current if not very high efforts are taken to improve its dielectric recovery performance (e.g. by pressurized air). In the ideal case the impulse is expected to be merely rectangular. In case of a dielectric breakdown of the test sample the generator will completely being discharged in form of a travelling wave process,

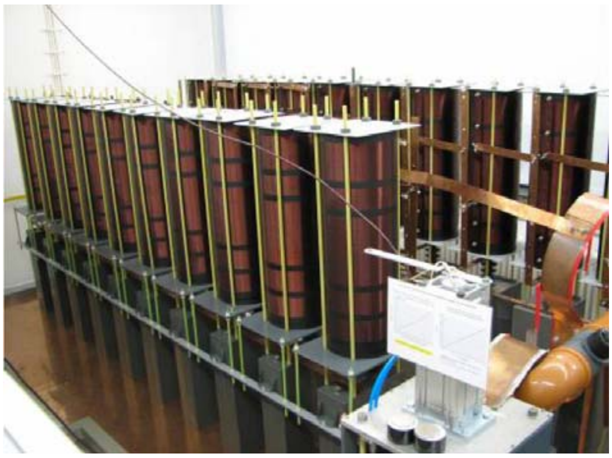

Fig. 2: Photo of the PFN circuit

which results in several polarity reversals and thereby extreme stress to the surge capacitors that drastically reduces their lifetime. **Figure 3** shows an oscillogram of the resulting current after a breakdown of the test sample.

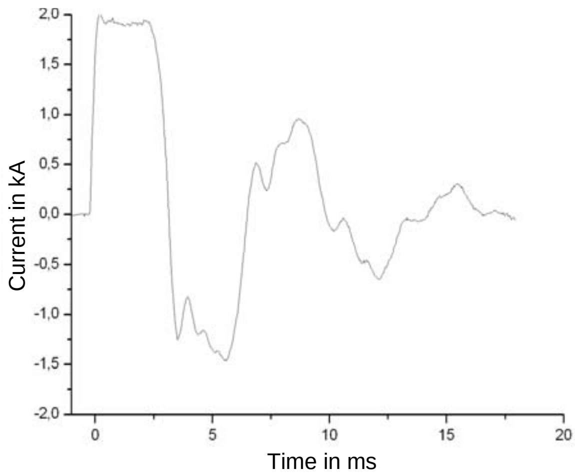

Fig. 3: Current impulse for a mismatched load when using a triggered spark gap

3 AC TEST TRANSFORMER

3.1 Test circuit

The ac test transformer is a Thoma-regulator with a fixed 6 kV primary voltage and a variable secondary voltage of 10 kV at maximum. The typical secondary short-time test current is approx. 500 A (peak) for several power-frequency cycles time duration, and the secondary short-circuit current is approximately 1.5 kA (r.m.s.), resulting in max. 2.5 kA (r.m.s.) on the primary side. **Figure 4** shows the equivalent circuit and **Figure 5** a photo of the setup.

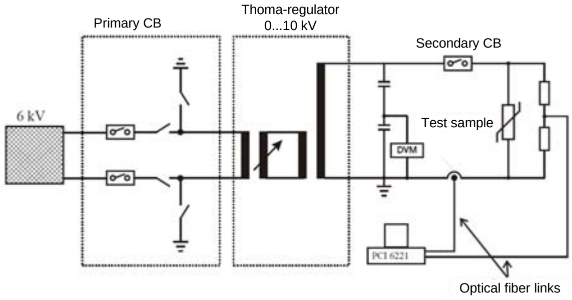

Fig. 4: Test circuit for ac testing

Fig. 5: Photo of test setup for ac testing

3.2 Impulse wave shape

The typical test current is limited to a peak value of 500 A, but after breakdown of the test sample due to energetic overloading the full short-circuit develops. This current will flow for four to five half cycles time duration because of the mechanical delay of the secondary vacuum breaker. This imposes extreme stress to the transformer and the grid on the primary side, and it makes any meaningful analysis of the failure mechanism of the test sample impossible, since the short-circuit current path is burned out after the test. **Figure 6** shows an oscillogram, where a breakdown of the test sample occurs in the 16th half-cycle of a current of approx. 150 A peak value. Afterwards, the short-circuit current of up to 1 kA amplitude flows for four half-cycles until it is finally interrupted by the vacuum breaker.

