IMPULSE CURRENT GENERATOR FOR THE QUALIFICATION-TESTING OF SURGE ARRESTERS USED IN DC POWER SUPPLY AND PHOTOVOLTAIC SYSTEMS

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Abstract: Qualification testing of surge protective devices (SPDs) for the protection of power supply and photovoltaic systems requires a test environment that offers the possibility to stress the SPD with defined surge-current impulses while connected to a power source having the same electrical characteristic than the real power supply system in which the SPD should operate. This is because the electric properties of a power supply system can affect the operation behaviour of SPDs significantly. The work presented describes a special test-setup for qualification-testing of SPDs for the protection of DC power systems. This includes a technical solution for the decoupling of the surge-current generator from the DC power supply system which demands a specific designed surge-current generator for the creation of unidirectional surge-current impulses. The performance of the entire test-setup is shown in case studies. Technical aspects to be taken into account during the development and operation of such a system are discussed.

1 INTRODUCTION

1.1 Surge Protective Devices used in DC Power Supply and PV Systems

DC power systems are nowadays frequently used in different business areas like telecommunications and photovoltaics industry. Due to the exposed installation sites of some of their components lightning and surge protection has to be considered in their system design in order to avoid damages and increase their availability [1],[2]. The protection against directly coupled lightning currents can be achieved with the installation of an external lightning protection system according to DIN/EN 62305, part 1-4 [3]. Above that, surge protective devices (SPDs) are used to protect the equipment against impulse currents, such as lightning and switching surges and various overvoltages.

The qualification-testing for SPDs, connected to low voltage power systems are described in IEC 61643-1 [4]. SPDs according to this standard are classified in class I (lightning current arresters) and in class II (surge-current arresters). Class I SPDs for the diversion of direct lightning currents are mostly based on spark gap technology, but nowadays metal oxide varistor (MOV) based class I arresters gain more and more market shares. Class II SPDs are commonly MOV based. The scope of IEC 61643-1 addresses SPDs for AC applications with a rated voltage of up to 1000 V AC and SPDs for DC applications with a rated voltage of up to 1500 V DC. But test procedures on qualification testing of SPDs connected to DC power systems are not described in this standard. In this context it has to be noted that the operation behaviour of a SPD, connected to an AC power system, can be completely different from the performance and operation behaviour of the same SPD connected to a DC power system. Above this, the operation behaviour of DC power systems can also differ significantly from one specific application to another application. Therefore, qualification tests according to IEC 61643-1 are not sufficient to prove functionality and safe behaviour of SPDs for the usage in DC applications. Nowadays, the manufacturers of SPDs for DC power systems define their own test methods and develop special test equipment to prove that the performance is suitable for a certain application and that the SPD can be operated safely.

1.2 Qualification-testing of Surge Protective Devices used in DC Power Systems

An essential test for SPDs qualification is a scenario in which operation conditions are simulated by the application of a defined number of specified current impulses to the SPD while it s connected to a power supply system having the same characteristic the real power supply system in which the SPD should operate. This requires the electrical coupling of the SPD with a power supply and a surge-current generator. The principle of the test-setup is shown in figure 1. The main purpose of this test is to determine the behaviour of SPDs after the surge-current stress.

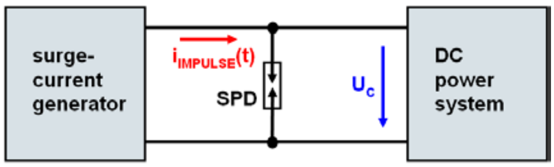

Figure 1: Principle of the test circuit for surge-load testing of SPDs under operating conditions

Specific test procedures for AC applications are described in IEC 61643-1 and prEN50539-11 [5] which is the draft for SPDs for the usage in photovoltaic applications. In general, the SPD has to withstand such a kind of stress without irreversible damages. Also a certain degree of robustness of the SPD against degradation effects is demanded. The presence of leakage currents, change of performance parameters and mechanical damages of the SPD after the surge-load are indicators and therefore suitable evaluation criterions for an SPD ageing or overload.

