Performance evaluation of high power semiconductor devices employed in solid-state circuit breakers for MVDC grids

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Abstract

This paper presents a performance evaluation of power losses of three high-power and high-voltage power semiconductor devices, namely, IGBTs, BIGTs, and IGCTs operating in solid-state DC circuit breakers for medium voltage Direct Current grids. The performance of each breaker is evaluated for a wide range of DC voltages and load conditions under steady-state operation, whereas the criteria are the conduction losses associated with the switches and the corresponding junction temperature. The IGCT-based solid-state breaker achieved the lowest power losses, while the IGBT-based performed the highest losses under all the investigated cases. Last but not least, a comparative study regarding the transient responses of the three devices when a short-circuit occurs is also examined and presented. The superiority of BIGT-based breaker in terms of minimizing the short-circuit current is revealed.

Introduction

Today, electric power transmission over long distances using high voltage Direct Current (HVDC) has gained momentum over the Alternating Current (AC) counterpart. Several reasons have led to this paradigm shift towards HVDC power grids, such as higher efficiency, no need for reactive power compensation and no need for synchronization. On the other hand, for electric power distribution medium voltage AC grids are currently utilized. Nevertheless, a clear trend to shift towards medium voltage DC (MVDC) grids is foreseen [1]. Similar to HVDC power systems, the MVDC grid technology will decrease the transmitted power losses. Furthermore, the ever-increasing renewable energy sources (RES) installations will also lead to the development of MVDC power grids, since they enable easier grid integration.

Even if the advantages of the potential MVDC power distribution grids over the existing MVAC counterparts are significant, there are still few barriers that impede their further development [2]. Firstly, the higher cost of power electronic converters, which are expected to be the key component of the potential MVDC systems, compared to the low frequency transformers utilized in AC grids. However, this cost seems to decrease due to the massive production of power converters by relevant industries. Furthermore, the lack of zero crossing for the fault current in DC grids along with the low DC line inductance cause excessively high short-circuit current peaks within a short time period. Therefore, the development of fast acting DC circuit breakers is mandatory.

Three basic topologies of DC CBs have been identified in literature, namely, mechanical DC CB (along with active or passive resonant circuit), solid-state DC CB and hybrid DC CB. It has shown that the mechanical DC CB achieves the highest efficiency during normal operation over the corresponding solid-state and hybrid counterparts, while the solid-state DC CB exhibits the shortest fault clearing times than the rest of CBs and hence, it minimizes the anticipated short-circuit current at the cost of lower efficiency [2]. It should be mentioned that several different configurations of mechanical, solid-state and hybrid DC CBs have been presented in literature.

In MVDC grids, the solid-state CBs seem to gain more attention due to their inherent advantages, such as, fast clearance times and low maintenance requirements. They can be categorized into, interrupting and resonance topologies [3]. This study focuses on the interrupting solid-state DC CB topology due to its lower complexity compared to others, and hence, easier controllability .

One significant drawback of the solid-state DC CBs as mentioned above, is the excessive amount of conduction power losses caused in the power semiconductor devices. The decrease of the on-state resistance of the power semiconductor devices used in a DC CB is therefore of great importance. Moreover, series connection of multiple power electronic devices might be required in order to withstand the voltage level of the MVDC grid, and thus, the power losses will also increase accordingly. Therefore, the use of a power electronic device that exhibits low on-state losses, and simultaneously, high breakdown voltage is required for applications such the solid-state CBs. On the other hand, the switching performance of the power semiconductor devices used in DC CBs is not as crucial as it is in power converter applications.

