Solid-State Circuit Breakers and Current Limiters for Medium-Voltage Systems Having Distributed Power Systems

Christoph Meyer, *Student Member, IEEE*, Stefan Schröder, *Member, IEEE*, and Rik W. De Doncker, *Fellow, IEEE*

***Abstract*—State-of-the-art mechanical circuit breakers in medium-voltage systems allow a safe handling of short-circuits if the short circuit power of the grid is limited. Using delayed turn-off times, the circuit breakers can be coordinated with lower level protection gear. Hence, a high *availability* of the grid can be guaranteed. However, during a short-circuit a significant voltage sag can be noticed locally in the medium-voltage grid. Sensitive loads such as computers will fail even if the voltage returns within a few seconds. A semiconductor circuit breaker, however, is able to switch fast enough to keep voltage disturbance within acceptable limits. The optimization and selection of power electronic switch topologies is critical. In this paper, different semiconductors are briefly compared considering the requirements of a solid-state switch integrated into a 20-kV medium-voltage grid. Based on these semiconductor characteristics, various switch topologies are developed, which are compared under technical and economical aspects. It is shown that solid-state circuit breakers offer significant advantages when compared to present solutions and can be used in today's medium-voltage power systems.**

***Index Terms*—Current limiters, semiconductors, solid-state circuit breakers.**

I. Introduction

CLASSICALLY, the availability of a given utility-grid is estimated and measured by the percentage of time in which electric power is statistically available. Short-time interruptions, e.g., due to lightning or short-circuits in neighboring networks, have little influence on the statistic and are simply not taken into account. Due to the integration of sensible loads, e.g., computers, embedded controllers in desktop as well as in industrial applications, the power quality of electrical grids becomes of utmost importance. Power quality is concerned with such effects as availability, voltage distortion, and deviations from nominal values (voltage, frequency) over short periods of time.

Power electronic converters and systems can be regarded as one solution to increase power quality in the grid and to integrate distributed renewable energy sources into today's power systems [1]–[3].

The handling of short-circuits in the grid is of great importance in order to provide safety and to achieve high availability on the one hand and high power-quality on the other. Handling short-circuits becomes problematic when considering the increased short circuit power resulting from increased distributed energy generation in medium-voltage systems. As a consequence, it is likely that in the near future classical mechanical circuit breakers will not be able to handle these currents. Classical breakers are solely designed to provide safety and to achieve high availability. In this paper it is shown that the proposed solid-state circuit breaker can substantially increase power quality and is capable of interrupting faults in medium-voltage grids with multiple energy sources.

As mentioned, present solutions dealing with short-circuit protection are mechanical circuit breakers. After having detected a short-circuit or an over-load situation, some time (several periods) elapses prior to open the switches mechanically. Subsequently, an arc occurs, which initially has little impact on the current. The current can only be quenched at its natural zero-crossing assuming that the plasma is significantly cooled down to avoid reignition. As a result, turning off a short-circuit will take at least 100 ms (without detection time), i.e., several line periods.

The main drawbacks of these classical solutions are the following.

1) The peak current cannot be influenced. Therefore, all network components have to withstand the peak current during the switching period. This current reaches peak values, which are typically 20 times higher than the maximum operating current. After this peak, the current drops to the thermal (steady state) short-circuit current. This current is below the transient peak current value but can still reach values up to ten times the nominal value. This high current puts the components in the grid both mechanically and thermally under stress, which leads to oversizing, resulting in an increase of costs.
2) Mechanical circuit breakers have a maximum short-circuit current rating. This current limit forces the grid designers to limit the short-circuit power of the grid, e.g., by using additional line inductances. However, these measures also reduce the maximum transferable power and the "stiffness" of the grid, leading to an increase of voltage distortions.
3) The number of high-current short-circuit clearances is limited to about 10 to 15 times for mechanical devices.
4) During the short-circuit time, the voltage on the complete medium-voltage grid is significantly reduced. Due to the long turn-off delay of the breaker, sensible loads require UPS support to survive this sag, which is costly and might not be feasible for a complete factory plant.

Manuscript received July 17, 2003; revised June 7, 2004. This work was presented in part at the IEEE CIEP Conference, Guadalajara, Mexico, 2002 and the IEEE PES Transmission and Distribution Conference, Dallas, TX, September 2003. Recommended by Associate Editor J. R. Rodriguez.

The authors are with the Institute for Power Electronics and Electrical Drives (ISEA), RWTH Aachen University, Aachen 52066, Germany (e-mail: my@isea.rwth-aachen.de; sc@isea.rwth-aachen.de; dd@isea.rwth-aachen.de).

Digital Object Identifier 10.1109/TPEL.2004.833454

Solid-state circuit breakers based on high power semiconductors potentially offer enormous advantages when compared to conventional solutions, since a solid-state breaker is able to switch in a few μs. Hence, the maximum current will never exceed two times rated current (1.8 kA) and the voltage distortion will just last for around 100 μs. Since a complete grid is rated with 1.8 kA, dynamic loads such as induction motors will not lead to a significant increase of the surge current because, in such an overload, the grid voltage would collapse. Induction motors only increase surge currents, considering the complete grid current, for a few percent, so there is still no problem for the circuit breaker.

In this paper, available high-power semiconductors are compared, considering the requirements of the solid-state breaker application. The specifications are considerably different compared to conventional power-electronic systems. Furthermore, different topologies are developed and analyzed for a solid-state breaker in a 20-kV medium-voltage grid. This assessment is based on technical and also economical aspects. Finally, the combination of a solid-state breaker and a current limiting device is briefly described.

II. Fundamental Behavior

To analyze the fundamental behavior of the proposed semiconductor switch, a single-phase equivalent circuit, as shown in Fig. 1, is used. The grid is represented by a voltage source and a line inductance. In this example, a pure resistive load is shorted by an ideal short-circuit with zero resistance.