In terms of spark gap based SPDs, the test is additionally focused on the follow current extinguish capability of the SPD, which is an essential performance characteristic of this technology. The follow current extinguish capability describes the ability of the SPD to limit and break the current-flowing through the SPD during and after the surge-current event. It is influenced by the current type (AC or DC), the nominal voltage of the system, the prospective short circuit current at the connection point of the breaker and the grid parameters (L/R ratio). Electronic controlled DC power supplies with their nonlinear time-depending voltage-current behaviour will also have a significant influence on the extinguishing behaviour of installed circuit breakers.

1.3 Focus of the Work

The work presented deals with different aspects to be taken into account in the development of a test-setup for qualification-testing of SPDs used in DC-systems. The main focus is laid on:

- The design of a surge-current generator for the generation of unidirectional current impulses.
- The design of a HV blocking diode which is required for the decoupling of the power source from the surge-current generator.
- Typical EMC problems, like potential increases in the test setup due to surge-currents and suitable protective measures are presented.
- The performance of the complete system.

2 SURGE-CURRENT GENERATOR

2.1 Surge-Current Impulse 8/20 µs

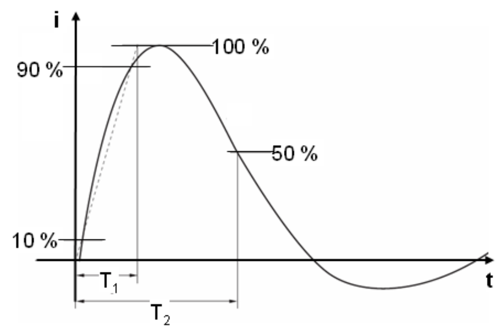

Figure 2: Surge-current impulse 8/20 µs

The 8/20 µs surge-current impulse, according to IEC 60060-1 [6], is essential for SPD qualification-testing. Figure 2 shows its waveform and characteristic parameters – the front time T_1 of 8 µs and the time to half-value T_2 of 20 µs.

This current impulse is usually generated by RLC-series impulse current generators. They consist of specific impulse capacitors, which are charged in parallel by a high DC voltage, up to a specified value. The stored energy equals to $½·C·U^2$. To generate the current impulse, the capacitors are discharged through a circuit which contains the wave forming elements (R_S, L_S), the impedances of the electric wiring of the generator (R_G, L_G) and the device under test (DUT, R_{DUT}, L_{DUT}). Usually triggered spark gaps (S1) are used to start the discharge process. The basic circuit for this generator type is shown in figure 3a. Figure 3b shows a simplified model with concentrated elements.

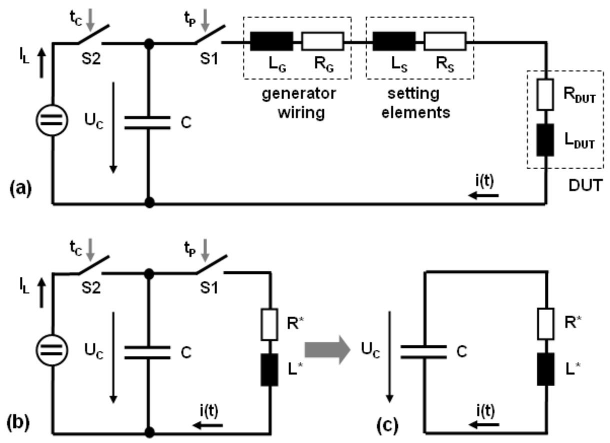

Figure 3: Basic circuit diagram of a RLC-series impulse current generator with concentrated impedances (a), simplified model (b), state after S1 has closed (c)

$R^* = R_G + R_S + R_{DUT}$ represents the total resistance and $L^* = L_G + L_S + L_{DUT}$ the resulting inductance. Assuming these idealized conditions the circuit after triggering of S1 can be described by a homogeneous, second-order ordinary differential equation:

$$d^2i/dt^2 + R^*/L^* \cdot di/dt + 1/(L^* \cdot C) = 0 \qquad (1)$$

with the initial values:

$$i(t = 0) = 0, \quad di/dt|_{t=0} = U/L^* \qquad (2)$$

Depending on the values of the coefficients three different solutions are possible. Figure 4 shows these solutions in principle. Technical details on the designs of impulse current generators are described in the literature, e. g. [7].

