1MW Bi-directional DC Solid State Circuit Breaker based on Air Cooled Reverse Blocking-IGCT

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***Abstract*—In this paper, we present the development of an air-cooled 1MW bi-directional DC Solid State Circuit Breaker (SSCB) based on recently developed 91mm, 2.5kV Reverse Blocking-IGCT (RB-IGCT). The power electronic switch (RB-IGCT) has been designed and optimized to have very low conduction losses, less than 1kW at 1kA (on-state voltage drop < 1V at 1kA, 400K) and high turn-off current capability (> 6.5kA at 1.6kV, 400K) which are the most important concerns of semiconductor based circuit breaker. We also present the simulation and experimental results at the system level i.e. analyzed the influence of the Surge Arrester (SA) on the over-voltage transients during current interruption. We also analyzed the thermal management for the newly developed SSCB using ANSYS Icepak and validated experimentally.**

Keywords—Solid State Circuit Breaker; Power Semiconductor Switch; IGCT; Reverse Blocking-IGCT, Cooling, Thermal Management

I. Introduction

The conventional electromechanical circuit breakers have been used for a long time to protect the electrical circuitry from damage due to an over current condition, such as a relatively high level short circuit or fault condition. Circuit breakers are capable of connecting and allowing currents to flow through the load under normal operating conditions and disconnecting the load under specified abnormal conditions such as fault condition. The conventional electromechanical low-voltage circuit breakers are a mature technology with a proven record of cost-effectiveness, reliability and long lifetime but there are two main drawbacks: the slow breaking action and the limited number of switching operations [1]. The SSCB i.e. the circuit breaker based on power semiconductor switch, eliminates these drawbacks but suffers from excessive power-losses due to the conduction losses of the power semiconductor devices which are optimized for relatively high switching frequecny applications [2-3]. However, not only the SSCB application demands the power semiconductor devices with low conduction losses: The modern trends towards operating at lower switching frequencies in many power electronics applications adopting multi-level topologies, along with special demands for high current carrying capabilities and/or high efficiency, is forcing the development of power semiconductor devices with low conduction losses.

The Integrated Gate Commutated Thyristor (IGCT) is a an ideal device, which will lend itself well to these adaptations due to its inherent low conduction loss thyristor properties on one hand, and the hard switched functionality on the other i.e. the IGCT conducts like a thyristor in the on-state, resulting in low conduction losses and turns-off like an Insulated Gate Bipolar Transistor (IGBT) in open base transistor mode (hard switching turn-off capability due to the integration of the low inductive gate unit) [4, 5, 6]. Therefore, the IGCTs have optimum plasma distribution in the conduction mode to achieve low on-state voltage drop compared to that of the IGBTs [7, 8].

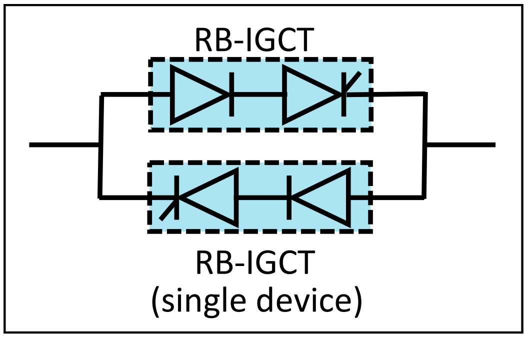
The RB-IGCT has been chosen for bi-directional DC SSCB application to increase efficiency, size-effectiveness and reliability (by reducing the parts count at the system level) of the circuit breaker compared to other semiconductor solutions such as Asymmetric (A)-IGCT or Reverse Conducting (RC)-IGCT as shown in Fig. 1. In bi-directional SSCB, the semiconductor switch or the arrangement of semiconductor devices should be able to block or allow the current flow both in forward & reverse directions. For this, three different semiconductor configurations are discussed in this paper.

RB-IGCT solution: This semiconductor switch is able to block both forward & reverse directions but conducts currents only in the forward direction, and in order to provide bi-directional current flow, two RB-IGCTs are connected in anti-parallel as shown in Fig. 1. Total semiconductor devices needed in this solution is 2.