The current and voltage waveforms are shown in Fig. 2. At approximately 5 ms, a short circuit occurs and the current rises very fast, until the switch is turned off. Due to the stored energy in the line inductance the voltage rises at that point. If no additional components are used, the voltage will reach a value of several 100 kV, which would certainly destroy the solid-state circuit breaker. To reduce the peak voltage, additional high-energy varistors are connected in parallel to the semiconductors.

By this measure, the magnitude of the voltage during turn-off is limited so that the circuit breaker is not damaged. Consequently, the line inductance becomes demagnetized resulting in a current decrease until it reaches zero. Subsequently, the switch has to block the neutral to line voltage of the grid.

III. Semiconductor Devices

As already mentioned, the nominal voltage typically reaches rms values of 20 kV. The maximum nominal current of a feeding transformer characteristically is 1.8-kA rms. Hence, the grid voltage is higher than the maximum voltage blocking capability of present semiconductor devices although their ratings have increased significantly [4]. Consequently, several semiconductors have to be connected in series. As a high reliability is of utmost importance, redundant devices will be integrated. It should be pointed out that devices in press-pack housing are preferable because they guarantee a short-circuit state in case of failure. Consequently, they assure that the switch is still operational even if a single semiconductor has failed.

Momentarily three different semiconductors are able to fulfill these requirements, namely insulated gate bipolar transistor (IGBT), gate commutated turn-off (GCT), and gate-turn-off (GTO). In contrast to inverter applications, the switching losses of these devices turns out to be a minor issue in this application. Here, the conducting behavior and conduction losses are essential. As a result, the IGBT has a disadvantage in circuit breaker applications. Especially, the on-state losses of IGBTs are significantly higher than the losses of a thyristor based semiconductor (up to three times higher per device) [4], [5]. However, the IGBT has the advantage that, as a transistor, it limits the current automatically. Hence, current cannot exceed a certain value. In contrast to this, the current is not limited in a thyristor type devices and the turn-off capability is limited. Thus, the detection time has to be short enough to assure a safe turn-off. Considering the stray inductance of a medium-voltage transformer and the speed of today's detection technology this delay can be minimized to noncritical values. In Fig. 3, the relative on-state losses of different semiconductors are shown. The losses of a special GCT (4.5 kV) with extra low on-state losses, a normal 4.5-kV GCT, a 6-kV GCT, a GTO, and an IGBT are depicted in Fig. 3. Due to the fact that 6-kV devices need fewer semiconductors placed in series, the losses of the switch are scaled relative to the needed number of semiconductors.

It becomes obvious that thyristor based semiconductors, such as GCT and GTO, are a much better choice for a solid-state switch because they have much lower on-state losses. In addition a turn-on snubber, which is mandatory for GTO and GCT in inverter applications is not needed, because the stray inductance of the feeding transformer (above 1 mH) is high enough to assure a low di/dt (< 30 A/μs).

When just considering the losses, only the special GCT (3 kW at 2 kA) would be chosen for the circuit breaker. Although the losses of the GTO are higher, the material costs nevertheless are

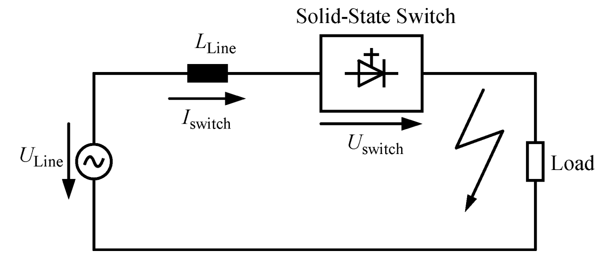

Fig. 1. Basic single-phase equivalent circuit.

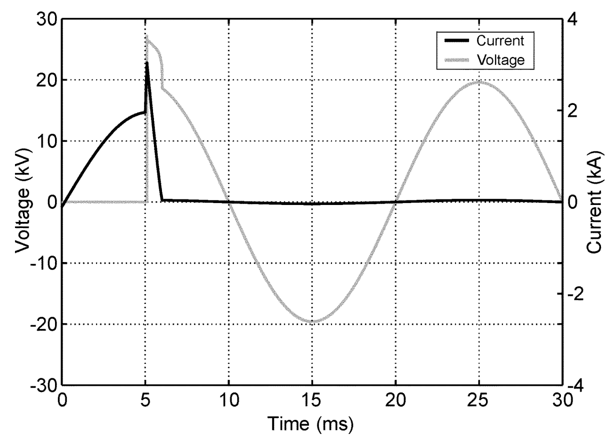

Fig. 2. Current and voltage during turn off.

much lower. So for the design of the solid-state switch, the GTO still has to be considered.

All used devices are 4.5-kV semiconductors although today also 6-kV and 9-kV semiconductors are available. The reason to select 4.5-kV devices is based on losses. As already shown in Fig. 3, the available 6-kV GCT have higher losses compared to the 4.5-kV special devices. Note that 4.5-kV GTOs and 6-kV GTOs offer similar relative losses. Consequently, it was decided not to consider 6-kV devices in this study.

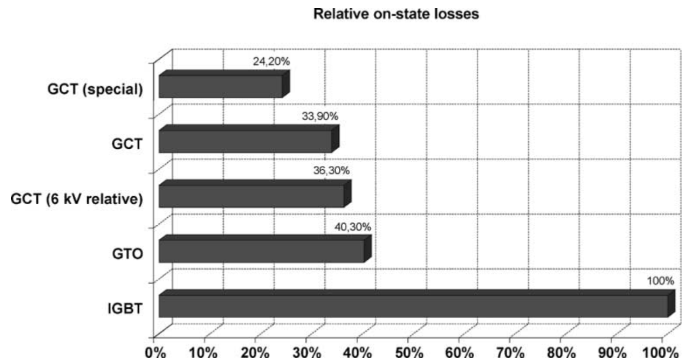

Fig. 3. Relative on-state losses.