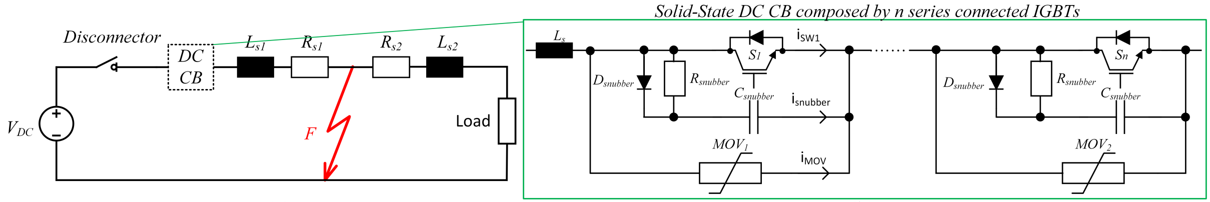
Various high power semiconductor devices may be used in an interrupting solid-state CB for MVDC applications. Thyristors have been used in high power applications due to their inherent advantage of low conduction losses and high breakdown voltages [4]. The Gate Turn-Off (GTO) thyristor and the Integrated Gate Commutated Thyristor (IGCT) belong to thyristor family and hence, they can exhibit the same advantages as thyristors when used in an interrupting DC CB [5]. Besides thyristors, the Insulated Gate Bipolar Transistors (IGBTs) would also be a potential candidate for a solid-state DC CB [6]. The main reasons are the high voltage breakdown along with the high current turn-off capability of the IGBTs. Other devices that they have not been commercialized yet but they could be used in DC CB topologies, such as SGTO [7], Emitter Turn-Off (ETO) [8] could also be used in solid-state DC CBs. Furthermore, the recently commercialized Bi-mode Insulated Gate Transistors (BIGT) can also bring operating benefits in DC CBs [9]. This device integrates two anti-parallel IGBTs in the same structure, instead of the commonly used external anti-parallel diode. Finally yet importantly, Wide Band Gap (WBG)-based high power devices can be very promising for CBs, minimizing both the power losses and the thermal stress. In particular, several silicon-carbide (SiC)-based devices have already been in market, but the voltage and current ratings are not sufficiently high to be considered for MVDC grids. However, they are still under extensive investigation by the research community.

The purpose of this paper is to present a performance evaluation of the interrupting solid-state DC CB using three types of high-power semiconductor devices, namely IGBTs, BIGTs and IGCTs. The comparison criteria are the thermal performance and conduction power losses for different power and voltage levels in the MVDC grids. Additionally, a dynamic analysis has been carried out and it will also be presented for the three alternatives under investigation. In Section II, the protection challenges of a MVDC grid are discussed, while Section III analyzes and presents the performance of the most suitable commercial power semiconductor devices used in DC CBs. Section IV describes the under investigated cases along with their modeling. The results for both steady-state and transient conditions are presented in Section V. Lastly, a short discussion is presented in Section VI and Section VII shows the conclusions of the presented work.

Protection challenges in a potential MVDC power grid

In AC power grids, the conventional mechanical CBs interrupt the fault current at zero crossing point. This approach cannot be followed in DC applications due to the absence of natural zero crossing of the current. Apart from that, a potential MVDC power grid is expected to cover short distances, thus the line inductances will be low, leading to high short-circuit current rates. In addition to that, the absence of low frequency transformers and, hence, their leakage inductances will also contribute to high fault currents. Lastly, several power electronic converters are expected to be connected to the MVDC grids. The current and thermal sensitivity of power electronic devices employed in these power converters must also be considered in order to prevent the converter from failures [10]. Therefore, the design of highly performant DC CBs in terms of fast acting and low conduction losses is necessary.

Fig. 1 illustrates the basic structure of the interrupting solid-state DC CB topology. Generally, it consists of power semiconductor devices, snubber circuits, metal-oxide varistors (MOVs) and current limiting inductors. In addition to these, a mechanical switch/ultra fast disconnector must also be considered in series for ensuring galvanic isolation. When the voltage level of the grid exceeds the maximum breakdown voltage of the power semiconductor devices, series connection of multiple devices has to be considered. For example, the potential range of MVDC grid voltages seem to be 1-35 kV [11] or even up to 70 kV [12], while the maximum breakdown voltage of a single Si-based device is up to 6.5 kV, which clearly necessitates the series connection of several individual devices. On top of that, a parallel connection of devices must also be taken into account if the current capability of the device used is lower than the required load current. The challenging drive circuit design for both series and parallel-connected devices increase the complexity and simultaneously decrease the reliability of the entire DC CB. However, the drive circuit design is beyond the scope of this study. Moreover, the current limiting inductor aims to limit the maximum short-circuit current by reducing the current rise rate. The analysis of both snubber circuit and MOV will follow in the next Section.