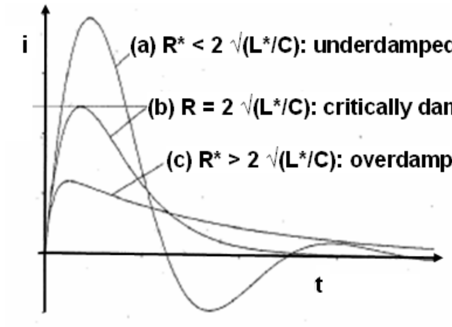

Figure 4: Current waveforms

2.2 Unidirectional Surge-Current Impulse

As mentioned in section 1.2 qualification-testing of SPDs requires a scenario in which operation conditions are simulated. For this purpose the SPD is stressed with current impulses while it is connected to a power supply system to be protected. To prevent damage especially in case of SPD failures, measures to protect the source against partial surge-currents are mandatory. When using a DC power supply systems HV blocking diodes are appropriate for the decoupling. But in case of a bipolar surge-current impulse (comp. figure 3a) only one polarity can be blocked by diodes and a destruction of the power source (electronic devices or insulation failures) by the non-blocked negative current, so called undershoot, can occur. Therefore, such a decoupling-concept requires a special designed generator for the generation of unipolar surge-current impulses having a waveform, like the one shown in figure 5.

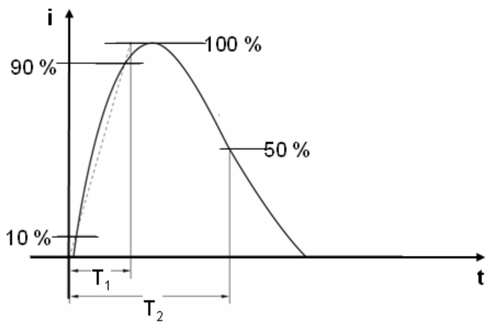

Figure 5: Unipolar surge-current impulse

The principle of a surge-current generator which fulfils the requirement to generate "unidirectional 8/20 µs impulses" is shown in figure 6.

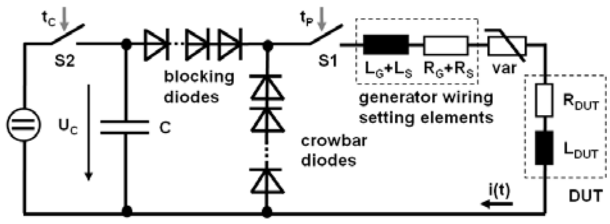

Figure 6: Surge-current generator for the generation of unipolar surge-current impulses

In general, the engineering and design of a surge-current generator requires at first information on the demanded waveform and amplitude of the surge-current impulse to be generated. Because of the fact that the impedance of the DUT has an influence on the waveform and amplitude, the demanded impedance range has to be defined and also considered in the generator design. With regard to this, it is recommended to adjust the impulse amplitude first by the variation of the charging voltage U_C. This allows an easy and fast handling in the practical use. Only if the amplitude cannot be achieved, a variation of the generator setup should be considered to reach the target amplitude and waveform. The elements R_G and L_G are mainly given by the generator design, e. g. geometry of the electrical wiring and the internal inductance of the capacitors. A variation of these parameters can only be realized in a small range. Therefore, the remaining configuration options are the variation of the capacitor bank C and the setting elements L_S and R_S. To obtain optimal settings circuit simulation is normally used. In this specific case the generator is designed for qualification-testing of MOV-based class II SPDs for the use at the DC-side of PV systems with a system voltage up to 1000 V (comp. [1]). Depending on the ratings of the used MOVs such SPDs can have impedances up to 300 mΩ at a current peak of 20 kA. A photo of the developed generator is shown in figure 7.

