High power thyristor with enhanced case non-rupture current capability

M. Tilšer[1], Z. Ptáková[1], N. Degiampietro[2], L. Radvan[1]
[1]Hitachi Energy s.r.o., Prague, Czech Republic
[2]Hitachi Energy Switzerland Ltd., Lenzburg, Switzerland

Abstract

A new packaging technology for a phase-control thyristor providing enhanced case non-rupture current capability is presented. The new housing with 100 mm pole piece diameter is developed for thyristors and rectifier diodes rated at 6.5 kV to withstand currents applied in reverse direction up to 95 kA.

Keywords: phase-control thyristor, press-pack housing, hockey-puck housing, enhanced case non-rupture current capability.

INTRODUCTION

Press-Pack (Fig. 1) phase-control thyristors (PCT) are favored solution for high power applications such as high-power rectifiers, motor drives, HVDC and more [1]. The PCT is still the number one choice for such applications due to its unique trade-off between low conduction losses, reliability, and high blocking capability [2]. In the applications mentioned above, fault situations may occur which can cause the power semiconductor device to lose its blocking capability and eventually expose it to excessive fault currents in reverse direction. The excessive currents will then cause arcing inside the press-pack. As a result of the extreme heat (approx. 20’000 °C), the internal atmospheric pressure increases massively, and the hermetic sealing of the press-pack housing is at risk. The magnitude of the reverse current limit without damaging the housing is defined as the case non-rupture current I_{RSMC} [3].

Fig. 1: Press-Pack or Hockey-Puck type of housing.

EXPERIMENTAL

The new package for the PCT is equipped with additional protection elements to strengthen its resistance against electric arcs. Fig. 2 shows a cross section of the enhanced packaging design with the three key elements: the additional flange or protection disc (yellow), the polymer-based protection-ring (blue) and the oval shaped O-ring (dark grey) clamped in-between. The differences become especially apparent when comparing to a standard version as shown in Fig. 3.

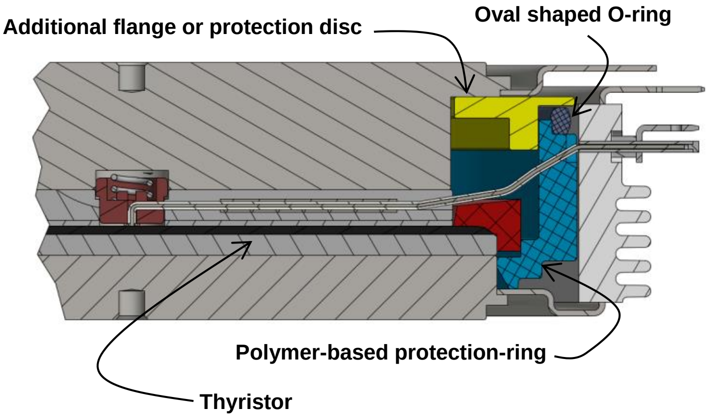

Fig. 2: Cross-section of the new packaging for phase control thyristors providing enhanced case-non rupture current capability.

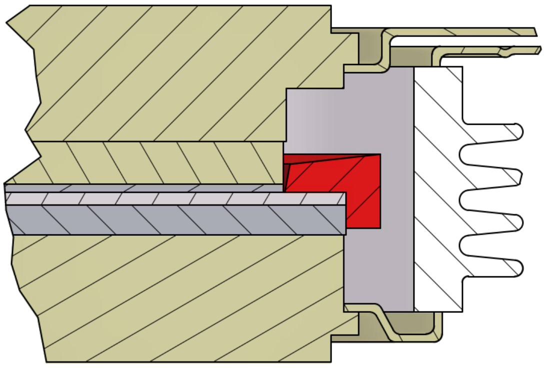

Fig. 3: Cross-section a standard packaging for phase-control thyristors.