A-IGCT solution: This semiconductor switch can only block in forward direction. Therefore an additional diode needs to be connected in series to the A-IGCT to provide reverse blocking capability. In order to provide bi-directional current flow, this set needs to be connected in anti-parallel as shown in Fig. 1. Total semiconductor devices needed in this solution is 4.

RC-IGCT solution: This semiconductor switch is able to conduct currents in both directions but blocks only in forward direction, and in order to provide reverse blocking capability two RC-IGCTs have to be connected in a common source configuration or back-to-back as shown in Fig. 1. Total semiconductor devices needed in this solution is 2.

In the A-IGCT and RC-IGCT solutions, there is always two devices which are in series in the main current conduction path which leads to high conduction losses compared to RB-IGCT solution even though the RB-IGCT is a thicker device than the A-IGCT or RC-IGCT.



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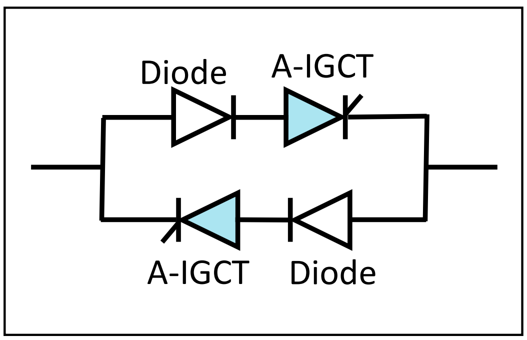

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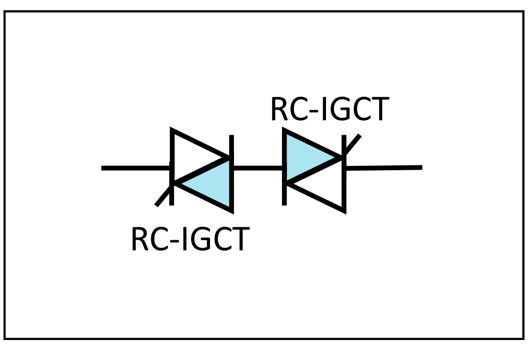
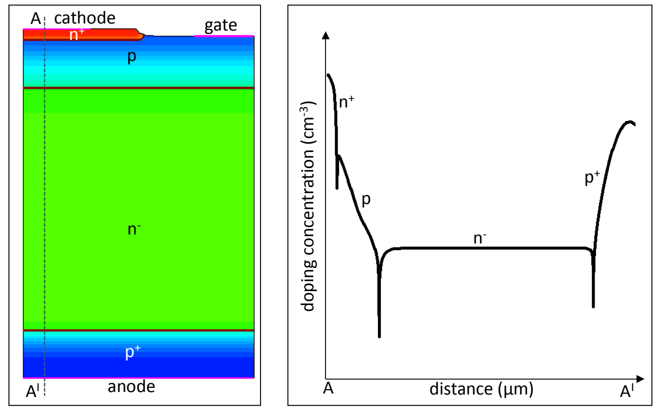


(c)

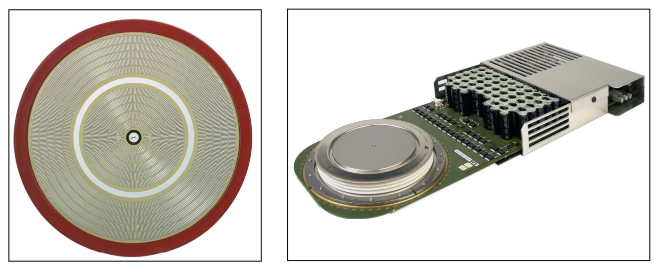
Fig. 1. The arrangement of the semiconductor devices for the bi-directional circuit breaker (a) RB-IGCT solution: two devices connected in anti-parallel, (b) A-IGCT solution: an additional diode is connected in series to the A-IGCT and this set is connected in anti-parallel, (c) RC-IGCT solution: two devices connected back-to-back.

II. Simulation and Experimental Results of the Semiconductor Device (2.5kV RB-IGCT)

As the switching losses are of least concern in the DC Circuit Breaker application, the 2.5kV RB-IGCT as shown in Fig. 2 is designed and optimized to keep the conduction losses as low as possible. We have optimized the device through anode engineering, device thickness and resistivity to achieve the required blocking capability of 2.5kV and to have very low conduction losses even at higher currents. In order to achieve very high turn-off current capability of the device, we have fabricated the 2.5kV RB-IGCT with the High Power Technology (HPT) process platform [9, 10].