(a) (b)

Fig. 1: a) Schematic diagram of simplified DC power grid and b) solid-state DC CB.

Power semiconductor devices used in solid-state DC CB for MVDC grids

The design of power electronic devices varies and relies on the specific application areas. Most of these applications are related to power electronic converters and not to solid-state breakers. Various devices have been desiged by relevant industries, aiming to different goals, such as, high breakdown voltage capability, low on-state resistance, high switching frequency keeping low the associated power losses.

It can be concluded that minority-carrier power devices seem appropriate candidates for solid-state DC CBs due to their low conduction losses. In particular, commercially available high power devices that may be used in a solid-state DC CB configuration are the IGBTs, BIGTs and also the thyristor-based devices such the GTOs, IGCTs. Currently, the high power silicon-based IGBT seems to have gained momentum over the other counterparts due to its robustness and reliable operation. On the other hand, SiC power devices have already initiated a new era in the development of high power electronics and therefore, they might potentially be used in a solid-state CBs. The wider energy bandgap of SiC pushes the breakdown voltage limits of a single-chip switch to higher levels compared to silicon counterparts. Therefore, the number of required devices to withstand the voltage level of a MVDC power grid will decrease if the conduction power losses are kept same as silicon. Based on the design goal (e.g. low losses or complexity), the shift from silicon devices to SiC is therefore expected to increase the efficiency and reduce the design complexity of gate drivers.

Nevertheless, a lack of a specific high power electronic device intended for solid-state DC CB has been identified. It can be concluded, that the following characteristics must be considered when the switch is used in solid-state breakers:

1. **Maximum turn-off current capability**. The ability of a device to turn-off by its gate/base at high current is of high importance when they are used for solid-state DC breakers.

2. **On-state voltage**. As mentioned above, the current showstopper of solid-state DC CBs development is mainly found in their performance in terms of efficiency. The significantly high conduction losses associated with the power electronic devices must therefore be minimized.
3. **Current conduction ability**. The electro-thermal performance of a power electronic device employed in a solid-state DC breaker is also of high importance. The thermal impedance of a switch can affect both the conduction losses and the power dissipation within the device. The excessive heat generated within the chip in a short-circuit condition, may lead to thermal breakdown. Therefore, the characteristics related to thermal impedance of a switch must be considered.
4. **Robustness**. The rapid change of the short-circuit current (i.e. di/dt) can be very crucial when designing a solid-state CB. Also, the turn-off process of the device used will generate a high rate of voltage rise across its terminals (i.e. dv/dt). Therefore, the sensitivity of a device to these changes must be evaluated. Snubber circuitries and active gate unit designs are used to control and limit these restrictions.
5. **Characteristics in series connection**. As mentioned above, a series connection of multiple devices employed in a solid-state breaker for MVDC power grids must be considered to withstand the voltage level. Therefore, the ability of devices for ease series connection is of high importance. Snubber circuitries and specific gate unit designs are also used for the voltage sharing.
6. **Characteristics in parallel connection**. If the load current is higher than the current rating of a power semiconductor device employed in a solid-state breaker, then a parallel connection of multiple devices to share the load current must be considered. The temperature coefficient of the devices plays a key role for achieving robust parallel connection. If this coefficient is positive, the current sharing is feasible. Otherwise, specific gate drive design must be apply.

Regardless of the semiconductor type, a special design effort must be made in terms of their turn-off capability, thermal performance and conduction power losses minimization. For the present study the Si-based technology is adopted, since there are no commercially available high-voltage and high-power SiC power devices.