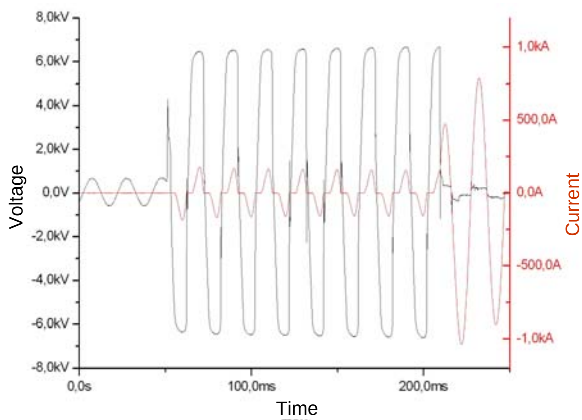

Fig. 6: Test current and voltage during ac test in the test setup with vacuum breaker

4 TRIGGERING THE SEMICONDUCTOR SWITCHES

In order to handle the required voltages, several thyristors have to be connected in series, as will be explained in further detail in the following sections. For triggering the series thyristors galvanic insulation is required for each thyristor. The trigger impulse has a maximum voltage of 10 V and should provide a current in the range of 0.5 A to 5 A. The impulse duration should be abut 2 µs or longer (all these parameters are dependent on the actually applied thyristor type). In order to trigger all thyristors at exactly the same time, which is crucial for correct operation, every thyristor (for the ac switch: every thyristor pair) has its own impulse transformer, and every transformer works like a current transformer for measuring on one common conductor.

Fig. 7: Insulated impulse transformers of the ac switch, mounted on one common primary conductor

In **Figure 7** the ten impulse transformer cores for triggering the twenty thyristors that are installed below can be seen. The secondary winding is directly wound onto the transformer cores, the primary winding is a metal rod covered by a PVC tube, pushed through the transformer cores. The insulation of the transformer can be optimized by the electrode radius and the diameter of the PVC tube, which in turn determines the inner ferrite core radius. For improved insulation and in order to prevent partial discharges it is also possible to mould the impulse transformer unit in epoxy resin. The common primary side of the impulse transformers is connected to an impulse source in case of the LD current impulse generator and to a high frequency inverter in case of the ac switch.

5 LD CURRENT IMPULSE SWITCH

The thyristor switch for the LD impulse current generator is made up from 50 thyristors type ST230C16C0 (International Rectifier). Every thyristor has a breakdown voltage of 1.6 kV and an average current carrying capability of 410 A [2]. The complete switch is made from five separate 10 kV-modules, and every module is protected by a directly connected MO varistor. The trigger unit is battery powered and activated by a fibre optical link, see **Figure 8**.

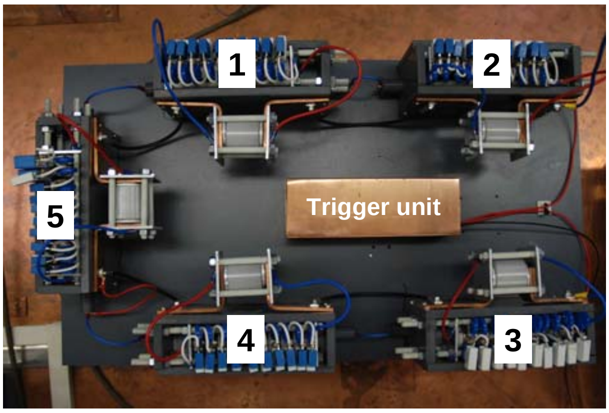

Fig. 8: Photo of the five-module thyristor switch for the LD current impulse generator

It is also important to protect each individual thyristor by an MO varistor and an RC snubber circuit. For dc symmetrization a high ohmic resistor is connected in parallel to every thyristor. The protection circuit for each thyristor is shown in **Figure 9**.

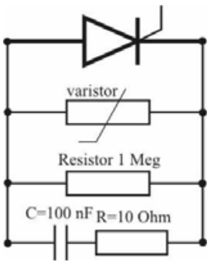

Fig. 9: Individual thyristor protection

An example of an LD current impulse switched by the new thyristor switch on a short circuit is shown in **Figure 10**. As it can be seen, despite the extreme mismatch the current is interrupted exactly at natural current zero. Any polarity reversal does not take place. Thus, application of such switches to PFN generators drastically simplifies the usually required adjustment of the generator. Its configuration has not to be changed and can be chosen independent of the load impedance.