(a) **(b)**



(c) **(d)**

Fig. 2. The 2.5kV RB-IGCT (a) The structure used in Sentaurus device simulations, (b) Doping distribution of the device along the cutline AA[1], (c) The fabricated 91mm, 2.5kV RB-IGCT wafer, (d) The RB-IGCT wafer in a hermetic package and with its integrated gate unit.

A. On-State and Blocking Characteristics

The on-state simulation and measurement results of 91mm, 2.5kV RB-IGCT at 400K are illustrated in Fig. 3. The simulation as well as measurement results show that the on-state voltage drop is as low as 0.9V @1kA and 400K, leading to system efficiency as high as 99.9% for 1MW SSCB (i.e. 1kV, 1kA).

Fig. 4 illustrates the forward and reverse blocking measurement results of the 91mm, 2.5kV RB-IGCT at 300K. The devices are fabricated with negative-negative bevel termination [11]. It can be seen from Fig. 4 that the device is able to block nearly the same voltage, i.e. about 3kV, both in forward and reverse direction. This is because the drift region

(n^--region) which supports the voltage is the same in both cases. In forward direction the pn^--junction on the cathode side is blocking (see Fig. 2), whereas in reverse direction it is the p^+n^--junction on the anode side.

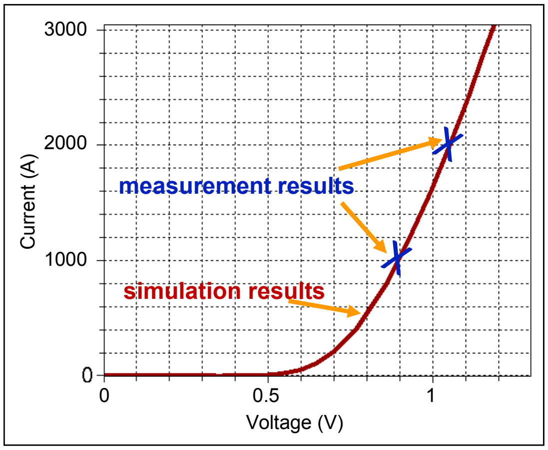


Fig. 3. Simulation and measurement results of the 91mm, 2.5kV RB-IGCT in the on-state.

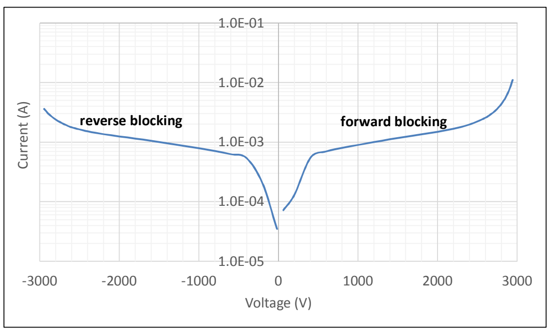


Fig. 4. Measurement results of the 91mm, 2.5kV RB-IGCT in forward and reverse blocking.

B. Turn-Off Characteristics

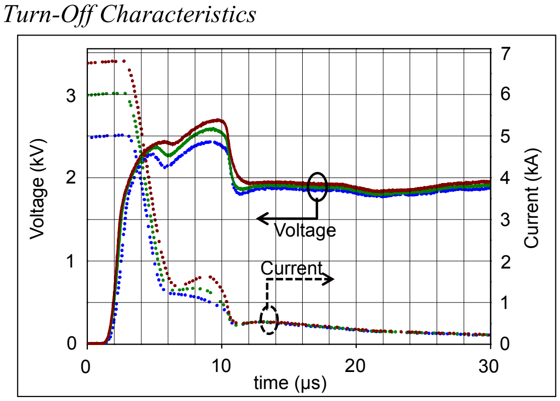


Fig. 5. Measurement results of the 91mm, 2.5kV RB-IGCT during turn-off. The device can successfully turn-off the currents up to 6.8kA at 1.6kV, 400K.