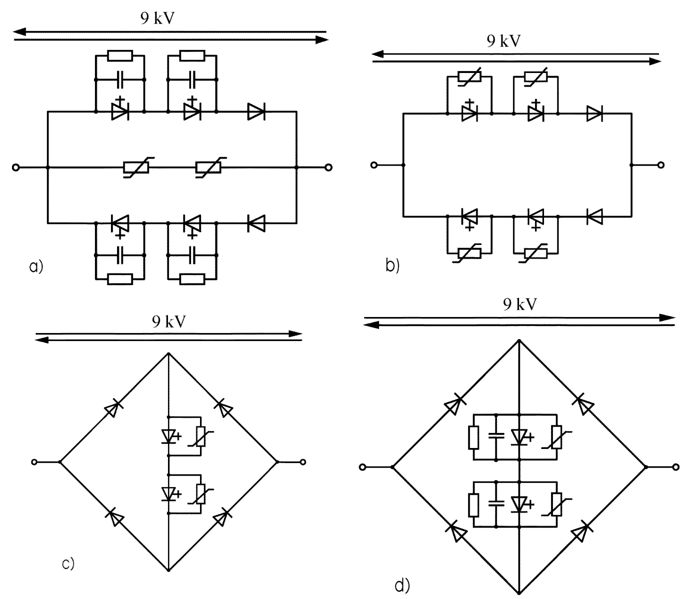

Fig. 4. Series connection and rectifier solutions of GTO and GCT.

IV. Solid-State Switch Topologies

The breaker should consist of several modules to achieve a flexible adaptation for different current and voltage levels. For example, in Germany there are two different medium-voltage grids, namely 10 kV and 20 kV. Another advantage is that the service of a single module is less expensive than changing single devices in the complete switch [6]. It has already been mentioned that the blocking voltage of the breaker must be higher than the maximum grid voltage. It was proven [7] that a switch in 20-kV grids including redundancy, should be able to withstand a peak voltage of at least 30 kV. The current rating can be calculated by considering the maximum power of a medium-voltage transformer, resulting in a maximum current of 2-kA rms.

A. Module Topologies

Most semiconductor devices available today are asymmetric, because the on-state losses of existing symmetric semiconductors are high. Consequently, additional diodes have to be connected in series. The diodes always switch at 50 Hz and only against the on-state voltage of the semiconductor. Therefore, no fast recovery diodes are needed and rectifier diodes can be used instead, which offer the lowest conducting losses.

To reduce the number of devices and thus increase reliability, the 4.5-kV active semiconductors were combined with 9-kV diodes. Hence, two GCTs or GTOs are in one module with one rectifier diode.

It has already been stated that additional varistors are needed to limit the voltage during turn-off. Since the GTO is not able to turn off without an auxiliary circuit, a capacitor and a resistor have to be connected in a parallel formation. In general, this snubber circuit is also needed for a series connection of GCTs to assure a symmetric voltage distribution between the semiconductors. However, for a single GCT, it is not needed. In this application, the voltage of a single device can be limited just by the varistor, this was already proven at a test bench [7]. As a consequence the snubber of the GCTs can be replaced by using a varistor in parallel to each semiconductor.

Both the technical specifications and the cost targets lead to the topologies shown in Fig. 4(a) and (b). Topology (a) consists of four GTOs with snubbers and two diodes. The maximum blocking voltage of this module is 9 kV. In the GCT topology (b) the snubbers were replaced by two additional varistors.

In the presented topologies, each semi-wave of the grid current flows either through the upper or the lower branch of the circuit. A third topology was developed, which reduces further the number of active semiconductors in an attempt to reduce costs.

This topology uses a full diode rectifier to reduce the number of active devices, as shown for the GCT solution in Fig. 4 [8]. For the GTO, the topology [topology (d)] is quite similar, as shown in Fig. 4(d). Compared to the GCT circuit, a snubber circuit is added similar to topology (a).

The total number of semiconductors is constant in all topologies, but in topology (c) and topology (d) two active semiconductors are replaced by two diodes, leading to reduced material costs. However, these topologies have increased on-state losses.

The complete switch consists of three modules to guarantee full blocking voltage. To ensure high reliability, redundancy should also be integrated into the solid-state circuit breaker. For this purpose, an additional module is used. Consequently, the breaker would require four modules in series for a 20-kV medium-voltage grid.

B. Comparison of Different Topologies

The major distinction between the topologies can be found in the differences between on-state losses and costs. To ensure the integration of power-electronic switches into the existing systems, it is essential to consider the costs of different solutions. In this section, the different topologies are first compared excluding the aspect of reliability, which is evaluated in the second part.

1) Cost Differences of Topologies: All topologies presented are compared by considering the costs for the switch itself and the costs during operation caused by losses.

Although the rectifier module [Fig. 4(c) and (d)] consists of the same number of semiconductors, it consists of fewer active devices and so it is the cheapest solution at first sight. However, the conduction losses are higher, because one additional diode has to be used which produces additional losses in each half period of the line current.