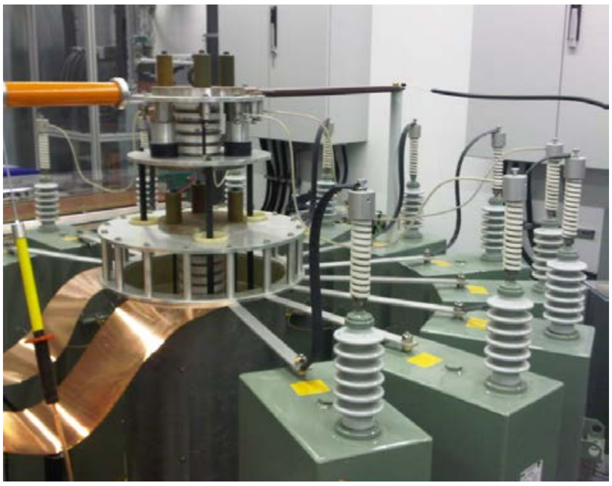

Figure 7: Developed surge-current generator for the generation of unidirectional current impulses

The overall capacitance can be adjusted in steps of 4 µF up to 16 µF. The maximum value of the charging voltage is 30 kV. The generator circuit resistance (wiring) is R_G= 0.9 Ω and its circuit inductance results in $L_G \approx 5$ µH. Compared to standard RLC-generators (comp. figure 3a) an additional diode configuration is required to generate the demanded unipolar surge-current impulse. The used diode type is D2601HN90T. It has tailored properties for this application [8]. Five of them are used as blocking diodes and eight serve as crowbar diodes.

The high reverse recovery behaviour of these blocking diodes avoids an ageing of the capacitors due to high frequency charge reversal effects. In forward direction these diodes allow the transmission of high current gradients. The occurrence of hot spots in the stacks due to an inhomogeneous current density can be minimized due to an especially designed connection technology. The MOV (figure 6, var) is required additionally to support the generation of unipolar surge-current impulses. The feedback reaction of the diode configuration on the current-waveform has also to be considered in the design and adjustment of the generator (charge flow). Figure 8 shows the qualitative influence compared to a standard RLC-circuit.

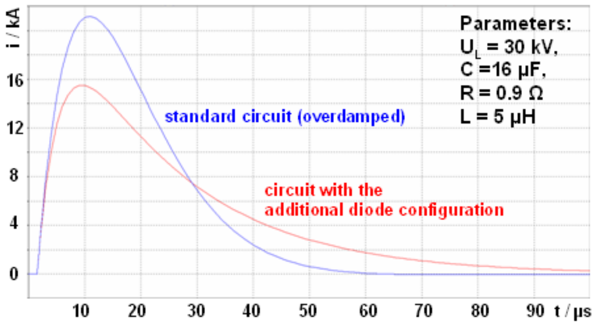

Figure 8: Impact of the diode configuration on the waveform compared to a standard RLC-circuit

2.3 Performance of the Developed Generator

For the verification of this concept, surge-current tests with different types of SPDs are performed. Among others, studies about the influence of the SPD-impedance on the waveform and amplitude of the current impulse are important aspects. These tests are carried out in short circuit mode of the generator and with three different types of MOV-based SPDs at charging voltage of 19 kV. The results are shown in table 1 and figure 9a. In further tests it can be shown that due to the variation of the charging voltage U_L the generation of 8/20 µs impulses according to the normative requirements (I_{peak} ± 10 %; T_1 = 8 µs ± 10 %; T_2 = 20 µs ± 10 %) having a peak value of 20 kA can be achieved (figure 9b).