The turn-off measurement results of the 91mm, 2.5kV RB-IGCT at very high currents against 1.6kV and 400K are illustrated in Fig. 5. The measurement results show that the device can maintain high levels of hard switching turn-off current capability, despite of having very low conduction losses. The 91mm, 2.5kV RB-IGCT is able to turn-off successfully the currents as high as 6.8kA at 1.6kV and 400K.

III. Simulation and Experimental Results at the System Level

The Sentaurus mixed mode simulations have been performed at system level to evaluate the energy dissipation and over voltage conditions during the breaker interruption i.e. turn-off of the semiconductor switch under fault condition. The non-linear resistor characteristics of the surge arrester has been modelled with an avalanche diode in the device simulations [12]. The simulation and measurement results show that for given circuit parameters, the semiconductor switch experiences more stress during turn-off with high residual voltage surge arrester as the peak turn-off voltage of the semiconductor switch is higher with high residual voltage surge arrester [12].

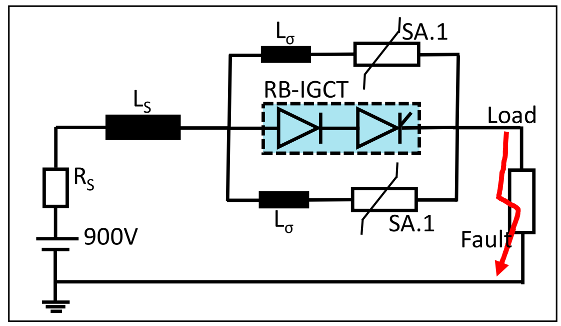


Fig. 6. The Switching circuit used in the Sentaurus mixed mode simulations for the case of two parallel surge arresters.

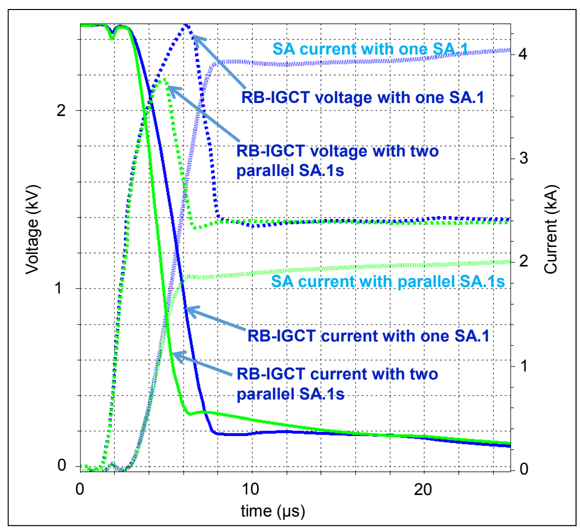
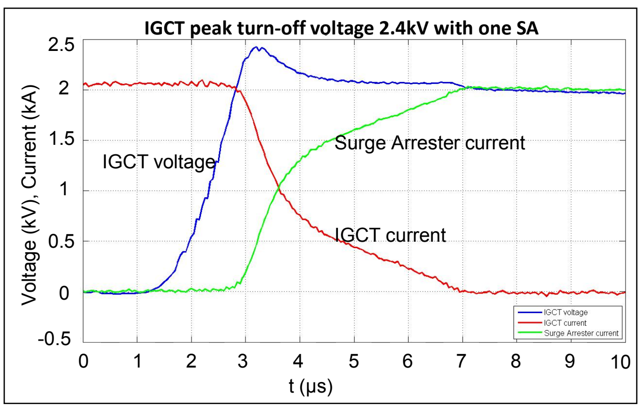


Fig. 7. Simulated turn-off waveforms of the 2.5kV RB-IGCT at 4.25kA, 400K in case of one surge arrester and two parallel surge arresters. Turn-off of the switch starts at time t=0.

The maximum turn-off peak voltage across the semiconductor switch can also be reduced by using two or more surge arresters in parallel to the semiconductor switch as shown in Fig. 6. The reason for the reduced turn-off peak voltage is the commutating di/dt slope which is low in case of two parallel surge arresters compared to the single surge arrester case. The simulation results show that (see Fig. 7) the maximum turn-off peak voltage across the switch is 2400V with one surge arrester whereas it is 2180V with the parallel combination of two surge arresters (the two surge arresters having same voltage and energy ratings). The authors of [13] proposed another possible solution to avoid high over-voltages across the semiconductor switch with two parallel surge arresters which are having different voltage and energy ratings (one small electronics surge arrester for over-voltage protection and another large power electronics surge arrester for energy absorption).