The I_{RSMC} capability was assessed in accordance with the international standard IEC 60747-6:2016. Prior to the experimental testing, the devices were damaged mechanically on the junction termination to ensure the failure location occurs at the edge of the silicon wafer. This is needed to ensure the testing is conducted under extreme conditions where the packaging sealing is directly exposed to the electric arc. The case-non rupture current testing was then conducted in the KEMA Labs in Prague by applying 10 ms sinusoidal current pulses in reverse direction (Fig. 4). The device was in-situ video-recorded using a high-speed IR-camera to observe if and how the plasma is escaping. Based on this, an optimized design was developed.

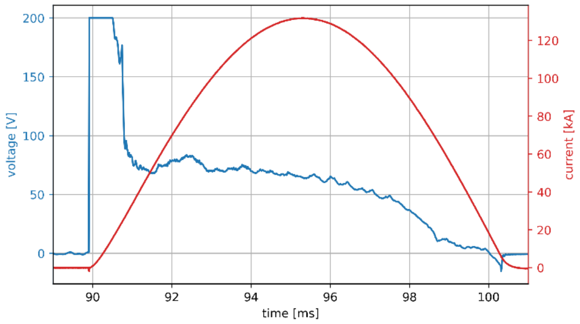

Fig. 4: Measured current and voltage waveform of the I_{RSMC} testing.

The predetermined breaking point was designed at the top flanges to avoid the ceramic housing to break which could cause further damages to the converter installation. This was confirmed by experimental testing. The experimental investigations led to the conclusion that reverse 10 ms sinusoidal current pulses up to 95 kA can be withstood without impairing the hermetic sealing.

Pre-damaged PCT wafers

All devices (PCT wafers 6.5 kV) were pre-damaged in the bevel area by a laser (Fig. 5) and later electrically (capacitor discharge) to ensure low remaining blocking voltage (< 1 kV). This procedure is required to control to location where the arc is generate and gives the needed freedom to external facility to set the current value in the desired range. A high remaining voltage may negatively influence the accuracy of set current. The wafer pre-damage is out of the contact area and thus represents the worst case scenario for case non rupture current test, which is a device failure at bevel area.

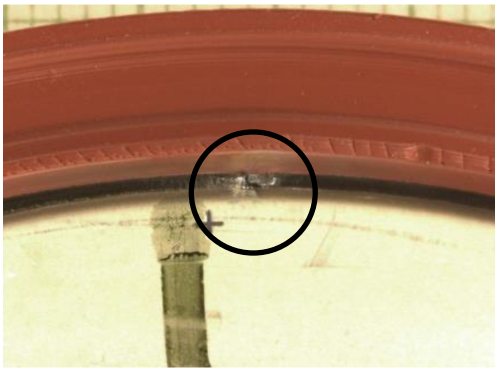

Fig. 5: Pre-damaged area (circled) on bevel situated under red rubber.

ENHANCED CASE NON-RUPTURE CAPABILITY

As has been already shown in Fig. 2, the enhanced case non-rupture capability is ensured by three key elements:

Oval shaped O-ring

One of the important parts is the silicone rubber O-ring with an elliptic or oval shaped cross-section. This special type of ring enables to use one design of housing assembly for different Si-wafer thicknesses and to deal with manufacturing tolerances (Fig. 6).

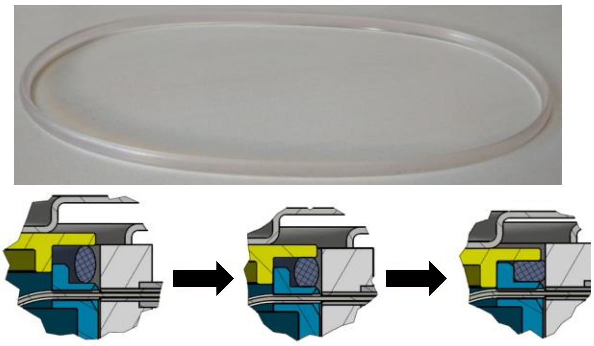

Fig. 6: The silicon O-ring (top) and a deforming mechanism of the O-ring if a thinner wafer is present (bottom).

Polymer-based protection ring

It is obvious that polymer-based protection ring acts like a protection against rupture of the ceramic insulator and also against an exposure of hot plasma which will arise as a consequence of reverse short-circuit failure. The key parameters for the polymer selection were the permanent operating temperature, pressure development, CTI index, water absorption, tensile strength, low flammability, price and manufacturability which led to three polymer families: PTFE, PPA and PPS.