In general, the losses of the semiconductors can be estimated with

$$P_{\mathrm{V}} = I_{\mathrm{rms}}^2 \cdot r_{\mathrm{t}} + \bar{I} \cdot V_{\mathrm{T0}} \tag{1}$$

(with r_{t} as slope resistance, V_{T0} as threshold voltage, and $\hat{I}$ as the peak value of a 50-Hz sinusoidal current)

$$\begin{aligned} I_{\mathrm{rms,series}} &= \frac{\hat{I}}{2}; \quad \bar{I}_{\mathrm{series}} = \frac{\hat{I}}{\pi} \\ I_{\mathrm{rms,rectifier}} &= \frac{\hat{I}}{\sqrt{2}}; \quad \bar{I}_{\mathrm{rectifier}} = \frac{2}{\pi} \cdot \hat{I}. \end{aligned} \tag{2}$$

Concerning the rectifier and the series topology, it has to be pointed out that the rms and average current of the active semiconductors differ. This deviation occurs because in the series connection only during one half period current is flowing through each device and in the rectifier solution both half-waves are carried by one active device.

Using these equations for the entire 36-kV switch (four modules in series), the losses for all three phases are presented in the subsequent equations. In this case, the slope resistance and the threshold voltage of the GCT are used. For the GTO only these values have to be adapted

$$\begin{aligned} P_{\mathrm{V,Tot,A,b}} = 3\Big(&2 \cdot \hat{I}^2 \cdot (2 \cdot r_{\mathrm{t,GCT}} + r_{\mathrm{t,D}}) \\ &+ \frac{8}{\pi}\hat{I} \cdot (2 \cdot V_{\mathrm{T0,GCT}} + V_{\mathrm{T0,D}})\Big) \end{aligned} \tag{3}$$

$$\begin{aligned} P_{\mathrm{V,Tot,c,d}} = 3\Big(&4 \cdot \hat{I}^2 \cdot (r_{\mathrm{t,GCT}} + r_{\mathrm{t,D}}) \\ &+ \frac{16}{\pi}\hat{I} \cdot (V_{\mathrm{T0,GCT}} + V_{\mathrm{T0,D}})\Big). \end{aligned} \tag{4}$$

To get a realistic cost model, price was based on a series of roughly 2000 devices. This would mean that about 100 three-phase switches for 20-kV grids would have to be built.

The total cost of the switch consists of two parts, the material cost and the cost caused by losses and maintenance, see also reliability Section IV-B2. Further aspects such as costs for cooling and system controls are not taken into consideration in this study. Operation costs are calculated with the average production costs for electrical power per kWh in Germany (0.034 Euro/kWh).

Since the rectifier solution has less GCTs but produces additional losses, there will be a break even point, at which the different topologies are equal in cost. It is obvious that this strongly depends on the transmitted power, i.e., on the application in the grid. At the break-even point, the difference of investment costs must be equal to the costs associated with additional losses. This leads to (5), with k electricity cost per kWh, ΔC the difference of the investment cost, T hours per year (8760), and a years

$$\Delta C = a \cdot T \cdot k \cdot \Delta P_{\mathrm{V}}. \tag{5}$$

Here, ΔP_{V} is the difference in losses. It can be calculated with (3) and (4) depending on the compared topologies. Due to the losses, this equation depends on the current as well as on the transmitted power. An equation can be derived which leads to a function of equal costs, contingent on the transmitted power S and the time a in years. The function, which describes the boundary where the two 9-kV GCT topologies (b, c) have equal costs is given in the subsequent equation. This equation is equivalent to the amortization of the two topologies

$$\begin{aligned} S(a) &= \sqrt{\frac{3}{2}} \cdot V_{\mathrm{N}} \cdot \left(\sqrt{X^2 + \frac{\Delta C}{3 \cdot k \cdot r_{\mathrm{t,Diode}} \cdot T \cdot a}} - X\right) \\ \text{with} \quad X &= \frac{2 \cdot V_{\mathrm{T0,Diode}}}{\pi \cdot r_{\mathrm{t,Diode}}}. \end{aligned} \tag{6}$$

A similar equation was also established to compare the GTO solutions [topologies (a) and (d)] with the two GCT versions [topologies (b) and (c)]. The equations for the comparison of the different solutions can be calculated in the same manner as shown above. These other amortization curves are not explicitly stated in this paper but are shown as curves in Fig. 5.

Due to the different investment costs and losses, the most cost effective solution strongly depends on the transmitted power and time. To have an idea of the typical power levels considered here, the maximum output power of a medium-voltage transformer is also plotted. Generally speaking, medium-voltage systems have an average power loading of 50% of the nominal operation power. This means that a 63-MVA transformer has an average output of 31.5 MVA during one year. Using this aspect, the calculated curves are multiplied with a factor of two.

All amortization curves for the different topologies were calculated, except for topologies (a) and (c), because in this case topology (c) has lower material cost and operation costs. Consequently, it always dominates topology (a).

Five areas are marked in Fig. 5 where different solutions set out to be most cost effective. In Area V the GTO rectifier topology (d) produces the lowest costs, and in Area II, III as well as in IV the GCT rectifier topology (c) is the least expensive. Although the GCT series connection has the highest investment cost, Area I indicates that this topology should be chosen for high power applications, as well as for the protection of the entire medium-voltage grids, closely followed up by feeding transformers.

Costs for conventional electric equipment, e.g., transformers, should amortize in roughly 20 years. So, if the circuit breaker is used to protect the whole grid at the feeding transformer, the GCT series connection should be chosen, because it provides the lowest losses and additional costs will be compensated during this time. If single loads or other low power parts (under 20 MW) have to be protected, the rectifier GCT module topology (c) or the GTO rectifier topology (d) should be used. It becomes obvious that the final topology needed for a circuit breaker must be chosen by considering the average power transmitted through the switch.