6 AC SWITCH

The ac switch for bidirectional current flow requires two times ten thyristors of the same type as used for the LD current impulse switch, connected in antiparallel configuration. As the voltage difference from one thyristor path to its antiparallel path is small – it does not exceed 1 kV – it is sufficient to use only one ferrite core for triggering one antipar-

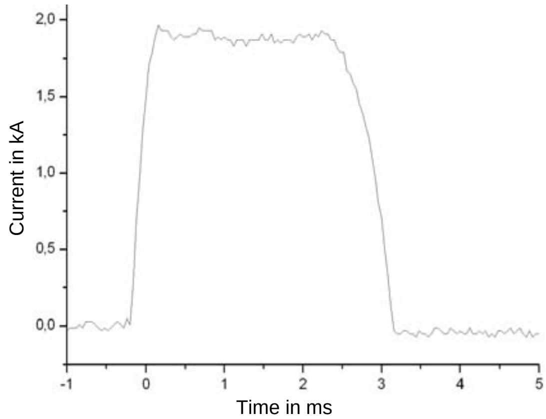

Fig. 10: LD current impulse to a mismatched load with thyristor switch

allel pair of thyristors. The trigger signal is a rectified 50 kHz rectangular alternating voltage. In order to avoid any interference between the two antiparallel thyristors the trigger signal is generated by a one way rectification with opposite phases between the two paths. Due to the high frequency (50 kHz) of the trigger voltage there is no relevant delay related to the switched current (50 Hz). The trigger circuit is shown in **Figure 11**.

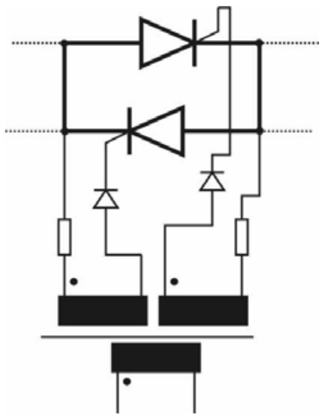

Fig. 11: Trigger circuit of the antiparallel thyristors

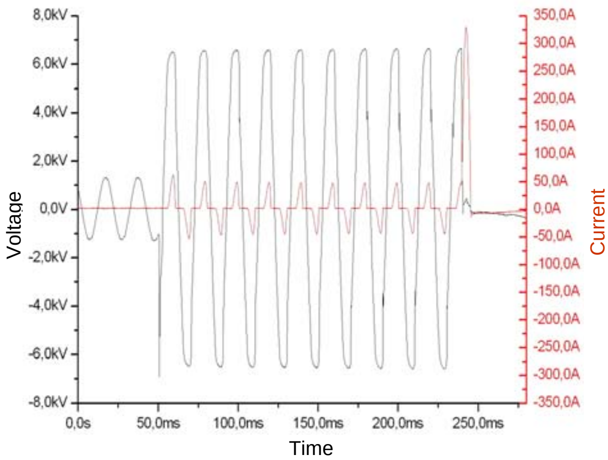

Fig. 12: Test current and voltage during ac test in the test setup with thyristor switch

Figure 12 is an oscillogram comparable to that of Figure 6. Now, quite evidently the short-circuit current after breakdown of the test sample flows for only one half-cycle and is then interrupted by the thyristor-switch.

7 CONCLUSION AND OUTLOOK

Two solutions have been presented where either the triggered spark gap or the vacuum circuit breaker of a current impulse generator for high-voltage MO varistor testing have successfully been replaced by thyristor switches. It could be demonstrated that even for LD current impulses switching with the help of semiconductors is not a problem. The benefit is obvious. In case of replacing a triggered spark gap, no adjustment of gap spacing is required any more, there is no erosion of the electrodes, and – most important – the current cannot change its polarity because thyristors do carry current in only one direction. Therefore, the test generator has not to be perfectly matched to the impedance of the test sample any more, and the impulse capacitors will have a much longer life time as they are not stressed by polarity reversal any more.

In case of replacing the vacuum breaker in an ac current impulse test circuit, main benefit is that the short-circuit current after breakdown of the test sample can flow for only one half-cycle of the alternating current until it is interrupted by the thyristor switch. Further improvement can be achieved by applying a short-circuiting shunt thyristor switch in addition. In that case, no short-circuit current through the test sample will develop at all. The current will be short-circuited by the shunt thyristor directly at the time instant of failure and then be interrupted by the series thyristor. A further benefit of using thyristors is the possibility of "switching on the point" in order to minimize inrush current of the test transformer.

Regarding economical aspects a semiconductor switch is not more expensive than a mechanical switch if standard semiconductors, especially thyristors are applied.

8 REFERENCES

[1] Max Reinhard, Volker Hinrichsen, Bernhard Richter, Felix Greuter (on behalf of Cigré WG A3.17): Energy Handling Capability of High-Voltage Metal-Oxide Surge Arresters - Part 2: A Results of a Research Test Program. Cigré Konferenz 2008, 25. – 29. August 2008, Paris, Report A3-309

[2] Datasheet IR ST230C16C0