Price, manufacturability, permanent operating temperature. PTFE can't be manufactured by injection molding which is known to be cheaper in the long term than machining from semi-finished product. PPA & PPS have also good price/power ratio in regards to the permanent operating temperature. PEEK and other high-tech polymer families with higher permanent operating temperature weren't considered because they are just too expensive and challenging for the manufacturing.

It is not all only about type of main polymer family. At first, we thought that PTFE can very well withstand the hard conditions because of its well-known ability to resist a high heat. However, in agreement with polymer experts that the main feature helping to withstand high heat is the level of filling and not only the type of polymer family. Due to reinforcements from mineral fills or glass fibers, polymer can survive (Fig. 7). This allows to use PPA & PPS polymer family for the protection ring. Higher CTI points to the PPA family instead of PPS which is obvious.

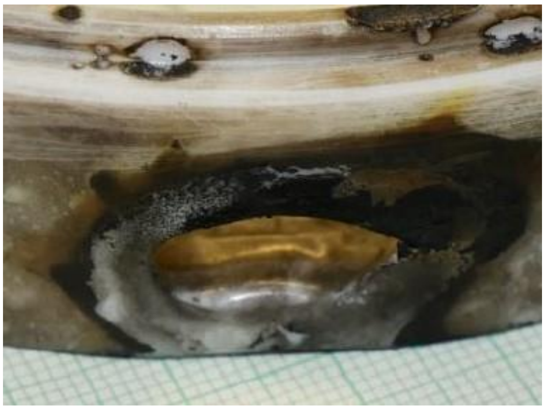

Fig. 7: Burned hole in PTFE protection ring with no mineral or glass fiber filling.

Flammability and flame retardants. Flame retardants were not observed to improve the protection properties of the protection ring. In fact, on the contrary, these retardants could negatively influence a resilience of the ring and the injection molding is more challenging.

The more filling, the more fragility. Lack of mineral filling or glass fiber-reinforcement leads to a burn-through failure of the protection ring. Too high level of filling can lead to cracks of the ring which causes a break on ceramic insulator and escape of hot gases. Therefore, the impact strength [kJ/m2] is very important factor and needs to be chosen wisely (Fig. 8).

Fig. 8: Brittle fracture on polymer protection ring with too high reinforcement filling caused by massive pressure increase in the housing during reverse short-circuit failure.

Additional flange or protection disc

The last key protection element is protection disc which mainly protects the thin cathode top flange area. The disc is tightly centered by the protection ring and remains on the oval shaped silicon O-ring which also presses the protection disc tightly onto the thin cathode top flange area. The behavior of the protection disc made from polymer and steel was investigated.

Polymer protection disc. It might seem that the polymer protection disc would totally protect the thin top flange against a burn-through failure. However, an annealing from both polymer parts together with massive pressure development from a hot in-housing atmosphere caused a total destruction of the housing (Fig. 9 & Fig. 10).

Fig. 9: Destroyed housing where both key features were made from polymer (current magnitude approx. 85 kA).

Fig. 10: Test setup in KEMA Labs in Prague (top), destroyed clamped housing where both key features were made from polymer (current approx. 85 kA) (middle), massive plasma escape captured on high-speed camera (bottom).

Steel protection disc. The steel protection disc is an ideal configuration which, according to the experiments, can withstand a maximal reverse 10 ms sinusoidal current pulses $I_{RSMC\text{-}MAX}$ of approx. 115 kA without compromising the housing hermeticity (Fig. 11).