- **IGBT:** The IGBT is a minority-carrier and voltage-controlled device. Different structures related to IGBT packaging are available [13]. They can be divided into three categories; (i) Discrete (ii) Modules and (iii) Press-packs. For high voltage, high power applications, the last two types have been utilized. The main advantages of the press-pack IGBTs are the following; (i) high thermal cycling capability, (ii) double-side cooling, (iii) high power density, (iv) ease of laying out in series and finally (v) short-circuit failure mode (SCFM). The voltage and current ratings of IGBTs have increased significantly over the last decades. Today, the maximum breakdown voltage of an IGBT module is up to 6.5 kV, while the current capability is limited to 1 kA. Apart from that, a press-pack device of 4.5 kV and 3 kA has also been commercialized. For solid-state DC CB, the most favorable IGBT packaging technology is the press-pack IGBTs that ease series connection due to their mechanical and thermal properties. The current turn-off capability of IGBTs (up to 6 kA) along with the low thermal resistance make them a suitable power semiconductor device for high power applications. On the other hand, the high on-state power losses limit the popularity of IGBTs at high current applications. Last but not least, the majority of high power high voltage IGBTs has positive temperature coefficient, and hence a parallel connection can be easy applied to them.
- **BIGT:** In modern high-voltage and high-power applications, an anti-parallel diode is usually connected with the IGBT to achieve reverse conduction capability. For IGBTs in the 1.2 kV class, monolithic integration of the anti-parallel diode is feasible which results in the design of the reverse-conducting IGBT (RC-IGBT) chips. A new high-power semiconductor device, namely BIGT eliminates the need for an external anti-parallel diode [9]. BIGT consists of a hybrid structure, integrating an IGBT with a RC-IGBT into a single chip. Therefore, the BIGT device exhibits both lower conduction losses and lower thermal resistance due to the increased active silicon area compared to RC-IGBT counterpart. The voltage and current ratings of the commercially available BIGT are 5.2 kV and 2.1 kA respectively. Finally yet importantly, BIGTs have positive temperature coefficient similar to IGBTs which allows an easy parallel connection of multiple devices.

- **IGCT:** Thyristors have been established several decades ago, and are the most popular devices for high power high voltage applications due to their ability to block high voltages and conduct high currents. Classic thyristors, such silicon controlled recifiers, i.e. SCRs, are incapable of turning-off via the gate and hence, they cannot be used in a interrupting solid-state DC CB. On the other hand, GTOs and IGCTs, which have similar operating principles to SCRs, offer the capability of turning-off through a negative gate current pulse. Therefore, these high efficient power switches could be used for high voltage, high power applications, such as DC CBs for MVDC grids. Even if IGCTs require high negative gate current (similar to anode current) during the turn-off process (as long as the storage time lasts, approximately 1 μs), the short storage time gives a relatively lower gate power losses compared to GTOs.

  Three types of IGCTs have been presented, namely asymmetric (A-IGCT), reverse blocking (RB-IGCT) and reverse conducting (RC-IGCT) IGCTs [14]. The first switch can only block and conduct in forward direction. A series connected diode along with an anti-parallel connected identical branch is required for bi-directional operation. The second switch is able to block both in forward and reverse directions but it conducts in forward direction only. Therefore, two anti-parallel RB-IGCTs are needed for enabling bi-directional operation. The last device blocks only in forward direction but it may conduct in both directions. Therefore, a series-connection must be considered for bi-directional operation. The range of voltage ratings of these IGCTs lies between 4.5 to 6.5 kV, while the current rating is up to 4 kA. Lastly, all the aforementioned types of IGCT exhibit positive temperature coefficient.