Fig. 8 illustrates the experimental turn-off waveforms of the 4.5kV A-IGCT with one surge arrester and two parallel surge arresters. The Sentaurus mixed mode simulations at the system level are qualitatively in good agreement with the experimental results as we have observed the same trend in the experiments such as the turn-off peak voltage across the semiconductor switch is minimized with two parallel surge arresters compared to single surge arrester. Therefore, the TCAD device simulations can be used to guess the right surge arrester for given circuit parameters in order to avoid much stress on the semiconductor switch.



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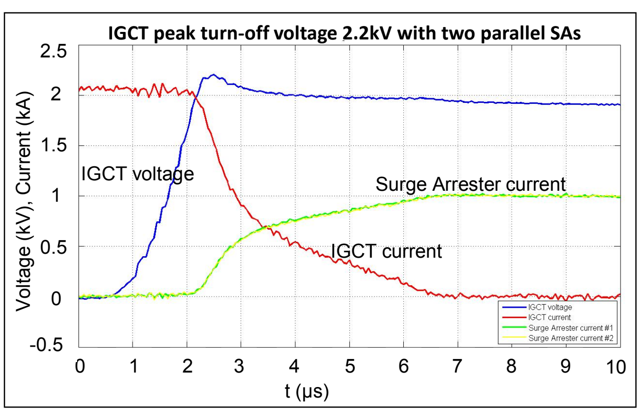


(b)

Fig. 8. Measured turn-off waveforms of the 4.5kV A-IGCT (a) Turn-off waveforms of the semicondcutor switch in case of one surge arrester, (b) Turn-off waveforms of the semiconductor switch in case of two parallel surge arresters.

IV. Analysis of the Thermal Management for the Solid State Circuit Breaker

Cooling of power semiconductors and electronic devices constitutes a continuous challenge for the heat transfer community. During the last decades we have experienced a continuous increase in power densities and a simultaneous reduction of the components size and weight pushing toward new limits in our field. In addition the power electronics community has, over time, pushed toward stricter requirements in terms of cooling approaches including reduced cost, reliability, servicing, safety, environmental compatibility. Thermal management remains one of the pillars for a safe and reliable operation of power electronics semiconductor devices.

In the present case an air cooled solution based on standard heat sink technology was chosen to enable a continuous operation of the semiconductor breaker system at optimum temperatures.

According to Fig. 9 the assembly of the cooling system is such that the two IGCTs are clamped between an upper and lower heat sink. Two IGCTs were mounted on the lower heat sink while the upper one is split in two parts: this design choice was taken to guarantee an optimal mechanical assembly and a uniform pressure distribution at the interface between power semiconductor and cooling unit. This approach enables more uniform contact thermal resistance between the semiconductor and the cooler and thus temperature uniformity.

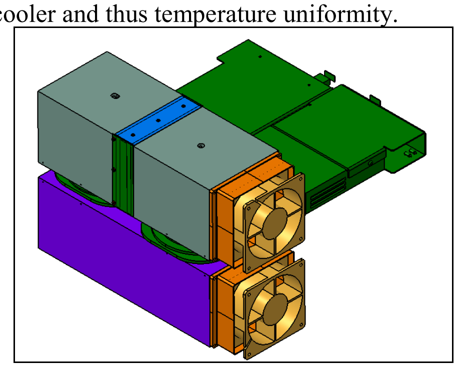


Fig. 9. Cooler assembly.

The air cooling system was optimized by means of a simulation carried out with Ansys Icepak 15 software. The simplified model is represented in Fig. 10.

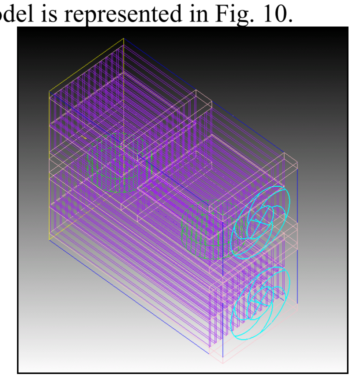


Fig. 10. Ansys Icepak model.