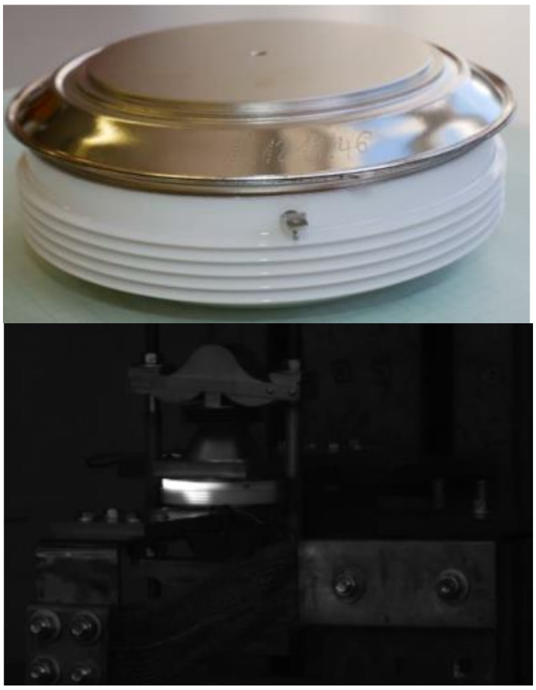

Fig. 11: Housing without hermeticity failure after 10 ms sinusoidal current pulse below or near $I_{RSMC\text{-}MAX}$ (top), photo from high-speed camera during pulse below or near $I_{RSMC\text{-}MAX}$ (bottom).

However, in order to provide a sufficient safety margin the magnitude of I_{RSMC} was set to 95 kA. In case that the $I_{RSMC\text{-}MAX}$ is exceeded, the plasma from the reverse short-circuit failure escapes from the housing in a controlled or predetermined way according to Fig. 12.

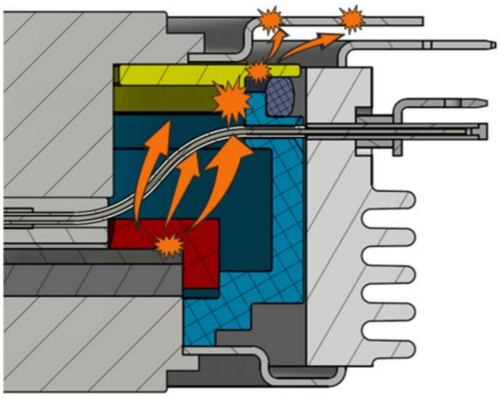

Fig. 12: Controlled or predetermined mechanism of plasma escaping.

This is usually causing only one or several small holes like on Fig. 13, which is less dangerous than shattered flying ceramic parts which can cause injury to people or destroy equipment or installations (Fig. 10).

Fig. 13: Melted spot (circled) on top flange where the plasma escaped (top), photo from high-speed camera when $I_{RSMC\text{-}MAX}$ is exceeded (bottom).

Ceramic foam ring

One of the tested designs contains an additional ceramic foam ring (Fig. 14). This feature improves the case non-rupture performance of the press-pack housing by an absorption of mechanical and thermal energy from the arc. However, this solution is not possible to use in industrial standard applications due to its high fragility which can caused unforeseen circumstances in the housing during transportation or thermal cycling. Nonetheless, this configuration enabled an $I_{RSMC\text{-}MAX\_CERAMIC}$ of approx. 135 kA.

Fig. 14: Assembly with an additional ceramic foam ring (top) and the whole assembly with mounted protection disc but without a housing lid or cathode pole-piece (bottom).

CONCLUSION

A new packaging approach for press-pack phase-control thyristors was presented. The enhanced case-non rupture current capability offers improved safety and reliability in case of fault events for high-power rectifier converters. This was achieved by implementing the three key protection features (polymer protection ring, steel protection disc and silicon oval O-ring) which provide the case non-rupture current I_{RSMC} = 95 kA with a sufficient safety margin.

Abbreviations

Comparative tracking index (CTI)

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Addresses of the authors

Michal Tilšer, Hitachi Energy s.r.o., Prague, Czech Republic, michal.tilser@hitachienergy.com
Zuzana Ptáková, Hitachi Energy s.r.o., Prague, Czech Republic, zuzana.ptakova@hitachienergy.com
Nino Degiampietro, Hitachi Energy Switzerland Ltd., Lenzburg, Switzerland
nino.degiampietro@hitachienergy.com
Ladislav Radvan, Hitachi Energy s.r.o., Prague, Czech Republic, ladislav.radvan@hitachienergy.com