Table 1: Influence of the SPD impedance on the waveform and amplitude of the current impulse

DUT	U_C	I_{peak}
Short circuit	19 kV	24.8 kA
2 x VAL-MS 230	19 kV	22.2 kA
2 x VAL-MS PV 600	19 kV	20.6 kA
2 x VAL-MS PV1000	19 kV	20.3 kA

The interferences at the beginning of the current flow are typical effects resulting from discharge processes in the used air spark gap S1 of the generator. As an improvement a pressurized air-filled spark gap or a vacuum switch could be used.

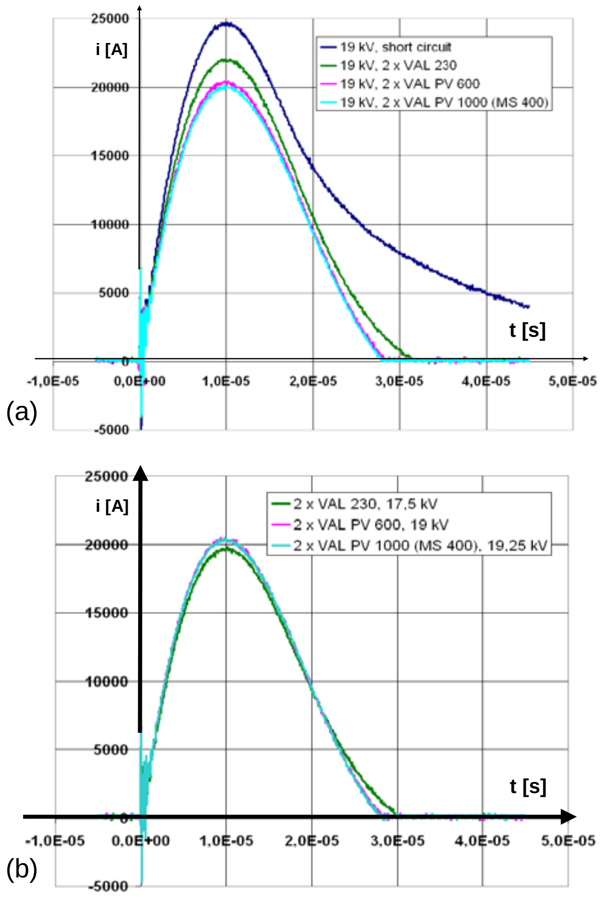

Figure 9: Influence of the SPD impedance on the waveform and amplitude of the surge-current impulse, constant U_C (a), variation of U_C to 20 kA (b)

3 COUPLING OF THE SURGE-CURRENT GENERATOR WITH A DC POWER SUPPLY

3.1 HV Blocking Diode

As mentioned in section 2.2, a decoupling of the DC power supply from the current impulse generator is demanded. This means, that the partial surge-currents which are not discharged by the SPD under test and can compromise the DC power supply, have to be blocked by a special designed HV blocking diode stack (figure 10).

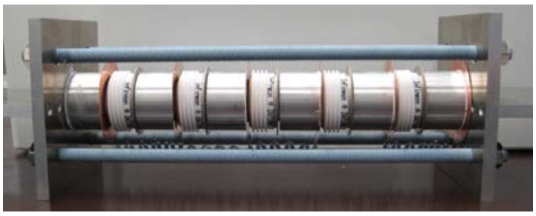

Figure 10: HV blocking diode for the protection of the DC power supply against partial current impulses

Based on the specified maximum charging voltage of the surge-current generator (30 kV) a series connection of 5 diodes (Infineon D471N90T) is used for decoupling. Each diode has a reverse voltage of 8.5 kV. So, the total reverse voltage of the HV blocking diode is 42.5 kV (safety reserve).

In the case of series connection of diodes attention should be paid to the nearly symmetrically voltage splitting across the diodes for stationary and also for the dynamic operations conditions. Otherwise it has to be controlled. Due to the non-uniform voltage distribution across the HV-blocking diode individual diodes can be subjected to voltages which exceed their rated values. Such kind of stress could damage the HV-blocking diode. For stationary operation a resistor connected parallel with each diode is used for the control of the voltage distribution across the HV-blocking diode (figure 11a). Also in case of dynamic operation conditions, e. g. switching the HV-blocking diode from forward to reverse blocking state, a non-uniform transient voltage distribution can occur. This behaviour is also founded in a variation of dynamic parameters of the single diodes. To achieve a smooth voltage sharing across the single diodes a capacitors network, shown in figure 11b, can be used to compensate this effect. A detailed description on this can be found in [9].