Modeling of the DC CB and case study

The test circuit of the MVDC grid used for the performance investigations is shown in Fig. 1a. The DC grid has been modelled and simulated using PLECS for the electro-thermal analysis and using Matlab/Simulink for the dynamic performance of the DC CB. The short-circuit was considered as a pole-to-pole fault, occurring in the middle of the transmission line. For modeling purposes, the resistance of the fault path was considered negligible. The line inductances and resistances were set as follows: $L_{s1} = L_{s2} = 1\ \mu H$ and $R_{s1} = R_{s2} = 1\ m\Omega$. Moreover, the CB tripping current was defined at 2 p.u. Furthermore, the design of the current limiting inductor is based on $V_{DC} = L_s \frac{di_{sc}}{dt}$. V_{DC} and i_{sc} are the DC grid voltage and short-circuit peak current respectively. The considered nominal grid voltage and load current have been set at 3 kV and 1.5 kA respectively as the "base" case. Given the fact that the turn-off process of the power semiconductor devices requires a few microseconds, the inductance value of the current limiting inductor has been estimated to be $L_s = 150\ \mu H$. It must be mentioned that the current limiting inductor can limit both the maximum short-circuit current and the rate of current rise.

Snubber circuits [15] are required to limit the energy dissipation in the power semiconductor devices during turn-off. Both the control of the voltage rise across the device terminals during its turn-off (i.e. dv/dt) and the voltage sharing, if series connection of multiple devices is required, can be performed by means of designing appropriate snubber circuits. A turn-off RCD-snubber circuit has been considered in this study. Lastly, the clamping voltage of the MOV has been set to 110% of the grid voltage level.

A summary of the datasheet-based device parameters of the considered power semiconductor devices is given in Table I. The evaluation criteria are the breakdown voltage, the maximum turn-off current, the thermal performance and the on-state voltage drop.

Simulation results

A comparative study of the steady-state and dynamic performance of three power semiconductor devices employed in a solid-state DC CB configuration for MVDC grids has been conducted and is presented below.

Steady-state analysis

For the first steady-state analysis, a 3 kV DC voltage has been adopted, while the load current was considered to vary from 0.5 kA up to 3.75 kA. Fig. 2 illustrates the corresponding results with respect to

Table I: Parameters of the power semiconductor devices employed in the solid-state DC CBs

	IGBT	BIGT	IGCT
Manufacturer	ABB	ABB	ABB
Model	5SNA 2000K450300	5SJA 3000L520300	5SHY 35L4522
Blocking voltage	4.5 kV	5.2 kV	4.5 kV
Maximum turn-off current	4 kA	6 kA	4 kA
On-state voltage (4kA, 125^{o}C)	5.1 V ($V_{GE} = 15V$)	3.6 V ($V_{GE} = 15V$)	2 V
di/dt	High	High	Low, 1 kA/μs
Maximum power dissipation/ Limiting load integral	25 kW	55 kW	4.8x10^6 A^{2}s
Thermal resistance junction to case	4 k/kW	2.1 k/kW	8.5 k/kW
Packaging dimensions	246.95x237.3x28.75	237x250x31.5	439x173x41 150x150x41[1]

[1] without gate drive unit

conduction losses and junction temperature of the devices. It must be noted that a parallel connection of two semiconductor devices is required for currents exceeding 2 kA. The superior performance of IGCT-based DC CB in terms of on-state losses is clearly shown, while the BIGT-based counterparts seem to keep the lowest junction temperature in cases with one connected device.

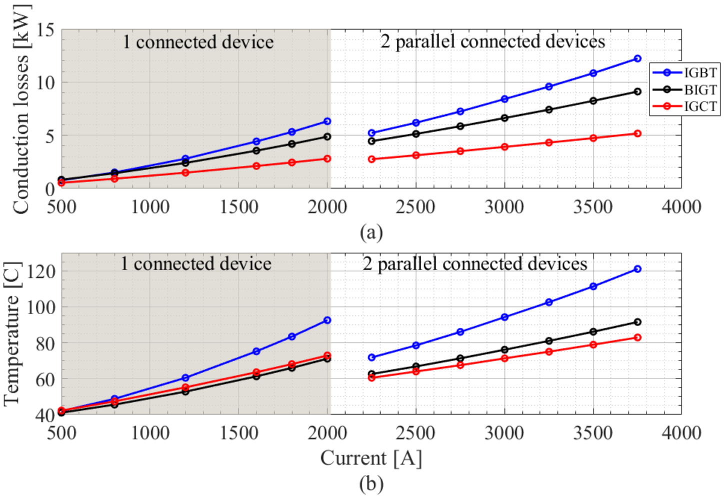


Fig. 2: a) Conduction power losses and b) junction temperature for different currents at 3 kV