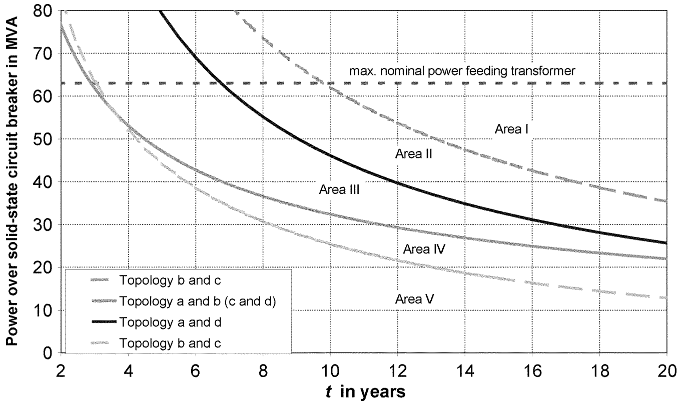

Fig. 5. Amortization curves.

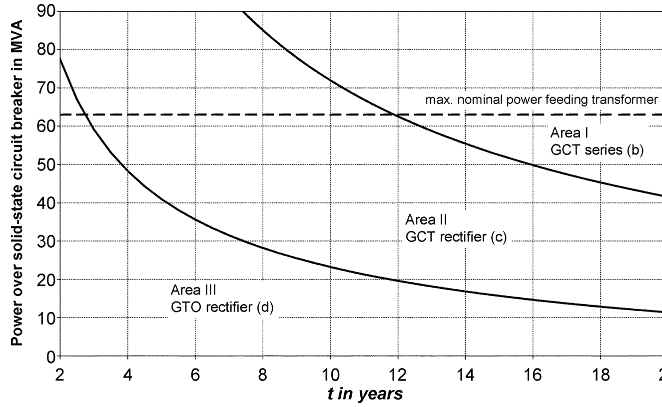

Fig. 6. Amortization curves with reliability.

TABLE I
STATISTIC RELIABILITY OF THE TOPOLOGIES

Topology	FIT	MTBF
(a) GTO (series)	9840	11.6 years
(b) GCT (series)	5040	22.6 years
(c) GCT (rectifier)	2880	39.6 years
(d) GTO (rectifier)	5280	21.6 years

2) Reliability of Different Topologies: Today reliability is of utmost importance in all technical fields, especially when it comes to power electronics. In the following subsection, the different reliabilities of the topologies will be taken into consideration. However, there will be no detailed analysis concerning the availability of the circuit breaker in this paper. Only cost effects of reliability will be taken into account.

If one module of the redundant switch fails, the switch is still operational but for safety issues this module will be replaced. Consequently, the additional investment costs of this module have to be considered.

The reliability of devices and components are measured in failure in time (FIT) or mean time between failure (MTBF). FIT is the unit for failure rates meaning one failure in 10^9 operation hours of the device. The values of the components are given by the manufacturers, as they are statistic values for a certain nominal usage of the devices.

In our case, the failure of any device results in the malfunction of a module. The complete breaker will still work but as mentioned above this module would have to be replaced. Once again this is not the MTBF rate concerning the functionality of the switch, which will be much higher, but instead it is just the time at which additional costs have to be considered. In Table I the FIT and MTBF of the different topologies for a three-phase switch are shown.

The failure rates for the GTO topologies are much higher because of the additional snubber capacitors. For the semiconductor itself, the values for both devices are quite similar. However, the capacitors have a rather low reliability and if one fails the module will be destroyed during the next turn-off sequence.

To show the cost effect of the different reliabilities of these topologies, the additional costs were considered in the equations for amortization. This second analysis is based on a life time of 25 years, so that consequently only topology (c) does not have to be renewed, resulting in an increase of material costs for (a), (b), and (d).

Due to the results of the amortization curves, only the GCT series topology (a), GCT rectifier (c), and GTO rectifier (d) are compared. The GTO series topology (a) is not cost effective and by considering reliability the material costs also increase. In Fig. 6, those modified amortization curves are shown.

When comparing this plot with the first amortization curves, it becomes quite obvious that the reliability has a strong impact on the selection of the most cost effective solution. Due to the fact that topology (c) has the highest reliability, the area where it sets out to be the most cost effective has significantly increased.

V. LINE DISTURBANCES USING SOLID-STATE CIRCUIT BREAKER

Conventional medium-voltage grids use mechanical circuit breakers for short-circuit protection. Since these devices need at least several line periods in order to react, the short-circuit current is not influenced at the beginning of the short. Consequently, the voltage of the complete medium-voltage grid is significantly reduced during a relatively long time, when a low resistive short-circuit occurs especially when it occurs near the feeding transformer.

In contrast to the mechanical breaker, the solid-state breaker can interrupt short-circuits so fast that the error-free part of the medium voltage grid is hardly influenced. To prove this and to analyze the remaining disturbances in detail, extensive simulations have been done using MATLAB/Simulink. The detailed behavior of the switch was simulated with the Power System Toolbox, whereas a medium-voltage grid was simulated with PLECS. Due to the fact that we are considering a 50 or 60-Hz system, the detailed behavior of a semiconductor in the μs range can be neglected.

In these simulations, characteristic medium-voltage networks are analyzed. The feeding transformer is modeled by three phase-shifted sinusoidal voltage sources; each with a series inductance, which represents the transformer stray inductance. The interconnection overhead lines or cables are modeled by their respective π-type equivalent circuits, because in medium-voltage grids the transmission length are quite low this circuit can be used. All these models are common in literature and have been verified several times [9]. Typical as well as worst-case scenarios have been considered in these simulations. All grid component values are from a 20-kV 50-Hz medium-voltage system, which is quite common in Germany.

During these simulations concerning different breaker topologies one could see that there were only marginal differences in behavior between these solutions. Consequently, the results of the simulation are shown simply for one solution.

The current waveforms are not shown here, because as already mentioned the current will never rise in any phase above 4 kA, which is a significant improvement compared to classical solutions.