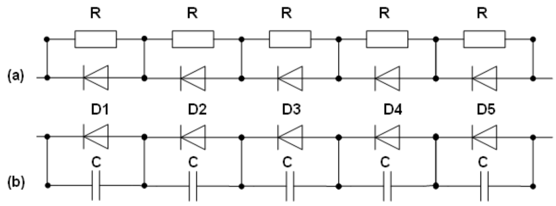

Figure 11: HV-blocking diode stacks, with additional resistors (a), with additional capacitors (b)

For the present application the HV-blocking diode is realised without an additional R/C-network. Practical DC- voltage tests show that even without an additional network the voltage distribution across the single diodes is nearly uniform distributed (table 2). Therefore, an overload of single diodes does not occur.

Table 2: Measured voltage distribution

	10 kV, DC test voltage	20 kV, DC test voltage	30 kV, DC test voltage
D5	2.05 kV	4.10 kV	6.34 kV
D4	2.04 kV	4.08 kV	6.14 kV
D3	1.99 kV	3.89 kV	5.93 kV
D2	2.00 kV	3.89 kV	5.91 kV
D1	2.2 kV	4.04 kV	5.87 kV

Similar results were also obtained for surge voltage tests with the curve shape 1.2/50 µs and 8/50 µs. It can be assumed that the voltage miss-sharing in this case plays a minor role because the rated values of the used diodes are oversized.

3.2 Representative EMC Problems

The design of a comprehensive protection concept for the developed test setup requires also the consideration of further typical EMC problems. These are e.g. potential increases along circuit impedances due to high surge-currents, which can cause insulation failures. Therefore, further protective measures are mandatory (figure 12, blue). A GDT-MOV combination is connected in parallel to the SPD under test (DUT) to limit the surge-voltage in case of a DUT failure. To avoid incorrect test results this combination must have a significantly higher response voltage compared to the tested SPD. A current measurement in the path of the GDT-MOV combination can provide evidence if there is an effect. Also such a combination is used for the limitation of surge-voltages occurring between the test circuit and ground. Additional a series connection of suppressor diodes is used for a further limitation of surge-voltages occurring between the active wires of the power supply.

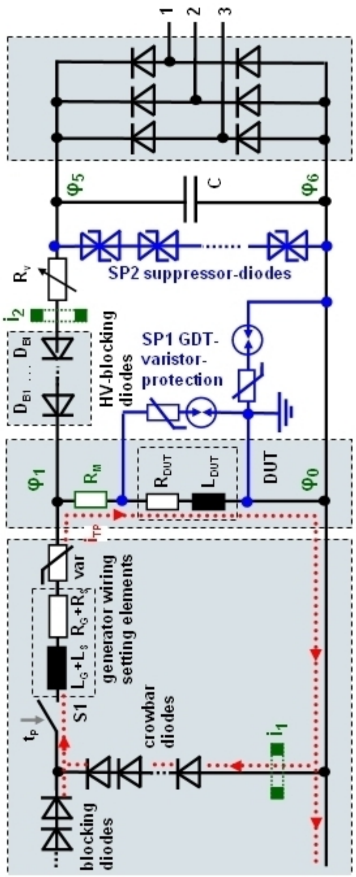

Figure 12: Setup for surge-load-testing of SPDs under real operating conditions

The effect of the additional surge protective measures is show in table 3. 8/20 µs impulses with an amplitude of 20 kA are used for the test. Under the intended operation conditions, that means SPD and the additional protective measures are inserted in the circuit, a limitation of surge-voltages at the output terminals of the power source to values < 2 kV can be obtained. In the case of a non-connected SPD or an SPD failure the peak voltage is limited to values ≤ 3.3 kV due to the higher response voltage of the GDT-MOV combination. Overall, the results show that transient voltages at the DC power side can be limited effectively.