Several heat sinks with different geometric parameters were simulated for different flow rates covering a range between 0.02 and 0.12m^3/s. The heat sink was selected to guarantee a junction temperature of the device below 125°C for ambient temperatures of 40°C. The design was such that the pressure drop and the flow velocities were kept as small as possible to limit the acoustic noise and the fan size. The fan curve, the simulated circuit pressure drop and the operating point of the system is represented in Fig. 11, this corresponded to a flow rate of 0.072 m^3/s.

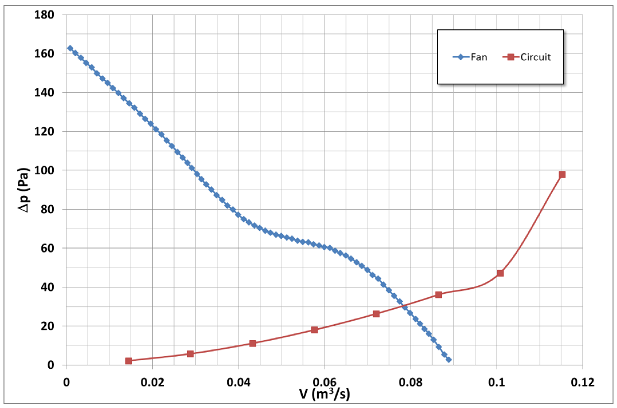


Fig. 11. Pressure drop and system operation point.

The target scenario accounted of total power losses of 1360W on a single IGCT device. A representation of the temperature contour lines on the cooling device for a flow rate of 0.058m^3/s is given in Fig. 12.

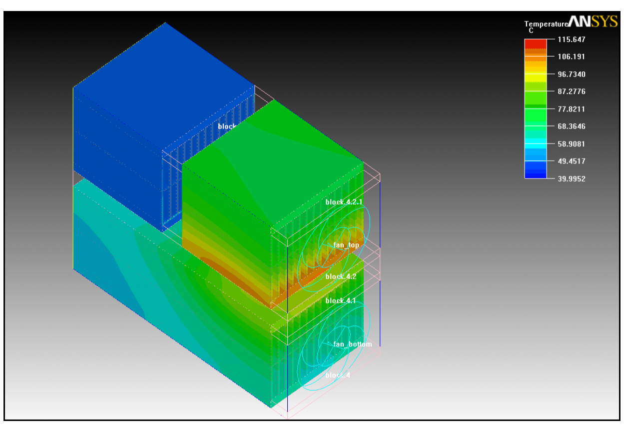


Fig. 12. Pressure drop and system operation point, 1360W and 0.072 m^3/s.

The maximum junction temperature as a function of the volumetric flow rate is represented in Fig. 13. At the operating points of the fan a maximum cooler temperature of 107.2°C was predicted while during the measurement campaign a value of 103.4°C was measured. The thermal model was found to be in good agreement with the experimental results. Standard air cooling solution is the most suitable approach in term of cost and performances for 1kA current. At higher current levels or where requirements in term of power densities are getting stringent, advanced air cooling solutions or water cooling schemes must be considered.

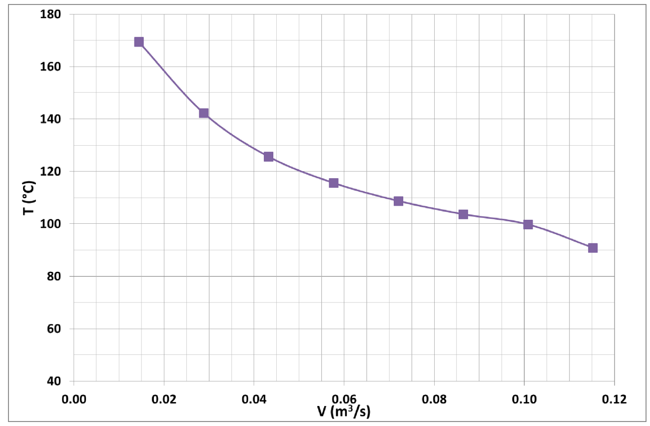
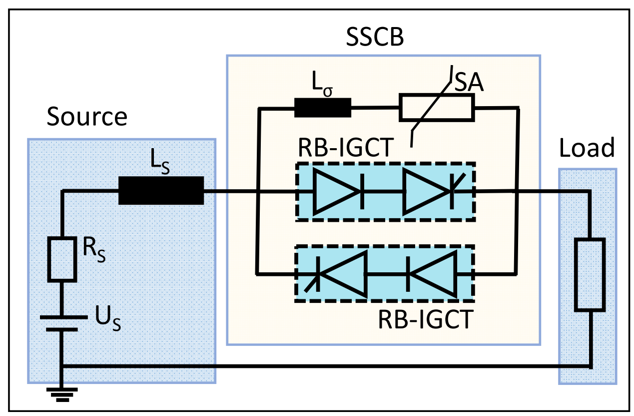