However, a much more important issue can be seen in the grid voltage during short circuit when a solid-state breaker is used (Fig. 7). At 20 ms, a three-phase short-circuit occurs in one part of the grid. When the short circuit occurs, the voltage drops significantly below the nominal value. During this time the failure is not yet detected and thus the breaker is not opened (Fig. 8 for zoomed view).

After the detection time, the solid-state breaker turns off within a few μs. Due to the stored energy in the grid, the voltage rises very fast to a peak value of 28 kV and drops afterwards to the nominal value. Fig. 7 depicts voltage waveforms occurring at a load nearby a failure (50-m distance). If the load has a greater distance to the failure, there are almost no disturbances left in the voltage waveform.

A detailed survey of disturbances occurring near the short-circuit event are presented in Fig. 8. The resulting overvoltage is not destructive, because all medium-voltage devices situated in a 20-kV grid must be able to withstand 50-kV RMS voltage for at least a minute [10]. Taking this into account, it becomes obvious that the voltage disturbance just lasts around 100 μs. Consequently, if such a solid-state switch is used, a three phase short circuit placed directly beside the load would not lead to a loss of power supply.

When taking a closer look at Fig. 8, one can see that the influences during a failure are significantly reduced by a solid-state circuit breaker when compared to conventional solutions. Consequently, the effects of a short circuit just last for some μs and not ms like in today's networks.

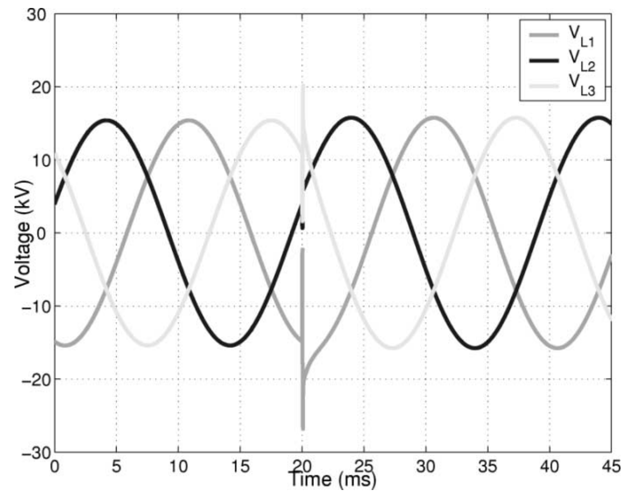

Fig. 7. Voltage during short circuit.

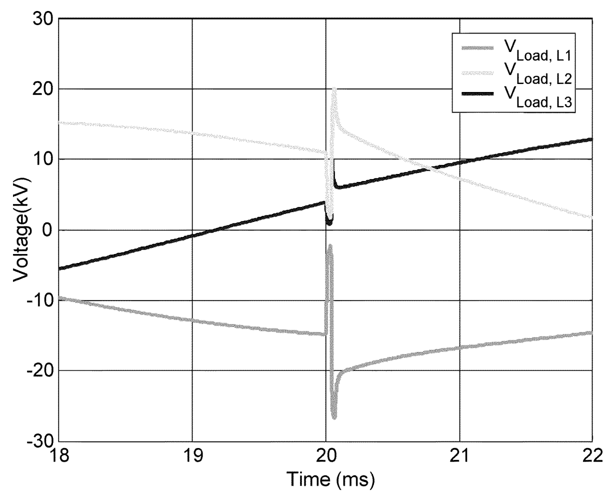

Fig. 8. Detailed view of voltage disturbance.

VI. MIGRATING SOLID-STATE SWITCHES INTO EXISTING INFRASTRUCTURES

Although an immediate interruption of short-circuits appears advantageous at first sight, a fast interruption conflicts with present day error detection mechanisms. For selective error detection, it is necessary that the overload current continues for some seconds to allow time for the "most selective" circuit breaker to act, leaving most of the network intact after a short-circuit.

This selective short-circuit protection will be briefly explained in the following using the medium voltage network in Fig. 9 as an example. In this figure, large transformer symbols represent the feeding transformers, which supply the medium-voltage from the high-voltage grid. The smaller transformer symbols represent the loads. These can be either low-voltage networks, consumers or generators (photovoltaic, wind turbines etc), which are connected directly to the medium-voltage grid. The circles represent switches which are open during normal operation, whereas the boxes represent (mechanical) short-circuit breakers.

Selective action of the breakers is achieved by assigning descending tripping delay times to the breakers in each chain. Herein, the breaker nearest to the feeding transformer have the longest delay time. For example, the breakers I to IV typically have tripping delays of 0.1 s, 0.5 s, 1.0 s, and 1.5 s, respectively. Consequently, only the breaker nearest to the short-circuit will open. For example, in Fig. 9, the four circuit breakers numbered from I to IV detect the short depicted by the "flash" symbol. However, only breaker I will trip, since it has the shortest delay.

It is anticipated that the error detection methodology will not be changed in the near future. Hence, only the breakers at the end of the branch, e.g., breaker I, can be replaced by fast acting solid-state switches. The other ones definitely require a longer delay time.

However, the strongest short-circuits with the highest impact on the grid occur near the feeding transformers. In the next section, it is explained how these can be handled using solid-state current limiters.

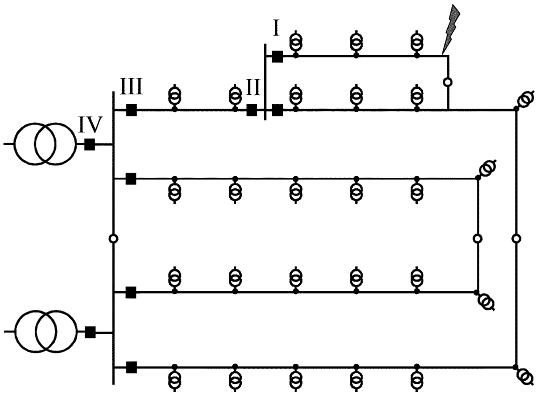

Fig. 9. State-of-the-art short-circuit protection.