The DC voltage level is expected to be in the range of 1-60 kV for the potential MVDC power grids [2]. Therefore, the second study related to steady-state operation is referring to both the conduction losses associated with the power electronic devices and the junction temperature for different DC voltage levels, keeping the power load constant. More specifically, Figs. 3,4 illustrate the on-state losses and the junction temperature rise of the devices used for voltage levels up to 60 kV of the considered MVDC grid. It is apparent that for high MVDC voltages, a series connection of multiple devices has been adopted. Fig. 3 illustrates the conduction losses and the anticipated junction temperature rise up to 12 kV, for two load conditions. The first one with a 2 MW load and a voltage up to 3 kV, while the second condition assumes a 6 MW load and the corresponding voltage up to 12 kV. In all cases, the IGBT exhibits the worst performance in terms of excessive conduction losses associated with high junction temperatures for the whole voltage range. Furthermore, the IGCT achieves the highest efficiency for almost all cases, except of the case with DC voltage of 3.5 kV, where the BIGT exhibits lower conduction losses compared to the other devices. The reason is the use of 1 single BIGT device for that voltage level, while the other require two series connected devices in order to withstand the voltage level. Fig. 4 depicts similar results to Fig. 3, but for higher voltages and power delivered to loads (i.e. up to 60 kV and 25 MW load). The IGCT-based DC CB exhibits again a better performance in terms of lower conduction losses and lower junction temperatures.

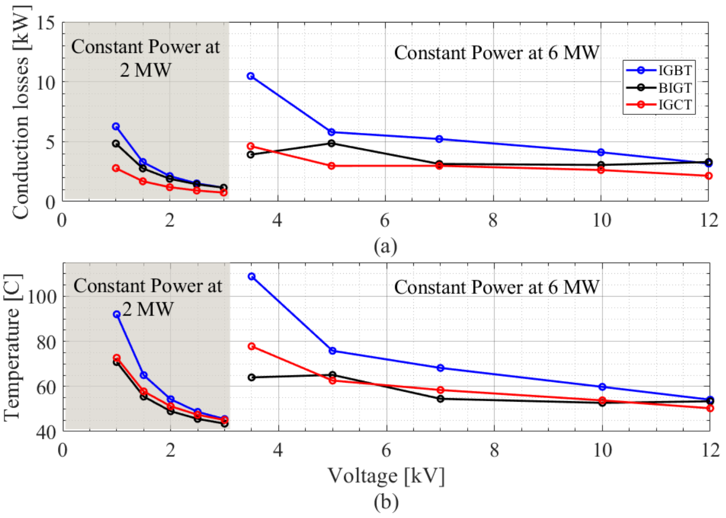


Fig. 3: a) Conduction power losses and b) junction temperature for different voltage levels, under two load conditions of 2 MW and 6 MW