Fig. 13. Maximum junction temperature at 1360W.

V. SSCB PROTOTYPE BASED ON RB-IGCT

We have built successfully a prototype of air-cooled SSCB based on 2.5kV RB-IGCT as shown in Fig. 14 for low-voltage such as 1kV, 1kA bi-directional DC applications.



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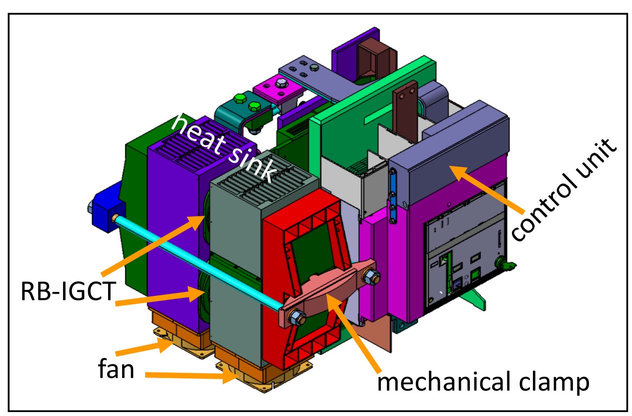

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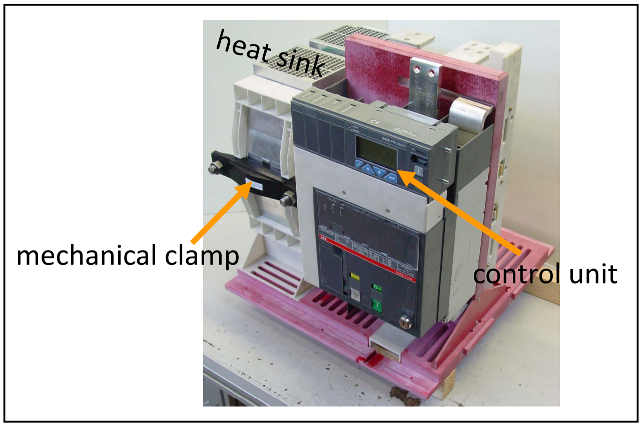

(c)

Fig. 14. Bi-directional DC SSCB prototype based on 91mm, 2.5kV RB-IGCT (a) Schematic switching circuit, (b) Schematic drawing of the prototype, (c) Prototype of the bi-directional SSCB.

VI. CONCLUSIONS

In this paper, we have presented the development of an air-cooled 1MW bi-directional DC SSCB (i.e. 1kA, 1kV) based on recently developed 91mm, 2.5kV RB-IGCT. The simulation and experimental results have shown that the power electronic switch i.e. 2.5kV RB-IGCT has very low on state voltage drop, as low as 0.9V @1kA, 400K and very high turn-off current capability, as high as 6.8kA against 1.6kV, 400K. We have observed by both simulation and experiments that for given circuit parameters, the turn off peak voltage across the semiconductor switch depends on the residual voltage of the surge arrester and can be minimized by using low residual voltage surge arrester and/or by using two or more surge arresters which are connected in parallel. We have also analyzed the thermal management for the newly developed SSCB using ANSYS Icepak and predicted maximum junction temperature of the device from the Icepak simulations is in good agreement with the experimental results.

ACKNOWLEDGMENT

Authors would like to thank Jesper Magnusson, Robert Saers and Lars Liljestrand from ABB Corporate Research in Sweden for providing the experimental results at the system level.

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