VII. Line Disturbances Using Solid-State Current Limiter

To combine the advantages of fast semiconductor switching (i.e., low disturbance) and selectivity, it is proposed to use a solid-state current-limiting switch. In parallel to the semiconductor switch, a reactive current limiter (e.g., inductor, capacitor, or both) is added. Fig. 10 shows the basic topology of the current limiter, which is connected in parallel to the circuit breaker. The limiter itself consists of a simple inductance, a capacitance (with a small inductance as a $\mathrm{d}i/\mathrm{d}t$ limiter in series) or a parallel LC-circuit. As soon as a short-circuit is detected, the solid-state switch opens immediately $(< 100\ \mu\mathrm{s})$. However, the current can still flow through the reactive element. This current is chosen (by the reactance) to be higher than the nominal current of this part of the grid but also to be significantly lower than the short-circuit current. Therefore, the disturbance in the remaining, i.e., error-free section of the grid is much lower than without the limiter. As a result, present day selective short-circuit protection can still be applied using only mechanical circuit-breakers downstream.

Inductive current limiters are commonly used in medium-voltage grids to reduce short-circuit power. However, if they are activated rapidly by the solid-state switch, significant overvoltages will occur in the grid until the short-circuit current is commutated to the inductor.

In contrast, no overvoltage occurs with capacitive limitation, since the current can instantaneously commutate to the capacitor. However, the current is not limited properly directly after the switching. Consequently, longer and deeper voltage sags occur with capacitive limitation.

Both mentioned disadvantages can be avoided, if a proper combination of inductor and capacitor is applied. In contrast to the solution presented in [11], [12] the large inductance is only integrated into the grid when the failure occurs and not during normal operation. Overvoltages appearing directly after switching are hindered by a comparatively small capacitor, whereby the inductor mainly controls the stationary value of the short-circuit current. To avoid undesired oscillations, a damping resistor is added in series with the capacitance.

This solution can be combined advantageously with the module topologies (c) and (d). Here, the single capacitor can be replaced by a series connection of one capacitor per module. Each capacitor is connected in parallel to the GCTs, i.e., behind the diode rectifier. The main advantages of this solution are

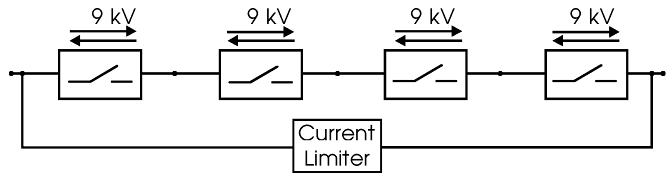

Fig. 10. Basic topology for the current limiter.

that these capacitors act as a large turn-off snubber on the one hand and that oscillations are significantly reduced once the capacitors are charged to the peak voltage on the other.

A typical result of this kind of limitation can be seen in Fig. 11 and Fig. 12. The first figure depicts the current running into the faulty part of the network. At 15 ms a short-circuit occurs and the solid-state switch opens after 100 μs. Within a few milliseconds, the short-circuit current reaches its final sinusoidal shape. However, a slowly decreasing dc-component is still present. The decreasing rate depends on the dc resistance in the short-circuit loop.

Fig. 11 shows the voltage disturbance occurring in the error-free part of the medium-voltage grid. It can be seen that only minor disturbances are present and that the sinusoidal shape is reached within a few milliseconds again. However, the voltage is slightly reduced, due to the relatively high current flowing into the faulty network. The problems of integrating fast switching elements into today's medium-voltage grids and combining different current limiting methods with solid-state switches are described in detail in [13].

VIII. Conclusion

In this paper, a fast acting solid-state breaker mend for medium-voltage systems is proposed. This fast acting solid-state breaker is ideal for avoiding drawbacks concerning state-of-the-art mechanical breaker, i.e., it increases power quality. If a solid-state breaker is used, the impact of a three-phase short circuit lasts only for 100 μs, in comparison to some 100 ms today. Since current semiconductor devices are not capable of blocking sufficiently high voltages, a series connection of modules (building blocks) is preferred. Using available semiconductors, a suitable topology was selected. Since the circuit breaker is rated for a maximum power of 63 MVA no parallel connection is needed for all present medium-voltage applications. From a thermal point of view, it can be used up to 100 MVA. Although if there is a need for higher current ratings a parallel connection should be examined. Due to the large time constant and low $\mathrm{d}i/\mathrm{d}t$ in the grid, it should be possible to connected modules in parallel.

This paper conveys that various topologies can be used for switching applications. Comparing their behavior in the grid, showed that no significant functional differences can be found. Consequently, the right choice for a certain application must be solely based on an economical examination. It is essential to consider the life-cycle costs of a system, to find the most economic and effective solution.

The impact of this fast acting switch on the grid is analyzed using simulations. It is shown that line disturbances during short-circuit are greatly reduced using this solid-state circuit-breaker. However, fast turn-off conflicts with present day selective short-circuit protection in medium-voltage grids.