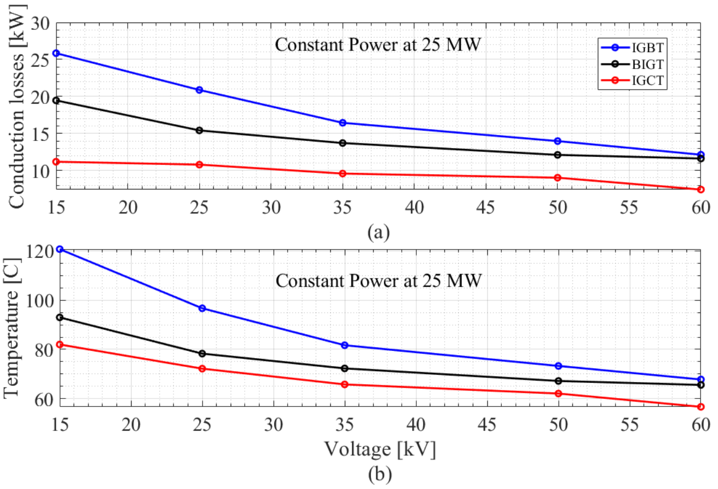


Fig. 4: a) Conduction power losses and b) junction temperature for different voltage levels, under constant load of 25 MW

Transient analysis

In the next analysis, a short-circuit condition in the grid has been considered. It occurs at the time instant of 200 msec. The DC voltage level was defined at 3 kV, while the nominal current equals 1.5 kA. Fig. 5 depicts the currents of the interrupting DC CB. The short-circuit current starts to rise when the fault happens. Then, the switch turns-off and the current commutates to the snubber circuit, while the voltage across the switch increases. Once the voltage rises up to MOV voltage operation, then the current commutates to MOV path.

Fig. 6 illustrates the three cases under investigation with respect to short-circuit current, current that flows through the switch and the voltage across the switch. The magnified figures show the differences among the three cases. In all the evaluated criteria, the IGCT-based DC CB achieved the worst performance, i.e. the highest current and voltage stress. The main reason for that is the longest delay time for turning-off of IGCT compared to IGBT and BIGT.

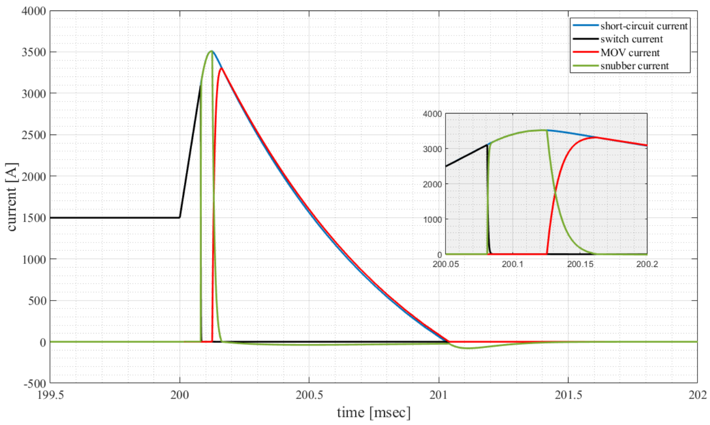


Fig. 5: Various currents in a DC CB configuration at short-circuit condition

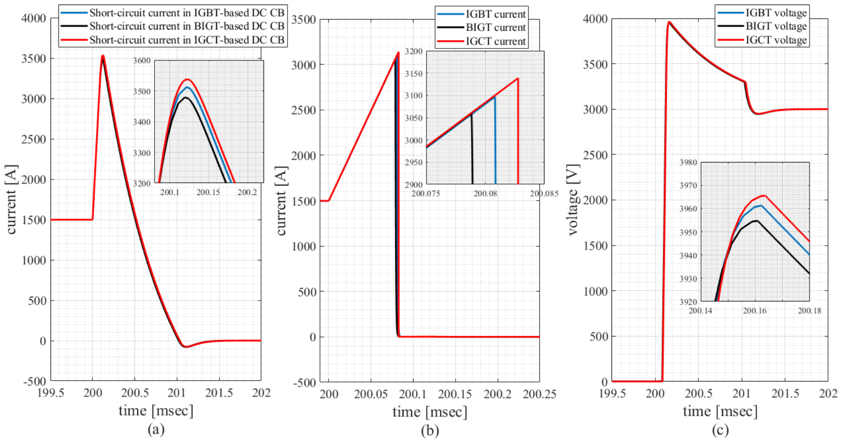


Fig. 6: Comparative diagrams for the three under consideration cases, with respect to a) short-circuit current, b) switch current and c) switch voltage

Furthermore, both the switch current and voltage waveforms are depicted in Fig. 7 for all the cases. However, the arising differences are not clear from this figure. From the magnified figures, the snubber contribution to minimize the power dissipation within the switches during the turn-off process by controlling the dv/dt, can be observed. Table II illustrates the numerical differences of peak short-circuit current, peak switch current, peak voltage current, fault clearance times and power dissipation for bipolar devices along with the load integral for the IGCT device. It is observed that all configurations achieved short clearance times, of approximately 1 msec. In addition to that, the least current stress is observed for the BIGT.