Table 3: Measured surge-voltages in the test setup

DUT	SP2	source	φ_i - φ_j	$\Delta\varphi$
no	no	disconnected	φ_5-φ_6	6,0 kV
no	yes	disconnected	φ_5-φ_6	3,3 kV
yes	yes	disconnected	φ_5-φ_6	2,8 kV
yes	yes	connected	φ_5-φ_6	1,8 kV

Figure 13 shows as an example the voltage at the output of the DC power source (φ_5-φ_6) during a qualification-test of a MOV-based SPD, stressed by a 20 kA impulse 8/20 µs. After the surge-current impulse a voltage decrease (duration < 200 µs) at the terminals of the B6 rectifier is detected.

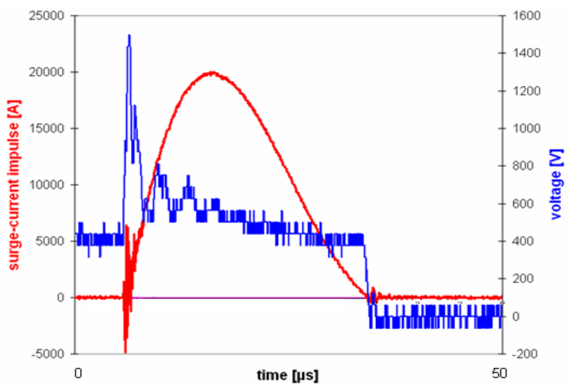

Figure 13: Voltage U_{56} (comp. figure 12) during a surge-current test with amplitude of 20 kA

A possible explanation for this phenomenon could be founded in the forward recovery behaviour of the HV blocking diode. The forward recovery time for the installed standard rectifier disc-diodes is not specified by the manufacturer. But it is known, that fast high-power rectifier disc-diodes have a forward recovery time in the magnitude of 4 µs [10]. Standard rectifier diodes have a forward recovery time of approx. 10 times greater. This means the measured time of 200 µs is within an order of magnitude of the forward recovery process. To verify this assumption, further tests have to be carried out. With regard to the interpretation of test results and therefore the operation behaviour of SPDs in real application this phenomenon should be considered. It can be assumed that compared to the use in a real application the operation behaviour of MOV-based SPDs (voltage limiting types) is not affected by this effect.

But in case of spark gap technology based arresters (voltage switching types), possible effects on the arc extinguishing behaviour cannot be fully excluded. This is an interesting aspect for further investigations. As an alternative, another method of decoupling can be expedient to avoid the effect of voltage decrease after the surge-current event. Such a concept can consist of well-dimensioned resistor instead of the blocking diode and a well-dimensioned MOV connected in parallel to the output terminals power source.

4 CONCLUSION

Qualification testing of SPDs for the use in DC power systems demands the possibility to stress the SPD with surge-current impulses while it is connected to a power source. For this purpose a surge-current generator for the creation of unidirectional surge-current impulses is developed. A special designed diode configuration is the function-determining-element in the generator design. In case of using MOV-based SPDs for the protection of the DC side of PV systems, it could be shown that 8/20 µs surge-current impulses up to 20 kA can be generated in a certain load-impedance range. The concept of using unidirectional surge-current impulses allows the decoupling of the DC power source from the generator by a HV blocking diode stack. It could be shown that the developed diode stack is suitable to protect the source against partial surge-currents. In combination with additional surge protective measures transient voltages at the DC power side are limited to uncritical values. In summery the developed test environment fulfils the requirements for qualification testing of the MOV-based SPD types mentioned above. However, it should be noted that immediately after the surge-current impulse has occurred, a short term decrease of the DC voltage of the power source takes place. In case of spark gap based arresters, effects on the arc extinguishing behaviour cannot be fully excluded. This aspect should be further investigated. Alternatively, another method of decoupling to avoid this effect should be tested as a future task.

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