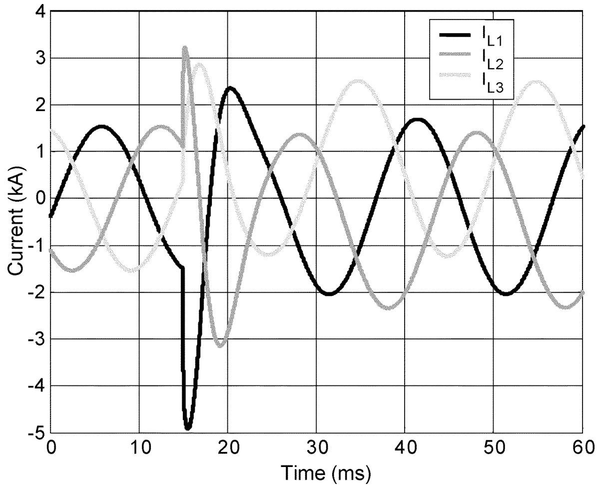

Fig. 11. Limited short-circuit current using solid-state circuit-breaker with LC-limiter.

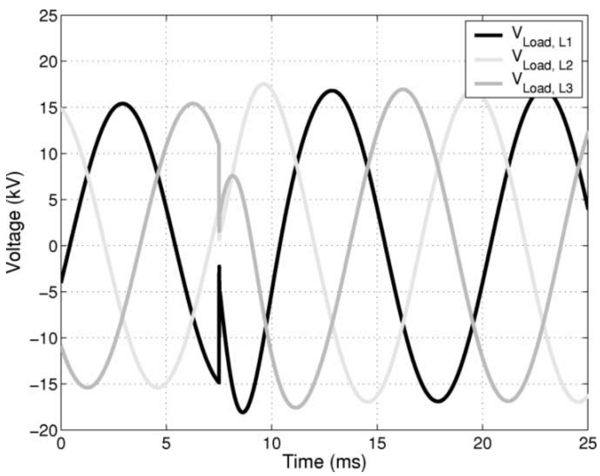

Fig. 12. Voltage in error-free grid during LC-limiter action.

To overcome this conflict, a solid-state current limiter is proposed and analyzed. It is shown that a significant reduction of the line disturbances is achieved with this technique without compromising existing protection concepts.

REFERENCES

[1] F. Tosato, "Voltage sags mitigation on distribution utilities," *Eur. Trans. Elect. Power*, vol. 11, no. 1, Jan./Feb. 2001.

[2] R. W. De Doncker, "Recent power electronics development for FACTS and customed power," in *Proc. Korea Germany Advanced Power Electronic Symp.*, 1998.

[3] R. K. Smith *et al.*, "Solid state distribution current limiter and circuit breaker: application requirements and control strategies," *IEEE Trans. Power Delivery*, vol. 8, pp. 1155–1164, July 1993.

[4] E. Caroll, *Power Electronics for Very High Power Applications*. London, U.K.: ABB, 1998.

[5] M. Russ, R. Sommer, and G. Zaiser, *Spannungszwischenkreisumrichter im Mittelspannungsbereich*. Bad Nauheim, Germany: ETG Tagung, 2002.

[6] J. W. Schwartzenberg and R. W. De Doncker, "15 kV medium voltage static transfer switch," in *Proc. 30th IAS Annu. Meeting (IAS'95)*, vol. 3, Oct. 8–12, 1995, pp. 2515–2520.

[7] L. Klingbeil, W. Kalkner, and C. Heinrich, *Fast Acting Solid-State Circuit Breaker Using State-of-the-Art Power-Electronics Devices*. Graz, Austria: EPE, 2001.

[8] A. Ekström, P. Bennich, M. De Oliveira, and A. Wilkström, *Design and Control of a Current-Controlled Current Limiting Device*. Graz, Austria: EPE, 2001.

[9] G. Hosemann and W. Boeck, *Grundlagen der Elektrischen Energietechnik*. Berlin, Germany: Springer-Verlag, 1979.

[10] International Engineering Consortium, "Isolationskoordination," Tech. Rep. VDE 0111, IEC/EN 60 071-1/2, 2004.

[11] G. G. Karady, "Concept of a combined short circuit limiter and series compensator," *IEEE Trans. Power Delivery*, vol. 6, pp. 1031–1037, July 1991.

[12] F. Tosato and S. Quaia, "Reducing voltage sags through fault current limitation," *IEEE Trans. Power Delivery*, vol. 16, pp. 12–17, Jan. 2001.

[13] C. Meyer, S. Schröder, and R. W. De Doncker, *Integration of Solid-State Switches Into Existing Medium-Voltage Grids*. Toulouse, France: EPE, 2003.

Christoph Meyer (S'01) was born in Düren, Germany in 1975. He received the M.S. degree in electrical engineering from Aachen University, Aachen, Germany, in 2001.

He joined the Institute for Power Electronics and Electrical Drives (ISEA), Aachen University, as a Research Associate in 2002. His main research interests are power electronic circuits and devices for electrical energy supplies.

Stefan Schröder (S'98–M'03) was born in Cologne, Germany, in 1970. He received the M.S. and Ph.D. degrees in electrical engineering from Aachen University, Aachen, Germany, in 1997 and 2002, respectively.

Since 1997, he has been a Research Associate at the Institute for Power Electronics and Electrical Drives (ISEA), Aachen University where, since July 2002, he has been Chief Engineer. His main research interests are power electronic circuits and devices, in particular high-power semiconductors.

Rik W. De Doncker (M'87–SM'99–F'01) was born in Leuven, Belgium, in 1958. He received the Ph.D. degree in electrical engineering from the Katholieke Universiteit Leuven, Leuven, Belgium, in 1986.

During 1987, he was appointed Visiting Associate Professor at the University of Wisconsin, Madison. In 1998, he joined the Corporate Research and Development Center, General Electric Company, Schenectady, NY. In 1994, he joined Silicon Power Corporation (formerly GE-SPCO) as Vice President of Technology. Since 1996, he has been a Professor at Aachen University, Aachen, Germany, where he leads the Institute for Power Electronics and Electrical Drives.