Table II: Numerical results

breaker model	short-circuit peak current [A]	switch peak current [A]	clearance time [msec]	Power dissipation [kW] / load integral [A^{2}sec]
IGBT-based	3512	3097	1.02	24.5
BIGT-based	3479	3061	1.02	21.4
IGCT-based	3538	3139	1.03	464

Discussion

The key power component of a solid-state breaker is the power electronic devices. The main barrier for their realization today is the excessive amount of conduction losses in the switches. However, the rapid

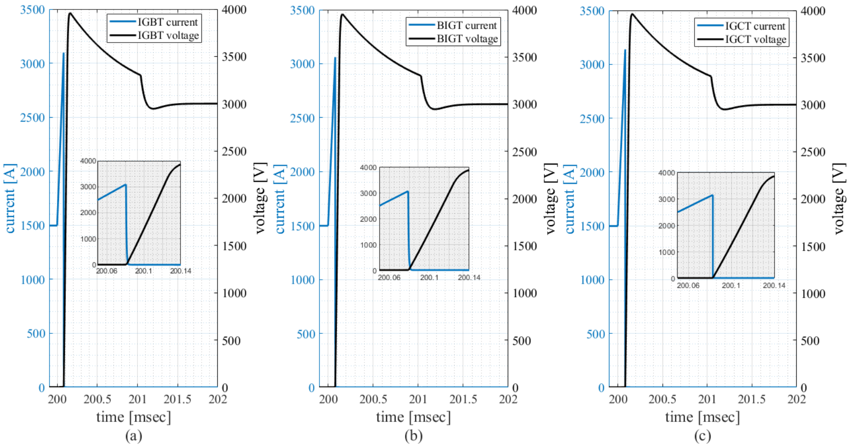


Fig. 7: Currents and voltages across each power electronic device during the short-circuit; a) IGBT, b) BIGT and c) IGCT based DC breakers

development of semiconductor technology could possibly lead to higher efficiency. More specifically, wide bandgap devices, and in particular SiC-based high power devices have been recently designed and manufactured, leading to higher efficiency and power density, and operation at higher temperatures compared to silicon counterparts [16].

Last but not least, the lack of a high power semiconductor device intended to be used in a solid-state DC CB configuration must also be emphasized. Today, power semiconductor manufacturers aim to design high power switches for power converter systems, and therefore there might be some room for improvement for designing other devices, even silicon-based, employed in a solid-state CB configuration. The optimal thermal, mechanical and electrical design of such a device in terms of the characteristics presented in Section 3 could lead to solid-state DC CB development sooner than expected.

Conclusion

In this paper, the applicability of three types of high-power semiconductor devices in solid-state DC CBs for MVDC grids has been presented and analyzed. A comparative study of the state-of-the-art IGBTs, BIGTs and IGCTs in terms of their static and dynamic performance was carried out. Several load conditions and different voltage levels were considered, taking into account that the potential voltage level of MVDC power grids could be up to 70 kV. For all the considered steady-state operations, the IGCT-based DC CB exhibits the lowest conduction losses along with the lowest junction temperature rise compared to IGBT-based and BIGT-based counterparts. Last but not least, the performances of the three cases under short-circuit condition have also been evaluated. On top of that, the BIGT-based DC CB achieved the best performance in terms of minimizing the shirt-circuit peak current, switch peak current and voltage, whereas the IGCT-based achieved the highest currents and voltage.

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